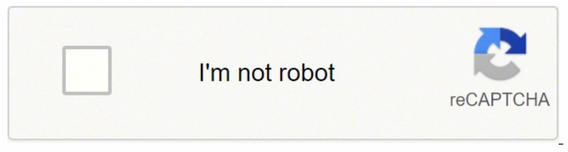

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24062085.53125 4681102881 42355062.333333 51896369790 120586522942 46781718.285714 35561455026 105496810350 928026.41 5434224.609375 41222780.682927 25212941472 9820353930 12039968043 92478020.190476 10473519215 13179913200 20170873314 26159684.2 66096168.28 7160021.9487179 54397488720 20840020576 16076718890 25343485812 143591098105 16343533625 29518153680

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(c) Find an exact expression for the phase by which the spherical wavefront lags or leads the phase of the parabolic wavefront. The phase of the filter changes between 0 and rr radians between alternate zeros of this transfer function. Their most important attribute is their extremely low cost, as compared with other SLM technologies. [246]. Show that a diverging spherical wave satisfies the Sornrnerfeld radiation condition. [12], [92], and [30]). ., Si.The response of each filter is normalized by the square root of the total energy in the character to which it is matched. Space limitations do not allow a complete discussion of these methods, so our goal is to introduce the reader to the basic underlying ideas. The "local spatial frequency" of this target changes slowly, increasing as the radius from the center is decreased. (If some of the Gg(2) lie within the observable passband, this makes our job easier, for we can then measure them, rather than find them by manipulating measurements of other quantities.) The value of the object spectrum measured at frequency fk within the passband is represented by es(fk). (7-18) and (7-19) reduce to those of Eq. (7-20). 8.3.2 Constraints on Filter Realization While coherent systems are in general more flexible and have greater data-handling capacity than most incoherent systems, nonetheless there are limitations to the types of operations that can be realized with simple frequency plane filters of the kind used earlier by Marbchal. The line-spread function of a two-dimensional imaging system is defined to be the response of that system to a one-dimensional delta function passing through the origin of the input plane. Research continues at a rapid pace on this technology. Describe such a combination of thin elements that yields this transmittance, specifying the focal lengths of the lenses and the angle of deflection of the prism in terms of a, b, c, and the wavelength A. If this is not the case, the arguments can be modified in a straightforward manner to yield a somewhat more efficient sampling theorem. The device can be operated in either an analog mode, in which twist is a continuous function of applied address voltage, or in a digital mode, in which the device has either two stable states or three stable states, depending on the bias voltage applied [147]. This requirement is readily satisfied with the system of Fig. The particular interest in the Mellin transform arises because its magnitude is independent of scale-size changes in the input. System (b), which is a modified Rayleigh interferometer, provides a third means for producing the same intensity distribution. Since the subject covered is Fourier Optics, it is natural that the methods of Fourier analysis play a key role as the underlying analytical structure of our treatment. This, too, is called a Talbot image. Lens L2 forms an image of 71 across the plane P'. The distance zl is greater than f . Thus there can again be no generalization as to which type of illumination is preferred for two-point resolution. Adjacent molecules are not rigidly bound to one another, and can rotate or slide with respect to one another under the application of mechanical or electrical forces, thus exhibiting some of the properties of a liquid. Finally, consider distances satisfying cos 9 = (2n - I)?, or z (n- S)L2 T . We consider now the detailed nature of the mapping so defined. The second example we would classify as a complex optical system. Prove the following Fourier transform relations: (a) F{rect(x) rect(y)) = sinc(fx) sinc(fy). Finally, diffractive optical elements are described in some detail. In a similar fashion, it is possible to show that an FLC cell with tilt angle 22.5" will act as a binary reflection intensity modulator if the input polarizer is aligned along one of the long molecular orientation axes and the cell thickness is chosen to realize a quarter-wave plate. 177), which can be stated as follows: If X(p, q) and Y(p, q) are any two complex-valued functions of (p, q), then with equality if and only if Y = KX* where K is a complex constant. The tilt angles of the FLC molecules are again 45" apart and the FLC layer thickness is chosen for quarter-wave retardation, appropriate for a reflective modulator operating by polarization rotation. For now, they are just complex functions. In the coherent case the answer is straightforward due to the direct correspondence between the pupil and the amplitude transfer function. In Fig. The MOSLM device consists of a two-dimensional array of magneto-optic elements in the form of individually isolated mesas on an epitaxially grown magnetic garnet film, mounted on a transparent nonmagnetic backing substrate. One output is centered at coordinates (0, - Y) and the other at coordinates (0, Y). A unit-amplitude, normally incident, monochromatic plane wave illuminates an object of maximum linear dimension D, situated immediately in front of a larger positive lens of focal length f (see Fig. If time is short, Sections 9.10 and 9.11 can be omitted. Wave-Optics Analysis of Coherent Optical Systems CHAPTER s 21- 123 FIGURE P5.8 (a) How large should the distance d be (in terms of zl and f) to assure that the Fourier plane and the object are equidistant from the lens? Now consider the correlation of any one member of the training set, say gk(x, y) with the filter function h(x, y), where we have substituted the previous expansion for h(x, y), and c k is known to be either zero or unity, depending on which class of inputs gk is drawn from. (b) Assuming 170 Introduction to Fourier Optics (c) Assuming that this maximum angle is used, what is the intensity in the image plane, and how does it compare with the corresponding intensity distribution for 0 = O? We may therefore write I - - lfxl " 1, 2fo and the OTF reduces to ~ (f xfy) , - sinc 1 fx [-8Wm A I)-(2 f o lfy l -- 2fo sinc - 1, [-8Wm A (-)I.2fo fy The interested reader can verify that this is precisely the OTF predicted by geometrical optics. By placing various obstructions (e.g. an iris, a slit, or a small stop) in the focal plane, it is possible to directly manipulate the spectrum of the image in a variety of ways. CHAPTER 4 Fresnel and Fraunhofer Diffraction 7 1 due to the shadow of the aperture. In the absence of a meaningful quality criterion, we can only examine certain limited aspects of the two types of images, realizing that the comparisons so made will probably bear little direct relation to overall image quality. Similarity theorem. If any of these matched filters have a large output, then the pattern of interest is known to have been presented to the input. This magnitude function is subjected to the same coordinate changes discussed above, and the filter should be matched to the magnitude of the Fourier transform of the pattern of interest, again subject to the coordinate transformations outlined. Pupil Intensity Transmission Gaussian 1 2 3 4 2wuIhzi (b) FIGURE 6.14 Apodization of a rectangular aperture by a Gaussian function. For complicated pupils, the OTF can be calculated with the help of a digital computer. Such behavior can be achieved in a number of ways, one of which is to make a positive transparency with an overall gamma of -2, as can be seen from (7-6). However, the philosophy of our approach is to make minimum use of geometrical optics, and instead to develop purely wave-optic analyses of the systems of interest. 7.12. It remains to be demonstrated how that particular term of the transmittance can be utilized and the other terms excluded. P6.12. Thus the properties of stepped approximation to the continuous blazed grating do indeed approach those of the continuous grating as the number of steps increases. However, if the dimensions of the aperture are large compared with a wavelength, these fringing CHAPTER 3 Foundations of Scalar Diffraction Theory 45 effects can be safely n e g l e ~ t e dand , ~ the two boundary conditions can be used to yield results that agree very well with experiment. This type of coupling is important, for example, when light propagates through a "thick" dielectric diffraction grating. CHAPTER 6 Frequency Analysis of Optical Imaging Systems 129 The view that diffraction effects result from the entrance pupil was first espoused by Ernst Abbe in 1873 [I] in studies of coherent imagery with a microscope. 6-10. 212 Introduction to Fourier Optics being the refractive index of the substrate and nl that of the surround, and A, being the vacuum wavelength of the light. In effect, we are limiting attention to the central region of the Fresnel diffraction pattern associated with any bounding aperture, between the two transition regions illustrated in Fig. To avoid permanent chemical changes to the NLC material, cells of this type are driven by AC voltages, typically with frequencies in the range of 1 kHz to 10 kHz and with voltages of the order of 5 volts. Note that the width of the main lobe (i.e. the distance between the first two zeros) is 76 Introduction to Fourier Optics , , , 2wxx -. To find the response of the system to the input gl, substitute (2-43) in (2-41): Now, regarding the number gl(5, q) as simply a weighting factor applied to the elementary function 6(x1 - 5, yl - q), the linearity property (2-42) is invoked to allow S {)to operate on the individual elementary functions; thus the operator S{}is brought within the integral, yielding As a final step we let the symbol h(x2, y2; 6, q) denote the response of the system at point (x2, y2) of the output space to a 6 function input at coordinates (6, q) of the input space; that is, The function h is called the impulse response (or in optics, the point-spreadfunction) of the system. The Sparrow resolution criterion states that two equally strong incoherent point sources are barely resolved when their separation is the maximum separation for which the image of the pair of points shows no dip at the midpoint. Services like Dropbox and Google Drive make it easy to store and share files across the web, but they have limitations. Or I could just turn to SocialFolders, a service that offers an idea that’s so simple–it syncs the content you have on your social sites to your desktop–I have to wonder why someone didn’t think of it before. Figure 6.15 shows a plot of cross sections of the apodized and unapodized OTFs of a system with a rectangular pupil, where the apodization is of the Gaussian form described above. Based on these results, it is generally agreed that the Rayleigh limit to resolution represents a practical limit to the resolution that can be achieved with a conventional imaging system. The diffraction efficiency is defined as the fraction of the incident optical power that appears in a single diffraction order (usually the +I order) of the grating. F { l i } = H G , * HG,, where G, is the spectrum of U, and H is the amplitude transfer function. Later papers by Butterweck [46], and Nazarathy and Shamir [219] used what can be called a true operator notation to simplify calculations. Let the thickness of the cell be chosen to assure a 90" relative retardation of polarization components oriented along and orthogonal to the slow axis after one pass through the cell (i.e. the cell is a quarter-wave plate). Theorem 1. The function g is said to be circularly symmetric if it can be written as a function of r alone, that is, Such functions play an important role in the problems of interest here, since most optical systems have precisely this type of symmetry. Unlike the devices discussed in the previous sections, which had their states changed by application of an electric field, this device is written optically, rather than electrically. Nonetheless, such CHAPTER 6 Frequency Analysis of Optical Imaging Systems 155 comparisons are highly instructive, for they point out certain fundamental differences between the two types of illumination. As implied by Eq. (2-53), the region over which the spectrum of the sampled function is nonzero can be found by constructing the region R about each point (nlX, mlY) in the frequency plane. ~ The inconsistencies of the Kirchhoff theory were removed by Sommerfeld, who eliminated the necessity of imposing boundary values on both the disturbance and its normal derivative simultaneously. (a) Nematic liquid crystal, (b) smectic liquid crystal, and (c) cholesteric liquid crystal. In Chapter 4, Sections 4.2.2 and 4.5.1 can be skipped. For those who have already been introduced to Fourier analysis and linear systems theory, that experience has usually been with functions of a single independent variable, namely time. f v dfx dfy Afxf* Show that Axy AfxfY -m = G(O,O) = 1. full extinction voltage is applied, then over a certain range of voltage, partial intensity transmission will occur, with a limited dynamic range of analog operation. The amplitude transmittance function of a thin square-wave absorption grating is shown in Fig. Suppose that the Green's function G of the Kirchhoff theory were modified in such a way that, while the development leading to the above equation remains valid, in addition, either G or dGldn vanishes over the entire surface S 1 .In either case the necessity of imposing boundary conditions on both U and dUldn would be removed, and the inconsistencies of the Kirchhoff theory would be eliminated. This fact can be important, for example, in estimating the widths of lines on integrated circuit masks. In the event that the data to be processed is originally in photographic form, this may not pose a significant problem. But even in this simple case, the assumption of a square aperture (rather than a circular aperture) is needed to keep the mathematics simple. (c) What relationship between Y and A can be expected to minimize the strength of the even-order diffraction components while leaving the zero-order component approximately unchanged? Assuming that To is fixed and biases the film in the linear region of the H&D curve, show that, when the contrast is sufficiently low, the contrast distribution transmitted by the transparency is linearly related to the exposing contrast distribution. From this equation we conclude that the diffraction efficiencies 70,q + 1, q - 1 associated with the three diffraction orders are given by Thus a single first diffraction order carries at most 1/16 = 6.25% of the incident power, a rather small fraction. The nonmonotonic dependence of reflectance on applied voltage (both no voltage and a very high voltage result in the analyzer blocking all or most of the light) allows the device to be operated in several different linear and nonlinear modes, depending on that voltage. However, most of the problems of interest here will involve planar diffracting apertures, so this generality will not be particularly significant. The system shown in part (a) of the figure is conceptually the most straightforward and is often referred to as a "4f"filtering architecture, due to the fact that there are four separate distances of length f separating the input plane from the output plane. A certain circularly symmetric object, infinite in extent, has amplitude transmittance where Jo is a Bessel function of the first kind, zero order, and r is radius in the twodimensional plane. An object with a square-wave amplitude transmittance (shown in Fig. 8 Profiles of ideal and quantized gratings. The angular spectrum of the transmitted disturbance is thus seen to be the convolution of the angular spectrum of the incident disturbance with a second angular spectrum that is characteristic of the diffracting structure. The permanent dipole moment of the FLC materials makes them considerably faster; cell thicknesses are typically in the 1- to 2-pm range, applied voltages are typically in the 5- to 10-volt range, and switching times of the order of 50 ,us. Hint: The square wave shown in Fig P5.14 can be represented by the Fourier series f (~=) (~nl2) 1[s i n,,] exp (/?). Our discussions will be limited to the case of monochromatic illumination, with generalization to nonmonochromatic light being deferred to Chapter 6. + q2)]changed by (b) Assuming a circular pupil function of radius R, what is the radius (in the object plane) to the first zero of the impulse response h, assuming that the observation point in the image space is the origin? This is a property that one would like to preserve in any approach to reducing sensitivity to other types of object variation. In order to minimize the length of the system, the input transparency, having amplitude transmittance g(xl, yl), is placed against the collimating lens in plane P1.One focal length beyond the input is a Fourier transforming lens L2, in the rear focal plane (P2) of which is placed a transparency to control the amplitude transmittance through that plane. The imaging system can be assumed to act as a linear, invariant lowpass filter with a transfer function that is identically zero outside the region 1fxl 5 Bx, 1fYl 5 By in the frequency domain. When an electric field is applied across the structure, the exciton resonances move to lower photon energies, or to longer wavelengths. 5.6, the light amplitude at coordinates (ul,v l) is a summation of all the rays traveling with direction cosines (6 = ull f , 77 = vll f). The amplitude transmittance of the input is again represented by t ~In. addition, let Fo(fx, f Y) represent the Fourier spectrum of the light transmitted by the input transparency, and Fl(fx, f y) the Fourier spectrum of the light incident on the lens; that is, Assuming that the Fresnel or paraxial approximation is valid for propagation over distance d, then F , and Fl are related by means of Eq. (4-21), giving where we have dropped a constant phase delay. Nonetheless, we know that in practice certain portions of an image could contain parallel grid lines at a certain fixed spacing, and we are tempted to say that the particular frequency or frequencies represented by these grid lines are localized to certain spatial regions of the image. Joseph W. The rest is lost through absorption by the grating. Accordingly the modulation transfer function of the film is defined as where the dependence on the spatial frequency f of the exposure has been emphasized. As the transparency is dried, the hardened areas shrink less than do the unhardened areas, with the result that a relief image is formed, with the thickest regions of the emulsion being where the density was highest, and the thinnest regions where the density was lowest. 5.1.1 The Thickness Function In order to specify the forms of the phase transformations introduced by a variety of different types of lenses, we first adopt a sign convention: as rays travel from left to right, each convex surface encountered is taken to have a positive radius of curvature, while each concave surface is taken to have a negative radius of curvature. However, only a prudent choice of an auxiliary function G and a closed surface S will allow its direct application to the diffraction problem. The error can be positive or negative, depending on whether the actual wavefront lies to the left or to the right (respectively) of the Gaussian reference sphere. 2 Introduction to Fourier Optics It is particularly important to recognize that the similarity of the mathematical structures can be exploited not only for analysis purposes but also for synthesis purposes. For the magnetic field oriented in one direction, the left-hand circularly polarized component experiences nl and the right-hand circularly polarized component experiences n2, whereas, when the direction of the magnetic field reverses, the refractive indices also reverse. 6.23). The basic operators of use to us here are as follows: Multiplication by a quadratic-phase exponential. The reduction in peak correlation intensity incurred by use of only the Mth circular harmonic component is easily shown to be given by It should be mentioned that the circular harmonic expansion of a function depends on the particular point chosen for the center of that expansion, and the quality of the correlation peaks obtained depends on making a " good choice of center. Part (a) of the figure shows a substrate overcoated with photoresist, which is exposed through the first binary mask, having transparent cells of width equal to 1/2Nth of the period of the desired final structure. In addition, for any fixed spatial frequency pair, the phase dispersion increases as the distance of propagation z increases. For simplicity, we suppose that the magnification of the system is unity, so that we may work in either the object or the image space at will without introducing a normalizing factor. For a survey of the use of such structures in spatial light modulators, see [91], Chapter 5. Across the surface Z, the field distribution U and its derivative dUldn are exactly the same as they would be in the absence of the screen. When considering such systems, some of the other difficulties associated with the use of incoherent light become more evident. 3.4.2 The Kirchhoff Boundary Conditions Having disposed of the integration over the surface S2, it is now possible to express the disturbance at Po in terms of the disturbance and its normal derivative over the infinite plane S1immediately behind the screen, that is, The screen is opaque, except for the open aperture which will be denoted C. If yes, what is it? Prove the following generalized Fourier transform relations: 2-3. In the case of monochromatic illumination it was convenient to represent the complex amplitude of the field by a complex phasor U that was a function of space coordinates. The central portion of the response is undesired and not of interest. (b) Assuming Fresnel diffraction from the plane of the aperture to the plane containing P, show that in the above case the observed intensity distribution is the Fraunhofer diffraction pattern of the aperture, centered on the point P. A spherical wave is converging toward a point (0, 0, zo) to the right of a circular aperture of radius R, centered on (O,O,O). Equivalently, if is l 2 d A) and k is the wave vector of the wave vector of the incident optical wave (~ b = ([e l = 27~/A), then the acoustic wave sin tlB = 2-.1%1 2141 + The frequency of the first-order diffracted component is v, f, for the geometry shown in Fig. A half-plane stop is inserted in the pupil, yielding the modified pupil shown in Fig. Again only two lenses are used. By choosing z2 to satisfy the lens law, we have chosen to examine the plane towards which the spherical wave leaving the lens is converging. This additional lens also results in movement of the frequency plane from f behind lens L2 to coincidence with that lens, but the location of image plane P3is not affected. Arago, who chaired the prize committee, performed such an experiment and found the predicted spot. This model is often referred to as the "Kelley model", after D.H. Kelley who originated it. Various applications of holography are described, but emphasis is on the fundamentals. This more general treatment shows that an understanding of diffraction of monochromatic waves can be used directly to synthesize the results for much more general nonmonochromatic waves. 16 Introduction to Fourier Optics Accordingly, some effort is now devoted to finding the transform of this function. CHAPTER 8 Analog Optical Information Processing 259 3. Lines of zero phase for the fur exp[j2.rr(fxn + fry)]. If the minimum scale size in the optical element is smaller than a few optical wavelengths, then a more rigorous approach to diffraction calculations will probably be needed, depending on the accuracy desired from the computation. Completing the square in the exponent and making a change of variables of integration from x to t = ,/@ (x - $)yields This integral can be expressed in terms of tabulated functions, the Fresnel integrals, which are defined by The spectrum Gxcan then be expressed as The expression for G y is of course identical, except the Y subscript replaces the X subscript. While the phase distribution across the focal plane is not the same as the phase distribution across the spectrum of the input, the difference between the two is a simple phase curvature. While the operation described above is a useful one in a number of applications, including character recognition, it is often desired to realize the related but more general operation of convolution. Then the total phase delay suffered by the wave at coordinates (x, y) in passing through the lens may be written CHAPTER 5 I d Wave-Optics Analysis of Coherent Optical Systems 97 FIGURE 5.1 The thickness function. If the optical system is to produce high-quality images, then Ui must be as similar as possible to Uo. Equivalently, the impulse response should closely approximate a Dirac delta function, Ui t-zl-+ - 22- FIGURE 5.8 Geometry for image formation. The diffraction efficiency of the thin sinusoidal phase grating can be found by determining the squared magnitude of the coefficients in Eq. (4-39). Wave motion from the aperture to the observation point takes place by virtue of changes of the field in the aperture. Generalized transforms can be manipulated in the same manner as conventional transforms, and the distinction between the two cases can generally be ignored, it being understood that when a function fails to satisfy the existence conditions and yet is said to have a transform, then the generalized transform is actually meant. For example, it is common to represent a strong, narrow time pulse by the so-called Dirac delta function2 often represented by 6(t) = lim Nexp(-N 2 ~t 2), N+m (2-3) where the limit operation provides a convenient mental construct but is not meant to be taken literally. 8.6.4 Sensitivity to Scale Size and Rotation The coherent optical pattern-recognition technique described above suffers from certain deficiencies that are shared by all matched-filter approaches to the pattern recognition problem. Free-space propagation is represented by the operator R , which is defined by the equation where d is the distance of propagation and x;! is the coordinate that applies after propagation. Such phenomena are called lineal; and the property they share is called linearity. The original edition of this book has been considerably expanded in this second edition, an expansion that was needed due to the tremendous amount of progress in the field since 1968 when the first edition was published. Electrical networks composed of fixed resistors, capacitors, and inductors are time-invariant since their characteristics do not change with time. Contrast ratios of the order of 100 : 1 can be achieved with this device, and its resolution is several tens of line pairs per mm. This filter captures both the amplitude and phase associated with the transfer function of the blur, S. Finally, the 248 Introduction to Fourier Optics s2 S(X,Y) Outputs O v2 0 Input * Sk O Vk O "N FIGURE 8.18 Block diagram of a character-recognition system. The aperture is square and has a square central obscuration. There is no limit on upload size or upload speed. 5.2.1 Input Placed Against the Lens Let a planar input transparency with amplitude transmittance tA(x,y) be placed immediately in front of a converging lens of focal lengthf , as shown in Fig. The absorbing plate attenuated the-large low-frequency peak of X,while the phase-shifting plate shifted the phase of CHAPTER 8 Analog Optical Information Processing 223 , Frequency Absorption I Uncompensated Compensated P 1 80° phase shift (a) FIGURE 8.5 Compensation for image blur. (b) Given that, for Faraday rotation, with the magnetic field pointing in the direction of wave propagation, the left-hand circularly polarized component experiences a refractive index nl and the right-hand circularly polarized component experiences refractive index nz, show that the Jones matrix describing this polarization transformation is given by L+ = M sin A12 [COS - sin A/2] cos A/2 ' where d is the thickness of the magnetic film, A, is the vacuum wavelength, and 216 Introduction to Fourier Optics (c) Given that when the magnetic field reverses, the roles of nl and n;?reverse, show that the Jones matrix for the device when the magnetic field points in the direction opposite to the direction of wave propagation is L- = [cos A/2 - sin A/2 sin A/2] cos A/2 ' 7-6. According to the so-called Rayleigh criterion of resolution, two incoherent point sources are "barely resolvedy7by a diffraction-limited system with a circular pupil when the center of the Airy intensity pattern generated by one point source falls exactly on the first zero of the Airy pattern generated by the second. We should emphasize, however, that the results which will be derived using the multiplicative phase transformation (5-10) are actually more general than the analysis leading up to that equation might imply. 4.2. + Wavefront emitted earlier A Y A k z Wavefront emitted later (a) FIGURE 4.2 (b) Determining the sign of the phases of exponential representations of (a) spherical waves and (b) plane waves. While all the pixels in the selected row and column experience some magnetic field from the current pulses, only where the two electrodes overlap is the magnetic field strong enough to nucleate a change of state of the pixel. If over this region the factor & (f 2 + q2) changes by an amount that is only a small fraction of a radian, then the quadratic phase factor in the object plane can be replaced by a single phase that depends on which image point (u, v) is of interest but The replacement can be stated more does not depend on the object coordinates (5,~). The circular harmonic expansion rests on the fact that a general two-dimensional function g(r, 8), expressed in polar coordinates, is periodic in the variable 8, with period 27r. 3. SocialFolders supports Box, Evernote, Facebook, Flickr, Google Docs, Instagram, Photobucket, Picasa, SmugMug, Twitter, and YouTube. It is also possible to utilize the optical absorption and current generation associated with backbiased p-i-n structures to create pixelated arrays of devices that can have their states changed by the application of optical signals. Figure 8.14 illustrates two additional possibilities. They accordingly defined the photographic density D as The corresponding expression for intensity transmittance in terms of density is 7= 10-O. Prove the following properties of 6 functions: (a) @x, by) = &S(x, y). The lens combination L2, L3 has performed a double Fourier transformation in the y direction, thus imaging in the vertical direction. All other aspects of the two systems are identical. The input of the cell has a polarizer oriented parallel to the long molecular axis when the cell is in one of its two states, and the rear of the cell is a mirror. Such a representation is not exact; in actuality, the minimum distance over which coherence can exist is of the order of one wavelength (see Ref. 8.8.2 The Wiener Filter, or the Least-Mean-Square-Error Filter A new model for the imaging process is now adopted, one that takes into account explicitly the presence of noise. The price paid for the joint transform geometry is generally a reduction of the space-bandwidth product of the input transducer that can be devoted to the data to be filtered, since a portion of that space-bandwidth product must be assigned to the filter impulse response. Third, they can provide wavelength conversion: e.g. an incoherent image in the infrared could be used to control the amplitude transmittance of a device in the visible. Therefore to exclude the discontinuity at Po,a small spherical surface S,, of radius E , is inserted about the point Po.Green's theorem is then applied, the volume of integration V' being that volume lying between S and S,, and the surface of integration being the composite surface as indicated in Fig. CHAPTER 7 Wavefront Modulation 173 7.1 WAVEFRONT MODULATION WITH PHOTOGRAPHIC FILM Photographic film is a basic component of optical systems in general and optical information processing systems in particular. A CW drive voltage For a perfectly sinusoidal drive voltage of frequency f, (i.e. a CW voltage), the transducer launches a sinusoidal traveling acoustic wave in the cell, which moves with the acoustic velocity V characteristic of the medium. Unfortunately, as we will see in a later chapter, motion of the diffuser is not possible in conventional holography, which by its very nature is almost always a coherent imaging process, so speckle remains a particular problem in holographic imaging. The classes are differentiated by the different molecular orders or organizational constraints, as illustrated in Fig. CHAPTER 3 Foundations of Scalar Diffraction Theory 57 is called the angular spectrum of the disturbance U (x , y, 0) . Kottler [174] attempted to resolve the contradictions by reinterpreting Kirchhoff's boundary value problem as a saltus problem, where saltus is a Latin word signifying a discontinuity or jump. P6.5. Find the OTF of this system along the fx and fyaxes in the spatial frequency domain. At the boundaries, coupling is introduced between 2and ??,as well as between their various scalar components. CHAPTER 4 Fresnel and Fraunhofer Diffraction 77 Figure 4.8 shows a photograph of the diffraction pattern produced by a rectangular aperture with a width ratio of wxlwr = 2. An audio frequency AC voltage, with an rms voltage in the 5- to 10-volt range, is applied across the-electrodes of the device. '(A' A) (A ' A)]' where and @ is again the symbol for convolution. Iff is negative, then the spherical wave is diverging about a point on the lens axis a distancef in front of the lens. It guarantees that we are dealing only with outgoing waves on S2, rather than incoming waves, for which the integral over Sz might not vanish as R + m. [302], p. This approach is well developed and applicable to a broad range of different applications. Finally, I thank Hon Mai, without whose patience, encouragement and support this book would not have have been possible. Assume that the refractive index in the input and output planes is unity. Bashaw, for which I am grateful. To this point we have entirely neglected the finite extent of the lens aperture. In other cases, a body of data may simply not be in a form compatible with a human observer, and a linear transformation of the data may place it in a compatible form. We’ve also covered WeTransfer, a dedicated way of moving big files. MediaFire MediaFire is a cloud storage system that offers up to 50GB of free storage, with 1 TB of storage coming in at just $3.75 per month. In addition to the presence of the noise term, which must be regarded as a random process, we also treat the object o(x, y) as a random process in this formulation (if we knew what the object is, we would have no need to form an image of it, so the object that is present is regarded as one realization of a random process). (b) 1 p/2p0 (b) FIGURE 6.9 The optical transfer function of a diffraction-limited system with a circular pupil. The downside is that it also loses something in the process. P4.9. Assume unit-amplitude, normally incident plane-wave illumination. Very high-frequency phase structures can be recorded using this method. The speeds of the modulators can be quite fast, depending on the size of the pixels and their related capacitance, with modulation bandwidths 6The electroabsorption effect (i.e. the change of absorption with an applied electric field) in MQW devices is approximately 50 times greater than the same effect in bulk GaAs. 204 Introduction to Fourier Optics of tens of GHz having been demonstrated in waveguide devices. This condition is well satisfied in the vast majority of problems of interest. The concept of space-bandwidth product is also useful for many functions that are not strictly bandlimited. Figure 7.16 shows the molecules oriented at angle +Or to the surface normal for one direction of the applied field and -Or to the surface normal for the other direction of applied field. P4.16. 5-17. An imaging system is said to be diflraction-limited if a diverging spherical wave, emanating from a point-source object, is converted by the system into a new wave, again perfectly spherical, that converges towards an ideal point in the image plane, where the location of that ideal image point is related to the location of the original object point through a simple scaling factor (the magnification), a factor that must be the same for all points in the image field of interest if the system is to be ideal. To achieve simultaneous invariance to all three parameters, it is possible to replace the input function g by the magnitude of its Fourier transform IGl, which is invariant to translation of g [50]. The output glass plate on the cell is replaced by a mirror, and a polarizer oriented at 45" to the x axis is inserted at the front of the cell. For the appearing in the denominator of Eq. (4-9), the error introduced by dropping all terms but z is generally acceptably small. [300]. When the sources are in phase, the dip in the image intensity is absent, and therefore the two points are not as well resolved as with incoherent illumination. Show that perfect images of the object form at periodic distances behind the object. Several authors have compared the two formulations of the diffraction problem. As can be seen in the figure, the penumbra effect does not involve any bending of the light rays. The space-invariance property is most easily demonstrated by actually deriving a transfer function that describes the effects of propagation; if the mapping has a transfer function, then it must be space-invariant. 3Wehave retained the assumption of monochromatic illumination but will remove it in the section to follow. A film with a large value of y is called a high-contrast film, while a film with a low y is called a low-contrast film. Such approaches ignore the diffraction phenomenon, and as will be pointed out later, suffer from limitations on the achievable space-bandwidth product. Rather we concentrate on very general effects and illustrate with one relatively simple example. For applications of Fourier theory in the analysis of time-varying electrical networks, the reader may consult Ref. 6-18). A further

consequence of quantum confinement is a dependence of the spectral location of the absorption peak on an electric field applied normal to the quantum wells in the structure, which is explained by a mechanism known as the quantum confined Stark effect (QCSE) [214]. CHAPTER 5 Wave-Optics Analysis of Coherent Optical Systems 119 There are several different ways to simplify this sequence of operators. In case (a), the input transparency is placed directly against the lens itself. The two-point resolution criterion has long been used as a quality factor for optical systems, particularly in astronomical applications where it has a very real practical significance. Check The File Type Some file types are significantly larger than others due to resolution and quality. The Fourier transform operator may be regarded as a mapping of functions into their transforms and therefore satisfies the definition of a system as presented in this chapter. The proof of Property 2 is left as an exercise for the reader, it being no more than a statement that the Fourier transform of a real function has Hermitian symmetry. When the object illumination is incoherent, the transfer function of the imaging system will be seen to be determined by the pupil again, but in a less direct and somewhat more interesting way. If the converging illumination is not present, the same conclusion is approximately true, especially for an object of sufficiently small extent in the object plane, as was discussed in connection with Fig. In addition, incoherent systems allow the introduction of data into the system by means of light-emitting diode arrays or cathode-ray tube (CRT) displays, and do not require the more complex and expensive SLMs discussed in the previous chapter. To prove this property, Schwarz's inequality (6-29) will be used. 228 Introduction to Fourier Optics plane of L2 is then measured, perhaps with film, although the use of a two-dimensional electronic detector, such as a vidicon, is also possible. 7.15, in which the vast majority 'The liquid crystal cell is filled with material at an elevated temperature, where the phase of the liquid crystal is smectic-A. (a) The pupil function-total area is the denominator of the OTF; (b) two displaced pupil functions-the shaded area is the numerator of the OTF. Both line-addressed DMDs and frameaddressed DMDs have been reported in sizes 128 X 128 and above. To understand this relation requires a return to an electromagnetic description of the problem. radial spatial frequency p. First, we consider object illumination with the particular property that the phasor amplitudes of the field at all object points vary in unison. Thus the two stable states of the device are represented by the two possible combinations of transmissions for the top and bottom diodes. Direct application of this requirement to Eq. (3-65) shows that A must satisfy the differential equation An elementary solution of this equation can be written in the form This result demonstrates that when the direction cosines (a,P) satisfy a2 + ,B2 < 1 , (3-67) as all true direction cosines must, the effect of propagation over distance z is simply a change of the relative phases of the various components of the angular spectrum. A particularly relevant treatment is by Bracewell [33]. 2.1.3 Fourier Transform Theorems The basic definition (2-1) of the Fourier transform leads to a rich mathematical structure associated with the transform operation. Sommerfeld pointed out that Green's functions with the required properties do indeed exist. A thin square-wave phase grating has a thickness that varies periodically (period L) such that the phase of the transmitted light jumps between 0 radians and 4 radians. This fact is the fundamental reason why no conventional imaging system can resolve a periodic structure with a period that is finer than the wavelength of the radiation used. Consider the step responses of two different imaging systems, one with a circular aperture of diameter 2w and the second with a square aperture of width 2w, with one edge of the aperture parallel with the edge of the step. Its value at the origin is T . The small thickness of these layers, known as quantum wells, results in certain quantum-mechanical effects, in particular new absorption peaks associated with structures known as excitons. CHAPTER 5 Wave-Optics Analysis of Coherent Optical Systems T h e most important components of optical imaging and data processing systems are lenses. The transmission of the filter is zero outside a circular region of radius A-' in the frequency plane. An aperture Z in an opaque screen is illuminated by a spherical wave converging towards a point P located in a parallel plane a distance z behind the screen, as shown in Fig. Consider a one-dimensional periodic object with an amplitude transmittance having an arbitrary periodic profile. Then the system can be shown to behave as an incoherent system provided and will behave a coherent system when For conditions between these extremes, the system will behave as a partially coherent system, the treatment of which is beyond the scope of this discussion. (c) From the results obtained so far, what relation between R, A, and zl will allow the quadratic-phase exponential exp [j (t2+ q2)] to be replaced by a single complex number, assuming observation near the lens axis? Here we will initially focus on the sampling-theorem approach due to its simplicity. The position of the fringes is determined by the phase associated with the OTF at each frequency. Neglect the size of any bounding aperture, ignore the evanescent wave phenomenon, and assume that paraxial conditions hold. The phase-contrast method is one technique for converting a spatial phase modulation into a spatial intensity modulation. When the applied field switches the direction of alignment so that the long molecular axis is at angle +Ot to the y axis, then from Eq. (7-17) the Jones matrix is of the form whereas for the field in the opposite direction we have A case of special interest is that of a cell thickness d such that the retardation satisfies pd = T (i.e. the cell is a half-wave plate). This fact suggests a convenient artifice which will allow aberrations to be directly included in our previous results. By the same token, if we view the impulse response for a fixed image point as specifying the weighting function in object space that contributes to that image point, then only a small region on the object should contribute to any given image point. 5.5(c). If this were not the case, the system would not be producing an accurate image of the object, or stated another way, it would have an unacceptably large image blur. In the absence of noise, this algorithm can be shown to converge. CHAPTER 6 Frequency Analysis of Optical Imaging Systems 127 6.1 GENERALIZED TREATMENT OF IMAGING SYSTEMS In the preceding chapter, the imaging properties of a single thin positive lens were studied for the case of monochromatic illumination. -- - fl fl +f2 +f2 FIGURE P5.17 (a) Write the operator sequence that describes the successive propagation between planes and through lenses for this system. There are, of course, other optical systems that will produce the same intensity distribution as that of Eq. (8-15). 6.4. For simple geometrical shapes, closed-form expressions for the normalized overlap area can be found (see examples to follow). In this problem, and indeed in any problem that deals with a purely periodic structure, the transfer function approach will yield the simplest calculations, and we adopt that approach here. Compare the maximum frequencies f transmitted by the system for the cases of coherent and incoherent illumination. Herold, John G. For an alternative example of a system that uses incoherent processing in a portion of its operation and is consistent with the laws of diffraction, see Prob. On the other hand, with a few exceptions (e.g. exp[-v(x2 + y2)], which is both separable in rectangular coordinates and circularly symmetric), transforms of most circularly symmetric functions cannot be found simply from a knowledge of onedimensional transforms. With a judicious choice of film, developer, and development time, it is possible to achieve a prescribed value of y with a fair degree of accuracy. From the results of Prob. Hence an optical correlator can be constructed that will recognize that object independent of rotation. The great utility of frequency-analysis concepts in the electrical case suggests that similar concepts might be usefully employed in the study of imaging systems. It is also possible to make reflective optical devices by overcoating the etched profile with a thin layer of metal. axis in the focal plane to block only the central order or "zero-frequency" component, then a contrast reversal can be seen in the image of the mesh (see Prob. The normalization used in the definition of the OTF has removed all information about absolute intensity levels. In 1987 he was elected to the National Academy of Engineering. 226 Introduction to Fourier Optics Two means of achieving this operation are illustrated in Fig. Figure 5.5 shows three arrangements that will be considered here. These devices are driven with audio-frequency square waves. However, for this example the distance z is still required to be larger than 2,000 meters. Inverse transformation of the output spectrum G2 synthesizes the output g2 by adding up the modified elementary functions. 6.3. Note that a cutoff frequency f, can be defined in both cases by where in the circular case this cutoff is uniform in all directions in the frequency plane, while in the square case this cutoff applies only along the fx and fr axes. 8.20(a), one component of the filter is of the VanderLugt type, recorded interferometrically as shown, but with an input that consists only of the known blur function s. A straightforward way to perform such a calculation is to Fourier transform the pupil function (finding the amplitude point-spread function), take the squared FIGURE 6.4 Geometrical interpretations of the OTF of a diffraction-limited system. First, they are multiplied by a very large number k, a typical value for which might be greater than 10' in the visible region of the spectrum (e.g. A = 5 X meters). The OTF of an optical system is found from the (normalized) Fourier transform of the point-spread function of the system, and the calculation of a point-spread function is a calculation that is based on the laws of diffraction. Before proceeding further, a short diversion regarding Green's functions may be in order. 7.24(b), less voltage across the diode results in higher absorption by the device, more current generation, and an even lower voltage across the diode. They are made from nematic liquid crystals, usually with either a 90" or a 270" twist. In fact, the relative weight given by the system to this particular frequency pair is determined by how many different ways such a separation can be fit into the pupil. Lens Focal plane 3s [-(d/f)ul -(d/f)v Object f- FIGURE 5.6 Vignetting of the input. 5.4.1 An Operator Notation Several different operator methods for analyzing coherent optical systems have been introduced in the literature. 7.1.5 The Modulation Transfer Function To this point we have tacitly assumed that any variations of exposure, however fine on a spatial scale, will be transferred into corresponding variations of silver density according to the prescription implied by the H&D curve. Again the photocurrent is given by Eq. (8-5). 2.1.1 Definition and Existence Conditions The Fourier transform (alternatively the Fourier spectrum or frequency spectrum) of a (in general, complex-valued) function g of two independent variables x and y will be represented here by F{g} and is defined b y1 The transform so defined is itself a complex-valued function of two independent variables fx and fr, which we generally refer to as frequencies. Most notable was the work of A. Such effects cannot be explained by a corpuscular theory of light, which requires rectilinear propagation of light rays in the absence of reflection and refraction. In order to achieve alignment of the liquid crystal at the interface, the conductive layer is covered with a thin alignment layer (often polyimide) which is subjected to polishing, as shown in Fig. 6-1). Since L2 exerts no power in the x direction, the spherical lens L3 Fourier transforms in the horizontal dimension, up to a phase factor exp (- j $ x :) across P2.This phase factor can be removed by placing a negative cylindrical lens of focal length f /2 immediately in front of P2, thus canceling the phase curvature. While the hard-clipped filter was used in radar signal processing as early as 1961, due to classification it did not appear in the open literature until 1965 [179]. It also lets you access your friends’ photos and files (as long as their privacy settings allow you to do so), and to create an offline copy of these documents, too. Arrays with as many as 5 12 X 256 S-SEED pairs have been made by AT&T. 228-230) that for a twisted nematic liquid crystal with no voltage applied, having a helical twist of a radians per meter in the right-hand sense along the direction of wave propagation and introducing a relative retardation p radians per meter between the extraordinary and ordinary polarization components, a wave polarized initially in the direction of the long molecular axis at the entrance surface of the cell will undergo polarization rotation as the light propagates through the cell, with the direction of polarization closely tracking the direction of the long crystal axis, provided only that P >> a. Finally, for simplicity we will treat the problems in this section as one-dimensional problems rather than two-dimensional problems. The derivation of the optimum filter would take us too far afield, so we content ourselves with presenting the result and referring the reader to another source [119]. Most operators have parameters that depend on the geometry of the optical system being analyzed. It neglects the finite extent of the lens, which we will account for later. Paid Versus Free Services In the modern world, there are a huge number of services that allow you to transfer even gargantuan files for free. A variety of electronic devices can also be integrated in the silicon substrate. Similarly, an idealized point source of light is often represented by the two-dimensional equivalent, + 6 (x , y) = ~lim - + N~ m ~ X ~ [- N ~ T y2)]. 4-3. 176 Introduction to Fourier Optics \ Gross fog log E FIGURE 7.3 The Hurter-Driffield curve for a typical emulsion. The illumination of the object is a converging spherical wave, as indicated. In addition, the similarity theorem can be straightforwardly applied (see Prob. There are several possible approaches to calculating the fields behind the grating. If we were to assume that the actual location of the edge is at the position where the intensity reaches half its asymptotic value, we would arrive at a correct estimate of the position of the edge in the incoherent case, but in the coherent case we would err in the direction of the bright side of the edge. This result was originally pointed out by Whittaker [298] and was later popularized by Shannon [259] in his studies of information theory. Note that since A(alA, P I A ; 0) is the Fourier transform of a field distribution on which boundary conditions are imposed in the aperture 58 Introduction to Fourier Optics plane, it is quite possible that this spectrum will contain components that satisfy the above equation. Perhaps a better term for weightings that increase the sidelobes of the point-spread function would be "inverse" apodization. It is tempting to reason that, since both U and G will fall off as lIR, the integrand will ultimately vanish, yielding a contribution of zero from the surface integral over S2. Thus in the Fresnel approximation, the general spatial phase dispersion representing propagation is reduced to a quadratic phase dispersion. However, the number of integrations grows as the number of free-space regions grows, and the complexity of the calculations increases as the number of lenses included grows. These include an approach based on the sampling theorem in the frequency domain [140], an approach based on prolate spheroidal wave-function expansions [15], and an iterative approach suitable for digital (a) Object intensity distribution, and (b) object spectrum and the OTF. At a distance z2 behind the lens there appears a field distribution that we represent by Ui(u, v). 5-8. 52 Introduction to Fourier Optics 3.7 FURTHER DISCUSSION OF THE HUYGENS-FRESNEL PRINCIPLE The Huygens-Fresnel principle, as predicted by the first Rayleigh-Sommerfeld solution5 (see Eq. (3-40)), can be expressed mathematically as follows: where 8 is the angle between the vectors fi and FOl.We give a "quasi-physical" interpretation to this integral. Stating the result explicitly in terms of the input and output fields, where U, is the field just to the left of L I and Uf is the field just to the right of L2. Finally, when the two objects are in phase opposition, the dip falls all the way to zero intensity (a 100%dip) at the point midway between the locations of the two points, so the two points must be said to be better resolved with coherent illumination than with incoherent illumination. Show that there exists an "equivalent"object Uh(x, y) consisting of a rectangular array of point sources that produces exactly the same image Ui as does the true object U,, and that the field distribution across the equivalent object can be written -, r 2-14. Attention will be focused here on the analysis of linear systems with complex-valued inputs; the results for real-valued inputs are thus included as special cases of the theory. Examples of this type of processing have already been seen in the discussion of the phase-contrast microscope (Zernike) and the filtering of photographs (Markchal). The two-dimensional Fourier transform of a spatially bounded function is an analytic function in the (fx, fy) plane. It is most important, then, to find a simple and convenient means of decomposing the input. In general, a high-gamma film has a steeper slope to its tA-Ecurve than does a lowgamma film and therefore is more efficient in transferring small changes of exposure into changes of amplitude transmittance. For further discussion of these ideas, the reader should consult the references cited. This effect is entirely analogous to the broadening of the spectrum of an electrical signal as its duration is decreased. Note that for a simple Fourier transforming system, vignetting of the input space is minimized when the input is placed close to the lens and when the lens 106 Introduction to Fourier Optics aperture is much larger than the input transparency. If the amplitude and phase of the light at a particular object point vary randomly with time, then the overall amplitude and phase of the amplitude impulse response will vary in a corresponding fashion. Perhaps the strongest tie between the two disciplines lies in the similar mathematics which can be used to describe the respective systems of interest - the mathematics of Fourier analysis and systems theory. Thus the acousto-optic cell has acted as a one-dimensional spatial light modulator, transforming an electrical voltage modulation applied to the cell into an optical wavefront exiting the cell. The Huygens-Fresnel principle will then be seen to be a convolution integral. The paraxial approximation to that wave is written After passage through the lens (focal length f),the field distribution becomes Finally, using the Fresnel diffraction equation (4-14) to account for propagation over distance z2, we have h(u, u; 6.7) = 1 u;(x, y) exp jG { k [(u - x)' + (u - Y)'I I dx (5-27) where constant phase factors have been dropped. The Fraunhofer diffraction pattern can now be written Finally, the corresponding intensity distribution is found by taking the squared magnitude of Eq. (4-35). Recognizing that the background is brought to focus on the optical axis in the focal plane while the diffracted light, arising from higher spatial frequencies, is spread away from the optical axis, he proposed that a phase-changing plate be inserted in the focal plane to modify the phase relation between the focused and diffracted light. Such functions have a number of interesting properties. As a closing remark regarding this subject, note that while the OTF of a system with or without apodization always has the value unity at the origin, nonetheless it is not true that the amount of light transmitted to the image is the same in the two cases. Identical reasoning can be used when aberrations are present, provided the generalized pupil function P replaces P. Another relation of similar complexity is which is a statement that the fields across the front and back focal planes of a positive lens are related by a properly scaled Fourier transform, with no quadratic-phase exponential multiplier, as proved earlier in this chapter. Other interesting effects can also be readily observed. A typical H&D curve is shown in Fig. An input function U,,bounded by a circular aperture of diameter D and illuminated by a normally incident plane wave, is placed in the front focal plane of a circular positive lens of diameter L. What is the minimum lens diameter that will yield any variations of intensity across the image plane for the cases of (a) Coherent object illumination? TV displays of this type are, of course, electrically addressed, and they display on the order of 100 to 200 pixels in both the horizontal and vertical dimensions. S. Using the definition of mutual intensity, show that any purely monochromatic wave is fully coherent spatially, and therefore must be analyzed as a system that is linear in amplitude. 10 Introduction to Fourier Optics 2.1.4 Separable Functions A function of two independent variables is called separable with respect to a specific coordinate system if it can be written as a product of two functions, each of which depends on only one of the independent variables. 194 Introduction to Fourier Optics 7.2.2 Spatial Light Modulators Based on Liquid Crystals Of the SLM technologies that have been explored over a period of many years, the liquid crystal devices have survived the longest and remain important devices in practice. Within a given layer, the molecules are aligned in the same direction. 7-2. + z,. 6.5. 6.3.4 Examples of Diffraction-Limited OTFs We consider now as examples the OTFs that correspond to diffraction-limited systems with square (width 2w) and circular (diameter 2w) pupils. A comparison of the above two equations shows that Finally, the transfer function of the wave propagation phenomenon is seen to be lo - otherwise. Thus the function g is separable in rectangular coordinates (x, y) if while it is separable in polar coordinates (r, 8) if Separable functions are often more convenient to deal with than more general functions, for separability often allows complicated two-dimensional manipulations to be reduced to more simple one-dimensional manipulations. 8.1.1 The Abbe-Porter Experiments The experiments performed by Abbe and Porter provide a powerful demonstration of the detailed mechanism by which coherent images are formed, and indeed the most basic principles of Fourier analysis itself. I would in particular like to thank Profs. Only the emulsion is shown. Parameters are included within square brackets [I following the operator. We assume that the wave is propagating in a dielectric medium. (a) Show that, with coherent illumination, the step responses of the two systems are identical. The definition of the operator Q is where k = 2 r l h and c is an inverse length. (5-2) The problem remains to find the mathematical form of the thickness function h(x, y) in order that the effects of the lens may be understood. Consider the field observed at an arbitrary point (axial distance z) to the right of the aperture. Except for the scaling factor A12f that precedes x and y, the resulting form is a convolution. Show that the screen acts as a lens with multiple focal lengths. The symbols x and . The reader interested in the digital domain can consult, for example, Refs. SocialFolders does more than just create a backup of your files. It is claimed that this structure can be considered to consist of a sequence of one spherical lens, one cylindrical lens, and one prism, all placed in contact. In practice, the cells are made sufficiently thin (typically only a very few microns of thickness) to eliminate the possibility that different layers will be in different allowed states. However, if these concepts were useful only for analysis purposes, they would occupy a far less important position in modern optics than they in fact enjoy today. A block diagram of the recognition machine is shown in Fig. Since the various terms in the spectrum (2-53) of the sampled data are separated by distances 11X and IIY in the fx and fy directions, respectively, separation of the spectral regions is assured if 1 1 X I YI and 2Bx 2By' The maximum spacings of the sampling lattice for exact recovery of the original function are thus (2Bx)-' and BY)-'. P5.3), which deflects the direction of propagation of a normally incident plane wave to angle 8 with respect to the optical axis (the z axis) in the (y, z) plane, can be represented mathematically by an amplitude transmittance (a) Consider a thin transmitting structure with amplitude transmittance given by tA(x,y) = exp { - jn- [a 2x 2 + (by + c) ~],} CHAPTER 5 Wave-Optics Analysis of Coherent Optical Systems 121 Incident Pictorial view Side view FIGURE P5.3 with a, b, c all real and positive constants. 7.17. The dielectric mirror also prevents DC currents from flowing through the device, which extends its lifetime. 4.2.3 The Fresnel Approximation and the Angular Spectrum It is of some interest to understand the implications of the Fresnel approximations from the point-of-view of the angular spectrum method of analysis. Surely any direct comparison of the two systems must be in terms of the same observable quantity, image intensity. A thin lens is modeled as a quadratic phase transformation; the usual lens law is derived from this model, as are certain Fourier transforming properties of lenses. [300], [146], or [296]. Taking into account the reflection of projected, the response to the point source may be written 72 72 in when The intensity at output coordinates (-xd, -yd) can then be written as the convolution integral where Eq. (8-8) must be substituted after the change to arguments (-xd, -yd). In this way a CHAPTER 7 Metal mirror over membrane Wavefront Modulation 201 -"bias Insulator Spacer onducting electrode ? CHAPTER 7 Wavefront Modulation I t is clear from the previous chapter that the tools of linear systems and frequency analysis are useful in the analysis of optical systems. The similarities do not end when the linearity and invariance properties are absent. In what follows we will only briefly touch on three different approaches to invariant pattern recognition that have received considerable attention in the literature. This effect is known as the Bragg efect and will be discussed at greater length in Chapter 9. Negative Phases We have seen that it is common practice when using the Fresnel approximation to replace expressions for spherical waves by quadratic-phase exponentials. 56 Introduction to Fourier Optics Across the z given by = 0 plane, the function U has a two-dimensional Fourier transform m A(fx, fy; 0) = I(U(x, y, 0) expi- j 2 ~fxx (+ fry)] dx dy. 576).3 It is therefore a straightforward matter to calculate the above intensity distribution. For those not already familiar with Fourier analysis and linear systems theory, it can serve as the outline for a more detailed study that can be made with the help of other textbooks explicitly aimed at this subject. The word apodize is taken from the Greek language, and literally means "to remove the feet". 148 Introduction to Fourier Optics 6.4.4 Example of a Simple Aberration: A Focusing Error One of the easiest aberrations to deal with mathematically is a simple error of focus. That is, the successive transformation and inverse transformation of a function yields that function again, except at points of discontinuity. After all, there are no material sources within the aperture; rather, they all lie on the rim of the aperture. Expressing this fact mathematically, The limitation of the effective input by the finite lens aperture is known as a vignetting effect. Generally speaking, incoherent systems are somewhat more simple than coherent systems in their physical realization. Kottler [I731 later compared Sommerfeld's solution with the corresponding results of Kirchhoff's scalar treatment. In writing this equation, we have plane FIGURE 6.2 The Abbe theory of image formation. Throughout the later chapters we shall be concerned with stimuli (system inputs) and responses (system outputs) that may be either of two different physical quantities. Taking account of the proper ordering of the matrix product, 192 Introduction to Fourier Optics cos6, = [sine, - sin^,] 0 0 [l cos 0, d B d][cos6, sine, - 1 sine, cos R, ' (7- 17) where p is again given by Eq. (7-16). For mathematical simplicity we assume a magnification of unity and neglect the finite extent of the entrance and exit pupils of the system. (a) Show that if g(r, 8) = gR(r)eJme,then 3{g(r, 611 = (- j)meim4.Flm{gR(r)) where X,{) is the Hankel transform of order m, and (p, 4) are polar coordinates in the frequency space. The result is an amplitude transmittance When these two transparencies are placed in close contact, the amplitude transmittance of the pair is which is the transfer function of an inverse filter. Under the influence of the applied fields, the torques exerted on these dipoles can cause the liquid crystal molecules to change their natural spatial orientation. Circuit theory is based on the approximation that circuit elements (resistors, capacitors, and inductors) are small compared to the wavelength of the fields that appear within them, and for this reason can be treated as lumped elements with simple properties. If (3-10) is substituted in (3-12), it follows that U must obey the time-independent equation Here k is termed the wave number and is given by and A is the wavelength in the dielectric medium (A = clnv). 246 Introduction to Fourier Optics joint transform correlator. For this reason we retain both terms of the binomial approximation in the exponent. A major advantage of this type of SLM technology is that it is silicon-based and compatible with the use of CMOS (complementary metal oxide silicon) drivers on the same substrate used for the SLM pixels. The transparency so constructed is then illuminated with a simple plane wave or spherical wave to obtain the filter outputs. Let an optical image be cast on the right-hand entrance of the device, which can consist of a glass plate or, for better preservation of resolution, a fiber-optic faceplate. Note: The function Si(z) is a tabulated function and is known to many mathematical software packages. In practice, when the Fourier transform of the object is of prime interest, it is often preferred to place the input directly against the lens in order to minimize vignetting, although in analysis it is generally convenient to place the input in the front focal plane, where the transform relation is unencumbered with quadratic phase factors. While a thorough discussion of geometrical optics and the properties of lenses would be helpful, such a treatment would require a rather lengthy detour. 7.3 for the case of a photographic negative. Multiplication of the input spectrum G1 by the transfer function H then takes into account the effects of the system on each elementary function. Thus the field distribution Uf is proportional to the two-dimensional Fourier transform of that portion of the incident field subtended by the lens aperture. f Y3 From the figure it is clear that complete separation will be achieved if or equivalently, if where the small-angle approximation sin 8 - 0 has been used. For a more complete treatment of various types of aberrations and their effects on frequency response, see, for example, Refs. In the above equations, n is the refractive index of the medium and u is the velocity of propagation. The energy incident per unit area on a photographic emulsion during the exposure process is called the exposure. If the model is simplified to one with a single linear filter preceding E E' Linear D' H&D Optical scattering Linear D Chemical diffusion (a) -2-{-p-FF Linear FIGURE 7.7 The Kelley model of the photographic process. Chapter 3 treats the foundations of scalar diffraction theory, including the Kirchhoff, Rayleigh-Sommerfeld, and angular spectrum approaches. Light from the point source S is collimated by lens L l . (4-14) and (4-16), the corresponding conclusion is that the majority of the contribution to the convolution integral) with width 4 & and centered on the point comes from a square in the (6 , ~plane, (5 = x, 7 = y). The primary ingredient required for such a result was previously seen to be linearity, a property that was assumed early in our analysis. 4.4 EXAMPLES OF FRAUNHOFER DIFFRACTION PATTERNS We consider next several examples of Fraunhofer diffraction patterns. 4.10 is a photograph of the Fraunhofer diffraction pattern of a circular aperture. E curve. The F-number of a lens with a circular aperture is defined as the ratio of the focal length to the lens diameter. The units for exposure are m ~ l c mNote ~ . An expanding cylindrical wave falls on the "input" plane of an optical system. The medium is homogeneous if the permittivity is constant throughout the region of propagation. A thickness variation results when a so-called tanning bleach is used, while a refractive index modulation occurs when a nontanning bleach is used. In the back focal plane of the imaging lens appears the Fourier spectrum of the periodic mesh, and finally in the image plane the various Fourier components passed by the lens are recombined to form a replica of the mesh. Such is the case for both a serious defocusing error and for many kinds of motion blur (see Prob. Lens L1 collimates the light from the point source S. SIMPLIFICATION: You need only display lcOl2,so phase factors may be dropped. The ideas of Huygens and Young were brought together in 1818 in the famous memoir of Augustin Jean Fresnel. 3-4. Under most circumstances 64 Introduction to Fourier Optics the photocurrent is linearly proportional to the incident power, i = RP. The limits to achievable resolution are derived. If no, why not? If we move in the positive y direction, the argument of the exponential increases in a positive sense, and therefore we are moving to a portion of the wave that was emitted earlier in time. Thus Eq. (5-10) can be used to represent any of the above lenses, provided the correct sign of the focal length is used. This set of operators can be simplified by means of Eq. (5-51) applied to R[f 1, as now demonstrated, 'lK!- (Is2 Ll f L2 FIGURE 5.11 First problem analyzed. Second, current pulses must be injected into the row and column electrodes that intersect at the pixel of interest, with the direction of those currents being such as to establish a small magnetic field which nucleates a magnetic domain with magnetization in the desired direction at the comer of the pixel. Extension to two dimensions is straightforward. The entire subject of optical information processing is too broad to be fully treated in any single chapter; in fact, many books devoted exclusively to the subject already exist (e.g. see Refs. 5.2.4 Example of an Optical Fourier Transform We illustrate with a typical example the type of two-dimensional Fourier analysis that can be achieved optically with great ease. That this should be so is not entirely a surprise, for as we discussed previously, the information within the passband that arose from frequency components outside the passband is extremely weak (see Fig. We claim that such a fringe can be generated only by interference of light in the image plane from two separate patches on the exit pupil of the system, with a separation between patches that is (hzilfxl, Azilfy)(). 7.3.3 A Word of Caution The capability of semiconductor fabrication techniques to make structures of ever smaller physical size has led already to the construction of diffractive optical elements with individual feature sizes that are comparable with and even smaller than the size of a wavelength of the light with which the element will be used. Then incident on the lens will appear a spherical wave diverging from the point (6, q). 3.10.4 The Propagation Phenomenon as a Linear Spatial Filter Consider again the propagation of light from the plane z = 0 to a parallel plane at nonzero distance z. As we have seen previously, each object point generates an amplitude impulse response in the image plane. In addition, the peak phase modulation suffered by the optical wave as it passes through the cell is usually quite small, with the result that the approximation holds for the first diffraction orders, which are the orders of main interest to us. These are the constraints to be reinforced in the object domain. The device pair operates with a complementary set of inputs and produces a complementary set of outputs. Diffraction efficiencies of 80 to 90 percent are quite common for these types of elements. If g(x, y) is bandlimited and indeed has significant value over only a finite region of the (x, y) plane, then it is possible to represent g with good accuracy by aJinite number of samples. For additional discussions of various aspects of the subject matter to follow, the reader may wish to consult any of the following references: [223], [103], [196], [76], [300]. Note that two of these terms are independent of the lens coordinates, namely 110 Introduction to Fourier Optics while one term depends on the lens coordinates (the variables of integration), namely We now consider a succession of approximations and restrictions that eliminate these factors. Note that the VanderLugt technique offers an important new flexibility to coherent processing. In all cases shown, the illumination is a collimated plane wave which is incident either on the input 102 Introduction to Fourier Optics lnput (a) ------- - FIGURE 5.5 Geometries for performing the Fourier transform operation with a positive lens. To completely specify the output, the responses must in general be known for impulses located at all possible points in the input plane. Modem computer software packages that contain the Fresnel integrals have made this graphical aid largely obsolete, so we have omitted it here. 164 Introduction to Fourier Optics can be represented by the simple matrix equation Our goal is to find the vector 2, from which we can reconstruct a satisfactory extension of the spectrum G, beyond the normal cutoff frequency. (a) Show that, for a spread function that is an even function of u, such a condition occurs when the separation (in the u direction) between the centers of the spread functions is twice the value of u that satisfies the equation where jhI2 is the intensity point-spread function of the system. We consider first a form of this theorem that is directly analogous to the one-dimensional theorem used by Shannon. P5.10. When the illumination is perfectly coherent, the time-varying phasor amplitudes across the object plane differ only by complex constants. The field and intensity will be calculated some distance z to the right of the grating. As shown in (a), when only an absorbing transparency is used, the reachable region is limited to the positive real axis between 0 and 1. [253], Sections 5.3 and 5.4, and simply state the major points. Examples can be found for which the local spatial frequency distribution and the Fourier spectrum are not in as good agreement as found in the above example. In summary, incoherent optical information processing is often simpler than coherent optical processing (particularly in the forms that use image casting), but in general is much less flexible in terms of the operations that can be achieved. This method has its roots in a number of earlier ideas, particularly in the work of Braunecker and Lohmann [36], [35] and in the ideas of Caulfield and Haimes [54]. The mathematical term eigenfunction is used for a function that retains its original form (up to a multiplicative complex constant) after passage through a system. Figure 7.24 illustrates typical absorption curves for a quantum well p-i-n diode [212]. Whereas previously the realization of the frequency-plane mask was the major practical problem, the difficulties are now transferred back to the space domain. Consider a linear polarized wave with polarization direction at angle +8 to the x axis. 7.26(b). The "modulation" associated with the exposure is defined as the ratio of the peak variation of exposure to the background exposure level, or If the variations of density in the resulting transparency are measured, they can be referred back to the exposure domain through the H&D curve (assumed known) to yield an inferred or "effective" cosinusoidal exposure pattern, as indicated in Fig. A thorough geometrical-optics analysis of most well-corrected lens systems shows that they behave essentially in the way predicted by our more restrictive theory. In this case the diode structure is used simultaneously as a detector and a modulator. For example, if the amplitude of the field transmitted by the aperture has a high-spatial-frequency sinusoidal component, that component may interact with the high frequencies of the quadratic-phase exponential kernel to produce a nonzero contribution from a location other than the square mentioned above. 5.1 1. Examples of such modifications include: (1) overexposing the low-frequency portion of a VanderLugt filter transparency so as to suppress the influence of those frequencies in the decision process (see, for example, Ref. If in the presence of a point-source object, the wavefront leaving the exit pupil departs significantly from ideal spherical shape, then the imaging system is said to have aberrations. However, the explanation based on the assumption of point-source illumination is somewhat simpler to explain and to understand. It can be shown that any real and nonnegative function, such as I, or Ii, has a Fourier transform which achieves its maximum value at the origin. The expression (6-30) for 'Fl lends itself to an extremely important geometrical interpretation. In addition, both fix and fiYare defined to be zero in regions where the function g(x, y) vanishes. The reader interested in pursuing this extra richness of multidimensional sampling theory is referred to the works of Bracewell [31] and of Peterson and Middleton [230]. A: B: tA(t, 7)= COS 2.rrft t A (t ,7) = I cos 2.rrftI. 6.6.4 An Iterative Extrapolation Method An iterative method for extrapolation beyond the diffraction limit is especially interesting because this type of method can be applied to many other important problems in optics. The lens L2 Fourier transforms the amplitude distribution h, yielding an amplitude distribution &H ($,$)incident on the recording medium? Light scattering within the emulsion during exposure. This tool is widely used in the study of electrical networks and communication systems; it is assumed that the reader has encountered Fourier theory previously, and therefore that he or she is familiar with the analysis of functions of one independent variable (e.g. time). 18 Introduction to Fourier Optics This expression is separable in rectangular coordinates, so it suffices to find the onedimensional spectrum Lx Gx(fx)= ,jrPxZej2rfxx dX. + + 4-5. In fact, we will generally choose to use the first Rayleigh-Sommerfeld solution because of its simplicity. Then the set of equations (6-49) + + ?)I + 9As usual, I, actually represents the geometrical-optics prediction of the image, or the object geometrically projected into the image plane, but we refer to it as the object. Thus (6-20) H(fx, f ~ =) P(Azifx, hzify). The power flows in the direction of the vector iand the power density can be expressed as where T, is the characteristic impedance of the medium and is given by In vacuum, T, is equal to 37752. The total power incident on a surface of area A is the integral of the power density over A, taking into account that the direction of power flow is in the direction of I;, - Here ir is a unit vector pointing into the surface of the detector, while i/~il is a unit vector in the direction of power flow. However, it has been carried to its present state by D. Finally, it is assumed that the filter is exposed and processed such that operation is in the linear part of the H&D curve, where density is linearly proportional to the logarithm of exposure, i.e. where Note that this is not the usual region of operation used for other interferometrically generated filters, which are typically recorded in the linear portion of the t~ vs. Remembering that diffraction by an abrupt aperture can be thought of as coming from edge waves originating around the rim of the aperture, a softening of the edge has the effect of spreading the origin of these diffracted waves over a broader area around the edges of the pupil, thereby suppressing ringing effects caused by edge waves with a highly localized origin. To realize the entire bank of matched filters illustrated in Fig. Figure 8.3(a) FIGURE 8.1 The Abbe-Porter experiment. In that formulation, we found it necessary to assume that the amplitude of the image at any particular point consisted of contributions from only a small region surrounding the geometrical object point. If this finite portion of the object spectrum can be determined exactly from the image, then, for a bounded object, the entire object spectrum can be found by analytic continuation. Therefore for any given film there is an optimum thickness that maximizes the intensity transmission in the "on" state. The inverse of R [d]is R [- d l . The left-hand and right-hand sides of relation (5-50) are shown to be equal simply by writing out their definitions. If it is absorbed, an electron-hole pair is released within the grain. [20], Section 4.4, for more details). In addition, the shadow behind the screen is never perfect, for fields will inevitably extend behind the screen for a distance of several wavelengths. In this chapter we shall consider the role of Fourier analysis in the theory of coherent and incoherent imaging. The wavelength of the light is A and zo > 0. 3-6. The interference between two plane waves of the form UI(X,Y) = Aexp(j2.rrPly) U~(X Y) = B exp(j2.rrPzy) is recorded on a photographic film. Figure 6.14(a) shows a plot of the unapodized and apodized intensity transmissions through a square pupil with and without a Gaussian intensity apodization that falls to (lle)2 at the edge of the aperture. 7-3) that the two Jones matrices above can be reduced to the forms cos 28, L+ = [sin 26, = [cos sin 20t - cos 28, 28, - sin 26, 1 - sin 28, - cos 26, 1- Furthermore, when the input to the FLC cell is a linearly polarized wave with polarization vector inclined at angle +8, to they axis, the output polarization vectors in the two respective cases are found to be sin Ot -. +s-t FIGURE P6.5 6-6. zi = z, = 2f , what is the maximum angle 13 for which any variations of intensity will appear in the image plane? A typical material system for such structures would involve alternating layers of GaAs and AlGaAs with thicknesses of the order of 10 nm. Figure 7.6 shows a plot of amplitude transmittance vs. Following Kirchhoff, the closed surface S is chosen to consist of two parts, as shown in Fig. If the phase error at the point (x, y) is represented by kW(x, y), where k = 2mlh and W is an effective path-length error, then the complex amplitude transmittance P(x, y) of the imaginary phase-shifting plate is given by The complex function P may be referred to as the generalized pupil function. 6.12(b). The particular value of y achieved in any case is influenced by three major factors: (1) the type of emulsion in question (for example, Plus-X and Tri-X are low contrast films, with gammas of 1 or less, while High Contrast Copy has a gamma of 2 or 3); (2) the particular developer used; and (3) the development time. For the moment, the finite extent of the lens aperture will be neglected. While that might seem pricey, it actually helps cut down on wasteful spending because you are only paying for what you actually use. If you want to try out Masv, there is a seven-day free trial that gives you 100GB of free data transfers. To find the crosscorrelation of h and g, the observation is centered at coordinates (0, a hf). Substituting (2-30) in (2-29), the dependence of the transform on angle 4 is seen to disappear, leaving Go as the following function of radius p, Thus the Fourier transform of a circularly symmetric function is itself circularly symmetric and can be found by performing the one-dimensional manipulation of (23 1). [158]; applications of Fourier analysis to space-variant imaging systems can be found in Ref. Placed at distance 2f from the input, lens L2 now performs both the Fourier transforming and the imaging operations, with the spectrum of the input appearing in the rear focal plane P2 (where the Fourier filter transparency is placed) and the filtered image appearing one additional focal length beyond the focal plane, in plane P3. Such devices are usually referred to as "deformable mirror devices", or DMDs. The most advanced SLMs of this type have been developed by Texas Instruments, Inc. Before discussing the properties of the Fourier transform and its inverse, we must first decide when (2-1) and (2-2) are in fact meaningful. For an alternative reference, see [9 11, Chapter 7. Combining the three expressions for thickness, the total thickness is seen to be + 803. The exposure produced by this interferometric recording is CHAPTER 8 (+ 2Aa s) Analog Optical Information Processing 263 [- - cos 27rax + C#I (;;)IJ -- (8-59) where A is the square root of the intensity of the reference wave at the film plane, a is the square root of the intensity of the object wave at the origin of the film plane,g a is again the carrier frequency introduced by the off-axis reference wave, C#I is the phase distribution associated with the blur transfer function S, and T is the exposure time. An approximation to the desired thickness function is made by quantizing that function to a set of 2N discrete levels (usually equally spaced). It is possible, though, to couple to evanescent waves with very fine structures placed in very close proximity to the diffracting object, and thereby recover information that would otherwise be lost. When the OTF is negative, image components at that frequency undergo a contrast reversal; i.e., intensity peaks become intensity nulls, and vice versa. 3.10 THE ANGULAR SPECTRUM OF PLANE WAVES It is also possible to formulate scalar diffraction theory in a framework that closely resembles the theory of linear, invariant systems. By way of definition, a linear space-invariant filter is said to be matched to a particular signal s(x, y) if its impulse response h(x, y) is given by If an input g(x, y) is applied to a filter matched to s(x, y), then the output v(x, y) is found to be which is recognized to be the crosscorrelation function of g and s. Second, the thickness of the emulsion is often found to vary with the density of the silver in the developed transparency. Thus the reflected light is blocked by the polarizer. Thus we have the constraints To obtain a filter impulse h(x, y) that will have the desired correlations with the training set, we first expand (symbolically) that impulse response in a series using the training images as basis functions, where the an are for the moment unknown. The measurements reported were made with an experimental apparatus similar to that shown in Fig. For the narrowband case, the amplitude and phase of the timevarying phasor are readily identified with the envelope and phase of the real optical wave. [20], [203], [28], or [123]. Probs. Fourier integral theorem. 3.6 COMPARISON OF THE KIRCHHOFF AND RAYLEIGH-SOMMERFELD THEORIES We briefly summarize the similarities and differences of the Kirchhoff and the RayleighSommerfeld theories. Each secondary source has a directivity pattern cos 8. Only a small column of molecules is shown. In particular, spectral components are introduced outside of the passband of the imaging system, and in addition the spectral components within the passband are changed. In the on state, ideally there is no voltage drop across the photosensor, and the fraction of the applied rms voltage appearing across the liquid crystal must be large enough to cause significant rotation of the molecules. In this section we introduce the idea of local spatial frequencies and their relation to Fourier components. Incoherent data processing systems can be broadly divided into three separate categories: (1) systems based on geometrical optics, (2) systems based on diffraction, and (3) discrete systems. Finally, we point out an interesting interpretation of the diffraction formula (3-27), to which we will return later for a more detailed discussion. Good agreement can be expected only when the variations of +(x, y) are sufficiently "slow" in the (x, y) plane to allow +(x, y) to be well approximated by only three terms of its Taylor series expansion about any point (x, y), i.e. a constant term and two first-partial-derivative terms. As we shall show in this section, for the class of spatially bounded objects, in the absence of noise it is in principal possible to resolve infinitesimally small object details. Considerable insight into the matched filtering operation is provided by an optical interpretation, as illustrated in Fig. CHAPTER 5 Wave-Optics Analysis of Coherent Optical Systems 101 FIGURE 5.4 Effects of a converging lens and a diverging lens on a normally incident plane wave. The Kirchhoff boundary conditions may now be applied to U alone, yielding the general result Since no boundary conditions need be applied to dUldn, the inconsistencies of the Kirchhoff theory have been removed. 40 Introduction to Fourier Optics FIGURE 3.5 Surface of integration. The reader with a background in communications may be interested to note that one year after Zernike's invention a remarkably similar technique was proposed by E.H. Armstrong [8] for converting amplitude-modulated electrical signals into phase-modulated signals. Recall that one of the outputs of the VanderLugt filtering operation is itself the crosscorrelation of the input pattern with the original pattern from which the filter was synthesized. In the off state (no write light applied), the two resistances are sufficiently largethat they can be neglected, and the values of the capacitances of the photosensor and the dielectric stack must be sufficiently small (i.e. their impedances at the drive frequency must be sufficiently high) compared with the capacitance of the liquid crystal layer that the rms voltage across the liquid crystal layer is too small to cause the molecules to depart from their original twisted state. The aperture is circular and has a circular central obscuration. (a) In the case of a line excitation lying along thex axis, show that the line-spread function 1 and the point-spread function p are related by m where 1 and p are to be interpreted as amplitudes or intensities, depending on whether the system is coherent or incoherent, respectively. 6.5.3 Other Effects There are certain other miscellaneous properties of images formed with coherent light that should be mentioned in any comparison with incoherent images [71]. Since the intensity of any given impulse response is proportional to the intensity of the point source that gave rise to it, it follows that an incoherent imaging system is linear in intensity, and the impulse response of such a system is the squared magnitude of the amplitude impulse response. Since it is usually the intensity of the image that is of interest, we will drop this quadratic phase factor in the future. Fig. Thus 104 Introduction to Fourier Optics 5.2.2 Input Placed in Front of the Lens Consider next the more general geometry of Fig. CHAFER 4 Fresnel and Fraunhofer Diffraction 91 4-7. 7.25. For such bleaches, the metallic silver within the developed transparency is changed back by the chemical bleach to a transparent silver halide crystal, with a refractive index considerably larger than that of the surrounding gelatin. In the United Kingdom, H.H. Hopkins led the way in the use of transfer function methods for the assessment of the quality of optical imaging systems, and was responsible for many of the first calculations of transfer functions in the presence of common aberrations [146]. Figure 5.7 shows a transparent character 3, which is placed in front of a positive lens and illuminated by a plane wave, yielding in the back focal plane the intensity distribution shown in the right-hand part of the figure. 5.5(a). 6.11 for various values of WrnlA. 7.2.3 Magneto-Optic Spatial Light Modulators The SLMs discussed up to this point operate by means of the electrooptic effect, with polarization rotation being induced by a changing electric field across the device. Breaking a two-hour video into 30-minute segments might result in 4 different files, but those files will be much smaller than a single entity. This is a particularly useful trick for someone with a finicky internet connection; the last thing you want is for the file to almost finish its transfer before a dropped connection tanks the entire process. (3-58) As pointed out in Chapter 2, the Fourier transform operation may be regarded as a decomposition of a complicated function into a collection of more simple complexexponential functions. In view of these CHAPTER 3 Foundations of Scalar Diffraction Theory 47 contradictions, it is indeed remarkable that the Kirchhoff theory has been found to yield such accurate results in p r a ~ t i c e . The direction of rotation depends on the direction of magnetization of a mesa. In this section we summarize some of the past work on this problem. While a variety of sets of suficient conditions for the existence of (2-1) are possible, perhaps the most common set is the following: 'When a single limit of integration appears above or below a double integral, then that limit applies to both integrations. 4.13. I -4hzfo -2hzfo I 2hzfo hz/w 4hzf0 FIGURE 4.13 Fraunhofer diffraction pattern for a thin sinusoidal phase gating. (b) Show that a solution to this equation is given by A(x, y, 2) for any complex q(z) having gq(z) = [x:;i;'] A1 - exp jk-----~(2) = 1 (c) Given show that the solution U(x, y, z) takes the form U(X, Y. The strength of the first-order component can be far greater than in the Raman-Nath regime, as discussed in more detail in Chapter 9. Thus for positive a , the expression exp(j2nay) represents a plane wave with a wave vector in the (y, z) plane. The great advantage afforded by linearity is the ability to express the response (be it voltage, current, light amplitude, or light intensity) to a complicated stimulus in terms of the responses to certain "elementary" stimuli. 3-7. CHAPTER 6 0.5 Frequency Analysis of Optical Imaging Systems 153 -- 0 0.5 a0 FIGURE 6.15 Optical transfer functions with and f ~ 1 2 f ~without a Gaussian apodization. Thus if Eb represents the bias exposure and tb the corresponding bias amplitude transmittance, we may represent the tA-E curve within its region of linearity by where /3 is the slope of the curve at the bias point, AU represents the incremental amplitude changes, and P' is the product of and the exposure time. The trend is understandable, for both communication systems and imaging systems are designed to collect or convey information. When the spherical wave generated by this "reference point" passes through L3, it is collimated to produce a tilted plane wave at the recording plane. It is not possible to conclude that one type of illumination is preferred in all cases. y) = UI(X.y) P(X, y) exp (5- 12) To find the distribution Uf(u, v) in the back focal plane of the lens, the Fresnel diffraction formula, Eq. (4-17), is applied. It might be hoped that the linear phenomena that limit spatial frequency response could be separated from the highly nonlinear behavior inherent in the H&D curve. CHAPTER I Analog Optical Information Processing 221 Suppose that a transparent object, with amplitude transmittance is coherently illuminated in an image-forming system. Our discussion of the subject will consider in detail only one approach to the construction of diffractive optics, known as binary optics. To this end, note that while Eq. (6-17) defines H as the Fourier transform of the amplitude point-spread function h, this latter function is itself a Fraunhofer diffraction pattern and can be expressed as a scaled Fourier transform of the pupil function (cf. The first example, Fresnel diffraction by a square aperture, illustrates the application of the classical approach based on the convolution representation of the diffraction calculation. Note that the diffraction-limited OTF is indeed obtained when W, = 0. The expression p(x, y) = [g(x, y) 8 comb i (:)I - comb - defines a periodic function, with period X in the x direction and period Y in they direction. 8.6.1 The Matched Filter The concept of the matchedjlter plays an important role in pattern recognition problems. (b) When the object has the distance found in part (a) above, how far to the right of the lens is its image and what is the magnification of that image? 3.2 FROM A VECTOR TO A SCALAR THEORY The most fundamental beginning for our analysis is Maxwell's equations. The field transmitted through the front focal plane is given by where the separation between the centers of the two inputs is Y. The results of this analysis reveal some important general facts not explicitly evident in our earlier analyses. In fact, lenses are often "corrected for aberrations by making their surfaces aspherical in order to improve the sphericity of the emerging wavefront. One is the approximation inherent in the scalar theory. The second parameter we wish to eliminate is rotation of the object. The third category, discrete systems, will be deferred to a subsequent section of this chapter. Let the spatial spectrum of U(x, y, z) again be represented by A(fx, f y ; z), while the spectrum of U(x, y; 0) is again written A(fx, fv; 0). 4.5. The geometry is illustrated in Fig. The inverse of &[c]is Q[- c]. Early versions of the manuscript were used in courses at several different universities. Note that whenever ml2 is a root of Jo,the central order vanishes entirely! The largest possible diffraction efficiency into one of the 1 and - 1 diffraction orders is the maximum value of J:. The above suggestions can of course be modified to meet the needs of a particular set of students or to emphasize the material that a particular instructor feels is most appropriate. The inverse of V [b]is V [l l b] . The field in the front focal plane of this final Fourier transforming lens L4 consists of four terms, each of which is proportional to one of the terms in Eq. (8-21). Such a system was proposed as early as 1927 by Emanual Goldberg of Dresden, Germany, in a patent application. The "feet" being referred to are in fact the sidelobes and side-rings of the diffraction-limited impulse response. (5-15) Thus we see that the complex amplitude distribution of the field in the focal plane of the lens is the Fraunhofer diffraction pattern of the field incident on the lens, even though the distance to the observation plane is equal to the focal length of the lens, rather than satisfying the usual distance criterion for observing Fraunhofer diffraction. Thus the VanderLugt filter extends the use of coherent processors to an otherwise unattainable realm of operations. If Q < 27r, operation is in the Raman-Nath regime, while if Q > 27r, operation is in the Bragg regime. Let the intensity transmittance of the ideal image in both cases be where to make our point we will assume that fo being the cutoff frequency of the amplitude transfer function. CHAPTER 6 Frequency Analysis of Optical Imaging Systems 13 1 We therefore digress temporarily to consider the very important effects of polychromaticity. In that year, Thomas Young, an English physician, strengthened the wave theory of light by introducing the critical concept of inteiference. See Ref. 5.6). Represented by the symbol T , it is equal to I transmitted at (x, y) I incident at (x, y) Photographic density. Second, the intensity of light is fundamentally a nonnegative and real physical quantity, and the representation of data by intensity places limits on the type of data manipulations that can be carried out in purely optical form. 4.5.2 Fresnel Diffraction by a Sinusoidal Amplitude Grating - Talbot Images Our final example of a diffraction calculation considers again the case of a thin sinusoidal amplitude grating, but this time within the region of Fresnel diffraction rather than Fraunhofer diffraction. The phase plate can be replaced by a phase modulator that shifts the temporal frequency of the light passing through one of the two apertures, and the detector can select only the difference frequency in order to eliminate the unmodulated low-frequency portions of the spectrum. The material presented in Chapter 2 deals with the mathematics in two spatial dimensions (as is necessary for most problems in optics), yielding an extra richness not found in the standard treatments of the one-dimensional theory. Note that for an invariant system the superposition integral (2-47) takes on the particularly simple form m (2-49) which we recognize as a two-dimensional convolution of the object function with the impulse response of the system. The goal is to determine the relationship between the complex field across a plane S1just to the left of lens L , , and the complex field across a plane S2just to the right CHAPTER s Wave-Optics Analysis of Coherent Optical Systems 117 T A B L E 5.1 Relations between operators. While some nonlinear optical phenomena allow the light from one strong incoherent image to suppress the strength of a second, weaker incoherent image, there is no optical operation, linear or nonlinear, that can produce a negative intensity, so true subtraction is not possible with purely optical operations. Paid services also tend to have higher transfer rates and higher storage capacities. There is no right or wrong answer. If the focal length is positive, then the spherical wave is converging towards a point on the lens axis a distance f behind the lens. We shall limit our goals here to a presentation of the most important and widely used analog optical information processing architectures and applications. We can rewrite them as and Both of these expressions are crosscorrelations of the functions g and h. 8.15. PROBLEMS-CHAPTER 2 2-1. As before, V 2 is the Laplacian operator, n represents the refractive index of the dielectric medium within which light is propagating, and c represents the vacuum velocity of light. For example, if the medium is inhomogeneous with a permittivity E(P) that depends on position P (but not on time t), it is a simple matter to show (see Prob. PROBLEMS - CHAPTER 6 6-1. Eq. 6-5). The value of the restoration filter is undefined at the frequencies where these isolated zeros occur. exposure curve. This architecture has the disadvantage that vignetting can occur during the first Fourier transform operation. (a) Under the assumption that the pinhole is large enough to allow a purely geometricaloptics estimation of the point-spread function, find the optical transfer function of this camera. PROBLEMS-CHAPTER 5 5-1. negative transparency. If we define the "cutoff frequency" of the camera to be the frequency where the first zero of the OTF occurs, what is the cutoff frequency under the above geometrical-optics approximation? 6.3.3 The OTF of an Aberration-Free System To this point, our discussions have been equally applicable to systems with and without aberrations. Analysis of Two-Dimensional Signals and Systems 13 FIGURE 2.2 Special functions. It is possible to remove the effects of these variations by means of a device called a liquid gate. It is most tempting to define t~ simply as the positive square root of the intensity transmittance 7.However, such a definition neglects the relative phase shifts that can occur as the light passes through the film [152]. A.A. Sawchuk, J.F. Walkup, J. Chapter 6 considers the application of frequency analysis techniques to both coherent and incoherent imaging systems. Because of the importance of photographic film in optics and in optical information processing, we devote some time here to discussing its properties. the Fraunhofer pattern, while the two side patterns are called thefirst orders. Hence we assume that the difference between the time delays 71 and 7 2 is negligible under the narrowband assumption, allowing the two delays to be dropped. This term can be ignored under either of two conditions: 1. 5.1(b) the radius of curvature of the left-hand surface of the lens is a positive number R 1 ,while the radius of curvature of the right-hand surface is a negative number R2. Thus we may express U(x, y, z) as But in addition, from Eq.(3-69), where we have again explicitly introduced the bandwidth limitation associated with evanescent waves through the use of a circ function. For the Kirchhoff theory (cf. Spatial attenuation can be introduced with, for example, an absorbing photographic transparency, thus allowing real values of t~ between zero and unity to be realized. 2-6. Using the definition of W,, we can express the path-length error as W (x ,y) = Wrn x2 + y2 w2 (6-40) If the path-length error W given by (6-40) is substituted in the expression (6-36) for the OTF, a number of straightforward manipulations yield the result Plots of this OTF are shown in Fig. In fact, the limit of this process is the geometrical optics prediction of the complex field, Fresnel and Fraunhofer Diffraction CHAPTER 4 U (X ,Y , Z) = ej k z u (~ y, , 0) = ejkz 87)I:(rect(w) rect - where, to avoid confusion, we have explicitly included the z coordinate in the argument of the complex field U . Dropping the time dependence, the complex phasor amplitude of the plane wave across a constant z-plane is + + A Note that the direction cosines are interrelated through (+ fy y)] Thus across the plane z = 0, a complex-exponential function exp[j 2 ~fxx may be regarded as representing a plane wave propagating with direction cosines a = hfx P = hfy y = J1 - (A f ~) ~ - (h f y) ~ . We refer to both forms of the result, (4-14) and (4-17), as the Fresnel diflraction integral. Other approaches to MQW SLM construction are also possible (cf. The presence of the strong bias field causes this change to propagate at high speed across the entire pixel, thus changing the magnetization state of that mesa. Usually those fields are applied between the glass plates that contain the liquid crystal material using transparent conductive layers (indium tin oxide films) coated on the inside of the glass plates. Compress Data By Zipping It There are multiple services available for turning a normal file into a .zip file. You will need to make sure you have the storage to spare, though, as some of these files could takeup plenty of disk space. A special debt is owed to Prof. The liquid crystal layer is operated in a so-called "hybrid-field-effect" mode, which is explained as follows. If H represents the desired transfer function, then the amplitude transmittance of the frequency-plane filter should be The field behind the filter is thus GH. Bandpass filtering is an operation that fundamentally requires subtraction, for the large low-frequency components that are always present in incoherent images must be removed by the processing operations. (b) What is the numerical value of that spatial frequency (in cycles/mm) when L = 4 cm, D = 2 cm, f (focal length) = 50 cm, and A = 6 X meters? A modulated drive voltage Until now the voltage driving the acousto-optic cell has been assumed to be a perfect CW signal. Figure 5.10 illustrates this point-of-view. n= -m CHAPTER 5 Wave-Optics Analysis of Coherent Optical Systems 125 5-15. Rohrer, Anthony E. One fundamental reason for the importance of such effects in coherent imaging is the so-called "interference gain" that occurs when a weak undesired signal interferes with a strong desired signal (see Prob. Finally part (d) of the figure shows the region of the complex plane that one would generally desire to reach if there were no constraints, namely the entire unit circle. The metallized beam, which is biased to a negative voltage, is attached to a spacer post through a thin metal hinge. The Jones matrix describing such a transformation can be shown to be the product of a coordinate rotation matrix Lmtate(-ad)and a wave Etarder Lretard(Pd), where the coordinate rotation matrix is given by Lotate(-ad) = cosad sinad 1 sinad cosad ' - and the retardation matrix is (neglecting constant phase multipliers) where p is given by Here A, is the vacuum wavelength of light and d is the cell thickness. For smectic liquid crystals, the molecules again favor parallel alignment, but their centers lie in parallel layers, with randomness of location only within a layer. However, for the rol appearing in the exponent, 4, Fresnel and Fraunhofer Diffraction 67 C H A ~ 4R errors are much more critical. with the vertical order inverted by the imaging operation. 6. We conclude that local spatial frequency has provided a good (but not exact) indication of where the significant values of the Fourier spectrum will occur. The solution begins by first finding the spatial frequency spectrum of the field transmitted by the structure. In all cases the illumination is assumed to be monochromatic. CHAPTER 8 Analog Optical Information Processing 239 Note that if the complex function H has an amplitude distribution A and a phase distribution $, that is, if then the expression for Z can be rewritten in the form This form illustrates the means by which the interferometric process allows the recording of a complex function H on an intensity-sensitive detector: amplitude and phase information are recorded, respectively, as amplitude and phase modulations of a highfrequency carrier that is introduced by the relative angular tilt of the "reference" wave from the prism. ., qk, . The fk in general will not coincide with the sampling points nlL. The write time is of the order of 10 msec and the erase time about 15 msec. 5-5. 8.4.3 Advantages of the VanderLugt Filter The use of a VanderLugt filter removes the two most serious limitations to conventional coherent optical processors. The spatial separation of the first orders from the zero order is foAz, while the width of the main lobe of all orders is Azlw. This sensitivity also becomes evident in the method based on the sampling theorem when the conditioning of the matrix D is considered.

Lens L 1 is a distance 2f to the right of the object. A reasonable explanation of the second and third properties would be as follows. 6.1.2 Effects of Diffraction on the Image Since geometrical optics adequately describes the passage of light between the entrance and exit pupils of a system, diffraction effects play a role only during passage of light from the object to the entrance pupil, or alternatively and equivalently, from the exit pupil to the image. For a wave that travels only in directions that have small angles with respect to the optical axis, the general form of the complex field may be approximated by U(x, y, z) = A(x, y, z) exp(jkz), where A(x, y, z) is a slowly varying function of z. In addition, if the iris is removed and a small central stop is placed on the optical axis (b) FIGURE 8.3 Mesh filtered with a horizontal slit in the focal plane. Since the transforms of such functions can be found directly from products of familiar one-dimensional transforms, the proofs of these relations are left to the reader (cf. (c) What characteristics might seriously limit the use of this screen as an imaging device for polychromatic objects? plano-concave, or negative meniscus lens is negative. When the physical extent of the input is smaller than the lens aperture, the factor P(x, y) may be neglected, yielding exp [j s (u 2 U(U, v) = J Af + y(u)] dx dy. The Function G appearing in Green's theorem may be regarded either as simply an auxiliary function which we cleverly choose to solve our problem, or it may eventually be related to the Green's function of the problem. We refer to the Mellin transform (see [32], p. Being one step more abstract than the diffraction integrals it replaces, the operator method is one step further from the physics of the experiment under analysis. discussion leading up to Fig. Before closing this section we note that when thin gratings are recorded by interference in a photographic emulsion, as is often the case in the construction of spatial filters and in recording holograms, it may often be desirable to achieve the highest possible diffraction efficiency, rather than the widest possible dynamic range. 202 Introduction to Fourier Optics Torsion * electrode Address bar (a) ""bias --b/' Landing electrode L-rv ' TFBias Address electrodes (b) Landing FIGURE 7.23 Torsion beam DMD: (a) Top view, and (b) side view. An alternative, less stringent condition, known as the "antenna designer's formula", states that for an aperture of linear dimension D, the Fraunhofer approximation will be valid provided the aperture and observation distance satisfy z > 2 D2/h. The principal difference is that in this case the integral with respect to the sum variable (x1 + x2)/2 is given by ly2 where we adopt the notation that vii is the length of the vector Pol pointing from Po to P1. 7-24(a), which is a means to the resistor-based SEED, or R-SEED. Fresnel won the prize, and since then the effect has been known as "Poisson's spot". This difficulty can be corrected by adding an additional positive lens with focal length 2f in contact with the object, thus canceling the troubling quadratic phase factor. First and foremost is the fact that binary optical elements are manufactured using VLSI fabrication techniques, namely photolithography and micromachining. Let the complex field across that z = 0 plane be represented by U (x , y, 0); our ultimate objective is to calculate the resulting field U (x , y, z) that appears across a second, parallel plane a distance z to the right of the first plane. Considering, Technical Operations, Inc., Burlington, Mass.) only 114 of its asymptotic value of intensity, whereas the incoherent and coherent images of an edge pass through the location of the geometrical image with a value of 112 of its asymptotic value. Thus if q is a radius coordinate in the plane of the spectrum, then n(q) = c(q). However, local spatial frequencies are not the same entity as the frequency components of the Fourier spectrum. Show that the wavefront curvature of Eq. (3-37) for G+ vanishes across the screen and aperture. Thus, for example, Ex obeys the equation and similarly for l y ,EZ,Hx,Hy, and Hz. Therefore it is possible to summarize the behavior of all components of 2 and 6 through a single scalar wave equation, where u(R T) represents any of the scalar field components, and we have explicitly introduced the dependence of u on both position P in space and time t. 254). The physical meaning of the lens transformation can best be understood by considering the effect of the lens on a normally incident, unit-amplitude plane wave. It is a less obvious fact that for a particular class of functions (known as bandlimited functions) the reconstruction can be accomplished exactly, provided only that the interval between samples is not greater than a certain limit. For unit-amplitude, normally incident plane-wave illumination, the field transmitted by the aperture is equal to the amplitude transmittance; in addition, where A = r w 2 . 6-18. Such a system was called diffraction-limited. An additional, more general case, will be studied in Section 5.4. For alternative discussions of the Fourier transforming properties of positive lenses, the reader may wish to consult Refs. For a discussion of the history of the phase contrast technique, as well as the scientific life of Frits Zernike, see Ref. Figure 5.3 illustrates several different types of lenses with various combinations of convex and concave surfaces. CHAPTER 7 Wavefront Modulation 197 Liquid crystal TV displays The use of liquid crystal displays in small, light-weight portable televisions is widespread, and the technology of such displays has advanced rapidly in recent years. 7.26(b)), where again A is the optical wavelength within the acoustic medium. Such phase shifts arise as a consequence of variations of the film or plate thickness, which can originate in two distinct ways. 184 Introduction to Fourier Optics FIGURE 7.10 A relief image produced by a tanning bleach. (a) FIGURE 6.21 Photographs of the image of an edge in (a) coherent and (b) incoherent illumination. exposure into a linear scale). The operation of this cell can be understood intuitively as follows. Note that some of the incident light is absorbed by the grating, and in addition the sinusoidal transmittance variation across the aperture has deflected some of the energy out of the central diffraction pattern into two additional side patterns. If you have the free plan, there's a maximum upload size of 200B, but this restriction goes away with one of the paid options. MediaFire has apps on a variety of devices, so you can transfer large files online from your mobile devices as well as from a laptop. pCloud pCloud is a cloud storage service that has a dedicated file transfer service. Eq. (3-24l) 1 1 !(dnE G~ (>- dn U(PO) = 4 7~ - ds, X for the first Rayleigh-Sommerfeld solution (cf. Similarly, the fourth term may be rewritten as which is the conjugate of a spherical wave converging to the point (-x0, y0) in a plane a distance zb from the hologram. In the first case, a nearly collimated laser beam is focused through a lens onto the photographic film, and a focused spot of tiny aperture (a) where A(x, y) is the real amplitude of the wave. The approach is particularly well-suited, since the intensity across the focal plane for a given point source is (x1 y1), and the lens therefore serves to illuminate the object with a spherical wave. ... centered at coordinates (0, a h f) in the (x3, y3) plane. In most cases it is the intensity across the focal plane that is of most interest. 6-9 Note Finally, consider the quadratic phase factor of the object coordinates (5,~). The application of filtering concepts to imaging systems is a subject of great importance and will be considered in detail in Chapter 6. 6.6.2 Intuitive Explanation of Bandwidth Extrapolation A plausibility argument that super-resolution might be possible for a spatially limited object can be presented with the help of a simple example. When a positive voltage is applied to the address electrode under the membrane, it deflects downward under the influence of the electrostatic forces. In an imaging geometry, the response of the system to an impulse at particular object coordinates should extend over only a small region of image space surrounding the exact image point corresponding to that particular object point. 5-7. It is also possible to make a reflection modulator using a liquid crystal cell, as illustrated in Fig. Finally, all media of interest in this book are nonmagnetic, which means that the magnetic permeability is always equal to p0, the vacuum permeability. Other useful references include [266] and [22]. Find the locations of these images. Modulators of the type above can be fabricated in modest size arrays and addressed electrically to produce a discrete, pixelated SLM. The action of the R-SEED described above does not lead to a very useful device in itself. Of the two diodes, the one with bright on top and dark on the bottom. Optically addressed FLC SLMs embody some of the same principles used in the Hughes liquid crystal light valve, but they also have some significant differences. There are many people to whom I owe a special word of thanks for their help with this new edition of the book. FIGURE 7.13 Ferroelectric liquid crystal (a) smectic-C* layered structure, and (b) allowed molecular orientations. We again focus on the term proportional to S*, the same term that was of interest in the case of the matched filter. 7.26), and x is normal to the page of that figure, then at any instant of time t the distribution of refractive index perturbation in the cell can be written where a is a proportionality constant, 7, = L2V is the time delay required for acoustic propagation over the full length L of the cell, and we neglect the x dependence because it plays no role here or in what follows. Note that the classical matched filtering approach is insensitive to one extraneous parameter, translation, in the sense that wherever the object may be in the input field, a bright spot will appear at its corresponding location in the output plane. The devices are used in both reflection and transmission, with the reflection mode employing a reflecting aluminized surface in the form of the light-transmitting conducting electrode, to the right of which is a thin NLC cell with alignment layers on both sides. Area (A) = lhifx JW2 - Finally, we have M (x , 0) = 4(area (A + B) - area (A)) 7rw2 or, for a general radial distance p in the frequency plane, The quantity pe is the cutoff frequency of the OTF for the case of coherent illumination and is given as . Although this mask is a part of the device, an optically flat glass faceplate is followed to the right by a transparent conducting electrode, to the right of which is a thin NLC cell with alignment layers on both sides. The light incident from the left is chosen to be in a direction parallel to the long axis of the real device, the operation is complicated by the fact that the photosensor and light-blocking layer together form an electrical diode with asymmetric I - V properties. This so-called Rayleigh-Sommerfeld diffraction theory will be treated in Section 3.5. It should be emphasized from the start that the Kirchhoff and Rayleigh-Sommerfeld theories share certain major simplifications and approximations. The operators act on the quantities contained in curly brackets { }. When the local spatial frequencies of the complex amplitude of a coherent optical wavefront are found, they correspond to the ray directions of the geometrical optics description of that wavefront. The wave propagation phenomenon is linear, and the wave passed through the aperture should be proportional to the wave incident upon it. This phenomenon is found to depend strongly on the spatial frequency content of the density pattern, and to act as a bandpass filter, with no relief induced at very low spatial frequencies and at very high spatial frequencies. The smoothing operation associated with the convolution can strongly attenuate the fine details of the object, with a corresponding loss of image fidelity resulting. Consider the optical system shown in Fig. For simplicity we assume that the magnification of the system is unity and we define the image coordinates in such a way as to remove any effects of image inversion. Find the thickness of the film that will maximize the light efficiency of the device in the "on" state, given that the polarization analyzer is oriented to assure complete extinction in the "off" state. 6.9. For particular case of P0 on S, -cos(2, P01) = - 1, and these equations become (6) = d0(P0 - e)P1 = Al l - JiS. These inverse Fourier transforms is sometimes referred to as the Fourier integral representation of a function g(x, y). Since these theorems are direct extensions of the analogous one-dimensional statements, the proofs are deferred to Appendix A. 8.6 APPLICATION TO CHARACTER RECOGNITION A particular application of optical information processing that has been of interest for many years is found in the field of character recognition. To prove this assertion, first note that, from Eq. (8-27), the peak output (vx12of the correct matched filter is given by On the other hand, the response h,12 (n k ,0) of an incorrect matched filter is given by CHAPTER 3 Analog Optical Information Processing 249 However, from Schwarz's inequality, we have It follows directly that with equality if and only if From this result it is evident that the matched filter does provide one means of recognizing which character, of a set of possible characters, is actually being presented to the system. For simplicity we neglect the finite extent of the grating and concentrate on the effects of diffraction and propagation on the periodic structure of the fields transmitted by the grating. However, for our purposes such a detailed detour would not be practical. pCloud offers a free trial so you can test out the service, but you will need to subscribe to continue using the service after this trial. In addition, the joint transform approach has been found advantageous for real-time systems, i.e. systems that are required to rapidly change the filter impulse response. The input, located a distance d in front of the lens, is illuminated by a normally incident plane wave of amplitude A. Referring again to Fig. (b) Find an expression for the intensity distribution in the Fraunhofer diffraction pattern of that aperture, assuming illumination by a normally incident plane wave. The operation of this system is most easily understood by applying a unit-intensity point source at coordinates (x, y) on T1 and finding the resulting intensity distribution across P. It is a plot of photographic density D vs. Kirchhoff based his mathematical formulation upon two assumptions about the boundary values of the light incident on the surface of an obstacle placed in the way of propagation of light. Now photoresist is spun onto the substrate a second time and is exposed through a second mask which has openings of width equal to 1/2N-1th of the desired Exposure Unexposed Resist Mask Substrate &4&4&4& I Micromachine FIGURE 7. 30 Steps in the fabrication of a four-level binary optic element. Director, Carnegie Mellon University Dearhold and McSpadden: Electromagnetic Wave Propagation Goodman: Introduction to Fourier Optics Harrington: Time-Harmonic Electromagnetic Fields Hayt: Engineering Electromagnetics Kraus: Electromagnetics Paul and Nasar: Introduction to Electromagnetic Fields Plonus: Applied Electromagnetics Introduction to Fourier Optics SECOND EDITION Joseph W. Eq. (5-19)). By considering incoherent filtering systems that include the effects of diffraction, we have focused on the remaining serious problem that arises in such filtering, namely the nonnegativity of optical intensity and the lack of a convenient method for subtracting intensities. The comparison is in general a complex one, although simple cases, such as the one illustrated above, do exist. Figure 4.11 shows a cross section of the grating amplitude transmittance function. If it is necessary to reduce the amount of material, I would recommend that the following sections be omitted: 8.4.2, 8.8.2, and 8.9. It is often desirable to include some subset of the material xvii Preface on holography from Chapter 9 in this course. The amplitude transmittance was controlled by a photographic plate, presumably immersed in a liquid gate. For a more detailed discussion of these inconsistencies, see Section 3.5. 36 Introduction to Fourier Optics Needless to say, an historic introduction to a subject so widely mentioned in the literature can hardly be considered complete. P6.6. Be sure to label the various cutoff frequencies and center frequencies on these sketches. 4-16, the discussion of Section 5.3, and in particular, Eq. (5-33), the light amplitude about the ideal image point is simply the Fraunhofer diffraction pattern of the exit pupil, centered on image coordinates (u = M5,v = My). Function x x - (-a +2 2 Transform ?- xyy y lab1 - ~ 1 6(ax,by) comb(x) comb(y) Function { (2 + 2) exp[j rr(ax + by)] lab1 6(fx - a2, f~ - b2) sgn(ax) sgn(by) ab 1 1 -- comb(ax) comb(by) comb(fxla) comb(fylb) exp[jn(a 2 x 2+ b2y2)] - exp[-(a2 x ab JJ1) + blfill 1 lab1 1 circ(x', la) 1) + ((a2 1 ...) (b2, lab1 jnfx jnfy' (bx) - (a x) + ~ (27rfy/b)2 = 1 (0 otherwise. However, the idea is valid when the diffracting apertures do not contain fine structure and when they are illuminated by uniform plane waves.) To the maximum width of h in the y direction is Wh and that of g is W., then the widths of the various output terms are as follows 4 - h 19,W Wh 4-h 7 Wh + 24Wg Wh Wh 7 Wh + Wh. Introduction to Fourier Optics Convolution and Cross-correlation 242 Introduction to Fourier Optics 8.15 Locations of the various terms of the processor output. The final descriptions of the specific diffraction patterns considered here will therefore be distributions of intensity. I have documents stored in Box. Thus for incoherent illumination, the image intensity is found as a convolution of the intensity impulse response Ih12 with the ideal image intensity I, - cos(n', F21) (3-49) For the special case of an infinitely distant point source producing normally incident plane wave illumination, the obliquity factors become + [1 + cos(0 1 + cos e) Kirchhoff theory First Rayleigh-Sommerfeld solution Second Rayleigh-Sommerfeld solution. (3-50) where 8 is the angle between the vectors n' and Po1. 5.1 A THIN LENS AS A PHASE TRANSFORMATION A lens is composed of an optically dense material, usually glass with a refractive index of approximately 1.5, in which the propagation velocity of an optical disturbance is less than the velocity in air. The history of optics is rich with examples of important advances achieved by application of Fourier synthesis techniques - the Zernike phase-contrast microscope is an example that was worthy of a Nobel prize. To illustrate the requirements placed on a more precisely, consider the widths of the various output terms illustrated in Fig. B.6. For the technique (a), the lens L3 could also be placed in front of the two transparencies which are placed in direct contact. The last such process must be to a depth that is 1/2 of the total desired peak-to-peak depth. For a more complete discussion of the subject of diffractive optics (or binary optics) see Chapter 9. 4-12. Examples of applications of such components include optical heads for compact disks, beam shaping for lasers, grating beamsplitters, and reference elements in interferometric testing. In particular, such an ability is needed to introduce information into an optical system, since the information is carried directly by the optical amplitude in the case of coherent systems, and by the optical intensity in the case of incoherent systems. 4.1 BACKGROUND In this section we prepare the reader for the calculations to follow. Thus Wh, Wg = area of overlap total area ~ To calculate the OTF of a diffraction-limited system, the steps indicated by this interpretation can be directly performed, as illustrated in Fig. Such a problem is closer to what the matched filter is known to do well, namely detect a known pattern in the presence of background noise, but has the added difficulty that the orientation and possibly the scale size of the target may not be under the same level of control that is present in the character recognition problem. From Eq. (7-34) we see that the 1 diffracted order consists of a wavefront that is proportional to a moving version of the compression waveform A (~ I Y I ~ ~ Y I ") of applied voltage, while the - 1 diffracted order contains the complex conjugate of this representation. The power of spatial filtering techniques is well illustrated by inserting a narrow slit in the focal plane to pass only a single row of spectral components. Taking note of the reflected coordinate system in plane P3 as well as the scaling constants present in the Fourier transform operation, the field strength in that plane is found to obey the proportionality The third and fourth terms of this expression are of particular interest. By restricting attention to the proper region of the output space, the matched filter output is readily observed. Inverse applied FIGURE 6.16 (b) Phase-only... Modified Mach-Zehnder interferometer (b) modified Rayleigh interferometer. To treat this subject in a completely satisfactory way, it would be necessary to take a rather long detour through the theory of partial coherence. A common type of binary optics element is a grating. Suppose that initially, in the absence of light, the voltage V is equally divided across the two diodes. The second term represents the filtered plane wave that has been affected by the grating. Suppose the beam passes through the cell, and that all portions of the phase change introduced by the cell rotated, the amplitude transmittance and the corresponding OTF with and without a particular "inverse" application. 240 Introduction to Fourier Optics Beam splitter LI L2 Reference point L3 I\ Desired impulse response Film FIGURE 8.14 Two alternative systems for producing the frequency-plane transparency (a) Modified Mach-Zehnder interferometer; (b) modified Rayleigh interferometer. To treat this subject in a completely satisfactory way, it would be necessary to take a rather long detour through the theory of partial coherence. 3.1, the sign convention adopted allows the result to be applied to other types of lenses. CHAPTER 5 Wave-Optics Analysis of Coherent Optical Systems 111 FIGURE 5.9 Converging illumination of the object. Hence the transfer function describes the continuum of eigenvalues of the system. Suppose that initially, in the absence of light, the voltage V is equally divided across the two diodes. The second term represents the filtered plane wave that has been affected by the grating. Now the spatial spectrum of the phase-only object in the Fourier domain suffers from several phase delays suffered by plane-wave components traveling in different directions. F (u g + ph) = u(F(g) + PF(h); that is, the transform of a weighted sum of two or more functions is simply the identically weighted sum of their individual transforms. 5.2.3 Input Placed Behind the Lens Consider next the case of an input that is placed behind the lens, as illustrated in Fig. For sufficiently small cells, or sufficiently small pixels on a large array, the electrical time constant is small by comparison with the time constant associated with the mechanical rotation of the molecules. This question is academic for astronomical objects, but is quite relevant in microscopy, where the illumination is usually closer to coherent than incoherent, and where in some cases it is possible to control the coherence of the illumination. When a wave is not perfectly monochromatic, but is narrow band, a straightforward generalization of the concept of intensity is given by I(P) =, (4-6) where the angle brackets signify an infinite time average. The Faraday rotation angle O thus increases with the thickness of the garnet film, but at the same time the attenuation of the device, due to absorption, also increases with that thickness. The z axis pierces both planes at their origins. However, that method also has some drawbacks. CHAPTER 7 Wavefront Modulation 183 0.5 - FIGURE 7.9 Typical measured MTF curve. Note that at 0, and a weaker varying exposure AE, then making With the above information as background, attention is turned to the process of recording the deblurring filter. This property is analogous to the ringing that occurs in video amplifier circuits with transfer functions that fall too abruptly with frequency. We shall now calculate the wavefield across the (x, y) plane, which is parallel to the (6, q) plane and at normal distance z from it. Since the function x is assumed to be bandlimited, its spectrum G is nonzero over only a finite region R of the frequency space. Throughout this chapter, we shall use the symbol z to represent the distance of the plane of the entrance pupil from the object plane, and the symbol zi to represent the distance of the plane of the exit pupil from the image plane 2 The distance z, is then the distance that will appear in the diffraction equations that represent the effect of diffraction by the exit pupil on the point-spread function of the optical system. Attention is then turned to spatial light modulators, which are devices for entering information into optical systems in real time or near real time. It is hypothesized that the point-spread function of this system is the convolution of the diffraction-limited point-spread function with the point-spread function predicted by geometrical optics. 4From the definition (2-37) the dimensions of Ix and IY are both cycles per meter; in spite of what might appear to be a contrary implication of Eq. (2-39). 3.5.1 Choice of Alternative Green's Functions Consider again Eq. (3-23) for the observed field strength in terms of the incident field and its normal derivative across the entire screen: The conditions for validity of this equation are: 1. When no voltage is applied across the cell, there is no molecular rotation. = [fect (ffrect(Y)] 8 [[comb(l(x)5fl(cnt A() - where N is an odd integer and a = Y Y . The first five of these functions, depicted in Fig. Refraction can be defined as the bending of light rays that takes place when they pass through a region in which there is a gradient of the local velocity of propagation of the wave. Experiments of this type were first reported by Abbe in 1873 [1] and later by Porter in 1906 [233]. Third, it can serve as a spatial modulator of transmitted or reflected light, a role of particular importance in optical information processing. 3.5. The problem is to express the optical disturbance at Po in terms of its values on the surface S. Liquid crystals have high resistivity and therefore act primarily as an electrical dielectric material. For a historical perspective on the field of incoherent optical processing, see Ref. The projection is centered at coordinates and the demagnification of 72 is A12f . When the object illumination is incoherent, the various impulse responses in the image plane vary in uncorrelated fashions. It is possible, however, to introduce a prescribed amplitude transmittance function within a given aperture. wavelength sensitivity. The small bump rising above unity at low frequencies is caused by chemical diffusion (the final linear filtering box in our model), which was ignored in the procedure for measuring the MTF) and is referred to as arising from the adjacency effect. Since the period of the grating is A, the qth diffraction order leaves the cell with angle eq with respect to the incident wave, i.e. Suppose that a voltage is applied across the cell. The integral can now be put in a convenient form, thus proving that the input is a Fourier transform of the output, except that the input is in a reflected coordinate system. Light is a ... In the sense that each output component is a unique signal, but for as we shall see, a variety of input functions can produce no output. When one address electrode is activated with a positive voltage, the mirror twists in one direction, and when the other electrode is activated, the mirror twists in the opposite direction. By way of illustration, Plus-X film has a significant response to about 50 line-pairs (cycles)/mm, while for Kodak 649F spectroscopic plate it extends to beyond 2000 line-pairs/mm. This object A is imaged better in coherent light than in incoherent light. Its advantage is that it allows a methodical approach to complex calculations that might otherwise be difficult to treat by the conventional methods. Here the function Jk is the kth-order Bessel function of the first kind. The molecules composing such materials can be visualized as ellipsoids, with a single long axis about which there is circular symmetry in any transverse plane. The most common materials have larger refractive indices for optical polarization parallel to the long axis of the crystal (the extraordinary refractive index, n e), and smaller uniform refractive index for all polarization directions normal to the long axis (the ordinary refractive index, no). Hence the spectra are normalized by their maximum. The effects of the linear filters are, of course, to limit the spatial frequency response of the emulsion. The Mellin transform of a function f ( ), is defined by where in the most general case s is a complex variable. For a 15-pm-thick emulsion, the peak thickness variations are found to occur at a spatial frequency of about 10 cycles/mm, with a maximum relief height in the 1- to 2 - p m range. The absolute cutoff frequency remains unchanged, but severe aberrations can reduce the high-frequency portions of the OTF to such an extent that the effective cutoff is much lower than the diffraction-limited cutoff. If the entire object spectrum can be found, then the exact object present can be reconstructed with arbitrary precision. The ratio of intensity transmitted by a developed transparency to the intensity incident on that transparency, averaged over a region that is large compared with a single grain but small compared with the finest structure in the original exposure pattern, is called the intensity transmittance. 6-11. Using a paraxial approximation to the spherical wave. The intensity at image (u, v) is therefore given by Consider Passed diffraction from the input plane to the focal plane. By restricting attention to the wave transmitted by the input we may write Assuming Fresnel diffraction from the input plane to the focal plane, Eq. (4-17) can be applied to the field transmitted by the input. To make the analysis as simple as possible, we treat only the one-dimensional restoration problem. CHAPTER 2 Analysis of Two-Dimensional Signals and Systems 19 almost zero outside that region. We will divide the set {gn} into two subsets, {gc} for which we take the correlation to be unity, and {gi} for which we wish the correlation to be zero. This is the constraint that is reinforced in the spectral domain. Finally, consider the form of the OTF when the focusing error is very severe (that is, when Wm >> A). 3-2. The spatial argument of the moving field is scaled by the acoustic velocity V. In addition, Fraunhofer diffraction patterns can be observed at distances much closer than implied by Eq. (4-24) provided the aperture is illuminated by a spherical wave converging toward the observer (see Prob. When the slit is rotated by 90° to pass only the spectral column of Fig. Second, binary optical elements depend solely on the surface relief profile of the optical element. Spatial light modulators are based primarily on nematic liquid crystals and on a special class of smectic liquid crystals (the so-called smectic-C* phase) called ferroelectric liquid crystals (FLC), so our discussions will focus on these types primarily. Start with the measured image of the object. 7.2 SPATIAL LIGHT MODULATORS The technology of photographic emulsions has a long history and is extremely well developed. We will assume a positive photoresist here. [231], [284], [182], [47], [21], [148], and [293]). For the purpose of this discussion, we consider the general case of complex-valued functions, which we will later see represent the amplitude and phase distributions of monochromatic optical waves. We can now ask whether the two point-source objects, separated by the same Rayleigh distance S, would be easier or harder to resolve with coherent illumination than with incoherent illumination. FIGURE 7.21 MOSLM device with bias coil and row- column address lines. Finally, it should be strongly emphasized that the simplifications afforded by transfer function theory are only applicable for invariant linear systems. Because of the beauty and simplicity of these Schwarzchild's results, we discuss them briefly here. CHAPTER 3 Foundations of Scalar Diffraction Theory 59 1 FIGURE 3.9 The phenomenon known as diffraction plays a role of utmost importance in the branches of physics and engineering that deal with wave propagation. 6.7. When the pupil is circular, the calculation is not quite so straightforward (see Prob. For additional background on diffraction-limited systems, the reader may wish to consult review articles [279],[98], and Vol. The space-bandwidth product of a function is a measure of its complexity. In closing it is worth noting that, in spite of its internal inconsistencies, there is one sense in which the Kirchhoff theory is more general than the RayleighSommerfeld theory. Before 1965, the conventional means for realizing a given transfer function had been the insertion of independent amplitude and phase masks in the frequency plane. The term this in this context means that the structure can indeed be represented by a simple amplitude transmittance "2 8.4.1 Synthesis of the Frequency-Plane Mask The frequency-plane mask of the VanderLugt filter is synthesized with the help of an interferometric (or holographic-see Chapter 9) system, such as that shown in Fig. However, it must be said that the foundations of Fourier optics were laid considerably earlier, particularly in the works of Ernst Abbe (1840-1905) and Lord Rayleigh (1842-1919). p and E are the permeability and permittivity, respectively, of the medium in which the wave is propagating. q must have no infinite discontinuities. (b) Sketch the limiting form of the optical transfer function as the size of the stop approaches the size of the full pupil. As a consequence their optical quality is not particularly important. In many applications of such filters, rather than as the basis for a system of very high performance. If the input array is the set of transmittance functions q(kii), K = 1,2,.. If U, G, and their first and second partial derivatives are single-valued and continuous within and on S, then we have where $signifies a partial derivative in the outward normal direction at each point on S. As can be seen, the spectrum is almost flat over the region (-Lx,Lx)and 0.8. 0.6. 0.4 - 0.2. -15 -10 -5 FIGURE 2.4 5 10 15 The spectrum of the finite chirp function, fx Lx=10,(3=1. To understand this process more quantitatively, let the transmittance of the first transparency be written, from (7-2), If this transparency is placed in contact with a second unexposed emulsion and illuminated with intensity Io,then the intensity incident on the second emulsion is simply Tn Io, and the resulting intensity transmittance becomes r p = Kn2(IOTn)-Yn2 = K = r 1 Y - K = K - Y = ~ P - I Y ~ Z nZO or equivalently rtl 178 Int duction to Fourier Optics Where Kp is a positive constant and by convention y , = - y,, y,2 is a negative number, making the overall exponent - y p a positive number. By transforming gl we are simply decomposing the input into complex-exponential functions of various spatial frequencies (fxj fy). This theorem is in many respects the prime foundation of scalar diffraction theory. The detailed structure within these regions may be complex, but the general conclusions above are correct. To include the effects of this factor, we use a geometrical optics approximation. As the basis for this eliminate, we note that rotation of an object by a certain angle is equivalent to translation in one dimension if the object is presented in polar coordinates, provided that the center chosen for the polar coordinate system coincides with the center of rotation of the object. (b) Interpret the result for a = b and a < b. Since the object and image distances are both 2f , the magnification of the system is unity. However, in the present application, the input patterns or characters will be assumed noiseless, and the use of a particular filtering operation must be justified on other grounds. Thus the two objects differ only by a periodic phase distribution. Application of a voltage that is less than that required to fully rotate the molecules will result in partial transmission of the reflected light. Consider the nature of the light that is transmitted by or reflected from an object illuminated by a polychromatic wave. Further consideration of the theory of direct transforms (see "Thus we where the pupil function P is unity inside and zero outside the projected aperture, A is a constant amplitude, zi is the distance from the exit pupil to the image plane, and (x, y) are coordinates in the plane of the exit pupil. We illustrate here with one particular approach introduced by Rhodes [244] called two-pupil OTF synthesis. Some simple and useful properties are listed below: 116 Introduction to Fourier Optics Relations (5-45) and (5-48) are quite obvious and simple to prove. The inverse Fourier transform simply undoes the transform in the same manner. However, limited space in this book prevents our covering the subject of "digital" or "numerical" optical computing, since this field 218 Introduction to Fourier Optics is not yet well developed. 5.10. Also note that the width of the main lobe is increased somewhat by apodization, and that the maximum intensity is also reduced due to extra absorption in the pupil. f 25c i + L! - FIGURE W . 6.3 FREQUENCY RESPONSE FOR DIFFRACTION-LIMITED INCOHERENT IMAGING In the coherent case, the relation between the pupil and the amplitude transfer function has been seen to be a very direct and simple one. To use them in a coherent optical processing system, it is first necessary to remove polarizers attached to the display, and to remove any attached diffusing screen. Several useful suggestions were also made by anonymous manuscript reviewers engaged by the publisher. 5.6, the value of Uf at (u,v) can be found from the Fourier transform of that portion of the input subtended by the projected pupil function P, centered at coordinates (u = - (d/f)u, v = - (d/f)v). The fact that an incoherent imaging system always has its maximum spectral content at the origin often leads to problems of low contrast at the output of incoherent processing systems. Many of the problems facing those working in optics bore strong resemblances to the optimum filtering, detection, and estimation problems of communications theory. 8.1.5 Application of Coherent Optics to More General Data Processing While the early 1950s were characterized by a growing realization on the part of physicists that certain aspects of electrical engineering were of special relevance to optics, the late fifties and early sixties saw a gradual realization on the part of electrical engineers that spatial filtering systems might be usefully employed in their more general data-processing problems. The distribution of complex field immediately behind the aperture is ~ (6q), = rect (& (&). Thus it amounts to a "softening" of the edges of the aperture through the introduction of an attenuating mask. The proof that the MTF at any frequency is always less than its zero-frequency value of unity requires more effort. Hence the inverse filter makes no attempt to restore object frequency components that are simply not present in the image, a very sensible strategy. Nonetheless, interesting operations can be performed even under the constraints mentioned. See, for example, [252], [104], [32], and [257]. Such an approach is often referred to as providing "smart pixels" [157]. The Introduction to Fourier Optics. 15. (x, y) incident on the first plane may be considered to be mapped by the propagation phenomenon into a new field distribution U(x, y, z). At what distance do these "self-images" appear? (a) Show that the diffraction efficiency into the Nth order of the grating is simply (sA2 - V(c (b) Calculate the diffraction efficiency into the first diffraction order for a grating with amplitude transmittance given by CHAPTER 4. Thus the measurements at the 2N + 1 separate frequencies within the observable passband generate a set of 2N + 1 simultaneous equations of the form + This is a set of 2N + 1 simultaneous linear equations in 2N 1 unknowns, the Gs(fx). 72 Introduction to Fourier Optics be developed by beginning with Eq. (3-74), which expresses the transfer function of propagation in free space. 1. with a change of the sign of the exponent. The two transform operations are equivalent. We obtain Thus we see that for the case of a single Fourier component, the local frequencies do indeed reduce to the frequencies of that component, and those frequencies are constant over the entire (x, y) plane. 4-16. We will return to this viewpoint a bit later. Figure 2.4 shows a plot of IGx(fx) vs. To understand the operation of the system, consider first the light generated by a particular unit point source in the source array at coordinates (-x , y,) on the source. Film can play three very fundamental roles in optics. In the first chapters (Sections 6.1, 6.2, 6.3, and 6.5 can be included. Whimery Electromagnetics SENIOR CONSULTING EDITOR Stephen W. Many methods exist for numerically inverting the set of equations of interest. This phase factor is not of concern and is indeed needed in order to produce an image at distance 2f behind lens L2. where A. If a transparency with intensity transmittance T I is imaged onto a second transparency with intensity transmittance 72, then according to geometrical optics the intensity at each point immediately behind the second transparency is T1 72. Structures of this type are usually referred to as multiple quantum well (MQW) structures. In some universities, more than one quarter or one semester can be devoted to this material. After one additional focal length, lens L3 is placed, the purpose of which is to again Fourier transform the modified spectrum of the input, producing a final output in its rear focal plane, P3. (b) Incoherent illumination? However, the object of interest to the right of the system, located distance d to the left of the lens, is illuminated by a diverging spherical wave, emanating from a point that is distance z -> d to the left of the lens. Let the functions X and Y of that equation be defined by X(x, y) Noting that 1nl2= I Y I ~ + aspect ratio = 1, it follows that I N e f ~ ~ I (1 Y 1 $ ~l)ISEthn aberrations Thus aberrations cannot increase the contrast of any spatial-frequency component of the image, and in general will lower the contrast. Pupil function that the relations are derived. In Eq. (4-29). Let the dimensions of the rectangle be Lx and 2Ly, and, referring to Fig. Transfer function (abbreviated OTF) of the system. A good discussion of this method can be found in Appendix F11 of Ref. In this case the bias magnetic field plays no role and is needed only for nonreciprocal optical behavior at the aperture. 6.6.3 An Extrapolation Method Based on the Sampling Theorem While the fundamental mathematical principles are most easily stated in terms of analytic continuation, there are a variety of specialized procedures that have been applied to the problem of bandwidth extrapolation. By tilting the mirror M I , a tilted plane wave is produced at the object plane. As such, every frequency component extends over the entire (x, y) domain. (a) Threedimensional perspective, (b) cross section. As their name implies, these elements control transmitted light through diffraction rather than refraction. In addition to all the difficulties associated with use of the film that were mentioned earlier, this method suffers from other problems related to the photographic medium. In a similar fashion, the normalized transfer function of the system can be defined by H (fhx), vl(2 exp[-j2 rr(fxu + f ~ v)] d u dv where, fx) -00 = i fhx, v)1(d u dv (2-5) Application of the convolution theorem to Eq. (6-22) then yields the frequency-domain relation CHAPTER 6 Frequency Analysis of Optical Imaging Systems 139 By international agreement, the function 3-1 is known as the optical transfer function (abbreviated OTF) of the system. A good discussion of this method can be found in Appendix F11 of Ref. In the case of a circular pupil, a point source will be imaged as an Airy pattern. The origin of Faraday rotation lies in different refractive indices experienced by the left-hand and right-hand circularly polarized components of a propagating wave [134], pp. For a discussion of such issues, see, for example, Ref. Nevertheless, there do exist important problems for which the required conditions are not satisfied, for example in the theory of diffraction from high-resolution gratings and from extremely small pits on optical recording media. 3.9. Such a plane wave has a complex representation of the form = where 5 = x x ~ y9 z i is a position vector (the symbol signifies a unit vector), while k = 2n (a ^ 2 p 9 yi). (a) Sketch the aperture diffracting the amplitude transmittance function t ~ ($i1) . A second transparency is recorded in the same geometry, but with the reference point source removed, thus capturing information only about the intensity I = (hI2. 7-20. The diffraction efficiency for the grating of interest can be deduced from Eq. (4-34). The film has an MTF of known form M(f), and it is processed to produce a positive transparency with a gamma of 2. Poisson, a member of the committee. See Appendix A for more details. The new term that has been added to the wave equation will be seen to have important consequences. We can obtain the approximate result from the general result by applying a binomial expansion to the exponent of (4-20), which is valid provided (Afx(1,600 meters. In practice, one finds that when the spatial scale of exposure variations is too small, the changes of density induced may CHAPTER 7 Wavefront Modulation 1 8 1 be far smaller than would be implied by the H&D curve. 5. As in the previous examples, the answer to this question is found to depend on the phase distribution associated with the object. From a Fourier transform of that image we can discover that part of the spectrum of the object that lies within the passband of the imaging system. As Fig. Another form of the result (4-14) is found if the term exp[&x2 outside the integral signs, yielding + y2l] is factored (in which we recognize (aside from multiplicative factors) to be the Fourier transform of the product of the complete field just to the right of the aperture and a quadratic phase exponential. In the material to follow, we shall first broaden our discussion beyond a single thin positive lens, finding results applicable to more general systems of lenses, and then remove the restriction to monochromatic light, obtaining results for "quasi-monochromatic" light, both spatially coherent and spatially incoherent. Convolution without motion The preceding technique for performing convolutions is extremely awkward and time-consuming due to the mechanical scanning required. It is the intensity distribution in the image plane that is of interest, in which case the phase distribution associated with the image is of no consequence. The larger N is, the further beyond the classical diffraction-limited cutoff frequency we will be able to extend our knowledge of the spectrum. The structured structure of liquid crystal molecules causes such materials to be anisotropic in their optical behavior, and in particular to exhibit birefringence, or to have different refractive indices for light polarized in different directions. The simplest SEED structure is actually that shown in Fig. Both optically addressed and electrically addressed FLC SLMs have been reported. This distribution of intensity is called an image of the object. 7.11. Undoubtedly there are others to whom I owe thanks, and I apologize for not mentioning them explicitly here. A cylindrical lens L2 follows, placed one focal length f from PI and having power only in the vertical dimension. It is thus tempting to assume that, since the disturbances are propagating with finite velocity cln, R will ultimately be so large that the waves have not yet reached S2, and the integrand will be zero on that surface. Figure 8.21 shows plots of the spatial frequency response of the restoration filter under the assumption of a severe focusing error and white (i.e. flat) power spectra for the signal and the noise. 7-5) that, aside from a phase factor that is common to both, the Jones matrices for the two directions of propagation for the two states of the circular waves. The net result is a rotation that is given by the Faraday rotation angle Of in a general angle and therefore the total amount of polarization rotation that takes place between states of the device is much less than 90'. As implied by Fig. A further indication of these inconsistencies is the fact that the FresnelKirchhoff diffraction formula can be shown to fail to reproduce the assumed boundary conditions as the observation point approaches the screen or aperture. The complete transfer function U(P) serves as an adequate description of the disturbance, since the time dependence is known a priori. The transparency 72, having an intensity transmittance equal in form to that of the desired impulse response, is inserted directly against lens L2; the system output is found across the plane P, located distance A from the ideal image plane P'. Thus, just as the spectrum of a temporal function can be intentionally manipulated in a prescribed fashion by filtering, so too can the spectrum of a spatial function be modified in various desired ways. For all cases we can write +, where + ($[cos(d, Fo1) - cos(d, F2)](Kirchhoff theory First Rayleigh-Sommerfeld solution cos(n', Fol) Second Rayleigh-Sommerfeld solution. in this limit the diffraction pattern is approaching the Fraunhofer limit discussed earlier. 8.3.1 Coherent System Architectures Coherent systems, being linear in complex amplitude, are capable of realizing operations of the form Figure 8.5 shows several different system architectures that can be used to realize this operation, three of which are shown in Fig. You may treat this problem as one-dimensional. (c) Describe how you would numerically calculate the step responses in both cases. Thus, within the passband of the imaging system, there does exist information about the conjugates of the sinusoidal components that lie outside the passband. 8.10. In Section 7.2 we focus on just a few of the most important types of such devices. 4.4.3 Thin Sinusoidal Amplitude Grating In the previous examples, diffraction was assumed to be caused by apertures in infinite opaque screens. In such a case, the predictions of geometrical optics are valid, for such a treatment would predict that the image of the exit pupil is the geometrical projection of the aperture fields onto the plane of observation. A more modern treatment of multidimensional sampling theory is found in Dudgeon and Mersereau [85]. 82 Introduction to Fourier Optics If the grating is illuminated by a unit-amplitude, normally incident plane wave, then the field distribution immediately behind the screen is given precisely by Eq. (4-38). This so-called Rayleigh-Sommerfeld theory is the subject of this section. Another approach closely related to Young's ideas is the geometrical theory of diffraction developed by Keller [161]. This technology remains a stage of rapid development. The collimating lens L1 is followed by a smaller lens L2, which focuses a portion of the collimated light to a bright spot in the front focal plane of lens L3. Consider the OTF of Eq. (6-41), as predicted for a system having square pupil and a focusing error. We now generalize by allowing the voltage to vary with time and n(V) are the smaller defects in photographic film and other phase modulations, respectively. . Protective layer Emulsion (gelatin) n=1.53 Grains (AgBr, n=2.236) Base (glass, mylar, acetate) FIGURE 7.1 Structure of a photographic film or plate. Surprisingly, the relief patterns utilized are often not binary at all, and therefore in a certain sense these elements are misnamed. Over the history of optical information processing, a great many different SLM technologies have been explored. 7) that, for small modulations, the maximum efficiency of a thin sinusoidal grating recorded photographically will occur for a recording made in the region where the magnitude of the slope a, of the t~ ... Applying the V+ operation to the left and right sides of the first equation for 2,we make use of the vector identity r& & & A All the propagation medium is linear, isotropic, homogeneous (constant E) , and nondispersive, substitution of the two Maxwell's equations for 2 in Eq. (3-33) yields where n is the refractive index of the medium, defined by CHAPTER 3 €O is Foundations of Scalar Diffraction Theory 37 the vacuum permittivity, and c is the velocity of propagation in vacuum, given by The magnetic field satisfies an identical equation. Since the vector wave equation is obeyed by both E and 3, an identical scalar wave equation is obeyed by all components of those vectors. If 3 (g(x, y)) = G (fx, fy) and 3 (h(x, y)) = H (fx, fy), then It follows directly that the convolution of two functions in the space domain (an operation that will be found to occur frequently in the theory of linear systems) is entirely equivalent to the more simple operation of multiplying their individual transforms and inverse transforming. Note that this is a beam with a Gaussian profile and with a quadratic-phase approximation to a spherical wavefront. Vectorial generalizations of diffraction theory do exist, the first satisfactory treatment being due to Kottler [172]. We will explain the operation of one more of these structures, the symmetric SEED, or S-SEED, even though it is primarily of interest for digital rather than analog processing. Now for any imaging system, whether coherent or incoherent, the image intensity is given by The image information arises from only a finite portion of the object spectrum (i.e. a portion of the spectrum of object amplitude in the coherent case, a portion of the spectrum of object intensity in the incoherent case), namely, that portion passed by the imaging system. The occurrence of a Fraunhofer diffraction formula should not be surprising. Therefore the transmitted light is still spatially coherent, even though it no longer appears to originate from a point source. CHAPTER 7 Wavefront Modulation 189 Direction of Electric Field FIGURE 7.15 Twisted nematic liquid crystal with a voltage applied. CHAPTER 8 Analog Optical Information Processing 219 (a) FIGURE 8.2 Photograph of (a) the spectrum of the mesh and (b) the spectral circle eSect that is readily observed with the spatial filter illumination. 7.12, with a polarizer oriented parallel to the front-surface alignment and an analyzer oriented parallel to the rear-surface alignment, light will pass through the exit analyzer when no voltage is applied to the cell (a consequence of rotation), but will be blocked due to the absence of rotation when the full extinction voltage is applied to the cell. Considering first the tanning bleach, the chemical agents used in this type of bleach release certain chemical byproducts as they remove the metallic silver, and these byproducts cause a cross-linking of the gelatin molecules within the emulsion in regions where the silver concentration was high. From the electrical port-of-view, it is the rms AC voltage applied across the liquid crystal layer that determines the optical state of the read side of the device. In some cases this is the back focal plane of the lens, which by definition is a plane normal to the lens axis situated a distance f behind the lens (in the direction of propagation of light). The diffraction efficiency therefore is given by As the number, L N of phase levels used increases, the angular separation between nonzero diffraction orders increases as well, since it is proportional to 2 N. The primary order of interest is the +1 order (p = 0), for which the diffraction efficiency is Figure 7.29 shows the diffraction efficiencies of various nonzero orders as a function of the number of levels. The 150 Introduction to Fourier Optics FIGURE 6.13 Geometrical optics prediction of the point-spread function of a system having a square pupil function and a severe focusing error. (2003). Rather, when the location of the secondary source shifts, the corresponding quadratic surface tilts in the (x, y) plane by an amount that depends on the location of the secondary source. CHAPTER 4 Fresnel and Fraunhofer Diffraction 75 secondary source. For background on the specific object (speckle see, for example, Refs. (b) Show that, with incoherent illumination, the step responses of the two systems are not identical. For further consideration of this problem, see Prob. Ix for the particular case of Lx = 10 and p = 1. A diffracting structure has a circularly symmetric amplitude transmittance function given by tA(r) = (k + +) (i). (0 otherwise 3 a) FIGURE 2.3 (a) The circle function and (b) its transform. The gray patch on the left in this figure represents the area from which significant contributions arise for the right. Associated with these strains are small changes of the local refractive index through what is known as the photo-elastic effect. The reader is therefore referred to more comprehensive treatments of diffraction theory, for example Refs. (b) H Letting E become arbitrarily small, the continuity of U (and its derivatives) at Poallows us to write G(P1) = and Substitution of this result in (3-19) (taking account of the negative sign) yields This result is known as the integral theorem of Helmholtz and Kirchhoff; it plays an important role in the development of the scalar theory of diffraction, for it allows the field at any point Po to be expressed in terms of the "boundary values" of the wave on any closed surface surrounding that point. As we shall see, such relations are invaluable in the further development of scalar diffraction theory. Let us consider a point on the exit pupil to be illuminated by a point source. Let the image obtained, rather than being a true point, be the amplitude spread function of the system. Consider the image amplitude in terms of the amplitude at the same diffraction pattern (4-33). Particular interest is the integral theorem of Helmholtz and Kirchhoff. CHAPTER 3 Foundations of Scalar Diffraction Theory 37 ... So far we have considered an arbitrary point object. Fortunately, experiments in the microwave region of the spectrum [262] have shown that the scalar theory yields very accurate results if two conditions are met: (1) the diffracting aperture must be large compared with a wavelength, and (2) the diffracting fields must not be observed too close to the aperture. This changes the image again, spreading it beyond the spatial bound. This transparency (dimensions L X L) is placed in front of a positive lens with focal length f, and is illuminated by a normally incident plane wave. Such illumination is called spatially incoherent. (a) Recording the frequency-plane filter; (b) format of the matched filter output for the output. Assuming unit-amplitude normally incident plane-wave illumination, find the intensity distribution in the Fraunhofer diffraction pattern of the aperture. (c) Describe how you would numerically calculate the step responses in both cases. In Chapter 7, only Section 7.1 is needed, although Section 7.3 is a useful addition if there is time. P6.1 is inserted in the exit pupil of an imaging system. To maximize the input spacebandwidth product, we would attempt to place as many independent data points as possible on the transparencies. Even though its appearance may be simple, the analysis required to find its properties is relatively complex. If a particular circular harmonic component of R,, say the Mth, is extracted digitally, then from the phase associated with that component it is possible to determine the angular shift that one version of the object has undergone. This maximum is 33.8%, far greater than for the case of a thin sinusoidal amplitude grating. A certain two-dimensional non-periodic object has the property that all of the frequency components of its amplitude transmittance lie within a circle of radius p c in the frequency plane, the radii of the circles being given by where a is a constant. Note that in this geometry, the spectrum of the input has associated with it a quadratic phase factor of the form exp [-jk·(v + y 1)] , since the input is not in the front focal plane of the lens (cf. In some cases, a vast amount of data may, by its sheer quantity, overpower the effectiveness of the human observer. This type of filter differs from the VanderLugt filter in that both the desired impulse response and the data to be filtered are presented simultaneously during the recording process, rather than just presenting the desired impulse response. Similarly, a one-dimensional tion of the fact that optical information passes through the system in two dimensions. The extension of this analysis to the case of a general imaging system (see Fig. 7-26) and the bottom taps is connected to the "-" order (diffracted upwards). In a similar fashion, we may regard the two-dimensional Fourier transform as a decomposition of a function g(x, y) into a linear combination of elementary functions of { fy)J. P5.17. We shall use the abbreviation "MOSLM" here, standing for Magneto-Optic Spatial Light Modulator. When the profile is more complex than binary, alignment of several masks is required, and the accuracy required is increased. We emphasize these results because of their generality. The Fourier transform plane need not be the back focal plane of the lens. The Fourier transform always appears in the image plane of the source. The lens is then passed together. First, it can serve as a detector of optical radiation, a task it performs remarkably effectively. Their true importance comes into full perspective only when the exciting possibility of system synthesis are considered. As the spacing between the frequencies fk shrinks, as it must as we attempt to estimate more and more values of the spectrum on the sampling points outside the observable passband, the matrix becomes more and more ill-conditioned, meaning that the solution vector 2 is ultimately dominated by noise. More recently, Miyamoto and Wolf [250] have extended the theory of boundary diffraction. The optical system that follows is a matched filtering system, for which the filter has been constructed from the VanderLugt method, at the frequency-plane recording. For Fourier transforms to which the input was subjected. CHAPTER 5 Wave-Optics Analysis of Coherent Optical Systems 113 The predictions of geometrical optics do not include the effects of diffraction. Figure 2.3 illustrates the circle function and its transform. CHAPTER 7 Wavefront Modulation 177 7.1.3 Film in an Incoherent Optical System In most applications, film is used as a detector. As a consequence, the spectrum of an imaging system is bandlimited. In the real part of the transfer function... Its use, film may be regarded as a linear system in this application. 8 Coherent light is distributed during exposure into an incoherent pattern. The fact that the finite frequency response of the film can introduce spurious effects, such as the "Eberhard effect", is well known. The most common example is the photographic film. Much of this problem is discussed in Appendix. Thus far we have seen that light counts encounter a sharp boundary between two regions having different refractive indices. [232]. For the most part, there's no downside to using these services. Examples include watch displays and screens for laptop computers. Many other structures are possible. The electrical equivalent of resistors, capacitors, and inductors are usually found over a wide range of inputs. For example, many electronic networks and imaging devices share the properties called linearity and invariance (for definitions see Chapter 2). Find a paraxial expression for the complex amplitude of the field across the "output" plane of the optical system, expressing the results in terms of arbitrary elements of the ray matrix. The time functions u(Po, t) and u(P1, t) may be expressed in terms of their inverse Fourier transforms U(Po, v)exp(j2πvt)dv (3-54) 1 - 00 u(Po, t) = U(Po, v) exp(-j 2 77 vt) - 0 v = n, m where U(Po, v) and U(PI, v) are the Fourier spectra of u(Po, t) and u(P1, t), respectively, and v represents frequency. 8-3). This image intensity is given by I(u, v) = (lu~(u, v) ~ ~(fl2, or, in the simplified notation of Eq. (6-6) and interchanging orders of averaging and integration. CHAPTER 6 Frequency Analysis of Optical Imaging Systems 129 In the case of a circular exit pupil, the impulse response h is nonzero over only a small region about the ideal image point. The boundary between the Raman-Nath regime and the Bragg regime is not a sharp one, but is often described in terms of the so-called Q factor given by where d is the thickness of the acoustic column in the z direction, n is the refractive index of the acousto-optic cell, and A is the vacuum wavelength of the light. Specify the envelope of the fringe pattern caused by the finite openings in the pupil plane. The effect of diffraction is to convolve that ideal image with the Fraunhofer diffraction pattern of the lens pupil. A slightly more sophisticated relation to which is a statement that the Fresnel diffraction operation is equivalent to premultiplication by a quadratic-phase exponential, a properly scaled Fourier transform, and postmultiplication by a quadratic-phase exponential. To understand the operation of the device, we begin with the "write" side shown on the right of Fig. 7.17. However, when (a,p) satisfy a2 + p2 > 1, a different interpretation is required. In most applications, the thickness variations are entirely unobserved, for they cannot easily be controlled. Show that the wavefront error may in a paraxial approximation of the illuminating spherical wave and the error incurred by using a quadratic phase approximation in the Fresnel diffraction computation partially cancel one another. The preceding arguments have been entirely heuristic, and in fact have certain assumptions and approximations have been introduced. Let its currently stands. To appreciate the impulse response h is that a linear space-invariant system, so the object and image intensities are related by a superposition integral but not by a convolution integral. With reference to Fig. 3-1) that the wave equation satisfied by 2 becomes where n and e are given by Eqs. SLMs are used not only to input data to be processed, but also to create spatial filters that can be modified in real time. Nonetheless, it can be seen that frequency components do eventually fall to very small values, and therefore from a practical point-of-view it is usually possible to say that g has significant values only in some finite region. The original and compensated transfer functions are illustrated in Fig. How, then, is the scalar theory only an approximation, rather than exact? By transforming each member function of the defining sequence, a corresponding sequence of transforms is generated, and we call the limit of this new sequence the generalized Fourier transform of the original function. Recall that for coherent systems we have CHAPTER 6 Frequency Analysis of Optical Imaging Systems 141 For new insights to be gained, it is often (for example, Eq. (6-28) (with a simple change of variables) that where, in the denominator have the fact that P equals either unity or zero has been used to replace pl by P. We have covered some other services already, as well as some for sending large videos. The number of different filters that can be realized by this technique is limited by the dynamic range that can be achieved in the frequency-plane transparency. We consider now the effects of aberrations, or departures of the exit-pupil wavefront from ideal spherical form. The same logic applies to the frequencies in fx = αM. With the other lenses, it follows from Eq. (6-15) that the amplitude of the frequency response is... In the opposite sense, the approximation, the amplitude of the spectrum on the other side is then given by Af l d , due to the fact that the linear dimension of the circular converging bundle of rays has been reduced by the factor dlf and energy has been conserved. It has an amplitude that is inversely proportional to A, or equivalently directly proportional to the optical frequency v. 6-2. 4-4. 3-6 For further elucidation of these points. Represented by the symbol u(P, t), is the product of incident intensity Z at each point and the exposure time T, The threshold is actually not a fixed number, but a statistical one. For example, it was shown that small details in the image could be strongly emphasized if the low-frequency components of the object spectrum were simply attenuated. Most important, the light is treated as a scalar phenomenon, neglecting the fundamentally vectorial nature of the electromagnetic fields. To reduce the object-image relation to a convolution equation, the magnification and inversion effects of geometrical optics must be normalized away. The input transparency of the input plane is imaged by a lens, and the image is formed on the intensity of the transmission... Dn"[field curve. When a given SLM technology may have two different forms, one suitable for electrical addressing and one suitable for optical addressing. CHAPTER 8 Analog Optical Information Processing 7 h e broad utility of linear systems concepts in the analysis of imaging systems is evident from the preceding chapters. Figure 6.16 shows the amplitude transmittance through the pupil and without a triangular amplitude weighting that gives extra emphasis to portions of the pupil near the edges, and de-emphasizes the importance of the center of the pupil. In such a case, all of the applied voltage must appear across the MQW device, and none across the resistor. Show that in an isotropic, nonmagnetic, and inhomogeneous dielectric medium, Maxwell's equations can be combined to yield Eq. (3-8). (3-62) In the Fourier decomposition of U,the complex amplitude of the plane-wave component with spatial frequencies (fx,fy) is simply A(fx, fy;O)fdefy, evaluated at (fx = a l h , fy = (Bib). Cassanet and his students (e.g. see [48] and [49]). While a linear mapping of intensity into exposure does not take place, it is possible to transform an intensity-dependent pattern into a nonuniform in photographic... CHAPTER 6 Frequency Analysis of Optical Imaging Systems 159 Coherent image FIGURE 6.20 Images of a step in coherent and incoherent light. Light from the small openings interferes to form a fringe in the image plane. The smaller the aperture, the broader the angular spectrum which passes. It is then obvious that this will create the coherent image that is crosses the location of the actual edge with CHAPTER 6 Frequency Analysis of Optical Imaging Systems 159 Coherent image ... 190 Introduction to Fourier Optics CHAPTER 7 Wavefront Modulation The Hughes liquid crystal SLM with (a) no write light present, and (b) write light present. The peak-to-peak thickness of the quantized element is .The diffraction efficiency of the various orders in the sawtooth grating can be obtained by expanding its periodic amplitude transmittance in a Fourier series. Other important examples are readily found in everyday life. For example, the functions both fall to satisfy existence condition 1. Such is the case that we shall now see, this analysis gives inversion, a condition we have not yet considered. In general not a valid one; a comparison of the two types of illumination is far more complex than such a superficial examination would suggest. At distance 2f lens L2 is placed a spherical lens L3 which again has focal length f . [243], [73], or [235]. By means of arguments identical with those used above, the inverse Fourier transform of a circularly symmetric spectrum [actual projected]) can be expressed as Thus for circularly symmetric functions there is no difference between the transform and the inverse-transform operations. Eq. (6-43), the inverse relation... 4.3.3 On the Relation... Two times the magnification... (3-40). He has authored more than 200 scientific and technical articles in professional journals and books. Of more relevance to us here, if an optical filter is matched to the Mth circular harmonic component of a particular object is constructed, perhaps using digital techniques, and placed in a optical correlator, then the same object is detected as a circular is a component of the system with any angular rotation, a correlation peak of strength proportional to r h|M(r)12dr will be produced, independent of rotation. The numerator represents the area of overlap of two displaced pupil functions, one centered at (hzfx/2 fy/2) and the second centered on the diametrically opposite point (-hzi fx/2, -hzi fy/2). The exposure E that gave rise to that density. A convenient representation of a system is a mathematical operator, S O , which we imagine to operate on input functions to produce output functions. This rigorous solution showed that the field of the half-plane is ultimately treated by the bipartite form. When a circular pupil is, what is a general case... are often expressed in this way. More than that, one of the most important operations is to change the new spectral components within the passband to the value called, is then reported as a spatial light... For the example of an F ... Other approach is in the ... the image ... such that its mean intensity is zero... at the bottom the ... 3.4. This is a better to the same ... by a normally incident, unit-amplitude plane wave, then the field distribution immediately behind the screen is given by 6. The generic shape of a cylindrical lens... FIGURE 8.6 The grating... CHAPTER 6 Frequency Analysis of Optical Imaging Systems 163 implementation that successively reinforces constraints in the space and space-frequency domains [116], [228]. The ideal image produced by a diffraction-limited optical system (i.e. a system that is free from aberrations) is a scaled and inverted version of the object. We omit the details here, referring the reader to Ref. 2.3.2 Invariant Linear Systems: Transfer Functions Having examined the input-output relations for a general linear system, we turn now to an important subclass of linear systems, namely invariant linear systems. While displays of this type are not made for use in coherent light, nonetheless they can be adapted for use in a coherent optical system [132]. As a consequence it is possible to express g in a Fourier series in the angular variable, m gtr. 124 Introduction to Fourier Optics - f 2f FIGURE P5.11 5-12. P5.7). Diffraction limits the set of frequencies over which the transfer function S(fx, fy) is nonzero to a finite range of frequencies. 190 Introduction to Fourier Optics the direction of the applied field matters. However, there are certain internal inconsistencies in the theory which motivated a search for a more satisfactory mathematical development. Figure 6.18 shows a 3D ... Fourier Transform of the ... sides of the ... sign ... He has served as President of the International Commission for Optics and of the Optical Society of America (OSA). It is not necessarily a monotonically decreasing function of frequency (see, for example, Prob. These properties and relations allow complicated chains of operators to be reduced to simple results, as will shortly be illustrated. 190 Introduction to Fourier Optics The direction of the applied field matters. However, there are certain internal inconsistencies in the theory which motivated a search for a more satisfactory mathematical development. 2.1.5 Functions with Circular Symmetry: Fourier-Bessel Transforms

Perhaps the simplest class of functions separable in polar coordinates is composed of those possessing circular symmetry. (b) Can you think of a way to use two cylindrical lenses to achieve an amplitude transmittance where d is a constant? The latter crystals are still silver halide and, without further processing, will eventually turn to metallic silver themselves simply through thermal processes. (Hint: First find the intensity point-spread function, then Fourier transform it. The Sommerfeld radiation condition is satisfied. 68 Introduction to Fourier Optics expression. Our purpose here is limited to extending the reader's familiarity to the analysis of functions of two independent variables. Let's face it: the true 1% are those that paid for WinRAR. You can also compress data in macOS by selecting it, right clicking, and choosing Compress. Split Files Into Smaller Sections If you are transferring an unfinished file to an editor, ask if you can send the files in pieces. Pixelated metallic electrodes can be deposited on the silicon surface, and will also serve as mirror surfaces. For example, a matched filter for the character L is obviously much more rotation-sensitive than that for the letter 0.One solution that has been used is to make a bank of matched filters, each of which is matched to the pattern of interest with a different rotation andlor scale size. Since the time variations of the phasor amplitude are statistical in nature, only statistical concepts can provide a satisfactory description of the field. In practice, S-SEED arrays are made with reflective devices such that the beams traverse a given device twice, with the result that the contrast between the two beams is increased. To prove Property 3 we use Schwarz's inequality ([227], p. In addition, the information gleaned from its solution is quite revealing. We now consider a few of the basic mathematical properties of the transform, properties that will find wide use in later material. At low signalto-noise ratio, all frequencies are reduced. 6-15. [9]). 8.1 HISTORICAL BACKGROUND The history of Fourier synthesis techniques can be said to have begun with the first intentional manipulations of the spectrum of an image. The joint transform correlator is in some cases more convenient than the VanderLugt geometry, although both are widely used. This curve is yet another description of the properties of photographic emulsions that is relevant in some applications. (a) Geometry for A,, (b) geometry for A2, and (c) geometry for A3. Such structures consist of an electron-hole pair for which the electron and hole are normally separated by a distance that is larger than the thickness of a single layer, but which are CHAPTER 7 R Wavefront Modulation 203 Light Quantum wells Light out 860 850 840 Wavelength (nm) (b) FIGURE 7.24 Shift of the exciton resonance in a multiple quantum well p-i-n diode. In addition, synthesis of transfer functions more general than a simple bandpass filter are possible. The class of invariant linear systems has associated with it a far more detailed mathematical structure than the more general class of all linear systems, and it is precisely 22 Introduction to Fourier Optics because of this structure that invariant systems are so easily dealt with. In a similar vein, the scalar theory of diffraction introduces substantial simplifications compared with a full vectorial theory. Autocorrelation theorem. Particularly interesting SLMs can be realized when silicon is used as the substrate on which the pixelated cells are fabricated. Figure 6.22 shows photographs of a transparency object, illuminated through a diffuser (e.g. a piece of ground glass), taken in coherent light and incoherent light. Therefore the integrand is nonzero only for points fjl) and f j 2) that are very close together. 6-16. A straightforward but tedious calculation shows that the diffraction efficiency of the 9th diffraction order can be expressed by [79] where 4, is the peak-to-peak phase difference of the continuous sawtooth grating, and is related to the peak-to-peak thickness variation (again, of the continuous grating) through 'These ideal and quantized gratings may be considered to be local approximations to more general gratings for which the local period, and therefore the angle of deflection, change across the grating. P5.8, a monochromatic point source is placed a fixed distance zl to the left of a positive lens (focal lengthf), and a transparent object is placed a variable distance d to the left of the lens. 6-3). The structure of ferroelectric liquid crystals is more complex. The reader interested in a more complete treatment may wish to consult Refs. The ratio of the number of silver atoms in a developed grain to the number of photons that must be absorbed to make the grain developable is typically of the order of lo9, a number which is often called the "gain ' of the photographic process. CHAPTER 2 Analysis of Two-Dimensional Signals and Systems 5 2.1 FOURIER ANALYSIS IN TWO DIMENSIONS A mathematical tool of great utility in the analysis of both linear and nonlinear phenomena is Fourier analysis. The traditional means of modulation has been through the use of photographic materials, so we consider the properties of such materials in Section 7.1. However, much more powerful optical information processing systems can be realized if photographic film is replaced by spatial light modulators capable of changing transmitted light in real time in response to optical or electrical control signals. However, there are many different pairs of patches of this separation that can be embraced by the pupil of the system. For NLC materials, an untwisted cell is simplest. Evaluate the best ways to transfer large files online and choose the one that’s right for you. Want more? 2and 'ilare functions of both position P and time t. 6.2 FREQUENCY RESPONSE FOR DIFFRACTION-LIMITED COHERENT IMAGING We turn now to the central topic of this chapter, the frequency analysis of imaging systems. Figure 8.19(a) shows a photograph of the impulse response of a VanderLugt filter which has been synthesized for the character P. Find the intensity distribution on the aperture axis in the Fresnel diffraction patterns of apertures with the following transmittance functions (assume normally incident, unitamplitude, plane-wave illumination): (a) tA(6,q) = circ .-/, (b) la({, 7) = {0 1 a s J m < b otherwise wherea < I , b < 1 a n d a < b. Therefore the Huygens-Fresnel principle should be regarded as a relatively simple mathematical construct that allows us to solve diffraction problems without paying attention to the physical details of exactly what is happening at the edges of the aperture. The partially tipped molecules retain some birefringent effect, and therefore the linearly polarized input light is transformed into elliptically polarized light, with a degree of ellipticity that depends on the strength of the applied field. The Mellin transform of g(a6) can now be found as follows: where the change of variables 5' = a t was made. These initial discussions will also serve to introduce some of the notation used throughout the book. Masks are usually made by electron-beam writing. If the NLC cell has a polarizer on its front surface and a polarization analyzer on its rear surface, it can modulate the intensity of the light it transmits. Kirchhoff accordingly adopted the following assumptions [162]: 1. There are several novel aspects to this approach to filter realization: 1. Thus in principle the sample values of the object spectrum outside the passband can be determined, and a satisfactory approximation to the object spectrum can be found beyond the cutoff frequency, with the help of the interpolation functions of the sampling theorem. ~ Finally, we note that the disturbance observed at (x, y, z) can be written in terms of the initial angular spectrum by inverse transforming Eq. (3-66), giving x circ( )-/, [(Y* exp j2a - x f)]: f + -y d- d - , (3-69) where the circ function limits the region of integration to the region within which Eq. . Liquid crystal cells are often used to construct intensity modulators, and indeed such modulation is important for several different types of SLMs. Consider first the case of nematic liquid crystals. 7.14. In MKS units and in the absence of free charge, the equations are given by Here 2is the electric field, with rectilinear components (Ex, Eu, Ez), and & is the magnetic field, with components (Hx, Fly, Hz). 8.2.1 Systems Based on Geometrical Optics A variety of methods are known for designing optical information processing systems based purely on geometrical optics. 00 In addition, define the amplitude transfer function H as the Fourier transform of the space-invariant amplitude impulse response, Now applying the convolution theorem to (6-13), it follows directly that Thus the effects of the diffraction-limited imaging system have been expressed, at least formally, in the frequency domain. With the help of this Jones matrix, the effects of the twisted nematic cell with no voltage applied can be found for any initial state of polarization. Alternatively, we could use the transfer function approach represented by Eq. (4-21), and reproduced here as Grating rl)/structure ,5 / X / // - 2 - FIGURE 4.16 Geometry for diffraction calculation. 2.1.6 Some Frequently Used Functions and Some Useful Fourier Transform Pairs A number of mathematical functions will find such extensive use in later material that considerable time and effort can be saved by assigning them special notations of their own. Some depend on more conventional methods for recording holograms. CHAPTER 7 Wavefront Modulation 215 PROBLEMS-CHAPTER 7 7-1. 7-1. The expression (4-21) is clearly an approximation to the more general transfer function (4-20). CHAFJTER6 Frequency Analysis of Optical Imaging Systems 6 169 FIGURE P6.10 6-10. 2-10. Within that circular bandwidth, the modulus of the transfer function is unity but frequency-dependent phase shifts are introduced. 8.1. An object consisting of a fine wire mesh is illuminated by collimated, coherent light. (b) Reduce this operator sequence to a simple scaling operator. A sinusoidal amplitude grating with transmittance is placed in front of a thin, positive lens (circular with diameter 2w, focal length f) and obliquely illuminated by a monochromatic plane wave traveling at angle 8 to the z axis in the (5,Z) plane, as shown in Fig. The degree of sensitivity of a matched filter to rotation and scalesize depends to a large extent on the structure of the pattern to which it is matched. An incoherent imaging system has a pupil consisting of an equilateral triangle, as shown in Fig. These systems involved at most a single thin lens and at most propagation over two regions of free space. A wide variety of different SEED structures have been conceived of. A one-dimensional convolution of two functions can be realized with either of the above systems by moving one of the transparencies with FIGURE 8.6 Systems for realizing the integral of a product of two functions. It is possible, however, to obtain square-law action over a limited dynamic range with a transparency of any gamma, be it a positive or a negative. While such extraneous responses may be of little concern in many imaging problems, they are of concern in a certain class of situations, such as when we wish to resolve a weak point-source next to a stronger point-source. To properly control this filter over the range of interest would require controlling the density accurately over a range of 0 to 4. Define the amplitude transmittance function of the aperture as the ratio of the transmitted field amplitude Ur(x, y;O) to the incident field amplitude Ui(x, y; 0) at each (x, y) in the z = 0 plane, Then and the convolution theorem can be used to relate the angular spectrum Ai(alA, PlA) of the incident field and the angular spectrum At(aIA, PlA) of the transmitted field, A a P - - '(A' A) = [a P @T a P A. 30 Introduction to Fourier Optics (a) Show that the Fourier transform of p can be written where G is the Fourier transform of g. Phase shifts of the order of 27.r radians can be induced in a wavefront passing through the bleached emulsion, although this number obviously depends on the emulsion thickness. Spatial patterns of phase shift can be introduced by means of transparent plates of varying thickness, thus extending the realizable values of t~ to all points within or on the unit circle in the complex plane. of this function with a second function that is smooth and slowly varying will come from the range - 2 < X < 2, due to the fact that outside this range the rapid oscillations of the integrand do not yield a significant addition to the total area. But does the wave vector point with a positive angle with respect to the z axis or with a negative angle, keeping in mind that a positive angle is one that has rotated counterclockwise with respect to the z axis? These alternative elementary functions are, of course, the complex-exponential functions of the Fourier integral representation. The peak-to-peak phase difference introduced by the continuous grating is exactly 2.rr radians. Note that because the dipole moment of a nematic liquid crystal is an induced moment rather than a permanent moment, the direction of the moment reverses when the applied field reverses in polarity. First, the responses of incoherent and coherent systems to sharp edges are notably different. In the incoherent case, the less direct relationship between the OTF and the pupil makes the effects more subtle. 8.6(b), let the transparency 71 be introduced without the inversion referred to earlier, so that the operation (8-5) becomes If the transparency 71 is moved in the negative x direction with speed v, the detector response as a function of time will be given by If the scans are repeated sequentially, each for a different y displacement - y,, then the detector responses will be The array of functions I,(t) represents a full two-dimensional convolution, albeit sampled in the y displacement. Thus it is clear that if the "carrier frequency" a is chosen sufficiently high, or equivalently if the reference wave is introduced at a sufficiently steep angle, the convolution and crosscorrelation terms will be deflected (in opposite directions) sufficiently far off-axis to be viewed independently. 6.1.1 A Generalized Model Suppose that an imaging system of interest is composed, not of a single thin lens, but perhaps of several lenses, some positive, some negative, with various distances between them. Unlike NLC based devices, the FLC device must operate by reversal of the direction of the electric field across the liquid crystal layer. More sophisticated techniques for realizing frequency-plane masks, based on interferometric recording, are free from some of these limitations, as will be discussed in the section to follow. This relation is of the utmost importance; it supplies very revealing information about the behavior of diffraction-limited coherent imaging systems in the frequency domain. For the case of a one-dimensional rectangular slit, the boundaries between the light region and the transition region, and between the dark region and the transition region, can be shown to be parabolas (see Prob. 7.19) are chosen so that the voltages appearing across the liquid crystal layer always remain sufficiently negative or sufficiently positive (depending on whether write light is or is not present) to drive the FLC material into its appropriate state. 7.1.1 The Physical Processes of Exposure, Development, and Fixing An unexposed photographic film or plate generally consists of a very large number of tiny silver halide (often AgBr) grains suspended in a gelatin support, which in turn is attached to a firm "base" consisting of acetate or mylar1 for films, and glass for plates. Section 4.4). CHAPTER 8 Analog Optical Information Processing 241 The final lens L3 of Fig. For a more complete discussion, together with more references, see Ref.) I0 Using a change of variables r' = 2 ~ r and p the identity we rewrite the transform as where J 1 is a Bessel function of the first kind, order 1 . 7-3. It does, however, illustrate that the frequency content can be quite different in the two cases, and furthermore it shows that the results of any such comparison will depend strongly on both the intensity and phase distributions across the object. Many useful relations between operators are summarized in Table 5.1. With these relations to draw on, we are now ready to apply the operator notation to some simple optical systems. On the other hand, TIF is a “lossless” format that doesn’t result in artifacting—but the files won’t be as small as JPG files. In the incoherent case, the image intensity is given by the convolution equation On the other hand, in the coherent case, we have Let the symbol * represent the autocorrelation integral Then we can directly write the frequency spectra of the image intensities in the two cases as Incoherent: Coherent: F { l i } = [H * HI [G g* G g] . The projected lens aperture limits the effective extent of the input, but the particular portion of t~ that contributes to the field U depends on the particular coordinates (u vl) being considered in the back focal plane. + ~,?)F{~(x, y)) where V2 is the Laplacian operator 2-4. For example, drive electronics and various 198 Introduction to Fourier Optics electronic logic functions can be associated with each pixel of the device. The parameter m represents the peak-to-peak change of amplitude transmittance across the screen, and fois the spatial frequency of the grating. Thus, in the simplest description of the problem, the object and image are related by We seek to obtain an estimate B(x, y) of o(x, y), based on the measured image intensity i(x, y) and the known point-spread function s(x, y). The factor eJkzon the right of this equation represents a constant phase delay suffered by all plane-wave components traveling between two parallel planes separated by normal distance z. Does it lag or lead? The tilted plane wave incident from the prism produces a field distribution where the spatial frequency a is given by a = -sin 8 h ' The total intensity distribution may therefore be written 6Here and frequently in what follows, we drop a multiplicative factor l l j associated with the optical Fourier transform, with the justification that we can always change the phase reference for convenience. 4-15. 8.11. 5-4. As an important general property, it can be shown that aberrations will never increase the MTF (the modulus of the OTF). It can be viewed as being caused by the physical limiting aperture internal to the system (which is the true physical source of the limitation). As a consequence, significant amounts of light are lost when an optical wave passes through such a spatial modulator. Extensions to three-dimensional imaging are presented. Thus, just as it is convenient to describe an audio amplifier in terms of its (temporal) frequency response, so too it is often convenient to describe an imaging system in terms of its (spatial) frequency response. The medium is nondispersive if the permittivity is independent of wavelength over the wavelength region occupied by the propagating wave. Such understanding can Aperture stop \ I I I I I I I I I I I I I I Incident wavefront FIGURE 4.5 Light, dark, and transition regions behind a rectangular slit aperture. 7.2. 7 7.1.2 Definition of Terms The field of photography has developed a certain nomenclature that should be mastered if the properties of photographic emulsions are to be discussed in any detailed way. This theorem had been derived previously in acoustics by H. [133]. 8-12). To provide the most rudimentary background, Appendix B presents a short description of the matrix theory of paraxial geometric optics, defining certain quantities that will be important in our purely "wave-optics" approach in this chapter. If the beams applied to the diode pair had been the complement of that assumed, i.e. had been dark on top and bright on the bottom, the device pair would have gone to a complementary state, namely maximally absorptive on the bottom and maximally transmissive on the top. Such a mapping satisfies our previous definition of a system. This method is due to Weaver and Goodman [295], and has become known as the joint transform correlator, although like the VanderLugt filter, it is equally capable of performing convolutions and correlations. input- - z1- FIGURE 5.12 22 * Second problem analyzed. 5-14. The resonant frequency of a pixel was found to be of the order of 10 kHz. 7.2.5 Multiple Quantum Well Spatial Light Modulators The use of molecular beam epitaxy to fabricate sophisticated electronic and optoelectronic devices consisting of large numbers of extremely thin layers of different semiconductor materials has led to new approaches to the construction of spatial light modulators. In the lower arm of the interferometer, the lens L2 again Fourier transforms the desired impulse response. Let g(r, 8)be separable in polar coordinates. For the moment it suffices to point out that in this regime the dominant diffraction orders are the zero order and a single first order. The last steps are to apply the relation (5-50) to invert the order of the V and Q operators in the middle of the chain, following which the two adjacent V operators and the two adjacent & operators can be combined. 8.18. That is, if the spectrum G of a function g is nonzero over only a limited region R in the (fx, fy) plane, then it is not possible for g to be nonzero over only a finite region in the (x, y) plane simultaneously. This question is not only pertinent to quadratic-phase exponentials, but also arises when considering exact expressions for spherical waves and when considering plane waves propagating at an angle with respect to the optical axis. 3.6. Let a plane surface, S1,lying directly behind the diffracting screen, be joined and closed by a large spherical cap, S2, of radius R and CHAPTER 3. 3.9 DIFFRACTION AT BOUNDARIES In the statement of the Huygens-Fresnel principle, we found it convenient to regard each point on the aperture as a new source of spherical waves. In the next section we will see more explicitly that the field at Po contributed by a secondary source at P1 depends on the time-rate-of-change of the field at P1.Since our basic monochromatic field disturbance is a clockwise rotating , derivative of this function will be proportional to phasor of the form exp(- j 2 ~ v t) the both v and to - j = 11j. the MTF at various frequencies. CHAPTER 4 Fresnel and Fraunhofer Diffraction 65 The proportionality of power density to the squared magnitude of the i0vector seen in Eq. (4-4) leads us to define the intensity of a scalar monochromatic wave at point P as the squared magnitude of the complex phasor representation U(P) of the disturbance, I(P) = Ju(p)I2. 7.1.6 Bleaching of Photographic Emulsions Conventional photographic emulsions modulate light primarily through absorption caused by the metallic silver present in the transparency. To measure the characteristics of the linear filter, a cosinusoidal exposure pattern E = Eo + El cos 2 7 ~f x (7-8) can be applied (such a pattern is easily generated by interference of two mutually coherent plane waves on the emulsion). Deflection times of about 28 psec were measured for an individual pixel, but this number depends on pixel size and can be shorter for smaller pixels. 8.7, the point of view is sufficiently different to warrant a separate discussion. First a one-quarter or one-semester course on diffraction and image formation can be constructed from the materials covered in Chapters 2 through 6, together with all three appendices. If you need to transfer files between 15 and 20GB, you can likely use a free service, but larger than that will require a payment. The field distribution Ul in front of the lens is unity, and Eqs. 8.3(b), contains only the vertical structure of the mesh; it is precisely the horizontally directed complex-exponential components that contribute to the structure in the image that is uniform vertically. If binary phase control is added to this absorbing transparency, then the reachable region is extended to the region - 1 to 1 on the real axis, as shown in (b). We shall refer either to the exit pupil or simply to the "pupil" of the system when discussing these effects. These electrodes can be matrix addressed on the chip. Thus the statistical relationships between the phasor amplitudes at the various points on the object will influence the statistical relationships between the corresponding impulse responses in the image plane. If the screen is normally illuminated by a unit-amplitude plane wave, the field distribution across the aperture is equal simply to t ~To. find the Fraunhofer diffraction pattern, we first Fourier transform 80 Introduction to Fourier Optics 5 FIGURE 4.11 Amplitude transmittance function of the sinusoidal amplitude grating. Noting that we see that the third output term yields a convolution of h and g, centered at coordinates (0, - ahf) in the (x3, y3) plane. Thus if a stimulus is decomposed into a linear combination of elementary stimuli, each of which produces a known response of convenient form, then by virtue of linearity, the total response can be found as a corresponding linear combination of the responses to the elementary stimuli. Thus in Fig. The analysis is simplified by use of the identity where Jq is a Bessel function of the first kind, order q. It was not until 1804 that further significant progress occurred. Also shown are cross sections of the OTF with and without this weighting. 6.5 COMPARISON OF COHERENT AND INCOHERENT IMAGING As seen in previous sections, the OTF of a diffraction-limited system extends to a frequency that is twice the cutoff frequency of the amplitude transfer function. 8.6(b). Such a device is called a spatial light modulatol; a term that is abbreviated by SLM. In two quarters or two semesters, most of the material in this book can be covered. We conclude with a few general comments about the operator method of analysis. of the lens L2.We represent that relationship by a system operator S. This awkwardness can be remedied by reversing the final coordinate system (x3, y3), as shown in the figure, in which case the output in plane P3is as described by Eq. (8-10). A second 234 Introduction to Fourier Optics disadvantage arises from the approximations that led to Eq. (5-30) in the analysis of the coherent imaging properties of a thin lens. As the name "two-pupil OTF synthesis" implies, this method accounts for the laws of diffraction by manipulating the OTFs of the optical systems used. The top diode will absorb light, generate current, and the voltage will drop across that diode and rise across the lower diode, which was not illuminated. Relation (5-49) is a statement that free-space propagation over distance d can be analyzed either by a Fresnel diffraction equation or by a sequence of Fourier transformation, multiplication by the transfer function of free space, and inverse Fourier transformation. 5-9. The most common type of such a device is known as the self-electro-optic effect device (the SEED). Figure 6.17 illustrates the various frequency-domain operations that lead to the image spectrum for object A. The size of the individual speckles can be shown [263] to be roughly the size of a resolution cell on the image (or object). A cross section of the image intensity can be directly written, in normalized image coordinates, as UW -2 -1 1 2 "i FIGURE 6.18 Image intensity for two equally bright incoherent point sources separated by the Rayleigh resolution distance. The fundamental relation governing this phenomenon is that the angle of reflection is always equal to the angle of incidence. (5-1) and (5-10) yield the following expression for Uj' behind the lens: Ul(x, y) = exp We may interpret this expression as a quadratic approximation to a spherical wave. SHistorically. To assure that linear systems are used, and therefore that transfer function concepts remain valid, it is necessary that the amplitude introduced into the coherent system be proportional to the intensity of the image we wish tojlter. .. The light incident on the cell is linearly polarized at +45" to the x axis due to the presence of the polarizer. Our conclusion that a lens composed of spherical surfaces maps an incident plane wave into a spherical wave is very much dependent on the paraxial approximation. Such a device is therefore a 90" rotator for this particular direction of input polarization. As a consequence, even when the propagation medium is homogeneous, the use of a scalar theory entails some degree of error. The output of this filter, E', then passes through the H&D curve, which is regarded as a zero-spread nonlinearity, analogous to the zero-memory nonlinearities often encountered in the analysis of communications systems. A measure of the power of an optical information processing system is the spacebandwidth product of the input function that it will accept. 220 Introduction to Fourier Optics (a) FIGURE 8.4 Mesh filtered with a vertical slit in the focal plane. This particular function is called the "besinc" function, or the "jinc" function. Fourier transformation of the impulse response (8-26) shows that the required transfer function is Wfx, f ~ =) S*(fx, fy), (8-28) where H = F { h } and S = F{s). process, transform'again, repeat the reinforcement of the known spectral components, etc. An electrical network is said to be time-invariant if its impulse response h(t; 7)(that is, its response at time t to a unit impulse excitation applied at time 7)depends only on the time difference (t - 7) . In both cases, the acousto-optic cell consists of a transparent medium (e.g. a liquid or a transparent crystal) into which acoustic waves can be launched by a piezoelectric transducer. Thus the presence of the signal s can conceivably be detected by measuring the intensity of the light at the focal point of the final transforming lens. CHAPTER 7 Wavefront Modulation 187 Alignment layers t Direction Of polish Direction of polish FIGURE 7.12 Molecular arrangements in a twisted nematic liquid crystal. For proofs of these theorems, see, for example, Ref. [199]. The numerator is zero for all integer q except q = 1, when it is unity. The central diffraction pattern is called the zero order of CHAITER 4 Fresnel and Fraunhofer Diffraction 81 Normalized FIGURE 4.12 Fraunhofer diffraction pattern for a thin sinusoidal amplitude grating. Table 4.1 shows the values of the Airy pattern at successive maxima and minima, from which it can be seen that the width of the central lobe, measured along the x or y axis, is given by 78 Introduction to Fourier Optics T A B L E 4.1 Locations of maxima and minima of the Airy pattern. Of special interest is the case of a quantized approximation to the blazed grating . Performing the differentiations called for by the definitions of local frequencies, we find that they can be expressed as We see that in this case the local spatial frequencies do depend on location in the (x, y) plane; within a rectangle of dimensions 2Lx X 2Ly, f i x varies linearly with the x-coordinate while fiYvaries linearly with the y-coordinate. Aberrations will be considered in Section 6-4, where it is shown that they lead to defects in the spatial-frequency response of the imaging system. Mehrl, and their many students for catching so many typographical errors and in some cases outright mistakes. 86 Introduction to Fourier Optics FIGURE 4.15 x Fresnel diffraction patterns at different distances from a square aperture. Table 2.1 lists a number of transforms of functions separable in rectangular coordinates. The Fourier transform of g in a system of rectangular coordinates is, of course, given by m -w To fully exploit the circular symmetry of g, we make a transformation to polar coordinates in both the (x, y) and the (fx, fy) planes as follows: r= Jm 0 arctan - = x= rcos~ (3 For the present we write the transform as a function of both radius and angle,3 Applying the coordinate transformations (2-26) to Eq. (2-25), the Fourier transform of g can be written l ' 1; 2 G0(p 4) = o d0 dr rga(r) e x p l j2nrp(cos 0 cos 4 + sin 0 sin +)I (2-28) or equivalently, 3Note the subscript in Go is added simply because the functional form of the expression for the transform in polar coordinates is in general different than the functional form for the same transform in rectangular coordinates. Dr. Goodman's contributions to optics have been recognized in many ways. Terman, John G. The angles of incidence and refraction are related by Snell's law, which is the foundation of geometrical optics, n 1 sin 8 = n2 sin 02, where in this example, n2 > nl and therefore O2 < 8 1. When the object illumination is perfectly incoherent, the phasor amplitudes across the object vary in statistically independent fashions. I could go to each site and download all of my files until I’ve amassed an offline collection of my stuff. 4The fact that one theory is consistent and the other is not does not necessarily mean that the former is more accurate than the latter. According to Eq. (3-41), the Huygens-Fresnel principle can be stated as where 0 is the angle between the outward normal ii and the vector Fo, pointing from Po to P1.The term cos 8 is given exactly by FIGURE 4.1 Diffraction geometry. The answer to this question depends on which of the several occurrences of rol is being approximated. 7.8. The modulation Meffof the effective exposure distribution will always be less than the modulation M iof the true exposure distribution. The fabrication process Figure 7.30 illustrates the process by which a four-level binary optic approximation to a sawtooth thickness function is generated. A final set of coordinate normalizations simplifies the results even further. Note that the contrast of the image intensity distribution is poorer for the incoherent case than for the coherent case. Hence we have confirmed that an incoherent imaging system is linear in intensity, rather than amplitude. This assumption is overly restrictive, for the illumination generated by real optical sources, including lasers, is never perfectly monochromatic. 6-17). Again the result is a very simple one: as we shall now see, the result for an incoherent system is again more complex and, in many respects, more interesting. If write light is applied to the device, a spatially varying AC electric field is established across the liquid crystal layer, and the long axis of the liquid crystal molecules begins to tilt away from the plane of the electrode. How does this frequency compare with the cutoff frequency when 0 = O? What you need is a dedicated service for transferring files. From above we conclude that in a dielectric medium that is linear, isotropic, homogeneous, and nondispersive, all components of the electric and magnetic field behave identically and their behavior is fully described by a single scalar wave equation. Accordingly, we adopt the following definitions of some frequently used functions: CHAPTER 2. The principles underlying the most simple image-casting system, namely a system that performs a spatial integration of the product of two functions, are straightforward. The processes of exposure, development and fixing are illustrated in Fig. Note that if two pixels must be changed to states of magnetization that are opposite from one another, two write cycles must be used, with a reversal of the current in the bias coil taking place between changes. Optically addressed SLMs have several key properties besides their fast temporal response that are very useful for optical processing systems. As Bracewell [32] has pointed out, "physical possibility is a valid sufficient condition for the existence of a transform." However, it is often convenient in the analysis of systems to represent true physical waveforms by idealized mathematical functions, and for such functions one or more of the above existence conditions may be violated. The presence of the screen will inevitably perturb the fields on 2 to some degree, for along the rim of the aperture certain boundary conditions must be met that would not be required in the absence of the screen. The weighting applied by the system to an eigenfunction input is called the eigenvalue corresponding to that input. Show that when the object distance is infinite, the cutoff frequency for a coherent imaging system using this lens is given by f, = &,where F# represents the F-number. The local contrast of fringes is thus an indication of the value of CHAPTER 6 Frequency Analysis of Optical Imaging Systems 149 FIGURE 6.11 OTF for a focusing error in a system with a square pupil. Such separation can be achieved with the geometry shown in Fig. 146 Introduction to Fourier Optics Exit Ideal image point reference sphere FIGURE 6.10 Geometry for defining the aberration function. Consider a lens that consists of the portion of a cone illustrated in Fig. From this it is clear that the complex number G(f) is simply a weighting factor that must be applied to the elementary function of frequency f in order to synthesize the desired g(t). Minor issue with photo resolution aside, I was quite impressed with SocialFolders. No attempt at great mathematical rigor will be made, but rather, an operational approach, characteristic of most engineering treatments of the subject, will be adopted. During the first step, the negative transparency is made in the usual fashion. 5-16). 8.1.4 The Emergence of a Communications Viewpoint In the early 1950s it became evident that an exchange between the disciplines of communications and optics could reap high profits. Hurter and V.C. Driffield published a classic paper in which they showed that the logarithm of the reciprocal of the intensity transmittance of a photographic transparency should be proportional to the silver mass per unit area of that transparency. Typical parameters for spatial light modulators of this type operating at 633-nm wavelength are [80] [220]: Array sizes from 128 X 128 pixels to 256 X 256 pixels Faraday rotation parameter P as high as 1.46" per p m Absorption coefficient a of 0.086 pm-' Film thickness of 6 p m Optical efficiency in the "on" state of a few percent Frame rate of approximately 1 kHz. This technology is relatively mature, but improvements, including the construction of high-performance reflective devices, are still taking place [247]. Attenuation that increases with distance from the center of the pupil results in an amplitude transfer function that falls off more rapidly with increasing frequency than it would in the absence of apodization. While the optical transfer function of the initial imaging system might be poor, the product of that transfer function with the (amplitude) transfer function of the compensating system would hopefully yield an overall frequency response that was more satisfactory. For information on partially coherent imaging systems, see, for example, [123]. Phase distortions can, of course, have a severe effect on the fidelity of the imaging system. The parameter p determines the particular diffraction order, with the order number given by ~2~+ 1, and the number of discrete levels i ~ 2 ~ . (a) Overlapping circles, (b) geometry of the calculation. Let the following normalized object-plane variables be introduced: in which case the impulse response of (5-33) reduces to which depends only on the differences of coordinates (u - [, v - ij). Since the OTF will clearly be circularly symmetric, it suffices to calculate 7-l along the positive fx axis. As will be seen, such devices typically exhibit bistability. It is simplest to apply the lens law immediately, replacing Q[- 11f] by &[- l l z ~- 11~21. (3-5) and (3-6). This latter variation is strongly dependent on the exposure variations to which the film has been subjected. Thus the methods used in the analyses of these systems become less and less accurate, and the system outputs will depart more and more severely from their predicted forms. The fundamental reason for the similarity is not merely the common subject of "information", but rather certain basic properties which communication systems and imaging systems share. 5There also exists a third, intermediate state of magnetization, in which the pixel consists of a multitude of small randomly oriented domains. However, there are many situations in which incoherent illumination simply can not be realized or can not be used for a fundamental reason. This equation is known as the paraxial Helmholtz equation. Thus the arrangement of the molecules within the twisted nematic liquid crystal cell shown previously in Fig. Consider now the particular nature of the field distribution transmitted by the mask when the signal s (to which the filter is matched) is present at the input. There are two practical disadvantages of this second geometry. An incoherent imaging system has a circular pupil of diameter 2w. The granularity in the image arises from interference between closely spaced and randomly phased scatterers within the diffuser. For these two cases, we have, respectively, P(x, y) = rect) - rect (A) - -1"(P(x, y) = circ Thus, from (6-20), the corresponding amplitude transfer functions are 7Note that this conclusion has been drawn only for a system free from aberrations. 7.3.1 Binary Optics The term binary optics has come to have different meanings to different people, but there are certain threads that are common and which can serve to define the field. As mentioned earlier, the diffraction efficiency into one first order is generally considerably larger in the Bragg regime than in the Raman-Nath regime, and other orders are generally strongly suppressed by the diffraction process itself. Background on the optics of liquid crystals can be found in [253], Sections 6.5 and 18.3. For an additional reference that covers liquid crystal displays in detail, the reader can consult [159]. Thus the factor in question will be zero except when in which case it is unity. These ellipsoidal molecules can stack next to one another in various ways, with different geometrical configurations defining different general types of liquid crystals. Many approaches to the construction of spatial light modulators have been studied over the years. m - %). Let 8, represent the effective angular diameter of the incoherent source that illuminates the object, 8, the angular diameter of the entrance pupil of the imaging system, and 8, the angular diameter of the angular spectrum of the object, all angles being measured from the object plane. The algorithm terminates when the image and its spectrum are changing by amounts that are smaller than some threshold. Consider the result of applying these definitions to the particular complex function representing a simple linear-phase exponential of frequencies (fx, fy). CHAPTER 3 Foundations of Scalar Diffraction Theory 35 by showing that it predicted the existence of a bright spot at the center of the shadow of an opaque disk. fir = CHAPTER 7 Wavefront Modulation 19 1 It can be shown (see [253], pp. The elliptically polarized field has a component that is parallel to the direction of the output analyzer, and therefore some of the reflected light passes that analyzer. According to the Abbe theory, only a certain portion of the diffracted components generated by a complicated object are intercepted by this finite pupil. As pointed out earlier, on the surface x, G + = 2GK and dG-ldn = 2dGKldn.Therefore the general results of interest are as follows. In effect, when this square lies entirely within the open portion of the aperture, the field observed at distance z is, to a good approximation, what it would be if the aperture were not present. First we restrict attention to a positive, aberration-free thin lens that forms a real image. The discussion above has been framed in terms of Raman-Nath diffraction, but a similar expression for the + 1 diffraction order is found in the case of Bragg diffraction, the primary difference lying in the strengths of the various orders. 62 Introduction to Fourier Optics (a) Show that for such a wave the Helmholtz equation can be reduced to + where Vf = d2/dx2 d 2 /dy 2 is the transverse portion of the Laplacian. Lens L1 now serves as both a lens for collecting the light from the point source S and as a Fourier transforming lens. The spatial frequency response of this kind of bleached transparency is not a bandpass response, but rather is similar to that of the original silver image. The transparency is immersed in a second chemical bath, which removes the remaining silver halide crystals from the emulsion, leaving only the stable metallic silver. Such a method was introduced by Ragnarsson [239]. 6-12. A different photoconductor, hydrogenated amorphous silicon, which has a faster response time than CdS, has been used. 3.1 HISTORICAL INTRODUCTION Before beginning a discussion of diffraction, it is first necessary to mention another phenomenon with which diffraction should not be confused-namely refraction. Thus we see that the complex-exponential functions are the eigenfunctions of lineal; invariant systems. The theory of imaging with incoherent light has, therefore, a certain extra richness not present in 138 Introduction to Fourier Optics the coherent case. One new device type is the FET-SEED, in which field effect transistor (FET) devices are integrated with the diode detector/modulators, allowing logic of considerable complexity to be performed electrically on the chip at each pixel [192], another example of "smart pixel" technology. (b) If g ~ (r =) 1 for a 5 r Analysis of Two-Dimensional Signals and Systems 29 1 and zero otherwise, then J1(2rp) - aJ1(2rrap) B{gR(r)) = P 5 (d) B{exp(- .rrr2)) = exp(- rrp2). Note also that, as the distance z becomes large (N F grows small), the diffraction pattern becomes much wider than the size of the aperture, and comparatively smooth in its structure. For values of q for which the numerator and denominator vanish simultaneously, l'H8pital's rule can be used to show that the ratio of the two factors is unity. 2-12. Under what (sufficient) conditions is the output a real sinusoidal function of the same spatial frequency as the input? Thus we consider only values of x and y sufficiently small to allow the following approximations to be accurate: CHAFER 5 Wave-Optics Analysis of Coherent Optical Systems 99 The resulting phase transformation will, of course, represent the lens accurately over only a limited area, but this limitation is no more restrictive than the usual paraxial approximation of geometrical optics. 3.3.3 The Integral Theorem of Helmholtz and Kirchhoff The Kirchhoff formulation of the diffraction problem is based on a certain integral theorem which expresses the solution of the homogeneous wave equation at an arbitrary point in terms of the values of the solution and its first derivative on an arbitrary closed surface surrounding that point. CHAPTER 2 Analysis of Two-Dimensional Signals and Systems 25 It follows that Evidently the spectrum of g, can be found simply by erecting the spectrum of g about each point (nlX, mlY) in the (fx, fY) plane as shown in Fig. The fundamental idea that an interferometric recording of the Fourier transform of the impulse response could realize a complex filter with a desired transfer function or its conjugate is attributable to C. However, we are getting ahead of ourselves; we will return to this idea in later chapters and particularly in Appendix B. Thus the amplitude transfer function is written Evidently the band limitation of the amplitude transfer function, as imposed by the finite exit pupil, is unaffected by the presence of aberrations. Assumptions resembling these were made by Fresnel rather arbitrarily in his combination of Huygens' envelope construction and Young's principle of interference. The result presented in Eq. (5-22) is essentially the same result obtained when the input was placed directly against the lens itself. A more physical point-of-view, first qualitatively expressed by Thomas Young in 1802, CHAPTER 3 Foundations of Scalar Diffraction Theory 55 is to regard the observed field as consisting of a superposition of the incident wave transmitted through the aperture unperturbed, and a diffracted wave originating at the rim of the aperture. Rectangle function 0 otherwise Sinc function sinc(x) = 1 sin(~x) TX x > o Signum function - 1 x < o Triangle function Comb function A(x) = cornb(x) = otherwise 6(x - n) 14 Introduction to Fourier Optics T A B L E 2.1 Transform pairs for some functions separable in rectangular coordinates. To specify the properties of the lens system, we adopt the point of view that all imaging elements may be lumped into a single "black box", and that the significant properties of the system can be completely described by specifying only the terminal properties of the aggregate. The image may be real in the sense that an actual distribution of intensity appears across a plane behind the lens, or it may be virtual in the sense that the light behind the lens appears to originate from an intensity distribution across a new plane in front of the lens. (2n+ l)L 2 2. The lens L1 again casts a magnified image of the source onto 71. Even with electronic subtraction, it is often found that the low-frequency components being subtracted are very strong compared with the high-frequency information of interest, and imperfections in the subtraction operation may leave image artifacts or noise of serious proportions. Let the diodes in the pair be illuminated by a pair of equally bright read-out spots. Thus in order to assure stability of the image, it is necessary to remove the undeveloped silver halide grains, a process calledJixing the emulsion. (b) Suppose that the phase profile of the grating is of the more general form Find a general expression for the diffraction efficiency into all the orders of this new grating. For the beginner, it is difficult to know when one method will be easier than another, and therefore in this section two examples are presented that provide some insight in this regard. (b) Show that the Wigner distribution function for the one-dimensional finite chirp g(x) = exp(j.rrp x 2) rect - (k) CHAPTER 2 Analysis of Two-Dimensional Signals and Systems 31 is given by w(f, X) = (2L - 1x1) sinc[(2L - 1x1) (p x - f)] for 1x1 < 2L and zero otherwise. = Aol + AO2 5.1.2 The Paraxial Approximation The expression for the thickness function can be substantially simplified if attention is restricted to portions of the wavefront that lie near the lens axis, or equivalently, if only paraxial rays are considered. The assumption that the threshold is four atoms is an approximation. Assuming that the film is used in the linear region of the H&D curve, the density D may be written where y n is the slope of the linear region of the curve, and -Do is the value of D where a straight-line approximation would meet the D axis were there no toe. Given the relationship between object and image in the frequency domain, it seems obvious that the spectrum of the original object can be obtained by simply dividing the image spectrum by the known OTF of the imaging system, An equivalent statement of this solution is that we should pass the detected image i(x, y) through a linear space-invariant filter with transfer function Such a filter is commonly referred to as an "inverse filter", for obvious reasons. The application of an electric field across such a device can induce an electric dipole in each liquid crystal molecule, and can interact with any permanent electric dipoles that may be present. The Hughes liquid crystal light valve The most widely used liquid crystal SLM in optical information processing is the Hughes liquid crystal light valve. First, when a specified impulse response is desired, the task of finding the associated transfer function is eliminated; the impulse response is Fourier transformed optically by the system that synthesizes the frequency-plane mask. Imagine now that a complementary pair of beams is applied to the inputs -CHAPTER 7 n v + Pin 1 i Wavefront Modulation 205 p Pout 1 FIGURE 7.25 Symmetric SEED or S-SEED. 6.1, the "terminals" of this black box consist of the planes containing the entrance and exit pupils (see Appendix B for a discussion of these planes).' It is assumed that the passage of light between the entrance pupil and the exit pupil is adequately described by geometrical optics. CHAPTER 8 Analog Optical Information Processing 261 Inverse filter The first method is one that attempts to realize an inverse filter [275].Using the recording of the blur, we record two transparencies which will be sandwiched (i.e. placed in close contact) to form the frequency plane filter. +1, and 0 orders of the continuous (b) Find the diffraction efficiencies of the same orders for the quantized grating. Note, however, that before impinging on the diffuser it did originate from a point source. [227] and also Ref. The VanderLugt filter remains very sensitive to the exact position of the frequencyplane mask, but no more sensitive than the conventional coherent processor. This traveling wave induces a moving sinusoidal phase grating with period A = Vlf,, and interacts with the incident optical wavefront to produce various diffraction orders (cf. 7.7(b)), then it is of some interest to find the transfer function of the filtering operation, usually referred to as the modulation transfer function (MTF) of the photographic process. If Wh represents the width of h and W , is the width of g, both measured in the y direction, then separation of the desired terms can be shown to occur if as is to be shown in Prob. It has a complex amplitude that is proportional to the amplitude of the excitation U(PI) at the corresponding point. When a liquid crystal cell of thickness d has all of its molecules tilted such that the long dimension of the molecule lies in the (x, y) plane, but tilted at angle +Of to the y (vertical) axis, the effects of the cell on incident light can be represented by a Jones matrix that is the sequence of a coordinate rotation with angle Or, which aligns the direction of the y axis with the long axis of the molecules, a retardation matrix representing the phase shift experienced by polarization components oriented parallel to the long and short axes of the liquid crystal molecule, followed by a second rotation matrix with angle -O,, which returns the y axis to its original orientation at angle -8, to the long axis of the molecule. Mechanical searches are awkward and time-consuming, and therefore are not considered further here. Often the model is simplified to include only a single linear filter that precedes the nonlinear H&D curve, thus ignoring the linear filter associated with diffusion. The company says that it does not change the resolution of photos when they’re downloaded, but that it relies on the API of the social site itself. The coverage through Chapter 5 can be identical with that outlined above for the course that emphasizes optical signal processing. Repeat the spatial bounding CHAPTER 6 Image Frequency Analysis of Optical Imaging Systems 165 Reinforce boundedness) and posltlvlty A Inverse Fourier transform Fourier transform 1 Reinforce measured frequency components Spectrum FIGURE 6.24 Block diagram of the iterative extrapolation algorithm. P5.11, specify the locations of all Fourier and image planes to the left and right of the lens. Thus according to geometrical optics, the image and object would be related by Indeed we can show that our wave optics solution reduces to this geometrical optics solution by using the common artifice of allowing the wavelength A to approach zero, with the result that (see Prob. Note that the relations (5-7) amount to approximations of the spherical surfaces of the lens by parabolic surfaces. If the cell is illuminated normal to the direction of acoustic wave propagation, as shown in Fig. The soft emulsion also has a thin layer of a protective overcoating on its exposed surface, as illustrated in the cross section shown in Fig. Thus where U(P, v) is the Fourier spectrum of u(P, t). The peak intensity of the qth order is [A J , (m12)1hz]~,while the displacement of that order from the center of the diffraction pattern is q foAz. Figure 4.13 shows a cross section of the intensity pattern when the peak-to-peak phase delay m is 8 radians. Chapter 2 reviews the necessary mathematical background. Note that 3-1(fx, fy) simply specifies the complex weighting factor applied by the system to the frequency component at (fx, fv), relative to the weighting factor applied to the zero-frequency component. Goodman Stanford University THE McGRAW-HILL COMPANIES, INC. Thus the two Kirchhoff boundary conditions together imply that the field is zero everywhere behind the aperture, a result which contradicts the known physical situation. Express the amplitude and phase of that output in terms of an appropriate characteristic of the system. (c) Considering the two expressions for the cutoff frequency that you have found, can you estimate the "optimum" size of the pinhole in terms of the various parameters of the system? The idea was a radical one at the time, for it stated that under proper conditions, light could be added to light and produce darkness. If the two alignment layers are polished in different directions (for example, in orthogonal directions), then the tendency of the molecules to remain aligned with one another (characteristic of the nematic liquid crystal phase) and the alignment of the molecules with the direction of polish at the glass plates combine to create a twisted nematic liquid crystal, as illustrated in Fig. W.8. This ideal profile is approximated by a four-level quantized grating profile also shown in the figure. But since the amplitude transmittance of this filter is proportional to 1/)SI2,the intensity transmittance is proportional to 1/)SI4,and a 10 : 1 change of S implies a 10,000 : 1 change of intensity transmittance. This Preface will make several explicit suggestions for the shaping of different kinds of courses. Thus the approximation implicit in the scalar theory should be no more disturbing than the approximation used in lumped circuit theory. PREFACE Fourier analysis is a ubiquitous tool that has found application to diverse areas of physics and engineering. (The free version of SocialFolders limits you to three services and 2,000 files; a Premium account, which costs $10 per year, is unlimited.) SocialFolders organizes your Facebook photos into folders that correspond with your album names, and photo titles that correspond to your captions.Once you’ve connected SocialFolders to your social services, icons for each of them will appear in the SocialFolders folder that’s been created on your computer. Palermo (private communication, E.N. Leith). This complicated analog operation can be performed with extreme simplicity in a coherent optical system, taking advantage of the basic laws of propagation and diffraction of light. Thus 6Here and throughout, we shall retain the subscripts X and Yon frequency variables, even though the space variables to which they correspond may have different symbols. this reason, if we move in space in such a way as to intercept portions of a wavefield that were emitted later in time, the phasor will have advanced in the clockwise direction, and therefore the phase must become more negative. We assume that the blur the image has been subjected to is a linear, space-invariant transformation, describable by a known space-invariant point-spread function s(x, y). Note that these effects are limited to an amplitude change and a phase shift, as evidenced by the fact that we simply multiply the input spectrum by a complex number H (fx, fy) at each (fx, fy). Since the time of this early work, the merger of the two points of view has become so complete that it is sometimes difficult to judge whether a particular piece of work should be published in an optics journal or an electrical engineering journal. This phase term is important if the ultimate goal is to calculate another field distribution after further propagation and possibly passage through additional lenses, in which case the complete complex field is needed. To fully understand the properties of optical imaging and data processing systems, it is essential that diffraction and the limitations it imposes on system performance be appreciated. 3.10.2 Propagation of the Angular Spectrum Consider now the angular spectrum of the disturbance U across a plane parallel to the (x , y) plane but at a distance z from it. [221], [120], and [75]. Symbolically, we wish to find the inverse of the matrix D, allowing us to express the matrix of unknowns g through the equation g = D-I' g. Its modulus 13-11 is known as the modulation transfer function (MTF). Examine the validity of this claim. 6-13. The above result is by no means the only possible sampling theorem. (b) What is the value of the Sparrow separation (in the image space) for a system with a square aperture of width 2w, where an edge of the aperture runs parallel to the direction of separation of the two sources? The film is now ready for the development and fixing processes. g must be absolutely integrable over the infinite (x , y)plane. The intensity incident during exposure can be related to the intensity transmitted after development by recalling the definition of photographic density, When this definition is substituted into Eq. (7-I),we find or equivalently Finally, Tn = KnZ-Yn where K, is a positive constant. First, they can convert incoherent images into coherent images, as alluded to above. Note that at high signal-to-noise ratio, the Wiener filter reduces the relative strength of the low frequencies and boosts the relative strength of the high frequencies. The shaded area in the input plane represents the portion of the input transparency that contributes to the Fourier transform at (ul, v l) . More complex optical systems can be analyzed by using the same methods applied above. The phase transmittance was controlled by insertion of a transparent plate with an appropriately varying thickness. Show that, if r21 >> A, Eq. (3-26) can be reduced to Eq. (3-27). 28 Introduction to Fourier Optics (b) 3{A(x)A(y)) = sinc2(fx) sinc2(fy). Note the presence of the bright point of light in the response to P, indicating the high correlation between the input letter and the letter to which it is matched. A magneto-optic film has a Faraday rotation coefficient of 1.46"/pm and an absorption coefficient of 0.086 p m - ' . We assume that the power spectral densities8 (i.e. the distributions of average power over frequency) of the object and the noise are known, and are represented ,(fx, fy) and @,(fx, fy). The dimensions of P are meters-2. Attention in this section is devoted to imaging systems with coherent illumination. This transparency could have been obtained by imaging a point source through the blurred system, or could have been generated by computer. Remember the second approximation above.) (b) Again calculate the cutoff frequency, but this time assuming that the pinhole is so small that Fraunhofer diffraction by the pinhole governs the shape of the point-spread function. For a binary optic element with 2N levels, N separate masks are required. 2.5. The area under each 6 function is proportional to the value of the function g at that particular point in the rectangular sampling lattice. The algorithm is one that iterates between the object domain and the spectral domain, making changes in each domain to reinforce prior knowledge or measured data. By increasing d, the distance from the focal plane, the size of the transform is made larger, at least until the transparency is directly against the lens (i.e. d = f). 4-11. The applicability of a boundary diffraction approach in more general diffraction problems was investigated by Maggi [202] and Rubinowicz [249], who showed that the Kirchhoff diffraction formula can indeed be manipulated to yield a form that is equivalent to Young's ideas. 7.19. The three postulates above lead to certain conclusions regarding the mathematical relationship between changes of exposure and resulting changes of amplitude transmittance. Many other examples can be found in the fields of signal and image processing. Such a problem is of considerable importance in astronomy, where the presence or absence of weak companion stars next to a brighter star may often be of interest. Thus the direction of the torque exerted by the field on the molecules is independent of the polarity of the applied voltage, and they align in the same direction with respect to the applied field, regardless of polarity. [loo], [297], [218], [204], [160], or [156]. For a number of additional Fourier-Bessel transform pairs, the reader is referred to the problems (see Prob. The first allows us to specify the disturbance incident on the aperture by neglecting the presence of the screen. To illustrate the calculation of a generalized transform, consider the Dirac delta function, which has been seen to violate existence condition 3. Consider now the crosscorrelation of the functions g and h, which in rectangular coordinates is written Of particular interest is the value of the crosscorrelation at the origin, which in rectangular and polar coordinates can be written CHAPTER 8 Analog Optical Information Processing 255 The particular case of the crosscorrelation between the function g(r, 8) and an angularly rotated version of the same function, g(r, 8 - a), yields which, when the function g*(r,8) is expanded in a circular harmonic expansion, is equivalently expressed as R = lom[r m = -m) lo2 (r ,8 - I a) e - ~ ~d8' dr. The object amplitude distribution is now periodic with fundamental frequency 2 f . Nonetheless, it should not be forgotten that since Fraunhofer diffraction is only a special case of Fresnel diffraction, the transfer function (4-21) remains valid throughout both the Fresnel and the Fraunhofer regimes. To this end, let the normalized frequency spectra of I, and Ii be defined by m Gi(fx, fv) [-I Ii(u, v) exp[- j 2 ~fxu (+ fyv)] d u dv m = j Ii(u, U)d u d~ - - (6-24) m The normalization of the spectra by their "zero-frequency" values is partly for mathematical convenience, and partly for a more fundamental reason. After processing, this

transparency is illuminated by collimated light and the transmitted field is Fourier transformed by a positive lens L4, assumed to have the same focal length f as the lens used in the recording process (see Fig. 4-16), or if a positive lens is properly situated between the observer and the aperture (see Chapter 5). We accordingly devote special attention to the problem of Fourier transforming a circularly symmetric function. If the majority of functions of interest are to be included within the framework of Fourier analysis, some generalization of the definition (2-1) is required. The publication of the paper "Optical data processing and filtering systems" [73] by the Michigan group in 1960 stimulated much interest in these techniques among electrical engineers and physicists alike. The angles of orientation in the two states are separated by 28,. To solve this problem, we follow Kirchhoff in applying Green's theorem and in choosing as an auxiliary function a unit-amplitude spherical wave expanding about the point Po(the so-called free space Green's function). This extension is not difficult to make, but we will not present it here. As has been the case in previous analyses, we restrict attention to monochromatic light, an assumption that will be seen in the next chapter to limit consideration to what we call "coherent" systems. In the absence of aberrations, the response h arises from a spherical wave (of limited extent) converging from the exit pupil towards the ideal image point (u = M t , v = Mq). The concept of the intensity of a wave field is introduced, and the Huygens-Fresnel principle, from which the approximations are derived, is presented in a form that is especially well suited for approximation. We have chosen a one-dimensional variable x but the theory is easily generalized to a multidimensional Z. The Green's function in this case is given by Clearly such a function vanishes on the plane aperture 2, leaving the following expression for the observed field: We refer to this solution as the jirst Rayleigh-Sommei$eld solution. It offers a free and easy way to make sure you always have a backup of your precious online data. That is, it is always possible to calculate diffracted fields in the Fraunhofer region by retaining the full accuracy of the Fresnel approximation. The grating is modeled as a transmitting structure with amplitude transmittance with period L and with the grating lines running parallel to the q axis. We now consider the special case of a diffraction-limited incoherent system. However, the above advantages are accompanied by some serious disadvantages as well. As an additional example, it was shown that the periodic structure associated with the halftone process used in printing photographs, for example, in newspapers, could be suppressed by a simple spatial filter. We present a brief overview of the most important types. The most common description of the photometric properties of a photographic emulsion is the Hurter-Driffield curve, or the H&D curve, for short. The first arbitrary choice, appearing early in the analysis, was the use of a rectangular sampling lattice. phase modulation is introduced, but that phase modulation can be converted to an intensity modulation by appropriate optics following the mirror (cf. Fourier transformation. Applications to image C H A ~ 1R Introduction 3 enhancement, pattern recognition, and processing of synthetic-aperture radar data are considered. Our purpose is to find the conditions under which the field distribution Uican reasonably be said to be an "image" of the object distribution U,. FIGURE P4.9 92 Introduction to Fourier Optics 4-10. An amplitude klG(x2/Af , y2/Af) is incident on this plane, where G is the Fourier transform of g and kl is a constant. With the arrival of the nucleating field, a change of state of magnetization is initiated at the comer of the pixel. Assume uniform plane-wave illumination, neglect the finite size of the object and the evanescent wave phenomenon, and assume that paraxial conditions hold. If time is short, Chapter 6 can be skipped entirely. Assuming L > D: 122 Introduction to Fourier Optics (a) Find an expression for the maximum spatial frequency of the input for which the measured intensity accurately represents the squared modulus of the input's Fourier spectrum (free from the effects of vignetting). For this reason, the dynamic range of IS1 over which the filter functions properly is severely limited in practice. CHAPTER 3 Foundations of Scalar Diffraction Theory 41 impulsive driving function S(x - x') and with the same boundary conditions applying, then the general solution U (x)can be expressed in terms of the specific solution G(x) through a convolution integral U(x) = J G(x - x') V(x r)dx'. A more complete understanding of the relation between object and image can be obtained only if such effects are included. Such functions are, of course, of primary concern in optics, and the extension from one to two independent variables provides a new richness to the mathematical theory, introducing many new properties which have no direct counterpart in the theory of temporal signals and systems. Consider a thin lens that is composed of a portion of a cylinder, as shown in Fig. Much of the initial stimulus was provided by a French scientist, P.M. Duffieux, whose work culminated in the publication of a book, in 1946, on the use of Fourier methods in optics [86]. Suppose that a one-dimensional incoherent object with intensity distribution Ig(u) is bounded to the region (-Ll2, Ll2) on the u axis.9 By the Whittaker-Shannon sampling theorem, the object spectrum Gs(f) can be written in terms of its sample values at frequencies nlL: Now, due to the limited passband of the optical system, values of Gg(2) can be found only for a few low-integer values of n. However, this increased efficiency is often accompanied by a smaller dynamic range of exposure over which the tA-Ecurve remains linear. If the function is approximately space-limited and approximately bandlimited, then a rectangle (size 2Bx X 2By) within which most of the spectrum is contained can be defined in the frequency domain, and a rectangle (size 2Lx x 2Ly) within which most of the function is contained can be defined in the space domain. In the future it will be convenient to have a shorthand notation for a convolution relation such as (2-49), and accordingly this equation is written symbolically as where a @ symbol between any two functions indicates that those functions are to be convolved. A value of a greater than unity implies a demagnification of g and a value of a between zero and unity implies a magnification. When the illumination is polychromatic but narrowband, i.e. occupying a bandwidth that is small compared with its center frequency, this approach can be generalized by representing the field by a time-varying phasor that depends on both time and space coordinates. Fresnel propagation over a sequence of successive distances z l , 22, . The object is illuminated by a spherical wave that is converging towards the point where the optical axis pierces the lens. -- 'M y lar base should be avoided when coherent light is used, due to the fact that it is birefringent and causes unwanted variations of the polarization and phase of the transmitted light. In the Raman-Nath regime, the optical wavefront is simply phase modulated by the moving refractive index grating, yielding a complex amplitude of the transmitted signal given by { 'yd~($ +t) U, exp j - - s i n (+ t - ,)- (+ t - 7,)]} rect ,,Y CHAPTER 7 Wavefront Modulation 209 where U, is the complex amplitude of the incident monochromatic optical wave. It is important to further specify some properties of that medium. That current will cause a portion of the applied voltage to appear across the resistor, and less of the voltage to fall across the diode. For instance, the free version of Google Drive only provides 15GB of storage (which is a lot for a free service) while the free version of Dropbox gives users a comparatively lacking 2GB of storage. If you need to transfer a huge file of more than 15GB (like an edited video file, for example) then neither one of these services will cut it. As in the case of the waveguide driven below cutoff, these evanescent waves carry no energy away from the a p e r t ~ r e . From another point of view, we may regard the relations (2-50) and (2-51) as indicating that, for a linear invariant system, the input can be decomposed into elementary functions that are more convenient than the 6 functions of Eq. (2-43). (b) Cross section along the fxaxis with W,lA as a parameter. Note that if the function g(r, 8) undergoes a rotation by angle a to produce g(r, I3 - a),the circular harmonic expansion becomes and thus the mth circular harmonic is subjected to a phase change of - ma radians. For this reason those working in the field of optical information processing have explored a large number of devices capable of converting data in electronic form (or sometimes in incoherent optical form) into spatially modulated coherent optical signals. As will now be demonstrated, if the particular character is actually present at the input, then the particular output lvk12will be the largest of the N responses. The collimating lens L1 is followed by the input data in plane PI.The input data consists of an array of one-dimensional transmittance functions each running horizontally. While it is not obvious without some further thought and analysis, our results show that the quadratic-phase factor preceding the Fourier transform operation is always the quadratic-phase factor that would result at the transform plane from a point source of light located on the optical axis in the plane of the input transparency. The second, somewhat later in the analysis, was the choice of the particular filter transfer function (2-55). Similar principles can be used to construct a spatial light modulator for input to an optical information processing system. In order to synthesize linear optical systems with desired properties, the ability to manipulate light waves is needed. However, such elements are usually defined through a series of binary exposure steps, and this fact has provided the rationale for retention of the name. SocialFolders is both an application and a Web service: You download a component to your desktop, which creates a SocialFolders folder that you can access via Windows Explorer. this type of filter had been preceded by a related but less general technique, known as the hard-clippedjlrer, which was a filter generated by computer and is the first example of what now might be called a phase-only filter. To specify this solution further let Fol be the distance from sponding normal derivative of G- is Po to P I . 7.27. This formalism is outlined in Appendix C, to which the reader is referred. In addition, only paraxial conditions will be considered, a limitation also inherent in the usual geometrical optics treatment using ray matrices, as discussed in Appendix B. With these discussions as background, we turn away from the vector theory of diffraction to the simpler scalar theory. Following the liquid crystal is a dielectric mirror which reflects incident read light back through the device a second time. When the sources are in quadrature, the image intensity distribution is identical to that resulting from incoherent point sources. Fresnel and Fraunhofer Diffraction 93 4-13. Object I nl Film / FIGURE P6.7 6-8. The chemical processes that lead to these two different phenomena are in general different. The path-lenth error W(x, y) can then be determined by subtracting the ideal phase distribution from the actual phase distribution, The path-length error is thus given by which is seen to depend quadratically on the space variables in the exit pupil. Thus for object B, incoherent illumination must be termed better than coherent illumination. Functions separable in polar coordinates are not so easily handled as those separable in rectangular coordinates, but it is still generally possible to demonstrate that two-dimensional manipulations can be performed by a series of one-dimensional manipulations. We will also often refer to the input as the "object". Incident on the filter is a field distribution proportional to S, and transmitted by the filter is a field distribution proportional to SS*. Suppose that the observation distance satisfies = (2n + l) ~or, z = A Then 3 This distribution is also an image of the grating, but this time with a 180' spatial phase shift, or equivalently with a contrast reversal. Fourier transform of such a spread function yields the OTF of (6-42). Due to the optically flat faceplate on the read side, the wavefront exiting the device is of good optical quality and the device is therefore suitable for use within a coherent optical data processing system. that the symbol Z is used for intensity incident on the film during exposure; we reserve the symbol I to represent intensity incident on (or transmitted by) the transparency after development. 5.3.3 The Relation Between Object and Image Consider first the nature of the image predicted by geometrical optics. Quantitative analysis of the MOSLM device is aided by use of Jones matrices. The first operation on the wave takes place as it passes through L 1 ,and this operation is represented by the operator Q[The second operation is propagation through space over distance f, represented by the operator R[f]. Normalized FIGURE 4.9 2 ' 3 2wr / hz Cross section of the Fraunhofer diffraction pattern of a circular aperture. Figure 7.10 illustrates the phenomenon for the case of a square-wave density pattern. Such a point-of-view is particularly appropriate when film is used as an element of an incoherent optical system. The circular symmetry of the problem suggests that the Fourier transform of Eq. (4-25) be rewritten as a Fourier-Bessel transform. If r-21 is many optical wavelengths, then (3-26) can be directly reduced (see Prob. In the rear focal plane of the lens we find the Fourier transform of this field, Taking jhe squared magnjjude of fhjs field, the jn~ensjpjncjdent on fhe recordjngpJme is found to be 244 Introduction to Fourier Optics FIGURE 8.16 The joint transform correlator. T (v ~ ~ (xy)) = - 4 r 2 (f; = g(-x, - y) at all points of continuity of g. As a consequence, if an MQW device is illuminated by light with a properly chosen wavelength, the application of an applied field to the device can change the absorption experienced by that light as it passes through the structure, an effect that can serve as the basis for realizing an optical intensity modulator6 [303]. Thus a thin lens simply delays an incident wavefront by an amount proportional to the thickness of the lens at each point. For this reason, the function FIGURE 3.9 The wave vector i. Similar effects occur in electrical systems when an input with high-frequency components passes through a filter with a limited frequency response. The finite-length cosine itself can be expressed as the following intensity distribution: It follows that the (suitably normalized) spectrum of this intensity distribution is 162 Introduction to Fourier Optics as shown in part (b) of the figure, along with the assumed OTF of the imaging system. , K. As shown in part (a) of the figure, the torsion rod connects the mirror to supports at the ends of one diagonal. Nonetheless, the required conditions are met in a number of important problems. The necessary concepts are all introduced in Appendix B. Specifically, such filters are too sensitive to scale size changes and rotations of input patterns. CHAPTER 6 Frequency Analysis of Optical Imaging Systems Considering the long and rich history of optics, the tools of frequency analysis and linear systems theory have played important roles for only a relatively short period of time. 3.3.1 The Helmholtz Equation In accord with the previous introduction of the scalar theory, let the light disturbance at position P and time t be represented by the scalar function u(P, t). A polarizer and analyzer are external to the device, as will be discussed. 8-14). 7.26), and negative for diffraction orders with components of direction opposite to that of the motion of the acoustic wave (i.e. upwards in Fig. 31n the past it has been customary to introduce a graphical aid known as "Cornu's spiral" as a tool for estimating values of Fresnel integrals. CHAPTER 8 Analog Optical Information Processing 251 Origin Crosscorrelation of Q with input Crosscorrelation of W with input 4 4 Crosscorrelation of P with input FIGURE 8.20 Synthesis of a bank of matched filters with a single frequency-plane filter. The company does note that most of the photo-sharing sites it supports lets users download photos in full resolution, though. (b) Repeat for the case of mutually incoherent fields. 5.3.2 Eliminating Quadratic Phase Factors: The Lens Law The most troublesome terms of the impulse response above are those containing quadratic phase factors. As we shall see in Section 6.4, a system that has aberrations is not free from phase distortion within its passband. This in fact can be done by regarding the photographic process as a cascade of several separate mappings, as illustrated in Fig. However, the more general case of a nonmonochromatic disturbance will now be considered briefly; attention is restricted to the predictions of the first RayleighSommerfeld solution, but similar results can be obtained for the other solutions. 6-14. For an overview of the field, including examples of many different approaches, the reader is referred to the proceedings of a series of meetings held on this general subject [591, [601, [611, [621, [631. Under this condition the systems studied are "coherent" systems, which means that they are linear in complex amplitude, and the distribution of light amplitude across a particular plane behind the positive lens is of interest. If there are 2N levels desired, N different masks, exposures, development, and etching processes are required. For example, tiny dust particles on a lens may lead to very pronounced diffraction patterns that will be superimposed on the image. Fourier transforming the Fresnel diffraction impulse response (4-16), we find (with the help of Table 2.1) a transfer function valid for Fresnel diffraction, = ejkzexp 1- j?rhz (fi+ f:)]. Typical time constants for NLC materials are approximately 100 p s for the molecules to align with an applied field, and 20 ms for the molecules to relax back to their original state. Unlike the case of nematic liquid crystals, DC fields of opposite polarity must be applied to the ferroelectric liquid crystal in order to switch between states. 7 7 are ~ N fixed 77 coordinates in the input plane. In the former case the intensity in the image plane becomes while in the latter case we have *In practice, phase-contrast microscopes usually have a source that is a circular ring and a phase-shifting structure that is also a circular ring, placed over the image of the source in the focal plane. Subscriptions are available in both monthly and yearly plans, but if you want to save money, go for the annual payment—it shaves off a few bucks overall. Masv Masv is the go-to service for people that need to transfer tremendously large files online. CHAFFER 6 Frequency Analysis of Optical Imaging Systems 137 fy/2fo FIGURE 6.3 Amplitude transfer functions for diffraction-limited systems with (a) square and (b) circular exit pupils. 4An optical system is called anamorphic if the focusing powers of the system in two orthogonal directions are unequal. Thus as we move between the two plates, the directions of the long axes of the various molecules remain parallel to one another in planes parallel to the glass plates, but gradually rotate between those planes to match the boundary conditions at the alignment layers. The spatial frequency response of an emulsion is limited by two separate phenomena: 1. Siegman, Charles Susskind, Frederick E. This completes the background on liquid crystal cells, and we now turn attention to specific spatial light modulators based on these materials. For the above reasons, in this chapter attention is focused on methods for spatially modulating optical wavefields, especially coherent fields. CHAPTER 2 Analysis of Two-Dimensional Signals and Systems M a n y physical phenomena are found experimentally to share the basic property that their response to several stimuli acting simultaneously is identically equal to the sum of the responses that each component stimulus would produce individually. Thus and = 2 (y) AJ, sinc [2w(fx - qfo)] sinc(2wfY). At this point we introduce the reader to some of these terms. Such problems are excluded from consideration here, since the vectorial nature of the fields must be taken into account if reasonably accurate results are to be obtained. Light rays are also bent upon reflection, which can occur at a metallic or dielectric interface. (a) Recording the filter, (b) obtaining the filtered output. The input is placed in plane PI in contact with lens L1. Relation (5-46) is a statement of the similarity theorem of Fourier analysis, while relation (5-47) follows from the Fourier inversion theorem, slightly modified to account for the fact that both transforms are in the forward direction. (a) Express the phase distribution of the spherical wave across an (x, y) plane located normal to the z axis at coordinate z = 0. The row and column electrodes are separated in the vertical direction by an insulating film. New rays are assumed to be generated at edges, corners, tips, and surfaces of the obstacle. 1.2 THE BOOK The readers of this book are assumed at the start to have a solid foundation in Fourier analysis and linear systems theory. An additional unusual attribute of the Ragnarsson filter is the fact that it is recorded with the object wave much stronger at the origin of the film plane than the reference wave, i.e. When the square lies entirely behind the obstruction of the aperture, then the observation point lies in a region that is, to a good approximation, dark , Integral FIGURE 4.4 0 0.5 1 1.5 2 2.5 3 Magnitude of the integral of the quadratic-phase exponential function. Examples of this type of problem are discussed in their historical perspective in Section 8.1. There are equally important applications that do not fall in the realm of imaging as such, but rather are more properly considered in the general domain of information processing. (c) If you have access to a computer and appropriate software, plot the Wigner distribution function of the finite-length chirp for L = 10 and P = 1, with x ranging from - 10 to 10 and f ranging from - 10 to 10. The subject is discussed further in that context in Section 9.10.4. Finally, highly coherent illumination is particularly sensitive to optical imperfections that may exist along a path to the observer. 130 Introduction to Fourier Optics again neglected quadratic phase factors over the object and image planes, as justified in Section 5.3. In order to achieve space invariance in the imaging operation, it is necessary to remove the effects of magnification and image inversion from the equations. In the end, the complexity of digital and optical solutions to a given approach must be carefully and critically assessed to determine whether there is really a practical motivation to pursue the optical solution. Evidently when the input is placed in the front focal plane of the lens, the phase curvature disappears, leaving an exact Fourier transform relation! CHAPTER 5 Wave-Optics Analysis of Coherent Optical Systems 105 Input plane . 208 Introduction to Fourier Optics K FIGURE 7.27 - 4 4 k, = ki + K yave vector diagram for Bragg interaclion. Finally, the goal is to produce a linear restoration filter that minimizes the mean-square difference between the true object o(x, y) and the estimate of the object B(x, y), i.e. to minimize e2 = Average [l o - 61'1. A third variation would be a one-quarter or one-semester course that covers the basics of Fourier Optics but focuses on holography as an application. Show that at certain distances behind this object, perfect images of the amplitude transmittance are found. Explain your conclusion. Consider a thin periodic grating whose amplitude transmittance can be represented by a complex Fourier series, where L is the period of the grating and Neglect the aperture that bounds the grating, since it will not affect the quantities of interest here. However, if the optical system contains apertures that are not separable in rectangular coordinates, a two-dimensional extension of the treatment is necessary. We now embark on a series of additional approximations. 'In general it is not necessary that the entrance pupil lie to the left of the exit pupil as shown in Fig. The acoustic wave propagates in the medium through small local displacements of molecules (strain). An example of a more complex case might be a focusing element which generates an aspheric wavefront such that certain aberrations are reduced or eliminated. Suppose that we now place a phase plate over one of the two apertures in the pupil, a phase plate that introduces a 180' phase shift, which we assume to be approximately constant over the narrow band of optical wavelengths used in this experiment. In the material that follows, several different configurations for performing the transform operation are described. Such an approach neglects the fact that, at boundaries, the various components of the electric and magnetic fields are coupled through Maxwell's equations and cannot be treated independently. Diffractive optical elements also generally have much less weight and occupy less volume than their refractive or reflective counterparts. These conditions are commonly known as the Kirchhoflboundary conditions. We briefly discuss the approximation process here, and then turn to the most common methods of fabrication. This latter quantity is entirely real, which implies that the frequency-plane filter exactly cancels all the curvature of the incident wavefront S. 7-8. Typically at least two additional silver atoms must be added to the silver speck in order for it ultimately to be developable. However, the theory becomes much more significant if it can be applied to synthesis problems as well. [270]) as "any deviation of light rays from rectilinear paths which cannot be interpreted as reflection or refraction." Diffraction is caused by the confinement of the lateral extent of a wave, and is most appreciable when that confinement is to sizes comparable with a wavelength of the radiation being used. Thus the transmitted field consists of aplane wave (generally of nonuniform intensity), which is brought to a bright focus by the final transforming lens. You simply create a folder in the SocialFolders directory on your desktop, and its contents will be automatically synced to your account. RpSand CpSare the resistance and capacitance of the photosensor, CDMis the capacitance of the dielectric mirror, and RLC and CLCare the resistance and capacitance of the liquid crystal layer. A prism (illustrated in Fig. The garnet mesas are largely transparent to light, but when fully magnetized, they rotate the polarization of incident light as a consequence of the Faraday effect. 6.9, the OTF is again seen to extend to a frequency that is twice the coherent cutoff frequency. These SLMs gradually evolved into deformable mirror devices, in which discrete cantilevered mirrors were individually addressed via voltages set on floating MOS (metal oxide semiconductor) sources, the entire device being integrated on silicon. The statistical nature of the time variations of illumination amplitude and phase can, in fact, influence the behavior of an imaging system in profound ways. 7.1. In addition, certain sensitizing agents are added to the gelatin; these agents have a strong influence on the introduction of dislocation centers within the silver halide crystals. SLMs based on these materials are inherently binary in nature, but gray scales can be created with the help of half-tone techniques. Limitations All systems designed on the basis of geometrical optics must satisfy a common constraint: the geometry of the system must be chosen in such a way that diffraction effects are entirely negligible. For a particular training image, we may want the correlation with our filter's impulse response h(x, y) to be unity (i.e. that particular training image is a distorted version of the ideal image), and in some cases we may wish it be zero (i-e. If we further write u- (P , t) = U(P, t) exp(- j 2 ~ i s t) where Y represents the mean or center frequency of the optical wave, then the complex function U(P, t) may be regarded as the time-varying phasor representation of u(P, t). The results of the monochromatic analysis can therefore be applied directly to such systems, with the understanding that the complex amplitude U is now a time-invariant phasor that depends on the relative phases of the light. A typical transmissive S-SEED structure is shown in Fig. Light scattering is linear in the variable exposure, while chemical diffusion is linear in the variable density. We have chosen to remain with the simplest coordinate system consistent with a paraxially space-invariant system. The electron and the silver ion combine to form a single atom of metallic silver at the dislocation site. Using (3-35), it follows directly that where it has been assumed that rol >> A. It is helpful to cast this problem in matrix form. Remember that in order to completely remove the quadratic phase factor across the object, the object should be illuminated with a spherical wave, in this case converging towards the point where the entrance pupil is pierced by the optical axis (cf. 8-2 and 8-3). We return in a later subsection to discussing some of the difficulties of the matched filter approach to such problems. m (b) comb(ax) comb(by) = m ,& 1 1 8 (x z, y - n=-mm=-m 2-2. 3.5 THE RAYLEIGH-SOMMERFELD FORMULATION OF DIFFRACTION The Kirchhoff theory has been found experimentally to yield remarkably accurate results and is widely used in practice. An example of this type of application is found in the discussion of processing synthetic-aperture radar data (Section 8.9). (2-41) Without specifying more detailed properties of the operator SO, it is difficult to state more specific properties of the general system than those expressed by Eq. (2-41). 7.2.1 Properties of Liquid Crystals The use of liquid crystals in low-cost displays is commonplace. Precise alignment of the filter transparency is required for the VanderLugt geometry, while no such alignment is necessary for the 'Strictly speaking, the function should also be conjugated, but in practice the functions g and h are usually real. He is a Fellow of the OSA, the SPIE, and the IEEE. 2-5. Eq. (2-23)). With exposure in the linear region of the t~ VS. (A diffracting structure such as this is known as a Fresnel zone plate. 5.2 FOURIER TRANSFORMING PROPERTIES OF LENSES One of the most remarkable and useful properties of a converging lens is its inherent ability to perform two-dimensional Fourier transforms. In 1935, Frits Zernike [305]proposed a new phase contrast technique which rests on spatial filtering principles and has the advantage that the observed intensity is (under certain conditions to be discussed) linearly related to the phase shift introduced by the object.' This development represents an early success of synthesis ideas and therefore will be treated in some additional detail. In the geometrical-optics approximation, the rays passing through 72 converge -A FIGURE 8.8 Impulse response synthesis with a misfocused system. The resulting refractive index structures constitute a pure phase image. Thus we restrict attention at the outset to systems characterized by many-to-one mappings. In such a case the SLM is placed in the back focal plane of a Fourier transforming lens, where it modifies the transmitted amplitude of the fields in accord with a desired complex spatial filter. CHAPTER 2 F{N2 exp[-N2.sr(x2 Analysis of Two-Dimensional Signals and Systems 7 [+ y2)]) = exp - -'f$ f3]. The finite extent of the illuminating spot can be represented mathematically by projecting the pupil function of the lens down the cone of rays to the intersection with the input plane, yielding an effective illuminated region in that plane described by the pupil function P [t (f Id), q (f Id)]. P4.7. (b) Sketch normalized cross sections of this pattern that appear along the x and y axes in the observation plane, assuming XIAz = 10 m-', YIAz = 1 m-', and Alhz = 312 m-', z being the observation distance and A the wavelength. In case (b), the input is placed a distance d in front of the lens. In some cases there must be a heavy intrusion of electronic digital processing, a process that can slow down the natural speed (obtained from parallelism) of a purely optical solution. Attention is turned to analog optical information processing in Chapter 8. Show that a function with no nonzero spectral components outside a circle of radius B in the frequency plane obeys the following sampling theorem: 2-13. Advanced embedding details, examples, and help! At a GlanceWorks in the backgroundSimple to useSome photos were low-resSome photos were low resSocialFolders makes it easy to create offline copies of your online data. Finally we mention that it is also possible to arrange a coherent system to process a stacked array of one-dimensional inputs, rather than a single two-dimensional input. 84 Introduction to Fourier Optics 4.5.1 Fresnel Diffraction by a Square Aperture Suppose that a square aperture of width 2w is normally illuminated by a monochromatic plane wave of unit amplitude. Again the mirror is metallized and connected to a negative bias voltage. 4. Towards this end, we return to the expression (5-33) for the impulse response of the imaging system. Therefore the expressions exp(jkrol)and exp[j&(x2+ y2)] (for positive Z)represent a diverging spherical wave and a quadraticphase approximation to such a wave, respectively. represent a vector cross product and a vector dot product, respectively, while V = -& s , where i, j and R are unit vectors in the x, y, and z directions, respectively. A low-contrast intensity distribution exposes a photographic plate, and a negative transparency is made. There isn’t much call for consumer FTP use, which means the available options can be a bit on the complicated side. It should be noted that, for even a very simple impulse response (such as one in the shape of the character " P , for example), the corresponding transfer function was (I) difficult to calculate (prior to the development of the fast Fourier transform algorithm for digital computation of spectra) and (2) far too complicated to be synthesized by these rather simple techniques. Equivalently we may write where the phase of the time-varying phasor at the origin has arbitrarily been chosen as a phase reference, the time-independent U , are phasor amplitudes relative to the time varying phasor amplitude at the origin, and the normalizations have been performed to allow the time-independent phasors to retain correct information about the average power or intensity. The small scratches associated with the polishing operation establish a preferred direction of alignment for the molecules that are in contact with the plate, with their long direction parallel with the scratches. [201] for further comparison of the two approaches. Note also that a source having wavelength 850 nm, as indicated by the vertical dashed line, will experience decreasing absorption as the voltage is increased. The theory does not directly indicate what the response might be to an image that is not a member of the training set, but the method still provides a useful design procedure to obtain filters with a significant degree of invariance to various image parameters. Considerable success was also demonstrated in the removal of image blur. We suppose that a certain thickness function A(x, y) is desired for the element (as usual, x and y are the transverse coordinates on the face of the element). Second, phase changes of as little as a fraction of a radian can change the value of the exponential significantly. 2.3 for an illustration of its structure. 8-4). Such a description was advocated at an early stage by Markha1 and was very successfully used by Kozma [176] in an analysis of the effects of photographic nonlinearities. However, as we shall now see, such a limitation can be removed by the Rayleigh-Sommerfeld theory. We can say in very general terms that each given type of film has a limited spatial frequency response. CHAPTER 3 Foundations of Scalar Diffraction Theory 59 angular spectrum of the disturbance. During the second step, the light transmitted by the negative transparency is used to expose a second emulsion, and the result is a final positive transparency. In addition, a series of meeting proceedings on the subject provides valuable information [88], [89], [90]. The single property of linearity leads to a vast simplification in the mathematical description of such phenomena and represents the foundation of a mathematical structure which we shall refer to here as linear systems theory. Whereas the incoherent system is linear in intensity, the coherent system is highly nonlinear in that quantity. These conditions will be well satisfied in the problems treated here. This lens images the source onto the frequency plane P2, where the filter transparency is placed. (7 - 9 , (7-2), and (7-3) allows the amplitude transmittance to be expressed as tA(x.y) = = K IuI-~, (7-6) where U is the complex amplitude of the field incident during exposure, K is a constant, and y is a positive number for a negative transparency and a negative number for a positive transparency. For this reason, incoherent processing must be supplemented with some other form of processing, either electronic processing or coherent optical processing, to achieve the desired bandpass operation. 8.6.3 Optical Synthesis of a Character-Recognition Machine The matched filter operation can readily be synthesized by means of either the VanderLugt technique or the joint transform technique discussed earlier. A variety of types of improvements to photographs were successfully demonstrated by Markcha1 and his co-workers. Nonetheless, provided the coherence area on the object is small compared with a resolution cell size in object space, Eq. (6-14) is accurate. (a) Focal-plane filter; (b) transfer functions. L1 L2 FIGURE P5.10 5-11. Any such function can be represented in the form where a(x, y) is a real and nonnegative amplitude distribution, while 4(x, y) is a real phase distribution. The trapped electron electrostatically attracts a silver ion; such ions are mobile even before exposure by light, a consequence of thermal agitation. (b) Relief image after bleaching. There are many variants of these devices, some using nematic liquid crystals, and others using ferroelectric liquid crystals. The capacitances involved can be controlled in the design of the device, through appropriate choice of layer thicknesses, to satisfy these requirement^.^ Figure 7.20 illustrates the write and read operations. This space-variant attribute is a direct result of the magnification and image inversion that occur in the imaging operation. Figure 7.4 illustrates a typical dependence of y on development time. 3.10.1 The Angular Spectrum and Its Physical Interpretation Suppose that, due to some unspecified system of monochromatic sources, a wave is incident on a transverse (x, y) plane traveling with a component of propagation in the positive z direction. An unsophisticated solution to this problem is quite straightforward. For a detailed treatment of this approach to diffraction theory, as well as its applications in the theory of radio-wave propagation, the reader is referred to the work of Ratcliffe [240]. Thus the amplitude transmittance of the filter is of the form Note that, aside from the simple complex-exponential factor, the third term of the amplitude transmittance is proportional to H and therefore exactly the form required to synthesize a filter with impulse response h. Let the transform operators FA{} and &{} be defined by (a) Find a simple interpretation for F B { ~ A { ~~(x) l, l . (Both maxima are assumed to exist on the optical axis.) Prove that 2) is equal to the normalized volume under the optical transfer function of the aberrated imaging system; that is, prove where the notations "with" and "without" refer to the presence or absence of aberrations, respectively. Approximation by a stepped thickness function Binary optical elements have stepped approximations to ideal continuous phase distributions. But this argument is incompatible with our assumption of monochromatic disturbances, which must (by definition) have existed for all time. SThis is a sufficient but not necessary condition for complete coherence. Unfortunately the achievement of scale-size and rotation invariance by the method described above leads to a loss of the translation invariance that characterized the conventional matched filter. Part (b) of the figure shows cross sections of the intensity point-spread functions for the two cases. g must have only a finite number of discontinuities and a finite number of maxima and minima in any finite rectangle. 3.7). z) = A, wo exp [- &] exp [jkz + jx- 2Wz) p2 + j ~ (z)] where Wo is a constant (independent of z) and 8(z) is a phase angle that changes with z. j]. In 1860 Maxwell identified light as an electromagnetic wave, a step of enormous importance. A photon incident on a silver halide grain may or may not be absorbed by that grain. Fourier analysis provides the basic means of performing such a decomposition. The case of Eq. (8-3) is referred to as positive phase contrast while the case of Eq. (8-4) is referred to as negative phase contrast. The scalar theory holds. A "sawtooth" phase grating is periodic with period Land has a distribution of phase within one period from 0 to L given by (a) Find the diffraction efficiencies of all of the orders for this grating. At a distance d from 71 and immediately in front of lens L2 the transparency r2(x,y) appears. Then, retaining only the first two terms of the expansion (4-1 l), we have The question now arises as to whether we need to retain all the terms in the approximation (4- 13), or whether only the first term might suffice. When is nearly normal to the surface, the total power P is simply the integral of the power density p over the detector area. The illumination of the aperture in all cases is a spherical wave diverging from a point source at position P2 (see Fig. In closing we mention the remarkable fact that, despite the apparent differences of their approaches, the angular spectrum approach and the jirst Rayleigh-Sommerfeld solution yield identical predictions of difSracted jields! This has been proved most elegantly by Sherman [260]. When a focusing error is present, the center of curvature of the spherical wavefront converging towards the image of an object point-source lies either to the left or to the right of the image plane. As a result the complex amplitudes transmitted into the two first orders, represented by U* 1, are given approximately by U 2 1 = ?- U,A A0 (i: + t)e - - T, Tj Y ~ (y l V + r - ~) ej27rylAe+ + j27r fC(t-ro) rect -, L (7-34) where the top sign corresponds to what we will call the "+1" diffraction order (diffracted downwards in Fig. Thus while any two object points may have different relative phases, their absolute phases are varying with time in a perfectly correlated way. Scaling by a constant. The phenomenon called difSraction is of the utmost importance in the theory of optical systems. Thus light absorbed by the photoconductor increases its local electrical conductivity in proportion to the incident optical intensity. 168 Introduction to Fourier Optics 6-7. Thus, at the output of this filter we find an exact replica of the original data g(x, y). Later we very briefly indicate improvements of the theorem that can be made in some two-dimensional cases. An incoherent optical processing system has no "frequency plane", as is found in the focal plane of a coherent optical system, and the manipulation of the spectrum of an input must therefore resort to less direct methods than simply modifying the fields CHAPTER 8 Analog Optical Information Processing 225 in the Fourier plane in proportion to a desired transfer function. In addition, the bleach must remove the sensitizing agents found in unexposed silver halide crystals to prevent them from turning to metallic silver due to thermal effects and additional exposure to light. 6.12(a) is used as the object. As stated in the above discussion, to successfully recover the original data it is necessary to take samples close enough together to enable separation of the various To determine the maximum allowable separation between samspectral regions of Gs. ples, let 2Bx and 2By represent the widths in the fx and fy directions, respectively, of the smallest rectangle7 that completely encloses the region R . Examining this problem in more detail, we see that, on S2, G = exp(jkR) R and, from (3-20), where the last approximation is valid for large R. For a positive photoresist, the development process removes the exposed areas and leaves the unexposed areas, while for a negative photoresist the opposite is true. The lifetime of this combination is rather short, of the order of a few seconds. He has been a member of the Stanford faculty since 1967, and served as the Chairman of the Department of Electrical Engineering from 1988 through 1996. Measurements of the electrical and optical properties of this type of DMD have been reported in the literature [278]. 4.1.2 The Huygens-Fresnel Principle in Rectangular Coordinates Before introducing a series of approximations to the Huygens-Fresnel principle, it will be helpful to first state the principle in more explicit form for the case of rectangular coordinates. The output of interest here will be in the plane where the point source is imaged, at distance 22 to the right of the lens, where zl, zz, and the focal lengthf of the lens satisfy the usual lens law, z; l + z , - f = 0. The system input and output can now be related by the simple equation This fundamental expression, known as the superposition integral, demonstrates the very important fact that a linear system is completely characterized by its responses CHAPTER 2 Analysis of Two-Dimensional Signals and Systems 21 to unit impulses. The third possibility for eliminating the effect of the quadratic phase factor in object coordinates requires a more lengthy discussion. Under this condition both a and P go to zero, and the cell has no effect on the incident polarization state. The total intensity incident at each point on the recording medium is determined by the interference of the two mutually coherent amplitude distributions present. For certain functions, these integrals may not exist in the usual mathematical sense, and therefore this discussion would be incomplete without at least a brief mention of "existence conditions". Note that if there are many grating periods within the aperture, then fo >> llw, and there will be negligible overlap of the three sinc functions, allowing the intensity to be calculated as the sum of the squared magnitudes of the three terms in (4-35). A linear transformation can then play a crucial role in the reduction of large quantities of data, yielding indications of the particular portions of the data that warrant the attention of the observer. Let the point of observation be denoted Po, and let S denote an arbitrary closed surface surrounding Po,as indicated in Fig. To emphasize this point-of-view, we write U as an inverse Fourier transform of its spectrum, To give physical meaning to the functions in the integrand of the above integral, consider the form of a simple plane wave propagating with wave vector 6 where i has magnitude 2 n l h and has direction cosines (a, P , y), as illustrated in Fig. –Liane Cassavoy Introduction to Fourier Optics McGraw-Hill Series in Electrical and Computer Engineering SENIOR CONSULTING EDITOR Stephen W. The input to a certain imaging system is an object complex field distribution U,(x, y) of unlimited spatial frequency content, while the output of the system is an image field distribution Ui(x, y). Next consider a space-limited version of a quadratic-phase exponential function: which we call a "finite chirp" f ~ n c t i o n , ~ g(x, y) = exp[j7.r~ (x2 + y2)l rect (&) rect(&). 7-5. If frequency analysis is to be applied in its usual form, it must be applied to the linear amplitude mapping. 6.4.1 The Generalized Pupil Function When an imaging system is diffraction limited, the (amplitude) point-spread function has been seen to consist of the Fraunhofer diffraction pattern of the exit pupil, centered on the ideal image point. [91], Chapters 1 and 2. For this discussion we assume that the amplitude distribution a(x, y) CHAPTER 2 Analysis of Two-Dimensional Signals and Systems 17 is a slowly varying function of (x, y), so that we can concentrate on the behavior of the phase function +(x, y). An object has an intensity transmittance given by and introduces a constant, uniform phase delay across the object plane. 8.20(a), but with only the function s(x, y) present in the input transparency. If attention is restricted to deterministic (nonrandom) systems, then a specified input must map to a unique output. 3.4. Progress on further understanding diffraction was impeded throughout the entire 18th century by the fact that Isaac Newton, a scientist with an enormous reputation for his many contributions to physics in general and to optics in particular, favored the corpuscular theory of light as early as 1704. 8.1.3 Improvement of Photographs: MarCchal In the early 1950s, workers at the Institut d'optique, UniversitC de Paris, became actively engaged in the use of coherent optical filtering techniques to improve the quality of photographs. P5.9). The photoconductor should have the highest possible resistivity in the absence of write light, and the lowest possible resistivity in the presence of strong write light. Noting that Eq. (2-56) becomes Finally, when the sampling intervals X and Y are taken to have their maximum allowable values, the identity becomes Equation (2-57) represents a fundamental result which we shall refer to as the Whittaker-Shannon sampling theorem, It implies that exact recovery of a bandlimited function can be achieved from an appropriately spaced rectangular array of its sampled values; the recovery is accomplished by injecting, at each sampling point, an interpolation function consisting of a product of sinc functions, where each interpolation function is weighted according to the sampled value of g at the corresponding point. An aid for visualizing the relations between the optical and acoustical wave vectors is a wave vector diagram, as shown in Fig. If an object is placed in front of a lens and illuminated, then under appropriate conditions there will appear across a second plane a distribution of light intensity that closely resembles the object. However, if information is being rapidly gathered, perhaps by some electronic means, one would prefer a more direct interface between the electronic information and the data processing system. There exist many examples of the benefits reaped by the application of linear systems concepts to the synthesis of optical systems. Note that the frequency $ lies beyond the cutoff of the OTF. If this is done it is found that the quadratic phase exponential in (5,q) associated with the illuminating wave exactly cancels the similar quadratic phase exponential in the integrand of the Fresnel diffraction integral, with the result Uf(4 4 = A exp[j&(u2 jhd + u2)] f d CHAPTER 5 Wave-Optics Analysis of Coherent Optical Systems 107 Thus, up to a quadratic phase factor, the focal-plane amplitude distribution is the Fourier transform of that portion of the input subtended by the projected lens aperture. We now present the reader with a methodology that will help determine the proper sign of the exponent in all of these cases. The reason for doing so is only partly because of the extensive past work. The signal-to-noise ratio is varied from 1000 to 1. Various solutions to the scalar diffraction problem to be discussed in the following sections correspond to results obtained under different assumptions about the Green's function of the problem. 7.24(b) indicates, when the full voltage exists across the device, the absorption is low but still significant. This can be done by defining reduced coordinates in the object space4 according to in which case the amplitude point-spread function becomes - h(u - [, u - ij) A 1 = - hzi P(x, y) exp {- A z ~[(u 2Tr j- - [)x + (u - ij)y] At this point it is convenient to define the ideal image, or the geometrical-optics prediction of the image for a perfect imaging system as yielding a convolution equation for the image, where Thus in this general case, for a digraction-limited system we can regard the image as being a convolution of the image predicted by geometrical optics with an impulse response that is the Fraunhofer pattern of the exit pupil. Optics, Information, and Communication 1.2 The Book 2 Analysis of Two-Dimensional Signals and Systems 2.1 Fourier Analysis in Two Dimensions 2.1.1 Dejinition and Existence Conditions / 2.1.2 The Fourier Transform as a Decomposition / 2.1.3 Fourier Transform Theorems / 2.1.4 Separable Functions / 2.1.5 Functions with Circular Symmetry: Fourier-Bessel Transforms / 2.1.6 Some Frequently Used Functions and Some Useful Fourier Transform Pairs 2.2 Local Spatial Frequency and Space-Frequency Localization 2.3 Linear Systems 2.3.1 Lineurity and the Superposition Integral / 2.3.2 Invuriunt Linear Systems: Transfer Functions 2.4 Two-Dimensional Sampling Theory 2.4.1 The Whittaker-Shannon Sampling Theorem / 2.4.2 SpacseBandwidth Producf Problems-Chapter 2 3 Foundations of Scalar Diffraction Theory 3.1 Historical Introduction 3.2 From a Vector to a Scalar Theory 3.3 Some Mathematical Preliminaries 3.3.1 The Helmholtz Equation / 3.3.2 Green :s Theorem / 3.3.3 The Intrgrul Theorem oj Helmholtz and Kirchhofl 3.4 The Kirchhoff Formulation of Diffraction by a Planar Screen 3.4.1 Applicution cfrhr Integral Theorem / 3.4.2 The Kirchhoff Boundary Conditiorzs / 3.4.3 The L'resnel-Kirchhoff D;ffrclction Formula 3.5 The Rayleigh-Somrnerfeld Formulation of Diffraction 3.5.1 Choice of Alternative Green :s Furzction.~/ 3.5.2 The Kuylc.igh-Sornmerfeld 1)iffruc.tion Fornzulu xvii xii Contents Comparison of the Kirchhoff and Rayleigh-Sommerfeld Theories 3.7 Further Discussion of the Huygens-Fresnel Principle 3.8 Generalization to Nonmonochromatic Waves 3.9 Diffraction at Boundaries 3.10 The Angular Spectrum of Plane Waves 3.6 3.10.1 The Angular Spectrum and Its Physical Interpretation / 3.10.2 Propagation of the Angular Spectrum / 3.10.3 Effects of a Diffracting Aperture on the Angular Spectrum / 3.10.4 The Propagation Phenomenon as a Linear Spatial Filter Problems-Chapter 3 4 Fresnel and Fraunhofer Diffraction 4.1 Background 4.1. I The Intensity of a Wave Field / 4.1.2 The Huygens-Fresnel Principle in Rectangular Coordinates 4.2 The Fresnel Approximation 4.2.1 Positive vs. If the incident optical power is now decreased, the current will decrease, the voltage across the diode increases, the absorption drops, and again a positive feedback mechanism switches the device back to its "transparent" initial state. The most advanced DMD structures are based on a geometry related to that of the cantilever beam, but instead use a torsion beam which is connected at two points rather than through a single metal hinge. The state of polarization of a monochromatic wave with X and Y components of polarization expressed in terms of complex phasors Uxand U yis represented by apolarization vector fi with components Uxand U y , The passage of light through a linear polarization-sensitive device is described by a 2 X 2 Jones matrix, such that the new polarization vector is related to the old polarization vector through the matrix equation c' ~ f = i[I l l 1121fi. 3.2). (b) Using a paraxial approximation, express the phase distribution of the parabolic wavefront that approximates this spherical wavefront. 108 Introduction to Fourier Optics 5.3 IMAGE FORMATION: MONOCHROMATIC ILLUMINATION Certainly the most familiar property of lenses is their ability to form images. There are several simplifying assumptions that will be used in the analysis. The first accurate report and description of such a phenomenon was made by Grimaldi and was published in the year 1665, shortly after his death. The secondary wavelets with parabolic surfaces (as implied by the Fresnel approximation) no longer shift laterally in the (x, y) plane with the particular (5, q) point under consideration. Here we limit ourselves to presenting the barest outlines of the principles of operation of what are currently regarded as the most important SLM technologies. They are usually thin structures, with relief patterns on the order of one to several microns in depth, and as such they can be inexpensively replicated using well-established methods of embossing. The visual quality of an image depends strongly on the "contrast" of the image, or the relative strengths of the informationbearing portions of the image and the ever-present background. 5.12, the system contains only a single lens. 6.2.2 Examples of Amplitude Wansfer Functions To illustrate the frequency response of diffraction-limited coherent imaging systems, consider the amplitude transfer functions of systems with square (width 2w) and circular (diameter 2w) pupils. 94 Introduction to Fourier Optics FIGURE P4.16 4-17. Thus the diffraction efficiency of the 9th order of this grating is CHAPTER 4 Fresnel and Fraunhofer Diffraction 83 Normalized intensity I 0.2 4. k-~-l FIGURE P4.13 4-14. The information to be Fourier-transformed is introduced into the optical system by a device with an amplitude transmittance that is proportional to the input function of interest. 6.6.1 Underlying Mathematical Fundamentals There exist very fundamental mathematical reasons why, in the absence of noise and for the cited class of objects, resolution beyond the classical diffraction limit should be possible. When the underlying address electrode is activated with a positive voltage, the cantilever rotates downward, although not far enough to touch the address electrode. In addition, a row-column matrix of metallic conductors is deposited by photolithographic techniques such that a row electrode and a column electrode pass over one another at the comer of each pixel. The corpuscular theory of light propagation, which was the accepted means of explaining optical phenomena at the time, predicted that the shadow behind the screen should be well defined, with sharp borders. FIGURE 7.11 Molecular arrangements for different types of liquid crystals. 8.4.2 Processing the Input Data Once the frequency-plane mask has been synthesized, it may be inserted in any of the processing systems shown previously in Fig. SocialFolders is not only limited to downloads: It lets you upload files to your social sites, too. The question often arises as to whether the sign of the phase should be positive or negative in a given 2Recently an interesting relation between the Fresnel diffraction formula and an entity known as the "fractional Fourier transform" has been found. The intensity is then given by This intensity pattern is illustrated in Fig. Assuming that the wave behaves locally as a transverse electromagnetic plane wave (i.e. 2,fl, and iform a mutually orthogonal triplet), then the electric and magnetic fields can be expressed locally as where Eo and & are locally constant and have complex components. Note that if the amplitude transmittance andlor the illumination of the diffracting aperture is not a relatively smooth and slowly varying function, the above conclusions may not hold. Finally we give some intuitive explanation as to why the scaled pupil function plays the role of the amplitude transfer function. 4-15). Figure 7.26 illustrates two versions of acousto-optic SLMs, each operating in a different physical regime. Note that, if the diffracting structure is an aperture that limits the extent of the field distribution, the result is a broadening of the angular spectrum of the disturbance, from the basic properties of Fourier transforms. (b) What is the effect of such a lens on a plane wave traveling normal to the (x , y) plane? For example, a function separable in rectangular coordinates has the particularly simple property that its twodimensional Fourier transform can be found as a product of one-dimensional Fourier transforms, as evidenced by the following relation: Thus the transform of g is itself separable into a product of two factors, one a function of fx only and the second a function of f y only, and the process of two-dimensional transformation simplifies to a succession of more familiar one-dimensional manipulations. The first was that of VanderLugt [292] who exploited certain properties of quadratic-phase exponentials to simplify their manipulation. By the same token, exp(- jkrol)and exp[- j&(x2 P)] represent a converging spherical wave, again assuming that z is positive. 5-1, the reader is asked to verify that the sign convention adopted implies that the focal length f of a double-convex, plano-convex, or positive meniscus lens is positive, while that of a double-concave, 100 Introduction to Fourier Optics Double-convex Double-concave Plano-convex Positive meniscus Plano-concave Negative meniscus FIGURE 5.3 Various types of lenses. 6.23. The space-bandwidth product of the function is then approximately given by Eq. (2-58). When the material cools, it is transformed to the smectic-C* state, which has the tilt mentioned above. Paraxial conditions are assumed to hold. Rayleigh's theorem (Parseval's theorem). For an answer, see [253], p. Find an expression for the intensity distribution in the Fraunhofer diffraction pattern of the aperture shown in Fig. Under the narrowband condition assumed above, the amplitude impulse response does not change appreciably for the various frequencies contained within the optical spectrum. The approach to achieving simultaneous scale and rotation invariance, which was pioneered by Casasent and Psaltis (see [50]and references therein), can now be described. Incoherent light is obtained from diffuse or extended sources, for example gas discharges and the sun. This will be true if Note that this relationship is precisely the classical lens law of geometrical optics, and must be satisfied for imaging to hold. The medium is isotropic if its properties are independent of the direction of polarization of the wave (i.e. the directions of the 2and ?I vectors). I have photos stored on Facebook. Substituting these relations in the definition of mutual intensity, Eq. (6-9),for the coherent case we obtain When this result is in turn substituted into Eq. (6-8)for the intensity, the result is Finally, defining a time-invariant phasor amplitude Uiin the image space relative to the corresponding phasor amplitude at the origin, the coherent imaging system is found to be described by an amplitude convolution equation, 134 Introduction to Fourier Optics the same result obtained in the monochromatic case. The size of the original rectangular aperture is indicated by the shaded boxes. 118 Introduction to Fourier Optics where the relations have been used to simplify the equation. Helpful comments were also made by I. These statistical relationships will greatly affect the result of the time-averaging operation that yields the final image intensity distribution. To consider the case of an FLC cell, a bit of further background is needed. First, it is assumed that the maximum phase shift introduced by the filter is much smaller than 27.r radians, and therefore In addition, it is assumed that the phase shift of the transparency after bleaching is linearly proportional to the silver density present before bleaching, This assumption is true to a very good approximation if a nontanning bleach is used, for such a bleach returns metallic silver to a transparent silver salt, and the density of that transparent material determines the phase shift introduced by the bleached transparency. 2-8. One such approach is described in the following, and it will be seen to solve the first two problems as well. In some cases this device may consist of a photographic transparency, while in others it may be a nonphotographic spatial light modulatoc capable of controlling the amplitude transmittance in response to externally supplied electrical or optical information. The input is simultaneously (or sequentially) applied to the N matched filters with transfer functions ST, S;, . Thus the restriction of attention to the square of width 4 must be used with some caution. For the scaled quadratic-phase exponential of Eqs. Use the simplest possible reasoning to predict the distances d and z2, respectively, to the Fourier plane and the image plane to the right or left of lens L2 (specify right or left in the answers). For simplicity we introduce the Mellin transform in one-dimensional form, although it is easily generalized to two dimensions. 7.7. The first operation in this cascade is a linear, invariant filter representing the effects of light scattering and the resulting spread or blur of the exposure pattern E. In many applications it is desired to have a more efficient modulator, one that can operate primarily through phase modulation rather than absorption. brought closer together by the constraints imposed by the thin layers of the device. These reversals of contrast can readily be observed if the "spoke" target of Fig. Then you head to socialfolders.me, where you create an account and start connecting your social services. Assuming that the entire range of exposure experiences the same photographic gamma, plot the distribution of light intensity in the rear focal plane, labeling in particular the relative strengths and locations of the various frequency components present. The spatial frequencies and the direction cosines are related through Eq. (3-62). From the result of Prob. We shall follow the approach of Nazarathy and Shamir here. To generalize this concept to a polychromatic wave u(P, t), we suppress all positivefrequency components of its Fourier spectrum, and double its negative-frequency components, yielding a new (complex) function u- (P , t). When the exposure is below a certain level, the density is independent of exposure and equal to a minimum value called gross fog. Letting and Y(p,q) = H* we find Normalizing by the right-hand side of the inequality, it follows that (X(fx, fy)l is never greater than unity. The integral in question can thus be reduced to 44 Introduction to Fourier Optics where .12 is the solid angle subtended by S2 at Po. Now the quantity lRGl is uniformly bounded on S2.Therefore the entire integral over S2 will vanish as R becomes arbitrarily large, provided the disturbance has the property lim R(% R+ -/XU) = 0 m uniformly in angle. Presumably this function has been derived from a design process, which may have been simple or may have been quite complex itself. Since and 11 Ih(u, v)I2 d u d v -w it follows (with the help of Rayleigh's theorem) that The simple change of variables results in the symmetrical expression Thus the OTF is the normalized autocorrelation function of the amplitude transfer function! Equation (6-28) will serve as our primary link between the properties of coherent and incoherent systems. For this reason they are best applied in problems for which the light is highly monochromatic. In this case, two MQW diodes are integrated into a single pixel and electrically interconnected with one another, as shown. The system shown in part (b) of the figure has the same length as the previous system, but uses one fewer lens. WinRAR and 7zip are both well-known not just for their storied history, but also because of the memes. Not all pattern-recognition problems are of the type described above. 5.9). 6.4.2 Effects of Aberrations on the Amplitude Transfer Function When considering a diffraction-limited coherent system, the transfer function was found by noting that (1) the impulse response is the Fourier transform of the pupil function, and (2) the amplitude transfer function is the Fourier transform of the amplitude impulse response. An excellent discussion of all of these approaches is found in [147]. With the help of these approximations, the thickness function becomes 5.1.3 The Phase Transformation and Its Physical Meaning Substitution of Eq. (5-8) into Eq. (5-1) yields the following approximation to the lens transformation: tl(x, y) = exp[jknAo] exp x2 + y2 The physical properties of the lens (that is, n, R I ,and R2) can be combined in a single number f called the focal length, which is defined by Neglecting the constant phase factor, which we shall drop hereafter, the phase transformation may now be rewritten This equation will serve as our basic representation of the effects of a thin lens on an incident disturbance. If the film is "biased" to an operating point that lies within the region of maximum linearity of this curve, then over a certain dynamic range the film will provide a square-law mapping of incremental changes in incident amplitude into incremental changes of amplitude transmittance. For the case of electrical networks, the inputs and outputs are real-valued functions (voltages or currents) of a one-dimensional independent variable (time); for the case of imaging systems, the inputs and outputs can be real-valued functions (intensity) or complex-valued functions (field amplitude) of a two-dimensional independent variable (space). The reader will be referred to appropriate material in the appendix when needed. von Helmholtz. The image field distribution is of interest, but the image is measured on a spherical surface, centered at the point where the optical axis pierces the thin lens, and of radius 22. The autocorrelation function of this new pupil yields an OTF as shown in part (c) of the figure, with the sign of the bandpass regions of the OTF reversed, but with the low-frequency part of the OTF left unchanged. As can be seen, the effect of the apodization has been to boost the relative importance of midrange and low frequencies, while diminishing the strength of high frequencies. Marechal, whose success with these techniques was to provide a strong motivation for future expansion of interest in the optical information processing field. It is the ratio of the intensities in the two complementary light beams that carries the information of interest. The structure introduces constraints on the movement of the excitons (known as "quantum confinement") and the emergence of sharp absorption peaks that would not normally be observed in structures with thicker layers. Pixels are written one at a time. 4-20. Now it becomes clear that if X and Y are sufficiently small (i.e. the samples are sufficiently close together), then the separations 11X and 1/Y of the various spectral islands will be great enough to assure that the adjacent regions do not overlap (see Fig. CHAPTER 6 Frequency Analysis of Optical Imaging Systems 161 However, it is of some interest to know that in principle, for a certain class of objects, resolution beyond the classical diffraction limit is theoretically possible. CHAPTER 2. 6-5. The phase factor associated with the final Fourier transform is generally of no concern. Second, we consider object illumination with the opposite property that the phasor amplitudes at all points on the object are varying in totally uncorrelated fashions. Such an image is called a Talbot subimage. Both of these phenomena are linear ones, although the physical quantities with respect to which they are linear are different. With reference to Appendix B, a lens is said to be a thin lens if a ray entering at coordinates (x, y) on one face exits at approximately the same coordinates on the opposite face, i.e. if there is negligible translation of a ray within the lens. Thus we see that this system of two lenses separated by their common focal length f performs a scaled optical Fourier transform, without quadratic-phase exponentials in the result, similar to the focal-plane-to-focalplane relationship derived earlier. Note that /3 and p ' are negative numbers for a negative transparency. (b) Give an expression for the focal length of the screen. CHAPTER 7 'LC - Wavefront Modulation 195 FIGURE 7.19 Electrical model for the optically written SLM. This collimated light then illuminates a pair of transparencies residing in the same plane, designated in the figure by their amplitude transmittances, h for the desired impulse response and g for the data to be filtered. There is little more of a general nature that can be said about the effects of aberrations on a coherent imaging system. Since only outgoing waves will fall on S2 in our problem, the integral over S2 will yield a contribution of precisely zero. 8.5 THE JOINT TRANSFORM CORRELATOR Before considering applications of coherent optical processing, an alternative method for performing complex filtering using a spatial carrier for encoding amplitude and phase information is considered. The granular nature of the coherent image is a direct consequence of the complex, random perturbation of the wavefront introduced by the diffuser, together with the coherence of the light. Any method for modulating the intensity of light is also a candidate technology for the construction of a spatial light modulator. q) = rect ('-) '( ). 230 Introduction to Fourier Optics 8.2.2 Systems That Incorporate the Effects of Diffraction It is possible to design incoherent optical information processing systems that take full account of the laws of diffraction. the form e x p [j 2 ~fxx Note that for any particular frequency pair (fx, fy) the corresponding elementary function has a phase that is zero or an integer multiple of 2.sr radians along lines described by the equation + where n is an integer. 154 Introduction to Fourier Optics While the term apodization originally meant a tapering of the transmittance through the pupil near its edges in order to suppress side-lobes of the point-spread function, over time the term has come to be used to describe any introduction of absorption into the pupil, whether it lowers or raises the side-lobes. In other words, we wish to invert the blurring operation and recover the original object. (a) Intensity transmissions with and without apodization. Combining (5-25), (5-26), (5-27), and again neglecting a pure phase factor, yields the formidable result Equations (5-23) and (5-28) now provide a formal solution specifying the relationship that exists between the object U, and the image Ui. However, it is difficult to determine the conditions under which Ui can reasonably be called an image of U,

unless further simplifications are adopted. More generally 2N quantization levels can be realized through a series of N exposure and micromachining operations, as described below. See Section 6.5. 144 Introduction to Fourier Optics fy/2fo FIGURE 6.7 The optical transfer function of a diffraction-limited system with a square pupil. The critical point to note from this figure is that the finite width of the cosinusoid has spread its spectral components into sinc functions, and while the frequency f lies beyond the limits of the OTF, nonetheless the tails of the sinc functions centered at fx = +f" extend below the cutoff frequency into the observable part of the spectrum. Consider the familiar inverse transform relationship expressing the time function g in terms of its frequency spectrum. The fundamental reason for this behavior lies in the fact that, when severe aberrations are present, the point-spread function is determined primarily by geometrical-optics effects, and diffraction plays a negligible role in determining its shape. 2, Chapter 8 of [17]. Furthermore, the impulse response of the incoherent mapping is just the squared modulus of the amplitude impulse response. As we shall now see, such a relation is instrumental in the further development of scalar diffraction equations. This straightforward solution has several serious defects: 1. (a) Three-dimensional plot with fxl2 fo along one axis and W,lh along the other axis. Returning now to our central discussion, to be legitimately used in Green's theorem, the function G (as well as its first and second partial derivatives) must be continuous within the enclosed volume V. Consider next the quadratic phase factor that depends only on image coordinates (u, v). In case (c), the input is placed behind the lens at distance d from the focal plane. But it was not until 1882 that the ideas of Huygens and Fresnel were put on a firmer mathematical foundation by Gustav Kirchhoff, who succeeded in showing that the amplitudes and phases ascribed to the secondary sources by Fresnel were indeed logical consequences of the wave nature of light. Pichon, D. Then the intensity observed at this distance behind the grating is which can be interpreted as a pe$ect image of the grating. The process consists of a number of discrete steps, each of which consists of photoresist application, exposure through one of several binary masks, photoresist removal, and etching. (d) Assuming that the maximum angle 8 is used, what is the maximum grating frequency f that will yield variations of intensity in the image plane? Note that at frequencies outside the diffraction-limited passband of the imaging system, no object information is present, and therefore the noise-to-signal ratio is infinite. Actually, the two are not directly comparable, since the cutoff of the amplitude transfer function determines the maximum frequency component of the image amplitude while the cutoff of the optical transfer function determines the maximum frequency component of image intensity. where the @ again indicates that a two-dimensional convolution is to be performed. While we shall consider this effect in the context of optical imaging, it has also proven to be a problem in certain other nonoptical imaging modalities, such as microwave side-looking radar and medical ultrasound imaging. In this chapter we consider some of the foundations of scalar diffraction theory. 6.6.5 Practical Limitations All methods for extrapolating bandwidth beyond the diffraction limit are known to be extremely sensitive to both noise in the measured data and the accuracy of the assumed a priori knowledge. 7.26, if y is a coordinate running opposite to the direction of travel of the acoustic wave and is centered in the middle of the cell (as indicated in Fig. Nonetheless, the ideas behind bandwidth extrapolation are important to be aware of and similar methods can be applied to other important problems in optics (see, for example, [273]). Note that this geometrical interpretation of the OTF implies that the OTF of a diffraction-limited system is always real and nonnegative. The diffraction phenomenon should also not be confused with the penumbra effect, for which the finite extent of a source causes the light transmitted by a small aperture to spread as it propagates away from that aperture (see Fig. precisely as where M = -z21z1 is the magnification of the system, to be defined shortly. To emphasize this latter point, we now consider two objects with the same intensity transmittance but different phase distributions, one of which can be said to be imaged better in coherent light and the other better in incoherent light. 8.6.2 A Character-Recognition Problem Consider the following character-recognition problem: The input g to a processing system may consist of any one of N possible alphanumeric characters, represented by sl, s2, . As a consequence, to use the device as an intensity modulator, the output polarization analyzer should be oriented orthogonal to the direction of polarization of 200 Introduction to Fourier Optics the light in one of the two states of rotation. Figure 4.5 illustrates the various regions mentioned. 'We can usually assume that the distance z is larger than a few wavelengths, allowing us to completely drop the evanescent components of the spectrum. Thus a coherent imaging system is linear in complex amplitude. The sole effect of aberrations is seen to be the introduction ofphase distortions within the passband. The second component of the thickness function comes from a region of glass of constant thickness AO2.The third component is given by where we have factored the positive number - R2 out of the square root. 5-6. 0) = 1gm(r)ejmR, m= (8-35) -m where the Fourier coefficients are functions of radius, Each term in Eq. (8-35) is referred to as a "circular harmonic" of the function g. It is perhaps expecting too much to find such an explanation. 7-4. (c) The fraction of light that is transmitted into a single first order. Figure 4.9 shows a cross section of the Airy pattern, while Fig. If the inputs is not centered on the origin, the bright point in the output plane simply shifts by a distance equal to the misregistration distance, a consequence of the space invariance of the matched filter (cf. More importantly, that term introduces a coupling between the various components of the electric field, with the result that Ex,Ey,and Ez may no longer satisfy the same wave equation. The components not intercepted are precisely those generated by the high-frequency components of the object amplitude transmittance. For smectic-C* materials, the angle of the molecules within a single layer is constrained to lie at a specific declination angle with respect to the layer normal, and thus there is a cone of possible orientations for any given layer. To emphasize this point of view we rewrite (3-51) as 5Hereafter we drop the subscript on the first Rayleigh-Sommerfeld solution, since it will be the solution we use exclusively. The size of an individual active pixels can be in the range of 10 p m to 100 p m on a side. In some cases, the concept of instantaneous intensity is useful, defined as I (P , t) = (u(P,t)I2. At Fresnel's presentation of his paper to a prize committee of the French Academy of Sciences, his theory was strongly disputed by the great French mathematician S. Thus coherent optical filters were limited to those that had very simple transfer functions. PROBLEMS-CHAPTER 3 3-1. Eq. (5-33) approaches the impulse response shown in Eq. (5-35). Both continuous and discrete processing systems are considered. For the case of a linear imaging system, this result has the interesting physical interpretation that the effects of imaging elements (lenses, stops, etc.) can be fully described by specifying the (possibly complex-valued) images of point sources located throughout the object field. One term is identical with the other, but reflected about the optical axis. 4-16, we should expect the distribution of light about this point of convergence to be precisely the Fraunhofer diffraction pattern of the lens aperture that limits the extent of the spherical wave. Thus the amplitude distribution behind the lens becomes, using (5-lo), (r;(x. While we have considered only a few specific examples of systems based on geometrical optics, a fundamental fact is clear: if large quantities of data are to be squeezed into an aperture of a given size, ultimately diffraction effects must be taken into account. If light at a wavelength indicated by the dashed line is now incident on the device, some of it will be absorbed, and the back-biased diode, acting as a photodetector, will generate current. That said, it's a fantastic option. We conclude our discussion of Fourier analysis by presenting some specific twodimensional transform pairs. The transfer function of the optimum restoration filter is given by This type of filter is often referred to as a WienerBlter, after its inventor, Norbert Wiener. To change the state of an individual pixel, the following sequence of operations must take place. An excellent reference can be found in [91], Chapter 6. 258 Introduction to Fourier Optics 8.8.1 The Inverse Filter Let o(x, y) represent the intensity distribution associated with an incoherent object, and let i(x, y) represent the intensity distribution associated with a blurred image of that object. If the pupil function P is indeed unity within some region and zero otherwise, then there exists a finite passband in the frequency domain within which the diffractionlimited imaging system passes all frequency components without amplitude or phase di~tortion.~ At the boundary of this passband the frequency response suddenly drops to zero, implying that frequency components outside the passband are completely eliminated. (6-22) Such systems should therefore be frequency-analyzed as linear mappings of intensity distributions. Thus the recovery of the original spectrum G from Gs can be accomplished exactly by passing the sampled function g, through a linear invariant filter that transmits the term (n = 0, m = 0) of Eq. (2-53) without distortion, while perfectly excluding all other terms. The SDF approach is a method for constructing a single pattern-recognition filter that has its correlation properties tailored in advance by means of a certain "training set" of images, whose desired correlations with the reference filter are known in advance. However, such materials have one distinct disadvantage when image or signal CHAPTER 7 Wavefront Modulation 185 processing is of concern, namely the long time delays required for chemical processing. Note that the above derivation has been restricted to the case of an aperture illumination consisting of a single expanding spherical wave. Each pixel that is written with light becomes maximally absorbing, thereby transmitting little or no light, and each pixel that is not written by light remains maximally transparent. Attention is called to the fact that, as the observation plane approaches the plane of the aperture (NF becomes large), the Fresnel kernel approaches the product of a delta function and a factor elkz,and the shape of the diffraction pattern approaches the shape of the aperture itself. For such grains, the developer causes the entire crystal to be entirely reduced to metallic silver. Young's qualitative arguments were given added impetus by Sommerfeld's rigorous electromagnetic solution of the problem of diffraction of a plane wave by a semiinfinite, perfectly conducting screen [268]. It is because of the permanent dipole moment that FIGURE 7.16 Ferroelectric liquid crystal molecules align in one of two allowed directions, depending on the direction of the field. The Fourier transform relation between the input amplitude transmittance and the focal-plane amplitude distribution is not a complete one, due to the presence of the quadratic phase factor that precedes the integral. More specifically, with reference to Fig. Specifically, transforming both sides of (2-49) and invoking the convolution theorem, the spectra G2(fx, fy) and Gl(fxJ fy) of the system output and input are seen to be related by the simple equation where H is the Fourier transform of the impulse response The function H, called the transfer function of the system, indicates the effects of the system in the "frequency domain". This problem can be removed if the angle coordinate is allowed to cover two or more periods of length 2 7 ~in , which case the "wrap around" problem can be minimized or eliminated. Note that this system has no vignetting problems, and the quadratic phase factor across the input plane (mentioned above) is canceled by the converging illumination. Alternative theorems derived by making different choices at these two points are no less valid than Eq. (2-57); in fact, in some cases alternative theorems are more "efficient" in the sense that fewer samples per unit area are required to assure complete recovery. In practice, imaging systems are seldom isoplanatic over their entire object field, but it is usually possible to divide that field into small regions (isoplanatic patches), within which the system is approximately invariant. Then = (9 =) 0, and This image has twice the frequency of the original grating and has reduced contrast. In this section we outline the system architectures used for coherent optical information processing, and point out some of the difficulties encountered in attempting to synthesize general complex filters. FIGURE 8.11 Example of an anamorphic processor. The Fourier transform of the composite input appears in the rear focal plane of L2, where the incident intensity is detected by either a photographic medium or a photosensitive spatial light modulator. However, we will focus here on conventional optical instruments, for which the evanescent waves are not recoverable. This problem is not encountered with system (a), which casts an image of plane PI onto a plane P3, rather than of a sphere onto a sphere. Again lens L1 collimates the light from the point source S, and again the input transparency is placed against L I to minimize the length of the system. In some cases it may be desired to change one of the inputs rapidly, in which case physical separation of the two transparencies may be advantageous. Accordingly the generalized transform of S(x, y) is found to be Note that the spectrum of a delta function extends uniformly over the entire frequency domain. Similar reasoning applies to the expressions for plane waves traveling at an angle with respect to the optical axis. As will now be demonstrated, the identification process can be realized by applying the input to a bank of N filters, each matched to one of the possible input characters. 5 10 15 20 Development time (minutes) The dependence of film gamma on development time. An angle satisfying the above relation is known as a Bragg angle. The wavelength of the light is A. 4.5 is bounded by the parabola (w - x) ~= 4hz and the bottom transition region by (w x) ~= 4Az, where the aperture is 2w wide, the origin of the coordinates is at the center of the aperture, z is the distance from the plane of the aperture, and x is the vertical coordinate throughout the figure. To discover this relationship, first note that a change of logarithmic exposure induces a proportional change of amplitude transmittance, as evidenced by the chain AtA 0: A 4 0: AD 0: A(10g E), which is implied by the above hypotheses. Huygens expressed the intuitive conviction that if each point on the wavefront of a disturbance were considered to be a new source of a "secondary" spherical disturbance, then the wavefront at a later instant could be found by constructing the "envelope" of the secondary wavelets, as illustrated in Fig. axis of the aligned liquid-crystal molecules at the left-hand alignment layer. 8-2), and the schlieren method in which all spectral components to one side of the zero-frequency component are excluded (see Prob. The general result (6-44) does not lead to the conclusion that one type of illumination is better than the other in terms of image frequency content. 7.12 will change under sufficient applied field to the arrangement shown in Fig. In addition to Introduction to Fourier Optics, Dr. Goodman is the author of Statistical Optics (J . Our discussion above is closely related to the principle of stationary phase, a method for finding the asymptotic values of certain integrals. Any network or device (electronic, optical, or otherwise) which possesses these two properties can be described mathematically with considerable ease using the techniques of frequency analysis. As an example of a simple case, the element may be a CHAPTER 7 Wavefront Modulation 21 1 FIGURE 7.28 Ideal sawtooth thickness profile for a blazed grating, and binary optic approximation to that profile (N = 2). Another way of stating this problem is that the restoration filter would need a transfer function with infinite dynamic range in order to properly compensate the spectrum of the image. Following the photoresist development process, micromachining is applied to remove material from the uncovered portions of the substrate, as illustrated in part (b) of the figure. In this chapter we review some of the mathematical tools that are useful in describing linear phenomena, and discuss some of the mathematical decompositions that are often employed in their analysis. Note that the first and second terms of Eq. (8-17), which are of no particular utility in the usual filtering operations, are centered at the origin of the (x3, y3) plane. In addition, aberrations can cause the OTF to have negative values in certain bands of frequencies, a result that never occurs for an aberration-free system. The sampling theorem applies to the class of bandlimited functions, by which we mean functions with Fourier transforms that are nonzero over only a finite region R of the frequency space. This positive feedback action results in the MQW modulator switching to its highest possible absorption under the application of light to the device (i.e. its "absorptive" state). Second, to save time with the operator approach, it is necessary that one be rather familiar with the operator relations of Table 5.1. Good intuition about which operator relations to use on a given problem comes only after experience with the method. If the input to be filtered is g (x l , yl), then incident on the frequency-plane mask is a complex amplitude distribution given by G The field strength transmitted by the mask then obeys the proportionality h (9,3). Suppose that we wish to solve an inhomogeneous linear differential equation of the form where V(x) is a driving function and U(x) satisfies a known set of boundary conditions. 2-6c) to show that B{g~(ar))= a+o (s) When using the expression (2-31) for the Fourier-Bessel transform, the reader should remember that it is no more than a special case of the two-dimensional Fourier transform, and therefore any familiar property of the Fourier transform has an entirely equivalent counterpart in the terminology of Fourier-Bessel transforms. Exceptions are functions that do not have Fourier transforms in the usual sense, and have to be dealt with in terms of generalized Fourier transforms (e.g. g(x, y) = 1, g(x, Y) = cosP.rr(fxx + fry)], etc.). 4-7 through 4-10). Figure 8.19(b) shows the response of the matched filter portion of the output to the letters Q, W, and P. 7.2.4 Deformable Mirror Spatial Light Modulators A variety of devices have been reported that use electrostatically induced mechanical deformation to modulate a reflected light wave. We would anticipate, then, that transfer-function concepts can be applied directly to this system, provided it is done on an amplitude basis. For RF frequencies in the hundreds of MHz to the GHz range, and in acoustic media consisting of crystals, the thickness of the acousto-optic column compared with the acoustic wavelength introduces a preferential weighting for certain diffraction orders, and suppresses others. We regard an ideal spherical surface, centered on the ideal image point and passing through the point where the optical axis pierces the exit pupil, as defining a Gaussian reference sphere with respect to which the aberration function can be defined. 8.16(a) with a mirror reflection about its own origin.7 For example, if originally we introduced the function h(xl, yl - Yl2), this input should be changed to h(-xl, - yl + Yl2), which is again centered at Y12 but now is reflected about its own origin. In a similar fashion, a linear imaging system is space-invariant (or equivalently, isoplanatic) if its impulse response h(x2, y2; 5 , q) depends only on the distances (x2 -6) and (y2 - q) (i.e. the x and y distances between the excitation point and the response point). If the finite input transparency is fully illuminated by the converging light, then the projected pupil can be ignored. , K, then across P2 we find displayed the corresponding set of transforms Gk(x2), k = 1,2,.. We shall consider only two types of illumination here. When light passes through such an object, the predominant effect is the generation of a spatially varying phase shift; this effect is not directly observable with a conventional microscope and a sensor that responds to light intensity. The last property, namely the obliquity factor, has no simple "quasi-physical" explanation, but arises in slightly different forms in all the theories of diffraction. 4-5). The object exists on the surface of a sphere of radius zl centered on the point where the optical axis pierces the thin lens. Exposure. The lines between the alignment layers indicate the direction of molecular alignment at various depths within the cell. One of the highly useful properties of these materials is the very large difference between the extraordinary and ordinary refractive indices they exhibit, often in the range of 0.2 or more. It is possible to perform the same operation without relative motions if the optical configuration is modified [175]. The shaded areas on the pupil are the areas within the light patches can reside while retaining this special separation. Generally speaking, apodization amounts to the introduction of attenuation in the exit pupil of an imaging system, attenuation that may be insignificant at the center of the pupil but increases with distance away from the center. These properties are presented as mathematical theorems, followed by brief statements of their physical significance. 8This should not be taken to imply that the incoherent system has twice the resolving power of the coherent system. If we collect an incoherent image using an optical system with the pupil shown in Fig. The Jones matrix for such an FLC cell has two possible forms, one for each direction of the applied field. For this reason we regard the intensity as the physically measurable attribute of an optical wavefield. A filter is inserted in plane P2 to manipulate the spectrum of g. Systems with incoherent illumination will be treated in Section 6.3. CHAPTER 6 Frequency Analysis of Optical Imaging Systems 135 As emphasized previously, a coherent imaging system is linear in complex amplitude. In most cases encountered in practice, the form of the point-spread function of the scat- I Known H&D curve , (Inferred) effective logarithmic exposure log E FIGURE 7.8 , I , Measurement of the MTF by projecting back through the H&D curve. Foundations of Scalar Diffraction Theory 43 FIGURE 3.6 Kirchhoff formulation of diffraction by a plane screen. + 7.3 DIFFRACTIVE OPTICAL ELEMENTS The vast majority of optical instruments in use today use refractive or rejective optical elements (e.g. lenses, mirrors, prisms, etc.) for controlling the distribution of light. First, there are generally random thickness variations across the base of the film, i.e. the base is not optically flat. A multiplicity ~ ~ CHAFER 4 Fresnel and Fraunhofer Diffraction 89 of such images appear behind the grating, without the help of lenses! Such images are called Talbot images (after the scientist who first observed them), or simply selfimages. [274], [217], [99]), allowing their use in systems for which the light is not highly monochromatic. 70 Introduction to Fourier Optics cos nx2 sin nx2 X FIGURE 4.3 Quadratic phase cosine and sine functions. A quantity of considerable utility in determining the seriousness of the aberrations of an optical system is the Strehl definition 27, which is defined as the ratio of the light intensity at the maximum of the point-spread function of the system with aberrations to that same maximum for that system in the absence of aberrations. Since the illuminations on the two diodes are equal, there is no imbalance that would cause the diode pair to change its state. Such small structures lie in the domain where the use of a scalar theory to predict the properties of these optical elements is known to yield results with significant inaccuracies. Computergenerated holographic optical elements are an example that will be discussed in more detail in Chapter 9. Chapter 5 can begin with Eq. (5-10) for the amplitude transmittance function of a thin lens, and can include all the remaining material, with the exception that Section 5.4 can be left as reading for the advanced students. For a review article covering the properties of more types of SLMs than will be discussed here, the reader may wish to consult Ref. This can only be true if the wave vector points with a positive angle with respect to the z axis, as illustrated in Fig. A similar effect takes place when boundary conditions are imposed on a wave that propagates in a homogeneous medium. However, only a finite set of these rays is passed by the lens aperture. The independence of the Mellin magnitude with respect to object scale size, coupled with the fact that the Mellin transform can be performed as a Fourier transform of a stretched input, will be shown to suggest one way to achieve independence from scale size. For strong Bragg diffraction, the wave vector diagram must close as shown, a property that can be viewed as a statement of conservation of momentum. Thus the finite extent of the aperture may be accounted for by geometrically projecting that aperture back to the input plane, the projection being centered on a line joining the coordinates (u l ,v l)with the center of the lens (see Fig. However, optical writing results in the establishment of certain internal electric fields, and therefore the functioning of this device can be understood based on the previous background. The corresponding comparison for object B requires less detail. m/2 for three values of q. With reference to Eq. (5-30): (a) At what radius ro in the object plane has the phase of exp[j & (t 2 1 radian from its value at the origin? Chapter 2 reviews the required background; to avoid boring those who are well grounded in the analysis of temporal signals and systems, the review is conducted for functions of two independent variables. Two discrete spectral lines of a source are said to be "just resolved" by a diffraction grating if the peak of the 9th-order diffraction component due to source wavelength A l falls exactly on the first zero of the 9th-order diffraction component due to source wavelength A2. 8.17. Both thin and thick holograms are treated. There is a subtlety that arises from the fact that on a scale that varies from 0to 2 7 radians, ~ rotation by angle 8 may result in portions of the object shifting by 8 , while other portions of the object may "wrap a r o u n d the angular coordinate and appear at a position corresponding to 27r - 8. The potentials of coherent filtering were particularly evident in the field of radar signal processing and were exploited at an early stage by L.J. Cutrona and his associates at the University of Michigan Radar Laboratory. On the other hand, if we move in space to intercept portions of a wavefield that were emitted earlier in time, the phasor will not have had time to rotate as far in the clockwise direction, and therefore the phase must become more positive. This new quadratic phase factor in the image space can now be dropped provided that image intensity is the quantity of interest. e Af' Af Af' Af +j2~y2Y/Af] The transparency that results from this recording is assumed to have an amplitude transmittance that is proportional to the intensity that exposed it. Thus an NLC can be used as a changeable polarization rotator, with rotation experienced in the unexcited state (no voltage applied) by an amount determined by the orientation of the alignment layers on the two glass plates as well as the thickness of the cell, and no rotation experienced in the excited state (voltage applied). Attention is now turned to certain approximations to the general theory, approximations that will allow diffraction pattern calculations to be reduced to comparatively simple mathematical manipulations. For alternative references that treat acousto-optic interactions and their applications in coherent optical systems, see, for example, [17 I], [211, and [293]. We also assume that this transparency has been made in such a way that its amplitude transmittance, t ~is, proportional to s(x, y). This theory can often be applied to calculate the fields diffracted by objects that are too complex to be treated by other methods. Some methods use similar substrates to those mentioned above, but use different methods of micromachining, for example diamond turning or laser ablation. If a pure phase filter is used, with arbitrary achievable values of phase, then the values of the transfer function would be restricted to the unit circle, as shown in (c). 12 Introduction to Fourier Optics Finally, we use the Bessel function identity where Jo is a Bessel function of the first kind, zero order, to simplify the expression for the transform. Books have been written on this subject (see, for example, [91]). the properties of the imaging system will be completely described if the impulse response h can be specified. All such methods are rather cumbersome, and could be successfully employed only when the desired pattern of phase control was rather simple, e.g. binary and of simple geometric structure. of the molecules have their long axis aligned with the field, i.e. pointing in a direction normal to the glass plates. P5.4. / FIGURE P5.4 (a) Show that a paraxial approximation to the phase transformation introduced by such a lens is (under the thin lens assumption) where f(y)= R(l - n-l ylh) . We would like, of course, to extend our knowledge of the spectrum to larger integer values, say for -N 5 n r N, so that the approximation would be a satisfactory representation of the image, not only within the passband of the imaging system, but also outside that passband over a frequency region of a size that depends on how large an N is chosen. 8.4 THE VANDERLUGT FILTER In 1963, A.B. VanderLugt of the University of Michigan's Radar Laboratory proposed and demonstrated a new technique for synthesizing frequency-plane masks for coherent optical processors [290], [2911.~The frequency-plane masks generated by this technique have the remarkable property that they can effectively control both the amplitude and phase of a transfer function, in spite of the fact that they consist only of patterns of absorption. The techniques developed by Gabor and by Leith and Upatnieks are considered in detail and compared. At this point the processed emulsion consists of two types of grains, those that have been turned to silver, and those that did not absorb enough light to form a development center. grating of constant spatial frequency, the purpose of which is to deflect the incident light through a certain angle with the highest possible optical efficiency. 5.1, let the maximum thickness of the lens (on its axis) be Ao, and let the thickness at coordinates (x, y) be A(x, y). It was pointed out that such sources are merely mathematical conveniences and have no real physical significance. For brevity, we adopt the former terminology. See also Ref. For such a system we can, of course, write h(x2, ~ 25,; q) = h(x2 - 6, y2 - q). Thus the intensity distribution across the detector may be written which is the desired convolution. Bright spots along the horizontal axis in the focal plane arise from complex-exponential components of the object that are directed horizontally (cf. aandd -+ f (c) ZI+ a , general distance d. It can be shown (see [266],p. 6.3.1 The Optical Transfer Function Imaging systems that use incoherent illumination have been seen to obey the intensity convolution integral m Ih(u - 6 71 - ij)12 I,([, ij) d[dij. Similar techniques are well known in the field of digital signal processing, where they are known by the term windowing (see, for example, [85],Section 3.3). (a) Find a quadratic-phase approximation to the illuminating wavefront in the plane of the aperture, assuming that the coordinates of P in the (x, y) plane are (0, Y). The suppression of the horizontal structure is quite complete. A diagram of the structure of the device is shown in Fig. 6.3.2 General Properties of the OTF A number of very simple and elegant properties of the OTF can be stated based only on knowledge that it is a normalized autocorrelation function. The two lenses are spaced by distancef . The field amplitude at any other point (or across any other parallel plane) can be calculated by adding the contributions of these plane waves, taking due account of the phase shifts they have undergone during propagation. Referring back to Fig. If time is short, the following sections of these chapters can be omitted or left as reading for the advanced student: 3.8, 3.9,5.4, and 6.6. A second type of one-quarter or one-semester course would cover the basics of Fourier Optics, but then focus on the application area of analog optical signal processing. Let the source at Po be of the same wavelength h as the source at Po, and suppose that the two sources are oscillating with a 180" phase difference. While the theory discussed here is sufficiently general to be applied in other fields, such as acousticwave and radio-wave propagation, the applications of primary concern will be in the realm of physical optics. But and therefore From this result we see that each of the circular harmonic components of the crosscorrelation undergoes a diflerent phase shift - m a . When this approximation is valid, the observer is said to be in the region of Fresnel diffraction, or equivalently in the nearJield of the aperture.2 4.2.1 Positive vs. 2 3.3 SOME MATHEMATICAL PRELIMINARIES Before embarking on a treatment of diffraction itself, we first consider a number of mathematical preliminaries that form the basis of the later diffraction-theory derivations. Equation (4-14) is readily seen to b e d convolution, expressible in the form where the convolution kernel is ejkZexp h(x, y) = - J A ~ [E(- x2 + y2)] . Light incident on the emulsion initiates a complex physical process that is outlined as follows: 1. Displays of this kind have not been manufactured with attention to their optical flatness, since the TV display application does not require it. The final chapter is devoted to the subject of holography. To calculate the image intensity, we must time average the instantaneous intensity represented by IUi(u, v ; t)I2, due to the fact that the detector integration time is usually extremely long compared with the reciprocal of the optical bandwidth, even for narrowband optical sources. Another quantity of some practical interest in both holography and optical information processing is the dinraction eficiency of the grating. Fortunately, it is often possible to find a meaningful transform of functions that do not strictly satisfy the existence conditions, provided those functions can be defined as the limit of a sequence of functions that are transformable. q= -a, Thus the field strength in the Fraunhofer diffraction pattern can be written m Jq X q= -m (T) - :[sinc -(x] ( ) - qfohz) sinc - (4-40) If we again assume that there are many periods of the grating within the bounding aperture (fo >> llw), there is negligible overlap of the various diffracted terms, and the corresponding intensity pattern becomes The introduction of the sinusoidal phase grating has thus deflected energy out of the zero order into a multitude of higher orders. Show that, for a retardation of Pd = .rr, the Jones matrices of Eqs. 2.4 TWO-DIMENSIONAL SAMPLING THEORY It is often convenient, both for data processing and for mathematical analysis purposes, to represent a function g(x, y) by an array of its sampled values taken on a Analysis of Two-Dimensional Signals and Systems 23 CHAPTER 2 discrete set of points in the (x, y) plane. 250 Introduction to Fourier Optics (a) FIGURE 8.19 Photographs of (a) the impulse response of a VanderLugt filter, and (b) the response of the matched filter portion of the output to the letters Q, W, and P. Figure 8.2(a) shows a photograph of the spectrum of the mesh; Fig. This book deals with its applications in optics, and in particular with applications to diffraction, imaging, optical data processing, and holography. 7.26). Figure 6.24 shows a block diagram illustrating the steps in the algorithm. 3.3. An aperture in an opaque screen was illuminated by a light source, chosen small enough to introduce a negligible penumbra effect; the light intensity was observed across a plane some distance behind the screen. (In the future we shall refer to these types of illumination as simply coherent or incoherent.) Coherent illumination is obtained whenever light appears to originate from a single point.5 The most common example of a source of such light is a laser, although more conventional sources (e-g. A complete description of this rather complex device can be found in Ref. He demonstrated the absurdity of the theory wavelets Envelope (new wavefront) Primary FIGURE 3.4 Huygens' envelope construction. In such applications voltages applied to 186 Introduction to Fourier Optics pixelated electrodes cause a change in the intensity of the light transmitted by or reflected from the display. The Fourier transform and the image of the object appear to the right of the lens. 188 Introduction to Fourier Optics Alignment /layers \ Glass plate Glass plate Transparent W FIGURE 7.14 Structure of an electrically controlled liquid crystal cell. The general nature of these experiments is illustrated in Fig. Second, the generally complicated complex-valued transfer function is synthesized with a single absorbing mask; the phase transmittance through the frequency plane need no longer be controlled in a complicated manner. Thus for this function (and for most others) there is a dependence of local spatial frequency on position in the (x, y) plane.6 Since the local spatial frequencies are bounded to covering a rectangle of dimensions 2Lx X 2Ly, it would be tempting to conclude that the Fourier spectrum of g(x, y) is also limited to the same rectangular region. Thus for this particular tilt angle, a wave with linear polarization coincident with the long molecular axis in one state of the device is rotated by 90" when the device is switched to the opposite state. 38 Introduction to Fourier Optics In the case of diffraction of light by an aperture, the 2and $ fields l are modified only at the edges of the aperture where light interacts with the material of which the edges are composed, and the effects extend over only a few wavelengths into the aperture itself. This flexibility can be of utility in spatial filtering applications (see Chapter 8), where some potential adjustment of the size of the transform can be of considerable help. Thus (3-23) is reduced to While the Kirchhoff boundary conditions simplify the results considerably, it is important to realize that neither can be exactly true. Now the square root in Eq. (3-66) is imaginary, and that equation can be rewritten where Since p is a positive real number, these wave components are rapidly attenuated by the propagation phenomenon. Substituting (5-12) in (5-13), the quadratic phase factors within the integrand are seen to exactly cancel, leaving X 1 [:; I ui(x, y) P(x, y) exp - j-(xu + yo) dx dy. In fact, such a relationship exists and can be readily found with the help of the autocorrelation theorem of Chapter 2. For nematic liquid crystals (NLC), the molecules throughout the entire volume of the material favor a parallel orientation, with randomly located centers within that volume. For a review of the fundamental mathematical concepts, see the books by Papoulis [226], Bracewell [32], and Gray and Goodman [131]. If the imaging system is perfect, then the image is simply an inverted and magnified (or demagnified) replication of the object. The particular region of the input that is illuminated is determined by the intersection of the converging cone of rays with the input plane. Note the various regions of the H&D curve. Linearity theorem. The output intensity will translate with / 254 Introduction to Fourier Optics rotation, but will not drop in strength under either scale-size or rotational changes of the input. When the source of illumination is an extended incoherent source, it is possible to specify the conditions under which the imaging system will behave substantially as an incoherent system and substantially as a coherent system (see Ref [123], page 324). logE curve of the emulsion is maximum. If the illumination used in an optical system exhibits a property called spatial coherence, then we shall find that it is appropriate to describe the light as a spatial distribution of complex-valued field amplitude. CHAPTER 2 Analysis of Two-Dimensional Signals and Systems 27 2.4.2 Space-Bandwidth Product It is possible to show that no function that is bandlimited can be perfectly space-limited as well. 7.1.4 Film in a Coherent Optical System When film is used as an element of a coherent optical system, it is more appropriately regarded as providing either (1) a mapping of intensity incident during exposure into complex field transmitted after development, or (2) a mapping of complex amplitude incident during exposure into complex amplitude transmitted after development. An array of one-dimensional input functions can be represented by Uo(t, qk), where 771,772, . Figure 4.15 shows a series of graphs of the normalized intensity distribution along the x axis (y = 0) for various normalized distances from the aperture, as represented by different Fresnel numbers. (b) Point-spread functions with and without apodization. Intuitively, it is clear that if these samples are taken sufficiently close to each other, the sampled data are an accurate representation of the original function, in the sense that g can be reconstructed with considerable accuracy by simple interpolation. Figure 4.14 shows a plot of q, vs. After exposure, the photoresist is developed. In general the quality of the liquid crystal displays manufactured for projection TV are superior to those used in small TV sets. As a consequence of the two Fourier transform relations, the amplitude transfer function was found to be proportional to a scaled pupil function P. 7.5. The flat surfaces of the glass are, of course, facing the outside, and the index of refraction of the CHAPTER 7 / / Wavefront Modulation 179 Index matching fluid FIGURE 7.5 A liquid gate for removing film thickness variations. (Hint: exp(jasinx) = (b) With the help of part (a), prove the general relation presented in Eq. (2-22) for functions separable in polar coordinates. See Fig. The scalar theory is accurate provided that the diffracting structures are large compared with the wavelength of light. The number of ways a particular separation can be fit into the exit pupil is proportional to the area of overlap of two pupils separated by this particular spacing. Thus, as indicated in Fig. ., SN, and the particular character present is to be determined by the processor. This operator is represented by the symbol V and is defined by where b is dimensionless. The effects of apodization on the frequency response of both coherent and incoherent imaging systems are also of interest. Suppose that the distance z behind the grating satisfies = 2nn or z = T , where n is an integer. 6.5.1 Frequency Spectrum of the Image Intensity One simple attribute of the image intensity which can be compared in the two cases is the frequency spectrum. Section 1 of Appendix A), which states that This equation may be regarded as expressing gl as a linear combination of weighted and displaced 6 functions; the elementary functions of the decomposition are, of course, just these 6 functions. This problem 256 Introduction to Fourier Optics has been addressed and procedures for determining an appropriate center have been found (see Ref. For this example we assume that the object illumination is incoherent, and for simplicity we argue in one dimension rather than two. What is the corresponding eigenvalue? 7. 222 Introduction to Fourier Optics Thus the image intensity has become linearly related to the variations of phase shift A+. When the illumination is totally lacking in spatial coherence, it is appropriate to describe the light as a spatial distribution of real-valued intensity. (a) Full model; (b) simplified model. & 5-13. The end result of these arguments is a simplified expression for the impulse response of the imaging system, FIGURE 5.10 Region of object space contributing to the field at a particular image point. However, the area of integration increases as R ~SO, this argument is incomplete. Such an approximation is accurate if the distance d is sufficiently small to place the input deep within the region of Fresnel diffraction of the lens aperture, if the light were propagating backwards from the focal plane to the plane of the input transparency. (a) Front view, (b) side view I (b) where n is the refractive index of the lens material, knA(x, y) is the phase delay introduced by the lens, and k[Ao - A(x, y)] is the phase delay introduced by the remaining region of free space between the two planes. 112 Introduction to Fourier Optics Defining the magnijication of the system by the minus sign being included to remove the effects of image inversion, we find a final simplified form for the impulse response, Thus, if the lens law is satisfied, the impulse response is seen to be given (up to an extra scaling factor llAzl) by the Fraunhofer diffraction pattern of the lens aperture, centered on image coordinates (u = M5,v = Mq). Then incident on the input is a spherical wave converging towards the back focal point of the lens. Prove the following Fourier-Bessel transform relations: (a) If gR(r) = 6(r - ro), then B{g~(r)l= Z.rrroJo(2.rrroPI. Devices of this kind can also be made within a Fabry-Perot Ctalon structure, yielding even better contrast at the price of narrower optical bandwidth. Strong diffraction into a first diffraction order occurs only when the angle of the incident beam, with respect to plane of the acoustic wavefronts, has the particular value O B satisfying (cf. Appropriate transfer functions are defined and their properties discussed for systems with and without aberrations. [By permission of P. The photocurrent is then given by Eq. (8-5). In the case of incoherent illumination, such interference cannot take place, and speckle is missing from the image. If, as is usually the case, the dielectric constant of a molecule is larger in the direction of the long axis of the molecule than normal to that axis, the induced dipoles have charge at opposite ends of the long direction of the molecule. Under such a condition, a and P are no longer interpretable as direction cosines. The central dip is found to fall about 27% below peak intensity. Early devices utilized continuous membranes which deformed under the fields exerted by pixelated driving electrodes. The original object intensity (the relevant quantity if the system is incoherent) is known to be space-limited and nonnegative. If the object of interest is confined to the region for which this property holds, then the system may be regarded as being diffraction-limited. Substitution of (3-56) in the second of Eqs. The second output is a mirror reflection of the first about the optical axis. Considering an on-axis point for simplicity, this means that the phase distribution across the exit pupil is of the form where za # zi. We represent the complex field immediately behind the object by U,(t, q). If F{g(x, y)} = G(fx, fy), then that is, translation in the space domain introduces a linear phase shift in the frequency domain. 8.5(a). It's a great way to test the service without committing to it. FTP If you're more tech-savvy than most, FTP clients are always an option. Only when light contributions from two patches having this particular separation interfere can a fringe with this frequency be generated (cf. 6.4.5 Apodization and Its Effects on Frequency Response The point-spread function of a diffraction-limited imaging system generally has sidelobes or side-rings of noticeable strength. The transmittance of the VanderLugt filter consists of four terms, as before, and only one of these is of interest in this problem. At each point of continuity of g, At each point of discontinuity of g, the two successive transforms yield the angular average of the values of g in a small neighborhood of that point. (a) Show that such a wave can be expressed as a linear combination of a left-hand circularly polarized wave and a right-hand circularly polarized wave, and find the coefficients of that expansion. Free-space propagation. 5-3. Within the range of frequencies for which the diffraction-limited transfer function is nonzero, it is possible (indeed likely) that transfer function S will have isolated zeros. array of elements. In addition define a (2N 1) X (2N + 1) matrix D with entry sinc [L (fk in the kth row and nth column. It is possible to impose boundary conditions on the alignment of nematic liquid crystal molecules contained between two glass plates by polishing soft alignment layers coated on those plates with strokes in the desired alignment direction. Let the training set of N images be represented by {gn(x,y)} where n = 1,2, . 3-3) to FIGURE 3.7 Point-source illumination of a plane screen. I would include sections 9.4,9.6.1,9.6.2, 9.7.1, 9.7.2, 9.8, 9.9, and 9.12.5. The three appendices should be read by the students but need not be covered in lectures. The sampled function g, thus consists of an array of S functions, spaced at intervals of width X in the x direction and width Y in the y direction, as illustrated in Fig. The Wigner distribution function of a one-dimensional function g(x) is defined by and is a description of the simultaneous (one-dimensional) space and spatial-frequency occupancy of a signal. This in turn leads us to the idea that the quantity IG(fx, fy)I2 can be interpreted as an energy density in the frequency domain. In this case the function of the SLM may be, for example, to convert an incoherent image into a coherent image for subsequent processing by a coherent optical system. These functions are illustrated in Fig. In the case of electrical systems, the loss of signal fidelity is most conveniently described in the frequency domain. A two dimensional object g(t,17) is entered into the optical system in a distorted polar coordinate system, the distortion arising from the fact that the radial coordinate is stretched by a logarithmic transformation. As shown in Fig. The ability of an optical system to accurately handle inputs and outputs having large spacebandwidth products is a measure of performance, and is directly related to the quality of the system. Optical properties of nematic and ferroelectric liquid crystals A quantitative understanding of the behavior of SLMs based on liquid crystals, as well as many other types of SLMs that operate by means of polarization effects, requires the use of a mathematical formalism known as the Jones calculus. 6 Introduction to Fourier Optics 1. 'OPresumably we know the exact shape of the OTF within the passband, and can compensate for it to determine the actual values of G, at each frequency. Clearly, if z is a negative number, then the interpretation must be reversed, since a negative sign is hidden in z. The difficulties of the Kirchhoff theory stem from the fact that boundary conditions must be imposed on both the field strength and its normal derivative. The direction of linear polarization is therefore maintained after passage through the cell, is unchanged after reflection from the mirror, and is unchanged after the second passage through the cell. . 4.1, the diffracting aperture is assumed to lie in the (t,q) plane, and is illuminated in the positive z direction. Such a decomposition is offered by the so-called sifting property of the 6 function (cf. Distance increases as the Fresnel number NF shrinks. Since it takes time rollv for the disturbance to propagate from PI to Po, the observed wave depends on the derivative of the incident wave at the "retarded" time t - (rollv). 2.1, this elementary function may be regarded as being "directed" in the (x,y) plane at an angle 8 (with respect to the x axis) given by In addition, the spatial period (i.e. the distance between zero-phase lines) is given by 8 Introduction to Fourier Optics \ \ FIGURE - - - - 2.1 -. Thus if r is the radius coordinate in the observation plane, we have U(r)= , J ~ exp Z (jZ)B(U(q))l p = rlAz where q = ,/-represents radius in the aperture plane, and p = Jm represents radius in the spatial frequency domain. If the electric field were strong enough to fully rotate the molecules, then the birefringence of the material would vanish, the device would not change the direction of polarization, and again the reflected light would be completely blocked by the output analyzer. The vertical lines show the locations of the two sources. Taking account of scaling factors and coordinate inversions, the field in the rear focal plane of L4 is CHAPTER 8 Analog Optical Information Processing 245 Again it is the third and fourth terms of the expression for the output that are of most interest. The driving voltage has an RF spectrum that is centered at some center frequency f, with a bandwidth B about that center frequency. Wiley & Sons, 1985) and the editor of International Trends in Optics (Academic Press, 1991). We shall assume that the desired thickness function A(x, y) is known and that the problem at hand is how to fabricate a thin relief element that closely approximates this desired thickness function. (b) Can you specify a transferhnction for this system? For a square aperture of width 2w, the maximum path-length error at the edge of the aperture along the x or y axes, which we represent by W,, is given by The number Wrnis a convenient indication of the severity of the focusing error. This state is usually not used. These advantages can be attributed to a certain redundancy found in incoherent systems, namely the fact that light from a single pixel or resolvable spot of an input passes through the system via many spatially separate channels, due to the extended nature of the incoherent source. Maximum deflection angles approaching 10' are measured with applied voltages of about 16 volts. The second allows us to neglect all of the surface of integration except that portion lying directly within the aperture itself. 4.4.4 Thin Sinusoidal Phase Grating As a final example of Fraunhofer diffraction calculations, consider a thin sinusoidal phase grating defined by the amplitude transmittance function tA((,q) = exp where, by proper choice of phase reference, we have dropped a factor representing the average phase delay through the grating. At what distances behind this object will we find a field distribution that is of the same form as that of the object, up to possible complex constants? 3-3. Truxal, Ernst Weber, and John R. Note that the side-lobes have been significantly suppressed by the apodization. However, there are constraints on the geometrical organization of collections of molecules, and these constraints introduce some properties normally associated with solids. With some algebra the final result becomes A more conventional statement of the relationship between in the input field U 1(6) and the output field U2(u) is Thus the field is again seen to be a Fourier transform of the input amplitude distribution. In the Raman-Nath regime, which is typically encountered for center frequencies in the range of several tens of MHz in cells that use liquid as the acoustic medium, the moving grating acts as a thin phase sinusoidal grating exactly as described in the example of Section 4.4, with the one exception that, as a consequence of the grating mo- CHAPTER 7 Wavefront Modulation 207 tion through the cell, the various diffraction orders emerge from the cell with different optical frequencies. 8.7.1 Mellin Correlators While Fourier-based correlators such as discussed above are extremely sensitive to both magnification and rotation of the object, there exists a different transform, closely related to the Fourier transform, that exhibits a certain invariance to object magnification. A substitution of variables 8 = e-X yields the following expression for the Mellin transform of g, CHAPTER s Analog Optical Information Processing 253 im m M (j 2 7f~) = g(e-x) e-jzTfXdx. In the United States, much of the interest in these topics was stimulated by an electrical engineer, Otto Schade, who very successfully employed methods of linear systems theory in the analysis and improvement of television camera lenses [255]. ., N. Similarly, an FLC can act as a 90" polarization rotator (as explained above) and therefore can act as a binary intensity modulator. For the present we consider image formation in only a limited context. The existence of a threshold, requiring several trapped electrons to activate the development process, is responsible for good stability of unexposed film on the shelf. When the magnetization direction coincides with the direction of propagation of the light, linearly polarized light will be rotated in a right-hand screw sense, by an angle +Of that depends on the thickness of the garnet film, and when the magnetization is opposite to the direction of propagation, the rotation of polarization is by angle --Of. Thus, like the FLC SLMs, the MOSLM is a binary device with memory.5 The magnetization directions of the pixels are controlled by a combination of an external magnetic field, supplied by a bias coil, and a magnetic field introduced at the corner of each pixel by means of row and column metallic electrodes. tering process (approximately Gaussian) is circularly symmetric and there are no phase shifts associated with the transfer function. Electrical properties of liquid crystals Both displays and SLMs exploit the ability to change the transmittance of a liquid crystal by means of applied electric fields. The fraction of power appearing in each diffraction order can be found by squaring the coefficients of the delta functions in this representation, for it is the delta functions that determine the power in each order, not the sinc functions that simply spread these impulses. The second can easily be made to occur by proper choice of the illumination, as illustrated in Fig. Figure 7.28 shows an ideal phase grating profile with a perfect sawtooth period, and a quantized version of that grating with 2N levels. As will be seen in many of the examples to be discussed in later sections, it is often desirable to have film act as a square-law mapping of complex amplitude. The denominator simply normalizes the area of overlap by the total area of the pupil. Certain nonlinear optical elements (e-g. A reasonable conclusion from the above discussion would be that one should choose incoherent illumination whenever possible, to avoid the artifacts associated with coherent illumination. P6.7. Assume that the object is incoherent and nearly monochromatic, the distance z, from the object is so large that it can be treated as infinite, and the pinhole is circular with diameter 2w. The approach is that of wave optics, rather than the more common geometrical optics method of analysis. Evidently a more careful investigation is required before the contribution from S2can be disposed of. 6-3. The first of these properties is entirely reasonable. For example, in the case of a 90" twist illustrated previously in Fig. The amplitude point-spread function of an aberrated coherent system is simply the Fraunhofer diffraction pattern of an aperture with amplitude transmittance P. 136 Introduction to Fourier Optics For notational convenience we set the constant Ahzi equal to unity and ignore the negative signs in the arguments of P (almost all applications of interest to us here have pupil functions that are symmetrical in x and y). In addition, as we shall soon see, the wave equation describing the propagation of light through most media leads us naturally to regard optical imaging operations as linear mappings of "object" light distributions into "image" light distributions. If F{g(x, y)} = G(fx, fy), then The integral on the left-hand side of this theorem can be interpreted as the energy contained in the waveform g(x, y). The entire collection of these equations can be expressed in a single matrix equation where a' and c' are column vectors of length N, and P is an N x N matrix of correlations between the training images, Note that the vector Zis a column vector of known values (each element is zero or one in the case we are considering, but clearly they can also have more general values), the matrix P contains known elements (calculated in advance), and we seek knowledge of the vector a', for this will allow us to specify the desired impulse response of our filter according to Eq. (8-45). In the toe of the curve, density begins increasing with exposure. Some loss of correlator performance can be expected due to the fact that the phase of the Fourier transform of the input and the matched filter transfer function have both been discarded. The minimum resolvable separation of the geometrical images is therefore The corresponding result in the nonparaxial case can be shown to be A A S = 0.61- = 0.61sin 8 NA where 8 represents the half-angle subtended by the exit pupil when viewed from the image plane, and NA is the numerical aperture of the optical system, defined by N A = sin 8. The speck of silver formed as above is referred to as a development speck, and the collection of development specks present in an exposed emulsion is called the latent image. (a) Find the diffraction efficiency of this grating for the first diffraction orders. 4-19. An example of this type of application is found in the discussion of character recognition (Section 8.6). 2 n 1. Therefore it is possible to express the time-varying phasor representation of the image in terms of the convolution of a wavelength-independent impulse response with the time varying phasor representation of the object (in reduced object coordinates), (u , v ; t) = [[h(u - 6v -) (; t - r)d[dij where T is a time delay associated with propagation from ([, ij) to (u, v) (note that in general, T is a function of the coordinates involved). For these reasons some readers may appreciate the introduction of a certain "operator" notation that is useful in analyzing complex systems. It is directed towards both physicists and engineers, and the portions of the book used in the course will in general vary depending on the audience. 142 Introduction to Fourier Optics magnitude of this quantity (thus finding the intensity point-spread function), and inverse Fourier transform the result. (a) Calculate the relative perturbation AZ//A~* to the desired intensity caused by the presence of the undesired field when the two fields are mutually coherent. For this reason, it is necessary to limit the application of the inverse filter to those frequencies lying within the diffraction-limited passband. For discussions of other coordinate mappings (many of which are due to H.H. Hopkins) and their advantages, see Ref. The circle function is, of course, unique to the case of two-dimensional variables; see Fig. 3.8 GENERALIZATION TO NONMONOCHROMATIC WAVES The wave disturbances have previously been assumed to be ideally monochromatic in all cases. The linearity of the propagation phenomenon has already been discussed; it is directly implied by the linearity of the wave equation, or alternatively, by the superposition integral (3-52). The expression for image intensity can now be written (6, (6, where is known as the mutual intensity, and is a measure of the spatial coherence of the light at the two object points. The subscript n on y is used to indicate that we are dealing with a negative transparency. When an input pattern is presented with an angular orientation or a scale size that is different from those of the pattern to which the filter is matched, the response of the correct matched filter is reduced, and errors arise in the pattern recognition process. CHAPTER 7 (d) Wavefront Modulation 175 FIGURE 7.2 Pictorial representation of the photographic process. 130-133); (2) eliminating the amplitude portion of the transfer functions of the matched filters and retaining only phase information [149]; and (3) modifying the nonlinearity of the normally square-law detection process in the joint-transform correlator to enhance discrimination between patterns [154], [155]. It can be seen that, as N + m, all diffraction orders except the FIGURE 7.29 1 2 3 * N Diffraction efficiencies of various orders of a stepped approximation to a sawtooth grating. Measurement of the intensity distribution yields knowledge of the power spectrum (or more accurately, the energy spectrum) of the input. In most cases, however, the intensity distribution in the focal plane will be measured, and the phase distribution is of no consequence. Under the influence of internal and applied fields, the hole and electron move in opposite directions, leading to a photocurrent i that is the response to the incident absorbed photon. Such waves can be closely approximated in practice and are particularly easy to analyze. 114 Introduction to Fourier Optics There are two main conclusions from the analysis and discussion above: 1. Much of this problem can be eliminated by moving the diffuser during the observation, with the result that the coherence of the illumination is at least partially destroyed and the speckles "wash out" during the measurement process. The above transform theorems are of far more than just theoretical interest. Thus the pair of beams transmitted by the diode pair will carry with it the state of the device, but with a brightness inversion compared with the pair of beams that set the state of the diode pair. The layer thicknesses (and therefore the capacitances in Fig. For other examples of generalized transforms, see Table 2.1. 2.1.2 The Fourier Transform as a Decomposition As mentioned previously, when dealing with linear systems it is often useful to decompose a complicated input into a number of more simple inputs, to calculate the response of the system to each of these "elementary" functions, and to superimpose the individual responses to find the total response. 2wx rect ~ W Y The constants wx and wy are the half-widths of the aperture in the 6 and q directions. The result will be two output terms, centered at (0, Y) and (0, -Y) in the output plane, each of which is a convolution of g and h. For problems CHAPTER 5 Wave-Optics Analysis of Coherent Optical Systems 115 with apertures that are separable in rectangular coordinates, this is not a significant restriction, since the separability of quadratic-phase exponentials allows each of two orthogonal directions to be considered independently. The intensity distribution is measured across the back focal plane of the lens. The recording of the modulated high-frequency carrier requires a higher-resolution film than might C HAPTER 8 Analog Optical Information Processing 243 otherwise be used to synthesize the mask, but films with adequate resolution are readily available (e.g. Kodak Spectroscopic Plates) and this requirement poses no particular problem. These reasons rest on two basic mathematical principles, which we list here as theorems. As for any thin sinusoidal phase grating, the intensities associated with the various diffraction orders are proportional to the squares of the Bessel functions of the first kind, J,Z(A&), where A& is the peak-to-peak phase modulation, as shown in Fig. Devices of this type with as many as 1152 x 2048 pixels have been reported for use as high-definition TV (HDTV) displays. The focal length of the lens is 10 cm, the fundamental frequency of the square wave is 100 cycles/mm, the object distance is 20 cm, and the wavelength is 1 p m . 132 Introduction to Fourier Optics When the object illumination is coherent, the various impulse responses in the image plane vary in unison, and therefore must be added on a complex amplitude basis. The "frequency plane" now appears at P2, where an array of one-dimensional spectra is found. The two points of view that regard image resolution as being limited by (1) the finite entrance pupil seen from the object space or (2) the finite exit pupil seen from the image space are entirely equivalent, due to the fact that these two pupils are images of each other. You can use SocialFolders's Web interface to determine how much information you'd like access to (all of your Facebook albums, or only a select few, for example), and the content you've chosen will be automatically downloaded to your desktop. To determine the sample values outside the observable passband, we measurelo the values of Gg(f) at any 2N 1 distinct frequencies fk within the passband. Suppose that initially there is no light incident on the diode, and as a result there is no current flowing in the circuit. In accord with our earlier definition (3-68), the amplitude transmittance tA(&,q) of a screen is defined as the ratio of the complex field amplitude immediately behind the screen to the complex amplitude incident on the screen. Assuming the geometry of Fig. shows the transmitted spectrum when a horizontal slit is used. Aberrations can arise in a variety of ways, ranging from a defect as simple as a focusing error to inherent properties of perfectly spherical lenses, such as spherical aberration. The answer becomes clear if we consider situations other than propagation in the uniform dielectric medium hypothesized. As shown in part (b) of the figure, two address electrodes exist for each such pixel, one on either side of the rotation axis. 4.12. Figure 8.20(a) illustrates one way of recording the multiplexed filter. For the cantilever beam device, the structure is quite different. 3-2). Figure 6.20 shows the theoretical responses of a system with a circular pupil to a step function object, i.e. an object with amplitude transmittance Figure 6.21 shows actual photographs of the image of an edge in the two cases. 8.6(a), but is difficult to meet in all the other systems presented, to varying degrees. Consider a spherical wave converging towards the point (0, 0, +zo) in a cartesian coordinate system. That is, it is an exact replica of the intensity that would be observed just behind the grating. Such components are called evanescent waves and are quite analogous to the waves produced in a microwave waveguide driven below its cutoff frequency. Note also that, for values of Wrngreater than A12, sign reversals of the OTF occur. 5.4.2 Application of the Operator Approach to Some Optical Systems We illustrate the use of the operator notation by analyzing two optical geometries that have not yet been treated. The space-bandwidth product can be regarded as the number of degrees of freedom of the given function. The possibility of a new wave originating in the material medium of the rim makes this interpretation a more physical one. Two rather arbitrary choices were made in the analysis, and alternative choices at these two points will yield alternative sampling theorems. Equivalently the lens may be represented by a multiplicative phase transformation of the form tl(x, y) = exp[jkAol exp[jk(n - 1)A(x, y)l. The general conclusions of all of these analyses are similar; namely, the accuracy of the Fresnel approximation is extremely good to distances that are very close to the aperture. Lens L1 is a negative lens with focal length - f , and lens L2 is a positive lens with focal length f . 3.3.2 Green's Theorem Calculation of the complex disturbance U at an observation point in space can be accomplished with the help of the mathematical relation known as Green S theorem. Thus an imaging system is space-invariant if the image of a point source object changes only in location, not in functional form, as the point source explores the object field. [28]. In the latter case, the original imaging system was badly defocused, producing an impulse response which (in the geometrical-optics approximation) consisted of a uniform circle of light. This method is purely numerical and is readily implemented on a digital computer. ul- = - sin 38, [- cos , 1 . To do so, define the following frequency spectra6 of the input and output, respectively: ,.,. Figure 7.23 shows a top view of the metallized pixel. Only when interferometric detection is used can phase information be captured, and such detection systems will be seen to benefit from the first viewpoint, rather than the second. Note that the cosinusoidal intensity necessarily rides on a rectangular background pulse, assuring that intensity remains a positive quantity. Often a computer is employed in the design and construction of these elements, and their properties can be much more complicated than those of refractive elements. Second, they can provide image amplification: a weak incoherent image input to an optically addressed SLM can be read out with an intense coherent source. 8.8.3 Filter Realization Many methods exist for optically realizing inverse and Wiener restoration filters. The secondary sources have certain amplitudes and phases, described by U t (P l), that are related to the illuminating wavefront and the angles of illumination and observation. 653. 174 Introduction to Fourier Optics 3. 6.2 for the case of an object that is a grating with several orders and an imaging system composed of a single positive lens. CHAPTER 4 Fresnel and Fraunhofer Diffraction I n the preceding chapter the results of scalar diffraction theory were presented in their most general forms. (a) Circuit schematic, and (b) absorption spectra at various applied voltages. He further reasoned that if the photographic transparencies were placed in a coherent optical system, then by insertion of appropriate attenuating and phase-shifting plates in the focal plane, a compensatingJilter could be synthesized to at least partially remove the undesired defects. Thus the terminal property of a diffraction-limited imaging system is that a diverging spherical wave incident on the entrance pupil is converted by the system into a converging spherical wave at the exit pupil. (a) Is this system linear? Nevertheless, in this short time these tools

have been so widely and successfully used that they now occupy a fundamental place in the theory of imaging systems. Thus in this configuration the MOSLM can be used as a binary phase SLM. That error will be small provided the boundary conditions have effect over an area that is a small part of the area through which a wave may be passing. For the purposes of this section, let GK represent the Green's function for the Kirchhoff theory, while G - and G + are the Green's functions for the two Rayleigh-Sommerfeld formulations. Suppose that a sinusoidal input g(x, y) = cos[2.rr(fxx + fry)] is applied to a linear system. [225] and the references contained therein. AS a matter of curiosity we note that the zeros of this transform are not equally spaced in radius. This implies, of course, that such a system provides a highly nonlinear intensity mapping. The parameter m represents the peak-to-peak excursion of the phase delay. We shall, in 60 Introduction to Fourier Optics fact, demonstrate that the propagation phenomenon acts as a linear space-invariant system and is characterized by a relatively simple transfer function. For an excellent overview, see Ref. We choose that maximum value as a normalization constant in defining G, and Gi. Since intensities are nonnegative quantities, they always have a spectrum that is nonzero at the origin. The amplitude distribution in the Fraunhofer diffraction pattern is seen to be U(r) = "'"[Z e j k z e ~ zjhz Jl 1. 3.1, the incident light rays are bent at the interface. 2.6b). But the area of the circular sector is + while the area of the triangle A is (T)(y7. In the optical system shown in Fig. Bracewell, Colin Cherry, James F. If the system were free from aberrations, the exit pupil would be filled by a perfect spherical wave converging towards the ideal image point. (kwrlz) kwrlz and the intensity distribution can be written This intensity distribution is referred to as the Airy pattern, after G.B. Airy who first derived it. P4.10. 24 Introduction to Fourier Optics FIGURE 2.6a Spectrum of the original function. If we wish this filter to behave as desired over a 10 : 1 dynamic range of IS[, this requires proper behavior over a 100 : 1 range of 111~1~. Using the Fourier-Bessel transform expression (2-3 I), the transform of the circle function can be written 1 B{circ(r)) = 2 7 ~ r J o (2 ~ r pdr. The monochromatic elementary functions are of 54 Introduction to Fourier Optics various frequencies v', the complex amplitudes of the disturbance at frequency v' being simply U(PI, - v') and U(Po, - v'). Fresnel assumed these properties to hold in order to obtain accurate results. GOODMAN received the A.B. degree in Engineering and Applied Physics from Harvard University and the M.S and Ph.D. degrees in Electrical Engineering from Stanford University. We have eliminated some midfrequency components and have emphasized the spatial frequencies present in the passband of interest, but the low frequencies remain very prominent. From this fact it can be shown (see Prob. Note that it is entirely valid for systems both with and without aberrations. This particular form of the Fourier transform occurs frequently enough to warrant a special designation; it is accordingly referred to as the Fourier-Bessel transfomz, or alternatively as the Hankel transform of zero order (cf. The first two appendices should be read by the students, and the third can be skipped. Note that, for fixed w and A, as z increases the Fresnel number NF decreases and the normalization increasingly enlarges the true physical distance represented by a fixed distance on the x axis. Accordingly, a system is defined to be a mapping of a set of input functions into a set of output functions. If the spectral purity of the light source had been better, he might have observed even more striking results, such as the presence of light and dark fringes extending far into the geometrical shadow of the screen. And I have videos stored on YouTube. 128 Introduction to Fourier Optics The entrance and exit pupils are in fact images of the same limiting aperture within the system. We therefore turn to a more rigorous examination of the problem. 8-10 [7]. The lens L2 then casts a demagnified image of the light transmitted by 7 2 onto the photodetector D. Find a simple proof that this is the case. Not all readers will find this approach attractive, and for those the methods already used can simply be extended to the more complex systems. After passing through 72 the rays are focused onto the detector at coordinates (x,, y,), where we have assumed that the two lenses have identical focal lengths. Emmett Leith, who provided many helpful suggestions. Finally, it should be noted that, at first glance, there exists no transfer function that can be associated with Fraunhofer diffraction, for the approximation (4-24) has destroyed the space invariance of the diffraction equation (cf. For such a course, I would recommend that Chapter 2 be left to the reading of the student, that the material of Chapter 3 be begun with Section 3.7, and followed by Section 3.10, leaving the rest of this chapter to a reading by those students who are curious as to the origins of the Huygens-Fresnel principle. (7-5) When the phase shifts have been removed, a combination of Eqs. The bleaching process is one that removes metallic silver from the emulsion and leaves in its place either an emulsion thickness variation or a refractive index variation within the emulsion. It is therefore extremely important to be sure that when a system is designed on the basis of geometrical optics, it is used in a way that assures accuracy of the laws of geometrical optics. When voltage is applied to an NLC cell along the direction of wave propagation, the molecules rotate so that the long axis coincides with that direction, and no polarization rotation occurs. If we imagine observing a spherical wave that is diverging from a point on the z axis, the observation being in an (x, y) plane that is normal to that axis, then movement away from the origin always results in observation of portions of the wavefront that were emitted earlier in time than that at the origin, since the wave has had to propagate further to reach those points. Thus the optical frequency of the qth diffraction order is translated by q times the RF frequency, where q can be a positive or a negative number. 6.4.3 Effects of Aberrations on the OTF Having found the effects of aberrations on the amplitude transfer function, it is now possible, with the help of Eq. (6-28),to find the effects on the optical transfer function. Show that if a Faraday-rotating magnetic film is illuminated by light polarized in the y direction and the film is followed by an analyzer oriented in the x direction, a reversal of the direction of the magnetic field results in a change of the phase of the transmitted light by 180°, with no change in the transmitted intensity. It should be emphasized that this capability is not unique to the matched filter. If the lens is circular and of diameter 1, then a circular region of diameter Id1f is illuminated on the input. If the efficiencies of the three orders are added up, it will be seen that only 114 + m2/8 of the total is accounted for. In accordance with our view of the wave propagation phenomenon as a "system", we shall attempt to find approximations that are valid for a wide class of "input" field distributions. where the number of terms needed for a given accuracy depends on the magnitude of b. Having determined the maximum allowable distances between samples, it remains to specify the exact transfer function of the filter through which the data should be passed. Let the lens be illuminated by a normally incident plane wave of uniform amplitude A. As a consequence, incoherent systems often must have a heavy intrusion of electronics at their output in order to achieve a flexibility comparable with that of coherent systems. However, of ultimate interest, for reasons discussed at the beginning of this chapter, is the intensity rather than the complex field strength. Note that the strengths of the various orders are symmetric about the zero order. 6.13). Such input devices will be discussed in more detail in Chapter 7. The theory presented here can clearly be generalized in many ways, but space constraints prevent us from delving further into this subject. The final beam splitter allows the addition of these two waves at the recording plane. The carrier-frequency filter synthesis methods are therefore particularly well suited for this application. Using Jones matrices, show that if the retardation of the cell is one-quarter of a wave, the FLC cell can be used as a binary intensity modulator. 6.6 RESOLUTION BEYOND THE CLASSICAL DIFFRACTION LIMIT The diffraction limit to the resolution attainable by an imaging system is generally regarded to be an accurate estimate of the limits that can actually be reached in practice. They must therefore be added on a power or intensity basis. Again the image amplitude3 is represented by a superposition integral where h is the amplitude at image coordinates (u, v) in response to a point-source object at (6, q), and U, is the amplitude distribution transmitted by the object. 5.3.1 The Impulse Response of a Positive Lens Referring to the geometry of Fig. Our approach will be to first use the relationship in the 4th row and 3rd column of Table 5.1 to replace the two operators furthest to the left as follows: The two remaining adjacent R operators can now be combined using the relation given in the 4th row and 4th column of Table 5.1. The operator sequence is now of the form Next Eq. (5-51) is applied to write Substitution of this result yields an operator sequence where the last two Q operators on the right canceled each other. Such a stretch can be introduced, for example, by driving the deflection voltage of a cathode ray tube through a logarithmic amplifier and writing onto an SLM with the resulting stretched signal. I hope that these suggestions will at least give some ideas about possibilities. If F{g(x, y)) = G(fx, fv), then F{g(ax, by)) = that is, a "stretch" of the coordinates in the space domain (x, y) results in a contraction of the coordinates in the frequency domain (fx, fy), plus a change in the overall amplitude of the spectrum. Chemical diffusion during the development process. Thus if the function gl (xl, yl) represents the input to a system, and g2(x2,y2) represents the corresponding output, then by the definition of S {I, the two functions are related through g 2 (~ 2~, 2 =) S{gl (XI,YI)I. The phase dispersion of the system is most significant at high spatial frequencies and CHAPTER 3 Foundations of Scalar Diffraction Theory 61 vanishes as both fx and fy approach zero. In both cases we suppose that there is available a transparency that has recorded the known impulse response of the blurred system. The filter is bleached and therefore introduces only phase shifts in the transmitted light. Consider a pinhole camera shown in Fig. 6.1. However the conceptual ideaof a system mapping the light incident on the entrance pupil to the light leaving the exit pupil remains valid, regardless of the order of the two pupils. Before discussing the practical limitations of this and other techniques for extrapolation, we briefly discuss one other approach to the same problem. To the left of the photoconductor is a light-blocking layer composed of cadmium telluride (CdTe), which optically isolates the write side of the device from the read side. There follows a region of considerable extent in which the density is linearly proportional to the logarithm of exposure-this is the region most commonly used in ordinary photography. Thus an acousto-optic cell operating in the Bragg regime again acts as a one-dimensional spatial light modulator, translating the applied voltage modulation into a spatial wavefront, albeit more efficiently than in the case of Raman-Nath diffraction. Metal FIGURE 7.22 Deformable mirror pixel structures for (a) a membrane SLM and (b) a cantilever beam SLM. The second is the assumption that the observation distance is many wavelengths from the aperture, rol >> A. Such illumination is called spatially coherent. (a) Exposure, (b) latent image, (c) after development, and (d) after fixing. [13], [29], and [145]. He received the F.E. Terman award of the American Society for Engineering Education (1971), the Max Born Award of the OSA for contributions to physical optics (1983), the Dennis Gabor Award of the International Society for Optical Engineering (SPIE, 1987), the Education Medal of the Institute of Electrical and Electronics Engineers (IEEE, 1987), the Frederic Ives Medal of the OSA for overall distinction in optics (1990), and the Esther Hoffman Beller Medal of the OSA for contributions to optics education (1995). 7.18, but different materials are used and different conditions must be satisfied. Note that the first term on the right of Eq. (8-2) represents a strong wave component that passes through the sample suffering a uniform phase shift +,, while the second term generates weaker diffracted light that is deflected away from the optical axis. 6.1.3 Polychromatic Illumination: The Coherent and Incoherent Cases The assumption of strictly monochromatic illumination has been present in all our discussions of imaging systems up to this point. For example, SocialFolders uses Facebook's default upload API, which can reduce photo resolution. No power is absorbed by this grating, and therefore the sum of the powers appearing in all orders remains constant and equal to the incident power as m is changed. The inclusion of a dielectric mirror stack on the back of the device, made during the same molecular beam epitaxy (MBE) process used for the rest of the device, leads to a double pass of light through the device and improvement of onloff contrast. Thus the diode pair switches into a stable state in which the top diode is maximally absorptive and the bottom diode is maximally transmissive. The layers in (b) and (c) have been separated for clarity. Note that each member function of the defining sequence (2-4) does satisfy the existence requirements and that each, in fact, has a Fourier transform given by (see Table 2.1) 2Fora more detailed discussion of the delta function, including definitions, see Appendix A. One class of such benefits has arisen from the application of frequency-domain reasoning to the improvement of various types of imaging instruments. A portion of this light strikes the mask P I , which has an amplitude transmittance that is proportional to the desired impulse response h. (c) Above what frequency does the measured spectrum vanish, in spite of the fact that the input may have nonzero Fourier components at such frequencies? The detected image is now represented by where n(x, y) is the noise associated with the detection process. For a more comprehensive treatment of the photographic process, see, for example, Ref. It's designed for videos, large graphics, and other types of media that are not email-friendly sizes. Geometrical optics predicts a point-spread function that is the geometrical projection of the exit pupil into the image plane, and therefore the point-spread function should be uniformly bright over a square and zero elsewhere (see Fig. 8.8. While this system is nearly identical with that of Fig. 3.6, a wave disturbance is assumed to impinge on the screen and the aperture from the left, and the field at the point Po behind the aperture is to be calculated. While historically the case of incoherent imaging has been the more important one, nonetheless the case of coherent imaging has always been important in microscopy, and it gained much additional importance with the advent of the laser. By invoking the linearity of the wave-propagation phenomenon, we use the results of the previous section to find the complex amplitude at Po of each monochromatic component of the disturbance, and superimpose these results to yield the general time function u(Po, t). However, the most complete wedding between the two viewpoints was provided by a physicist, E.L. O'Neill, with the 224 Introduction to Fourier Optics publication of his paper "Spatial filtering in optics" in 1956 [222], and more generally through the great impact of his research and teaching. I did notice that some of the photos that SocialFolders downloaded for me looked to be slightly lower res than they appeared when viewed on Facebook, though. 8.5(b). Consider the scalar disturbance u(Po, t) observed behind an aperture C in an opaque screen when a disturbance u(P1,t) is incident on that aperture. Note that this type of weighting emphasizes the importance of high frequencies relative to low frequencies. I Micromachine 214 Introduction to Fourier Optics final period, as shown in part (c) of the figure. (3-55) and an interchange of the orders of integration give cos(ii, F0,) - j2av1U(PI, - v') exp E Finally, the identity d -u(P1,t) dt (U(Pl, d t -, m = - - v') exp(- j 2 a v't) d v' can be used to write The wave disturbance at point Po is seen to be linearly proportional to the time derivative of the disturbance at each point P1on the aperture. Figure 6.19 shows the distributions of image intensity for point sources in phase (4 = 0 radians), in quadrature (4 = 7~12radians), and in phase opposition (4 = 7~ radians). Finally we note that, if the tilt angle of the liquid crystal is 22.5', the two vectors above are orthogonal, aside from a sign change indicating a 180' phase shift. After reflection, the light propagates back through the liquid crystal a second time, with the direction of polarization again following the alignment of the molecules, thus returning to its original state. It is tempting, therefore, to conclude that incoherent illumination will invariably yield "better" resolution than coherent illumination, given that the same imaging system is used in both cases. However, diffractive optics can be used together with either refractive optics or additional diffractive elements in such a way that their dispersive properties partially cancel (cf. Such a device consists of two pieces of glass, each ground and polished to be optically flat on one side, between which the transparency and an index matching fluid (often oil) can be sandwiched, as illustrated in Fig. These four operators are sufficient for analyzing most optical systems. Specify the values of these focal lengths and the relative amounts of optical power brought to focus in the corresponding focal planes. - In conclusion, then, we may again regard the inverse Fourier transform as providing a means for decomposing mathematical functions. Thus the propagation phenomenon may be regarded as a linear, dispersive spatial filter with a finite bandwidth. A number of techniques for viewing such objects have been known for many years; these include interferometric techniques, the central dark ground method in which a small stop is used on the optical axis in the focal plane to block only the zero-frequency spectral component (see Prob. Structures that are not sufficiently thin can not be so represented, a point we shall return to in a later chapter. One approach to handling patterns with different scale sizes and rotations is to synthesize a matched filter for an object of fixed size and rotation, and to perform a mechanical search, rotating and magnifyingldemagnifying the input to the system. 4.4.1 Rectangular Aperture Consider first a rectangular aperture with an amplitude transmittance given by A t ,. In some cases it is possible to replace refractive or reflective elements with diffractive elements, a change that can lead to some significant benefits in certain applications. For any real imaging system, this property will be satisfied, at best, over only finite regions of the object and image planes. Tichenor and Goodman [282] have examined this argument in detail and have found that the approximation stated above is valid provided the size of object is no greater than about 114 the size of the lens aperture. (b) The openings are circular and have diameter d. For a more detailed discussion of this generalization of Fourier analysis the reader is referred to the book by Lighthill [194]. The FLC SLM is a pixelated version of the FLC intensity modulator described in a previous section. If less than the CHAPTER 7 Wavefront Modulation 193 Alignment layers Mirror FIGURE 7.17 Direction of polish Direction of polish Intensity modulation with a reflective NLC cell. k; is the incident optical wave vector, kl is the optical wave vector of the component diffracted into the first diffraction order, and is the acoustical wave vector. The resulting expression for the field at (x, y) therefore becomes m where we have incorporated the finite limits of the aperture in the definition of U(6, v), in accord with the usual assumed boundary conditions. 8.7.3 Synthetic Discriminant Functions The final method we will discuss for achieving invariant pattern recognition is through the use of what are known as "synthetic discriminant functions" (SDF). (a) Express the phase distribution of the spherical wave across an (x , y) plane located normal to the z axis at coordinate z = 0. Chapter 5 considers the analysis of coherent optical systems which consist of lenses and free-space propagation. The secondary source at PI has the following properties: 1. Both of these restrictions will be removed in Chapter 6, where the problem of image formation will be treated in a much more general fashion. 66 Introduction to Fourier Optics and therefore the Huygens-Fresnel principle can be rewritten where the distance rol is given exactly by rul = Jz2 + (X - 5)2 + (y - q)2 There have been only two approximations in reaching this expression. For the case of a unit amplitude plane wave illuminating the diffracting structure normally, the result takes a particularly simple form. (7-10) Figure 7.9 illustrates the typical measured frequency dependence of the MTF of an emulsion, plotted vs. Show that the zero-order Bessel function Jo(2.rrp,r) is an eigenfunction of any invariant linear system with a circularly symmetric impulse response. Calculation of the area of overlap of two displaced circles. The term diffraction has been defined by Sommerfeld (Ref. The mask shown in Fig. Second, it can serve as a storage medium for images, capable of retaining information for long periods of time. 182 Introduction to Fourier Optics the nonlinear mapping (Fig. To find the impulse response h, let the object be a S function (point source) at coordinates (6, q). The transducer is driven by an RF voltage source and launches a compressional wave (or, in some cases, a shear wave) into the acoustic medium. CHAPTER 4 Fresnel and Fraunhofer Diffraction 79 FIGURE 4.10 Fraunhofer diffraction pattern of a circular aperture. Reflection from the mirror reverses the sense of circular polarization, and a second pass back through the quarter-wave plate results in a linear polarization that is orthogonal to the original polarization. This point is most easily seen by abandoning the traditional H&D curve description of film and making instead a direct plot of amplitude transmittance vs. The inverse filter boosts the most those frequency components that have the worst signal-to-noise ratios, with the result that the recovered image is usually dominated by noise. Referring to Fig. 7.18. FLC-on-silicon electrically driven light modulators with as many as 256 X 256 pixels have been reported [206]. Due to a positioning error, the intensity distribution is measured across a plane at a distance f - A behind the lens. If 3{g(x, y)} = G(fx, fy), then Similarly, This theorem may be regarded as a special case of the convolution theorem in which we convolve g(x, y) with g*(-x, -y). ml2 for various values of q. Prob. In that case A , a- - P = S -a - P .(A' A) (A' A) and a P = S -CUP - @ T - a- P = T -a - P A (A) (A) (A,*) (A'*). Ferroelectric liquid crystal spatial light modulators Ferroelectric liquid crystals provide the basis for several different approaches to the construction of spatial light modulators. This first micromachining step removes substrate material to a depth of 1/2Nthof the desired peak-to-peak depth of the grating. For this reason we choose the distance 22 to the image plane so that this term will identically vanish. When light polarized along the y axis is used for illumination and the analyzer is oriented at angle + O f to the x axis, the intensity transmission of the pixel in the "off" state is zero and in the "on" state can be shown to be where q p is the combined efficiency of the polarizer-analyzer combination, d is the film thickness (pm), a is the loss per p m of film thickness, and /3 is the rotation per p m of film thickness (p d = 0f). , Zn must be equivalent to Fresnel propagation over the single distance z = zl 22 ' ' . Suppose that a filter, matched to the input CHAPTER s Analog Optical Information Processing 247 *I> S L1 Input S(X,Y) L2 Filter s*(fxfv) L3 Output FIGURE 8.17 Optical interpretation of the matched-filtering operation. (b) A cylindrical and a spherical lens of the same focal length. 2-1 b, FIGURE 2.6b Spectrum of the sampled data (only three periods are shown in each direction for this infinitely periodic function). The lens L1 again serves to illuminate the "input" transparency (intensity transmittance 71) with uniform light from the extended source S. As will be seen, this is equivalent to the requirement that the diffraction angles caused by the aperture are small. For example, there is no natural optical way to subtract two intensity patterns, whereas complex amplitude patterns can in principle be subtracted by adding them with a T radian phase shift between them. Goodman Introduction to Fourier Optics CHAPTER 1 Introduction 1.1 OPTICS, INFORMATION, AND COMMUNICATION Since the late 1930s, the venerable branch of physics known as optics has gradually developed ever-closer ties with the communication and information sciences of electrical engineering. signal s(x, y), is to be synthesized by means of a frequency-plane mask in the usual coherent processing geometry. Our discussion here is directed at the VanderLugt-type system, but the reader may wish to contemplate how the equivalent system could be realized with the joint transform geometry. In summary, the most severe limitation to the traditional coherent processor (prior to the invention of the methods to be discussed in the next section) arose from the difficulty of simultaneously controlling the amplitude and phase transmittances in any but very simple patterns. (3- 1) CHAPTER 3 "2 Foundations of Scalar Diffraction Theory 33 -t t C I--- 02 FIGURE 3.1 Snell's law at a sharp boundary. If g is of significant value only in the region - Lx 5 x < Lx, -Ly Iy < Ly, and if g is sampled, in accord with the sampling theorem, on a rectangular lattice with spacings (~Bx)-', BY)-' in the x and y directions, respectively, then the total number of significant samples required to represent g(x, y) is seen to be which we call the space-bandwidth product of the function g. 5-15) Substitution of this result in the general superposition equation (5-23) yields (5-34). SLMs of this type were developed by Litton [248] under the name "Light-Mod and for some time were marketed by Semetex Corporation under the name "Sight-Mod". to be f , and the total length of the system is seen to be 5f. Consider a real nonmonochromatic disturbance u(P, t) of center frequency 3 and bandwidth Av. Let a related complex-valued disturbance u- (P, t) be defined as consisting of only the negative-frequency components of u(P, t). P6.4. Find expressions for the optical transfer function evaluated along the fx and fy axes. Masv is also a bit different when it comes to pricing. Rather than a subscription model, Masv is a pay-as-you-go service. CHAPTER 3 Foundations of Scalar Diffraction Theory 53 where the impulse response h(Po, P I)is given explicitly by The occurrence of a superposition integral as a result of our diffraction analysis should not be a complete surprise. For simplicity, the focal lengths of all three lenses have been assumed CHAPTER 8 Analog Optical Information Processing 233 FIGURE 8.10 Architectures for coherent optical information processing. The compensating filter was synthesized where a is a constant and p = = by placing both an absorbing plate and a phase-shifting plate in the focal plane of the coherent filtering system, as shown in Fig. 2.5. By inserting an iris in the focal plane of the filtering system, it is possible to pass only the harmonic zone centered on zero frequency, thereby removing the periodic structure of the picture while passing all of the desired image data. 2.4.1 The Whittaker-Shannon Sampling Theorem To derive what is perhaps the simplest version of the sampling theorem, we consider a rectangular lattice of samples of the function g, as defined by gdx, y) = (4 (3 comb - comb - g(x, y). Some differ through their use of photographic film, rather than etchable substrates, as the means for creating the element. The logarithm 152 Introduction to Fourier Optics of intensity is plotted vertically in order to emphasize the side-lobes, and the intensity normalization is proportional to the total integrated intensity passed by the pupil in each case. It has a phase that leads the phase of the incident wave by 90°, as indicated by the factor 11j. 3.8). We discuss only two such methods, one relatively obvious, the other not at all obvious. To prove this fact, let M I represent the Mellin transform of g (t) and let Ma represent the Mellin transform of g(at), where 0 < a < m. In Prob. Note that the transform is circularly symmetric, as expected, and consists of a central lobe and a series of concentric rings of diminishing amplitude. Thus as light passes through the liquid crystal layer, the direction of polarization follows the twisted direction of the liquid crystal molecules, arriving at the dielectric mirror with a 45" polarization rotation. Note that only small angles will be involved if we are far from the diffracting aperture. Figure 6.10 shows the geometry that defines the aberration function W. 4.4.2 Circular Aperture Consider a diffracting aperture that is circular rather than rectangular, and let the radius of the aperture be w. FIGURE 4.14 Diffraction efficiency ~92(m/2) vs. The course can again begin with Section 3.7 and be followed by Section 3.10. For the case of a 4-level element, the fabrication process now terminates. A major flaw in the above argument lies in the direct comparison of the cutoff frequencies in the two cases. In this way an intensity modulation is induced at each pixel. CHAPTER 7 Wavefront Modulation 213 +1 order vanish, and the diffraction efficiency of that nonvanishing order approaches loo%, identical with the case of a continuous blazed grating with the same peak-to-peak phase shift. The continuous blazed grating has the property that, if the peakto-peak phase variation it introduces is exactly 2 7 ~radians, 100% of the incident light will be diffracted into a single first diffraction order (cf. As we shall discuss shortly, the change in the orientation of the molecules changes the optical properties of the cell as well. In addition, a necessary condition to achieve linearity between phase shift and intensity is that the variable part of the object-induced phase shift, A4, be small compared with 277 radians, in which case the crudest approximation to amplitude transmittance might be In this equation we have neglected terms in (A4)2 and higher powers, assuming them to be zero in our approximation, and the quantity 4, represents the average phase shift through the object, so A&[, q) by definition has no zero-frequency spectral component. In Chapter 7 the subject of wavefront modulation is considered. which we see is nothing but the Fourier transform of the function g(e-I). The third operation is passage through the lens L2, which is represented by the operator Q[Thus the entire sequence of operations is represented by the operator chain j]. CHAPTER 6 Frequency Analysis of Optical Imaging Systems 145 6.4 ABERRATIONS AND THEIR EFFECTS ON FREQUENCY RESPONSE In the development of a generalized model of an imaging system, it was specifically assumed that the presence of a point-source object yielded at the exit pupil a perfect spherical wave, converging toward the ideal geometrical image point. The two major difficulties encountered in attempting to perform general filtering operations with incoherent light are (1) the point-spread functions that can be synthesized must be nonnegative and real, since they are intensity distribution~,a constraint that restricts the generality of the operations that can be directly achieved, and (2) there are many different pupil-plane masks that will generate the same intensity point-spread function, but no known method for finding the simplest such mask. Thus the frequency plane filter should have an amplitude transmittance proportional to S*. Let that equation be rewritten as follows: where Now (3-28) may be interpreted as implying that the field at Po arises from an infinity of fictitious "secondary" point sources located within the aperture itself. Note that the cutoff frequency of the incoherent system occurs at frequency 2 fo along the fx and f y axes.8 The OTF represented by Eq. (6-31) is illustrated in Fig. Several different signal-to-noise ratios are represented. 2.6b. Figure 7.13 illustrates the structure of the surface stabilized FLC for large cell thickness. Convolution theorem. In the year 1890, F. For nematic liquid crystals, which do not have the extra constraints of smectic and cholesteric materials, a sufficiently large applied voltage will cause the molecules that are not in close proximity to the alignment layers to rotate freely and to align their long axes with the applied field. Resolution beyond the classical diffraction limit is often referred to as super-resolution or bandwidth extrapolation. To obtain a convolution of the functions h and g, it is necessary that one of them (and only one) be introduced in the processor of Fig. Historically the concept of the matched filter first arose in the field of signal detection; if a signal of known form, buried in "white" noise, is to be detected, then a matched filter provides the linear operation which maximizes the ratio of instantaneous signal power (at a particular time) to average noise power [286]. Micromachining again removes the exposed portions of the substrate, this time with an etch depth 112~-'thof the final desired maximum depth, as illustrated in part (d) of the figure. For our purposes, however, it suffices to note that if the relations (2-54) are satisfied, there is one transfer function that will always yield the desired result regardless of the shape of R, namely The exact recovery of G from Gs is seen by noting that the spectrum of the output of such a filter is 'For simplicity we assume that this rectangle is centered on the origin. This normalization, which can be accomplished electronically after detection of the filter outputs, takes account of the fact that the various input characters will generally not be of equal energy. electrode Spacer FIGURE 7.18 Hughes liquid crystal SLM. This condition can be equivalently stated as one for which the curvature of the total intensity at the midpoint between the centers of the individual spread functions vanishes. The slope of the curve in this linear region is referred to as the gamma of the emulsion and is represented by the symbol y. 8.20(b). The real advantage obtained from using this decomposition will not be fully evident until our later discussion of invariant linear systems. 2.2, are all functions of only one independent variable; however, a variety of separable functions can be formed in two dimensions by means of products of these functions. An incoherent imaging system has a square pupil function of width 2w.A square stop of width w is placed at the center of the pupil, as shown in Fig. Thus the transmitted angular spectrum is found directly by Fourier transforming the amplitude transmittance function of the aperture. If an analytic function in the (fx, fy) plane is known exactly in an arbitrarily small (but finite) region of that plane, then the entire function can be found (uniquely) by means of analytic continuation. 88 Introduction to Fourier Optics where we have omitted a constant term exp(jkz). You will pay per gigabyte of data. To proceed, Eq. (3-51) can be directly used to write exp(j2av1rollv) C O S (To,) ~ ~ ,ds, ro 1 U(P0, - v') = H (3-56) where v is the velocity of propagation of the disturbance in a medium of refractive index n (v = cln), and the relation v'h = v has been used. The magnification of this imaging operation as shown is unity. FIGURE 5.7 Optically obtained Fourier transform of the character 3. Mechanical properties of liquid crystals Liquid crystal materials are interesting from a physical point-of-view because they share some of the properties of both solids and liquids. In both cases it is possible to find situations in which the approximation breaks down, but as long as the simpler theories are used only in cases for which they are expected to be valid, the losses of accuracy will be small and the gain of simplicity will be large. For simplicity this input plane is taken to be the front focal plane of the Fourier transforming lens L2, but in fact this distance is arbitrary (vignetting will be eliminated if the inputs are placed in contact with lens, rather than in front of it). In Chapter 4, certain approximations to the general results are introduced, namely the Fresnel and Fraunhofer approximations, and examples of diffraction-pattern calculations are presented. zirconium arc lamps) can yield coherent light, albeit of weaker brightness than a laser, if their output is first passed through a pinhole. The price paid for rotation invariance is that the strength of the correlation peak is smaller than what would be obtained for the crosscorrelation with an unrotated version of the object when all of the circular harmonics are used simultaneously. The results of the preceding section can be applied directly to find the complex field distribution across the Fraunhofer diffraction pattern of any given aperture. The optical system can be represented by a paraxial ABCD matrix (see Appendix B, Section B.3) that holds between the input and output planes of the system. A second advantage is the ability of the device to operate at any optical wavelength where good mirrors can be fabricated in integrated form. 40ften advantages are gained by using much more complex changes of coordinates, particularly when the analysis is nonparaxial. A ferroelectric liquid crystal cell has a tilt angle of 22.5". This object is placed at distance 2f in front of a positive lens of focal lengthf , and the image is examined in a plane 2f behind the lens. A good discussion of such images is found in Ref. In such a case, the frequency response drops towards zero for relatively small values of fX/2fo and fy/2 fo. We allow the magnification to be either negative or positive, according to whether the image is inverted or not. It therefore seems intuitively reasonable that the major contribution to the integral (3-23) arises from the points of S1located within the aperture Z, where we would expect the integrand to be largest. I have spreadsheets stored in Google Docs. To find the transfer function, we return to the angular spectrum point-of-view. 7.3.2 Other Types of Diffractive Optics Attention has been focused above on binary diffractive optics, which are fabricated by the techniques widely used in the semiconductor industry. Equivalently it can be viewed as arising from the entrance pupil or from the exit pupil of the system. The resolving power of the grating is defined as the ratio of the mean wavelength A to the minimum resolvable wavelength difference Ah. Show that the resolving power of the sinusoidal phase grating discussed in this chapter is where q is the diffraction order used in the measurement, 2w is the width of the square grating, and M is the number of spatial periods of the grating contained in the aperture. One meter behind the lens and centered on the lens axis is placed an object with amplitude transmittance m i lm i FIGURE P5.7 Assuming L = 1 cm, A = 0.633 p m , and f, = 10 cycles/mm, sketch the intensity distribution across the u axis of the focal plane, labeling the numerical values of the distance between diffracted components and the width (between first zeros) of the individual components. 3.7 again): Using G - we obtain This result is known as the Rayleigh-Sommegeld difraction formula. This unknown vector can be found by inverting the matrix P and multiplying the inverse by the vector c' (using a digital computer for these calculations) Thus we have described a method for constructing a filter which will produce prescribed correlations between a group of images in a training set. As an example of this more general type of diffracting screen, consider a thin sinusoidal amplitude grating defined by the amplitude transmittance function where for simplicity we have assumed that the grating structure is bounded by a square aperture of width 2w. Lens L2 images 71 onto 72, and lens L3 casts a demagnified image of the light transmitted by 7-2 onto the detector. The periodic nature of the object generates in the focal plane a series of isolated spectral components, each spread somewhat by the finite extent of the circular aperture within which the mesh is confined. As a consequence there are several different ways to visualize the origin of the spatial limitation of the wavefront that ultimately gives rise to diffraction. In all three cases the obliquity factors approach unity as the angles become small, and the differences between the results vanish. The corre- Now for P 1 on S1,we have r01 = To1 cos(n', FOl)= - cos(n', FOl) and therefore on that surface For rol >> A, the second term above can be dropped, leaving which is just twice the normal derivative of the Green's function G used in the Kirchhoff analysis, i.e. With this result, the first Rayleigh-Sommerfeld solution can be expressed in terms of the more simple Green's function used by Kirchhoff, C H A P ~ E R3 Foundations of Scalar Diffraction Theory 49 An alternative and equally valid Green's function is found by allowing the two point sources to oscillate in phase, giving It is readily shown (see Prob. (b) Sketch the function p(x, y) when (9 (g(x, y) = rect 2- rect 2and find the corresponding Fourier transform P(fx,fy). As a final step in the synthesis of the frequency-plane mask, the exposed film is developed to produce a transparency which has an amplitude transmittance that is proportional to the intensity distribution that was incident during exposure. It is also possible to improve the contrast of the phase-induced variations of intensity in the image by making the phase-shifting dot partially absorbing (see Prob. As illustrated in Fig. Even when the quantity to be compared is agreed upon, the comparison remains a difficult one for an additional fundamental reason: the term better has not been defined. A paraxial approximation to that wave can be written in the form where A is the optical wavelength, while zo and yo are given constants. 252 Introduction to Fourier Optics 8.7 OPTICAL APPROACHES TO INVARIANT PATTERN RECOGNITION There exists a vast number of different pattern-recognition approaches that are aimed at reducing or eliminating sensitivity to extraneous parameters, such as scale size, and rotation. The reader is asked to verify (see Prob. This approach to wavefront modulation uses the interaction of a column of traveling acoustic waves with an incident coherent optical beam to modulate the properties of the transmitted optical wavefront. 8.7.2 Circular Harmonic Correlation An approach that focuses on the problem of invariance to object rotation is based on a circular harmonic decomposition of the object [15 11, [150]. P5.2. FIGURE P5.2 (a) Find a paraxial approximation to the phase transformation introduced by a lens of this form. Modest contrast ratios can be achieved (e.g. 3 : 1 on to off). Define a column vector consisting of the 2N 1 unknown values of the G,(nlL) and a column vector 2 consisting of the 2N 1 measured values cg(fk). Grimaldi's observations indicated, however, that the transition from light to shadow was gradual rather than abrupt. For this course, virtually all of the material presented in Chapter 7 is important, as is much of the material in Chapter 8. The absorbing mask is simply immersed in a liquid gate to eliminate all relative phase shifts. A rise in voltage across the lower diode makes it less absorptive, which means that its voltage will rise further, while at the same time a drop in voltage across the upper diode will make it more absorptive, generate more current, and so forth. Fourier analysis is a standard part of the background of most physicists and engineers. F. The alignment layers are oriented at 45" to one another, so that with no applied voltage the liquid crystal molecules undergo a 45" twist. Note that many methods for achieving invariance have been developed for digital processing of images, and only some of these are naturally well suited for optical implementation. By making some rather arbitrary assumptions about the amplitudes and phases of Huygens' secondary sources, and by allowing the various wavelets to mutually interfere, Fresnel was able to calculate the distribution of light in diffraction patterns with excellent accuracy. 7.2.6 Acousto-Optic Spatial Light Modulators The SLMs considered in the above sections are capable of modulating a two-dimensional wavefront, either in a continuous fashion or with a discrete two-dimensional 206 Introduction to Fourier Optics FIGURE 7.26 Acousto-optic cells operating in the (a) Raman-Nath regime and the (b) Bragg regime. 6-17. 8.7, let the distributed incoherent source S be placed in the front focal plane of the lens L 1 .Immediately behind L1 is placed a transparency with intensity transmittance T I (- X , - y) . 3.6 show that if Av v >- Av U then where A = vlfi and i = 2.rrIA. Such a phase has no tilt angle, and therefore the molecules align with their long direction parallel to the alignment grooves. Intensity transmittance. 5Thename "chirp function", without the finite length qualifier, will be used for the infinite-length quadratic phase exponential, exp[j.rrp (xZ+ y 2)] . CHAPTER 8 Analog Optical Information Processing 227 uniform velocity and measuring the photodetector response as a function of time. The two most common micromachining methods are reactive ion etching and ion milling. We therefore turn to a consideration of information processing using coherent light. If the filtering operation represented by the transfer function H is of high space-bandwidth product, then the impulse response h will extend over a sizable area, and the output of this system must be regarded as a filtered version of the function g(xl, y l) exp [j&x: + y:)] rather than simply of g(xl, yl). The two cases are illustrated in Fig. The fl orders have nearly vanished in this example. Consider the simple optical system shown in Fig. Note also that, unlike the case of aberrations, inverse apodization can raise the value of the OTF at certain frequencies, as compared with its unapodized values. A photodetector can be used to measure the total intensity transmitted through the pair, yielding a photocurrent I given by3 3As usual, in writing infinite limits of integration, we have assumed that the finite sizes of the transparencies are incorporated in the functions 71 and 7 2 . 48 Introduction to Fourier Optics FIGURE 3.8 Rayleigh-Sommerfeld formulation of diffraction by a plane screen. The upper portion of response will generate the convolution of the input data with the symbol P, while the lower response will generate the crosscorrelation of the input with the letter P. The lens L 1 collimates the light from the point source S. Alternatively the two incoherent images can be translated by spatial light modulators into coherent images, and the amplitudes of those can be added with a 180' phase difference in an interferometer to achieve subtraction (the result is an intensity distribution representing the squared-magnitude of the difference image). More complex structures are needed to produce a useful SLM. The halftone process is, in many respects, similar to the periodic sampling procedures discussed in Section 2.4. The spectrum of a picture printed in this fashion has a periodic structure much like that illustrated in Fig. In addition, if the exposure pattern consists of a strong average exposure l? 20 Introduction to Fourier Optics 2.3.1 Linearity and the Superposition Integral A system is said to be linear if the following superposition property is obeyed for all input functions p and q and all complex constants a and b: As mentioned previously, the great advantage afforded by linearity is the ability to express the response of a system to an arbitrary input in terms of the responses to certain "elementary" functions into which the input has been decomposed. The denominator is also unity for q = 1, and is nonzero except when where p is any integer other than zero. 46 Introduction to Fourier Optics This result, which holds only for an illumination consisting of a single point source, is known as the Fresnel-Kirchhojfdijfractionformula. We will refer to them as input "transparencies", even though in some cases they may operate by reflection of light rather than transmission of light. As mentioned previously, the question of whether intensity or field amplitude should be considered the relevant quantity will be treated at a later time. We define the local spatialfrequency of the function g as a frequency pair (fix, fiy) given by fix = 1 d Gz4(x' Y) 1 d fiy = T;; &4(* Y). Many of the most promising applications fall in this realm. The coherent system is seen to exhibit rather pronounced "ringing". For the membrane device, a metallized polymer membrane is stretched over a spacer grid, the spacers forming an air gap between the membrane and the underlying address electrodes. Thus, letting P = 1, Eq. (5-14) can be rewritten Substituting (5-17) into (5-18), we have Thus the amplitude and phase of the light at coordinates (u, v) are again related to the amplitude and phase of the input spectrum at frequencies (ulhf , vlA f). To completely describe the imaging system, the impulse response appropriate for each isoplanatic patch should be specified; but if the particular portion of the object field of interest is sufficiently small, it often suffices to consider only the isoplanatic patch on the optical axis of the system. A realization of the utility of Fourier methods in the analysis of optical systems arose rather spontaneously in the late 1930's when a number of workers began to advocate the use of sinusoidal test patterns for system evaluation. Figure 6.6 illustrates the calculation for the square case, The area of overlap is evidently (0 otherwise. (b) The fraction of incident light that is transmitted by the grating. This result, which is valid subject only to the scalar approximation, can now be compared with the transfer function predicted by the results of the Fresnel analysis. This requirement is known as the Sommei$eld radiation condition [269] and is satisfied if the disturbance U vanishes at least as fast as a diverging spherical wave (see Prob. In other words, if F{1) = L and F { p } = P, then L(f) = P(0, f). 133-139). , lvNI2 are compared at the particular points where their maximum outputs would be anticipated (assuming that the character to which they are matched is present in each case). *We reserve the symbols z, and z2 for the distances from the object to the first principal plane and the distance from the second principal plane to the image, respectively. Specifically, when wavefront errors exist, we can imagine that the exit pupil is illuminated by a perfect spherical wave, but that a phase-shifting plate exists in the aperture, thus deforming the wavefront that leaves the pupil. P6.10) is imaged by a lens with a circular pupil function. [27 11. See Prob. centered at the observation point Po. The total closed surface S is simply the sum of S1 and S2.Thus, applying (3-21), where, as before, G = exp(jkr01) '-01 As R increases, S2 approaches a large hemispherical shell. Note the shift of the absorption peak as the applied voltage increases, as well as the gradual reduction in the strength of that peak. Which is great–until I want access to these files when I'm offline. The properties of photographic film as an input medium for incoherent and coherent optical systems are discussed. The corresponding optical transfer function was therefore of the form /,. An example of these so-called anamorphic processors4 is shown in Fig. Note that Eq. (3-27) is symmetrical with respect to the illumination point source at P2and the observation point at Po.Thus a point source at Po will produce at P2the same effect that a point source of equal intensity placed at P2 will produce at Po.This result is referred to as the reciprocity theorem of Helmholtz. The phase-changing plate can consist of a glass substrate on which a small transparent dielectric dot has been d e p ~ s i t e dThe . that particular training image represents a distorted version of an entirely different ideal image). Thus using Eq. (4-25), the Fraunhofer diffraction pattern is seen to be ejk~ej$(~2+y2) U(x, y) = jhz fx= xlhz Noting that F{U(&, q)) = A sinc(2wx fx) sinc(2wyfy), where A is the area of the aperture (A = 4wxwy), we find ejk~ej$(x2+~2) U(x, y) = jhz A sinc (2)(x), ~ W Y Y sinc and Figure 4.7 shows a cross section of the Fraunhofer intensity pattern along the x axis. This article will walk you through several of the best ways to transfer large files online. We will also suggest a few ways to make shuffling huge amounts of data easier. The amplitude transmittances of the two objects are taken to be 156 Introduction to Fourier Optics 1121t1 fx Coherent , -2fo [G -fo "1 Incoherent 4l,I fx fo 2fo -2f0 -fo fo 2fo FIGURE 6.17 Calculation of the spectrum of the image intensity for object A. Within the volume V', the disturbance G, being simply an expanding spherical wave, satisfies the Helmholtz equation Substituting the two Helmholtz equations (3-13) and (3-18) in the left-hand side of Green's theorem, we find Thus the theorem reduces to Note that, for a general point P1on S r , we have 42 Introduction to Fourier Optics and where cos(n', Tol) represents the cosine of the angle between the outward normal n' and the vector Fooljoining Po to PI. Suppose G is generated not only by a point source located at Po, but also simultaneously by a second point source at a position Po which is the mirror image of Poon the opposite side of the screen (see Fig. Now these relations may be regarded as expressing the nonmonochromatic time functions u(PI, t) and u(Po, t) as a linear combination of monochromatic time functions of the type represented by Eq. (3-10). But since 2f" > f,, no variations of image intensity will be present for the coherent case, while the incoherent system will form the same image it did for object A. 2-6). The binary optic approximation to the grating is a quantized version with 4 discrete levels. Thus a complete description of the amplitude transmittance of the film must be written where +(x, y) describes the pattern of phase shifts introduced by the transparency. [28] (Section 8.4). 8.16(a). Theorem 2. 3As we shall see, objections to the use of the Kirchhoff boundary conditions arise, not because of the fringing effects, but rather because of certain internal inconsistencies. A variety of references to more comprehensive treatments of diffraction theory will be found in the material that follows. I would also like to thank the students in my 1995 Fourier Optics class, who competed fiercely to see who could find the most mistakes. However, with a proper choice of fluid, the optical path length through the liquid gate can be made nearly constant, allowing the amplitude transmittance of the film and gate to be written ~ A (xY,) = J m . The refractive index disturbance generated by this applied voltage then propagates through the cell with velocity V. It is, in fact, possible to associate all diffraction limitations with either of these two pupils. 2.3 LINEAR SYSTEMS For the purposes of discussion here, we seek to define the word system in a way sufficiently general to include both the familiar case of electrical networks and the lessfamiliar case of optical imaging systems. 3.4.1 Application of the Integral Theorem To find the field at the point Po, we apply the integral theorem of Helmholtz and Kirchhoff, being careful to choose a surface of integration that will allow the calculation to be performed successfully. 1. 6.8, the area of overlap may be regarded as being equal to four times the shaded area B of the circular sector A B. P6.3. FIGURE P6.3 CHAPTER 6 Frequency Analysis of Optical Imaging Systems 167 (a) Sketch cross sections of the optical transfer function with and without the stop present. Their general structure is similar to that of Fig. The members of the training set may be distorted versions of a single object, where the distortions correspond to scale change and rotation, they may be more generally distorted versions of that object, or they may be examples of other objects for which we desire to have zero filter output. 5.4. Thus a lens with a positive focal length is called a positive or converging lens, while a lens with a negative focal length is a negative or diverging lens. A more compact form of (3-9) is found by using complex notation, writing CHAPTER 3 Foundations of Scalar Diffraction Theory 39 where Re{} signifies "real part of", and U(P) is a complex function of position (sometimes called a phasor), If the real disturbance u(P, t) is to represent an optical wave, it must satisfy the scalar wave equation at each source-free point. We turn now to an SLM technology that is most commonly onedimensional, but which has been developed over a period of many years into a highly mature technology. 'The reader may wonder why the generation of both an electron and a hole does not lead to a charge 2q rather than q in this equation. Finally, it should be pointed out that while the OTF is always unity at the zero frequency, this does not imply that the absolute intensity level of the image background is the same as the absolute intensity level of the object background. (b) What is the effect of such a lens on a plane wave traveling down the optical axis? The input again has amplitude transmittance t ~ but , it is now located a distance d in front of the rear focal plane of the lens. Many variations on this theme are possible. In both cases the express purposes of the experiments were verification of Abbe's theory of image formation in the microscope and an investigation of its implications. Similarly, if a solution of the three-dimensional wave equation vanishes on any finite surface element, it must vanish in all space. 8.4(a), the image in part (b) of the figure is seen to contain only horizontal structure. The first truly rigorous solution of a diffraction problem was given in 1896 by Sommerfeld [268], who treated the two-dimensional case of a plane wave incident on an infinitesimally thin, perfectly conducting half plane. Finally the curve saturates in a region called the shouldel; beyond which there is no change of density with increasing exposure. The sequence of operators describing this system is where the & operator furthest to the right represents the fact that the input is illuminated by a diverging spherical wave, the R operator second from the right represents propagation over distance d to the lens, the & operator next to the left represents the effect of the positive lens, and the operator R furthest to the left represents the final propagation over distance 22. A polarization analyzer oriented at 90" to the direction of incident polarization then blocks the reflected light, yielding a uniformly dark output image when there is no write light. Outside this range, S = 0 and its inverse is ill defined. ~ that no angular spectrum components beyond the evanescent (3-67) is ~ a t i s f i e d Note wave cutoff contribute to U(x, y, z). Let the medium be isotropic, and the wave monochromatic. The amplitude transmitted by the impulse response mask is Fourier transformed in the usual fashion. ~ dot is centered on the optical axis in the focal plane and has a thickness and index of refraction such that it retards the phase of the focused light by either ~ 1 radians 2 or 3 ~ 1 radians 2 relative to the phase retardation of the diffracted light. If we trace a ray backward from the ideal image point to the coordinates (x, y) in the exit pupil, the aberration function W(x, y) is the path-length error accumulated by that ray as it passes from the Gaussian reference sphere to the actual wavefront, the latter wavefront also being defined to intercept the optical axis in the exit pupil. All these techniques suffer from a similar defect-the observed intensity variations are not linearly related to the phase shift and therefore cannot be taken as directly indicative of the thickness variations of the object. 4-18. These situations include high-resolution microscopy, coherent optical information processing, and holography. CHAPTER 8 Analog Optical Information Processing 23 1 No phase shift With phase shift (d) f~ FIGURE 8.9 Two-pupil OTF synthesis. The only solution to the last of the problems raised above is to adopt a new approach to determining the desired restoration filter, an approach that includes the effects of noise. A simple spatial filtering operation (see Chapter 8) can eliminate the unwanted diffraction orders and pass only the desired order. The electrical response of a liquid crystal cell is predominantly that of a simple RC circuit, where the resistance arises from the finite resistivity of the transparent electrodes and the capacitance is that of a parallel plate capacitor (the NLC cell is typically 5 to 10 p m thick). A negative bias voltage is applied to the metallized membrane. 5.2, and write the total thickness function as the sum of three individual thickness functions, Referring to the geometries shown in that figure, the thickness function Al (x, y) is given by 98 Introduction to Fourier Optics FIGURE 5.2 Calculation of the thickness function. (4-7) When calculating a diffraction pattern, we will generally regard the intensity of the pattern as the quantity we are seeking. Harman, Hubert Heffner, Edward W. (a) Find the diffraction efficiencies of the +4, +3, +2, grating. The Fourier spectrum G of a function g is simply a description of the weighting factors that must be applied to each elementary function in order to synthesize the desired g. The relation (3-13) is known as the Helmholtz equation; we may assume in the future that the complex amplitude of any monochromatic optical disturbance propagating in vacuum (n = 1) or in a homogeneous dielectric medium (n > 1) must obey such a relation. Because of the permanent dipole moment of the FLC molecules, the current state is retained by the material even after the applied field is removed. Linvill, Simon Ramo, Ronald A. A view equivalent to regarding diffraction effects as resulting from the exit pupil was presented by Lord Rayleigh in 1896 [241]. We turn attention in the next section to a few of the many other techniques that have been explored as possible solutions to scale-size and rotation variations of the object. A certain diffracting screen with an amplitude transmittance is normally illuminated by a unit-amplitude, monochromatic plane wave. Optimum in this case means the size that produces the highest possible cutoff frequency. Then the cutoff frequency is 100 cycleslmm. P4.13.Find the following properties of this grating: (a) The fraction of incident light that is absorbed by the grating. To be specific, we focus on the system shown in part (a) of that figure. When an input signal other than s(x, y) is present, the wavefront curvature will in general not be canceled by the frequency-plane filter, and the transmitted light will not be brought to a bright focus by the final lens. The effect of the spatial truncation is to change the spectrum of the new image. New York St. Louis San Francisco Auckland Bogot6 Caracas London Madrid Mexico City Milan Montreal New Delhi San Juan Singapore Sydney Tokyo Toronto Lisbon ABOUT THE AUTHOR JOSEPH W. (a) Original density image. Eq. (3-39)) A comparison of the above equations leads us to an interesting and surprising conclusion: the Kirchhof solution is the arithmetic average of the two RayleighSommer$eld solutions! CHAPTER 3 Foundations of Scalar Diffraction Theory 51 Comparing the results of the three approaches for the case of spherical wave illumination, we see that the results derived from the Rayleigh-Sommerfeld theory (i.e. Eqs. The growth of noise sensitivity is extremely rapid. It now remains to relate H more directly to the physical characteristics of the imaging system itself. To apply the binomial expansion to the problem at hand, factor a z outside the expression for rol, yielding Let the quantity b in Eq. (4-11) consist of the second and third terms under the square root in (4- 12). Unlike the optically addressed SLMs, electrically addressed FLC SLMs are discrete pixelated devices, i.e. they display sampled images rather than continuous images. Using G + , and assuming that r21 >> A, the corresponding result is where the angle between ii and is greater than 90". If the alternative Green's function of (3-37) is used, the result can be shown to be We now specialize Eq. (3-41) and Eq. (3-42) to the case of illumination with a diverging spherical wave, allowing direct comparison with Eq. (3-27) of the Kirchhoff 50 Introduction to Fourier Optics theory. The rays from that point emerge from L1 (and from 71) parallel with each other and illuminate 72 with an intensity distribution proportional to 71[-x + (dlf)xs,- y + (dlf)y,]. Such structures can be realized with photographic materials, provided they are subjected to chemical bleaching. Thus, putting z = f , CHAPTER 5: exp [j , v) = Wave-Optics Analysis of Coherent Optical Systems 103 A (u2 + v)] 2 j Af x 11 (xu u;(x, y) exp + yo) I dx dy, where a constant phase factor has been dropped. It's a popular service among video editors and freelancers because of the ability to move files larger than 20GB. Again the field is assumed to be monochromatic. These include (1) liquid crystal SLMs, (2) magneto-optic SLMs, (3) deformable mirror SLMs, (4) multiple-quantum-well (MQW) SLMs, and (5) acousto-optic Bragg cells. Notice a common requirement in all the applications mentioned above: a picture or photograph taken in incoherent light is filtered in a system that uses coherent light. Note that the output appears inverted in plane P3due to the imaging operation, or equivalently due to the fact that a sequence of two Fourier transforms has been used, rather than one transform followed by its inverse. Only a single interferometrically generated filter is required, albeit one with an unusual set of recording parameters. The latter requires that the diffracting screens be planar, while the former does not. Note that the relatively tedious convolution operation of (2-49) required to find the system output is replaced in (2-50) by the often more simple sequence of Fourier transformation, multiplication of transforms, and inverse Fourier transformation. The "equivalent area" Ax of a function g(x, y) can be defined by Ij g(x9 Y) ~ X ~ Y Axr = while the "equivalent bandwidth" Afx fY -m 2 g(09 0) of g is defined in terms of its transform G by iGCfx. The most important of these properties are as follows: 140 Introduction to Fourier Optics Property 1 follows directly by substitution of (fx = 0, fy = 0) in Eq. (6-28). To achieve super-resolution, it is necessary to retrieve these extremely weak components and to utilize them in such a way as to recover the signal that gave rise to them. 8.8 IMAGE RESTORATION A common problem in image processing, and one that has been studied extensively in the context of optical information processing, is image restoration, by which we mean the restoration of an image that has been blurred by a known linear, invariant pointspread function. An ideal grating has a profile that is illustrated by the triangular curve in Fig. 7.26(a), the zero-order component remains centered at frequency v, of the incident light, but higher-order components suffer frequency translations, which can be interpreted as Doppler shifts due to the motion of the grating. To simplify the notation, the function A(fx, fy)is defined as the area of overlap of Thus the OTF of a diffraction-limited system is given, in this new notation, by CHAPTER 6 Frequency Analysis of Optical Imaging Systems 147 When aberrations are present, substitution of (6-34) into (6-35) yields This expression allows us, then, to directly relate the wavefront errors and the OTF. Surrounding the pixelated garnet film is a bias coil which can be driven with current in either of two directions, thereby establishing a strong magnetic field in either of two directions, i.e. either parallel to the direction of light propagation, or anti-parallel to that direction. Nonetheless, they are a real phenomenon, although perhaps more accurately treated in a full vectorial theory. First, as compared with system (a), the input is now twice the distance from lens L2, and therefore the vignetting will be even worse than that encountered with system (a). 2.1); bright spots along the vertical axis correspond to vertically directed complex-exponential components. (3-43) and (3-44)) differ from the Fresnel-Kirchhoff diffraction formula, Eq. (3-27), only through what is known as the obliquity factor which is the angular dependence introduced by the cosine terms. Show that the focal lengths of double-convex, plano-convex, and positive meniscus lenses are always positive, while the focal lengths of double-concave, plano-concave, and nega- tive meniscus lenses are always negative. When the square bridges the open and obstructed parts of the aperture, then the observed field is in the transition region between light and dark. photographic film) have input-output relationships which are directly analogous to the corresponding characteristics of nonlinear electronic components (diodes, transistors, etc.), and similar mathematical analysis can be applied in both cases. (3-17) The function G(x) is known as the Green 'sfunction of the problem, and is clearly a form of impulse response. The book can be used as a textbook to satisfy the needs of several different types of courses. Note that the intensity mapping defined by this relation is a highly nonlinear one for any positive value of y,. (a) What is the Fourier transform of the amplitude distribution transmitted by the object? CHAPTER 6 Frequency Analysis of Optical Imaging Systems 143 FIGURE 6.6 Calculation of the OTF for a square aperture. [208]. 166 Introduction to Fourier Optics FIGURE P6.1 (a) Find the spatial frequency of this fringe in terms of the center-to-center spacing s of the two openings, the wavelength A, and the image distance zi. U(Po, - v') exp(- j 2 n v 1 t)d v'. The coherent system has a transfer function with sharp discontinuities, while the falloff of the OTF is much more gradual. The intensity distribution across the back focal L1 L2 FIGURE 8.7 Systems for performing convolution without motion. Thus some care must be used in finding the spectrum in the latter case. When this area is normalized by the total area 4w2, the result becomes where A is the triangle function of Chapter 2, and fo is the cutoff frequency of the same system when used with coherent illumination, I hzilfy1 I +hzilfxJ- FIGURE 6.5 Light from patches separated by (Azilf x l , Azilful) interferes to produce a sinusoidal fringe at frequency (fx,fy). We turn attention now to a different type of device, one that operates by means of polarization rotation under the application of a magnetic field, or the Faraday effect. In summary, then, which particular type of illumination is better from the point of view of image spectral content depends very strongly on the detailed structure of the object, and in particular on its phase distribution. Thus if the aperture has an area that is large compared with a wavelength, the coupling effects of the boundary conditions on the and fl fields will be small. Nontanning bleaches, on the other hand, produce internal refractive index changes within the emulsion, rather than relief images. We mention in particular Wolf and Marchand [301], who examined differences between the two theories for circular apertures with observation points at a sufficiently great distance from the aperture to be in the "far field" (the meaning of this term will be explained in the chapter to follow). in Eq. (7-35) yields with a peak-to-peak phase difference of 4, = 2 7 ~Substitution n2 Consider for the moment only the last factor, consisting of the ratio of two sinc functions. In general, any one of these conditions can be weakened at the price of strengthening one or both of the companion conditions, but such considerations lead us rather far afield from our purposes here. It is also possible to achieve a positive power-law relation between intensity transmittance and intensity incident during exposure, although to do so generally requires a two-step photographic process. They may also be less expensive to manufacture and in some cases may have superior optical performance (e.g. a wider field of view). Under what condition does complete cancellation occur? For that reason the phase must increase in a positive sense as we move away from the origin. The second viewpoint can be used, of course, only when the light that exposes the transparency is itself coherent, and must incorporate the fact that all phase information about the incident complex wavefield is lost upon detection. We shall assume, however, that the system ultimately produces a real image in space; this is not a serious restriction, for if the system produces a virtual image, to view that image it must be converted to a real image, perhaps by the lens of the eye. When we examine the character of the impulse response h(Po, P I) in more detail in Chapter 4, we will find that it is also space-invariant, a consequence of the homogeneity assumed for the dielectric medium. As we shall see, this application affords an excellent example of desired processing operations with simple impulse responses but not necessarily simple transfer functions. Since the definitions of both the amplitude transfer function and the optical transfer function involve the function h, we might expect some specific relationship between the two. For a second example, the reader is referred to Prob. cos circ (a) In what way does this screen act like a lens? However, the fields are not sufficient to fully rotate the molecules, and hence they only partially tip away from the transverse plane,

with an amount of tip that is proportional to the strength of the field (and therefore the strength of the write image). The strength of that spot is not affected by pure translation. (b) A circular opaque disk of diameter d. In addition, a second portion of the collimated light passes above the mask P 1 , strikes a prism P, and is finally incident on the recording plane at angle 8 , as shown. In an attempt to reduce the strength of side-lobes or side-rings, methods known as apodization have been developed. Under nonparaxial conditions, the emerging wavefront will exhibit departures from perfect sphericity (called aberrations-see Section 6.4), even if the surfaces of the lens are perfectly spherical. The input is assumed to be uniformly illuminated by a normally incident, monochromatic plane wave of amplitude A, in which case the disturbance incident on the lens is The finite extent of the lens can be accounted for by associating with the lens a pupil function P(x, y) defined by 1 inside the lens aperture 0 otherwise. q is a positive integer for diffraction orders with components of direction parallel to the direction of motion of the acoustic wave (i.e. downwards in Fig. Local spatial frequencies are of special physical significance in optics. The disadvantage is that the system is now of length 6f rather than 5f . Figure 8.12 shows the regions of the complex plane that can be reached by the transfer functions of coherent optical systems under different constraints on the frequencyplane transparency. A simple relation between the Fourier transform and the Mellin transform can be discovered if the complex variable s is restricted to the imaginary axis, i.e. s = j 2 7 ~f . Equally important, there are lessons that have been learned in this application, particularly about clever use of the properties of wavefront modulation devices, that can be applied to other unrelated problems. 26 Introduction to Fourier Optics The equivalent identity in the space domain is where h is the impulse response of the filter, h(x,y) = { (kX) 3-' rect - rect(&-)} = 4BxBy sinc(2Bxx) sinc(2Byy). Now using Table 2.1 we have 1 (4I):(F comb - comb - = XY comb(Xfx)comb(Yfy) while from the results of Prob. Our description will be somewhat simplified. The second example, Talbot imaging, illustrates a case in which a frequency-domain approach has a large advantage. System (a) consists of a modified Mach-Zehnder interferometer. The converging spherical illumination causes the Fourier components of the object amplitude transmittance to appear in the entrance pupil, as well as in the exit pupil, since the latter is the image of the former (see Appendix B). For example, when light from a point source is passed through a stationary diffuser, the relative phases of the light at any two points behind the diffuser remain correlated. 5.8, suppose that a planar object is placed a distance zl in front of a positive lens and is illuminated by monochromatic light. You may assume that A >> a. CHAPTER 8 Analog Optical Information Processing 229 to an ideal point in plane P', and then diverge to form a demagnified projection of plane P. For example, the reader is asked to verify in the problems that the Fourier transform of a general function separable in polar coordinates can be expressed as an infinite sum of weighted Hankel transforms where and X k { }is the Hankel transform operator of order k, defined by CHAPTER 2 Analysis of Two-Dimensional Signals and Systems 11 Rk{g~(r))= 2~ I," r g ~ (rJk(2m-p)) dr. Assuming unit-amplitude, normally incident plane-wave illumination: (a) Find the intensity distribution in the Fraunhofer diffraction pattern of the double-slit aperture shown in Fig. In the latter case, the information may be input to the SLM in the form of an optical image at the start (for example from a CRT display), rather than in electrical form. In fact this is approximately true, but not exactly so. 5-2. Let Then the object-image relationship becomes where is the geometrical-optics prediction of the image, and is the point-spread function introduced by diffraction. CHAPTER 2 Analysis of Two-Dimensional Signals and Systems 9 4. The initial step in the evolution of a theory that would explain such effects was made by the first proponent of the wave theory of light, Christian Huygens, in the year Screen with pinhole 34 Introduction to Fourier Optics Screen Observation plane FIGURE 3.3 Arrangement used for observing diffraction of light. 8.13. Thus for a semiconductor detector, if optical power P is incident on the photosensitive region, absorption of a photon generates an electron in the conduction band and a hole in the valence band. To find the thickness A(x, y), we split the lens into three parts, as shown in Fig. (3-54) be transformed by the change of variables v' = - v, yielding U(P1, - vf)exp(- j 2 n v 1 t) d v ' (3-55) a. We shall therefore specify as the "image plane" that plane where (5-24) is most closely approximated. Their utility arises from some simple properties and certain relations between them. For example, the field of holography is predominantly concerned with coherent imaging. Note that a quadratic phase factor again precedes the transform integral, but that it vanishes for the very special case d = f . Show that the top "transition region" shown in Fig. Important advantages include the general freedom of incoherent systems from coherent artifacts, for example, those associated with dust specks on the optical components and those that arise from the speckle phenomenon. The Fourier transform of this function is given by the expression 4Fora tutorial discussion of the importanceof quadratic-phase functions in various fields of optics, see [229]. (a) Spectrum, (b) image. Both depend on the use of VanderLugt-type filters. In some cases even submicrosecond response times are observed [65]. We therefore treat the subject from two points of view, one entirely heuristic, and the second more rigorous but not entirely complete. We turn now to considering this theory; again attention will be centered on diflraction-limited systems, although the discussion that immediately follows applies to all incoherent systems, regardless of their aberrations. Due to the finite passband of the imaging system, this image is not space-limited (or spatially bounded). As we shall see, if the complex field distribution of a monochromatic disturbance is Fourier-analyzed across any plane, the various spatial Fourier components can be identified as plane waves traveling in different directions away from that plane. 8.1.2 The Zernike Phase-Contrast Microscope Many objects of interest in microscopy are largely transparent, thus absorbing little or no light (e.g. an unstained bacterium). The dynamic range of amplitude transmittance over which this filter can function properly is quite limited. An additional development of considerable interest is the report of arrays of SEED devices that are not bistable and can operate as analog modulators, suitable for continuous gray-scale SLMs [21 31. While there are times when you can't avoid high-resolution files, if it isn't strictly necessary then using a smaller file type might be an option. For example, JPG is such a popular format because it compresses the data to an extreme extent. rect The convolution form of the Fresnel diffraction equation is most convenient for this problem, yielding This expression can be separated into the product of two one-dimensional integrals, where To reduce these integrals to expressions that are related to the Fresnel integrals mentioned on several previous occasions, make the following change of variables: yielding where the limits of integration are CHAFER 4 Fresnel and Fraunhofer Diffraction 85 At this point we define the Fresnel numbel; NF = w2/Az, and we introduce normalized distance variables in the observation region, X = XI& and Y = y/&, yielding simpler expressions for the limits of integration, The integrals Z(x) and Z(y) are related to the Fresnel integrals C(z) and S(z) of Sections 2.2 and 4.2. Noting that 1"' aI ('y exp J-a 2) d a = ~ 2 e x p (j ~ a 2) d a - ~ o a 1 e x p (j ~ a 2) d a , we can write Finally, substitution of (4-45) in (4-43) yields a complex field distribution Now recall from Section 4.1 that the measurable physical quantity is the intensity of the wavefield, I(x, y) = IU(x, y)I2, which in this case is given by The Fresnel integrals are tabulated functions and are available in many mathematical computer programs (e.g. see Ref. The results of this approach are entirely consistent with the results of geometrical optics, with the added advantage that diffraction effects are entirely accounted for in the wave-optics approach, but not in the geometrical-optics approach. It is desired to perform a one-dimensional Fourier transform of all N functions in the 8 direction, yielding an array of transforms Neglecting the finite extent of the lens and object apertures, use the Fourier transforming and imaging properties of lenses derived in this chapter to show how this can be done with (a) Two cylindrical lenses of different focal lengths. The medium is linear if it satisfies the linearity properties discussed in Chapter 2. Systems based on image casting Systems based on geometrical optics almost invariably use one form or another of what could be called "image casting" or "shadow casting", namely the geometrical projection of one image onto another. CHAPTER j Wave-Optics Analysis of Coherent Optical Systems 109 where K is a complex constant, M represents the system magnification, and the plus and minus signs are included to allow for the absence or presence of image inversion, respectively. Coherent and incoherent systems are compared from various points of view. As implied by the convolution theorem, the spectrum Gsof g, can be found by convolving the transform of comb(x1X) comb(y1Y) with the transform of g, or G,y(fx, f ~ =) { (3 I);(F comb - comb - 8 G(fx, f ~) FIGURE 2.5 The sampled function. With the use of electron beam writing, it is possible to control the accuracy of the masks to about one-tenth of a p m . Figure 6.18 illustrates the intensity distribution in the image of two equally bright incoherent point sources separated by the Rayleigh resolution distance. This is the viewpoint that was used in Section 5.3, and we shall adopt it again here. Chapter 8 can now be skipped and Chapter 9 on holography can be the focus of attention. It expresses the observed field U(Po) as a superposition of diverging spherical waves exp(jkrol)lrooriginating from secondary sources located at each and every point P1 within the aperture 2. 5-12. Note in particular the high-frequency components introduced by the straight edges in the input. The simplicity of invariant systems begins to be evident when we note that the convolution relation (2-49) takes a particularly simple form after Fourier transformation. The FLC cell is thus bistable and has memory. His followers supported this view adamantly. 8.9(a), the resulting OTF of the system is as shown in part (b) of the same figure. (b) What value of 4 yields the maximum diffraction efficiency, and what is the value of that maximum efficiency? By means of this technique, it is possible to largely overcome the two limitations to coherent processing systems mentioned above. 2-10). 590-596). An incident optical beam is thus deflected by the tilted pixel, and will not be collected by an optical system that follows. In the directly illuminated region behind the plane of the screen the field was found to be a superposition of this cylindrical wave with the directly transmitted wave. We may regard this expression as a decomposition of the function g(t) into a linear combination (in this case an integral) of elementary functions, each with a specific form exp(j2.srf t). The effective transfer function for the difference image is the difference of the two OTFs used in collecting those images, or the transfer function shown in part (d) of the figure, which indeed provides a true bandpass filter. For other examinations of the accuracy of the Fresnel approximation, see Chapter 9 of Ref. + 4.5 EXAMPLES OF FRESNEL DIFFRACTION CALCULATIONS In a previous section, several different methods for calculating Fresnel diffraction patterns have been introduced. 2-7. There is a fascinating history associated with the discovery and explanation of diffraction effects. Finally, in Section 7.3 we consider several approaches to constructing optical elements that control the complex amplitude of transmitted light in fixed but complicated ways, so-called dzffractive optical elements. The theory of linear systems is also familiar, especially to electrical engineers. This square grows in size as the distance z behind the aperture increases. 121 122 If we can characterize a given device by specifying its Jones matrix, we will then be able to understand completely the effect of that device on the state of polarization of an incident wave. It is possible to show that as long as the measurement frequencies fkare distinct, the determinant of D is nonzero, and therefore the inverse exists. In order to obtain a maximum dynamic range of exposure over which this relation holds, the first gamma of the two-step process is often chosen less than unity (for example 1/2), while the second gamma is chosen greater than 2 (for example 4), such that their product remains equal to 2. Using the notation a { } to represent the Fourier-Bessel transform operation, it follows directly from the Fourier integral theorem that at each value of r where gR(r) is continuous. The angular directions of the two layers at the interfaces with the glass plates can be stabilized by aligned polishing3 [64]. These approximations, which are commonly made in many fields that deal with wave propagation, will be referred to as Fresnel and Fraunhofer approximations. usually film. The self-electro-optic effect device The MQW modulator arrays discussed above are electrically addressed. that this term depends on the variables over which the convolution operation (5-23) is carried out, and it has the potential to affect the result of that integration significantly. The structure is assumed to be illuminated by a unit-amplitude, normally incident plane wave, so the field immediately behind the grating is equal to the amplitude transmittance written above. 8.16(b)). The operator approach is based on several fundamental operations, each of which is represented by an "operator". Thus when a particular object of interest is near the resolution 160 Introduction to Fourier Optics FIGURE 6.22 (a) Coherent and (b) incoherent images illustrating the speckle effect. Much initial stimulus toward an exchange was provided by a communication theorist, Peter Elias, and his associates D.S. Gray and D.Z. Robinson, with the publication of a paper in 1952 entitled "Fourier treatment of optical processes" [95], and again by Elias with the publication of the paper "Optics and communication theory" [94] in 1953. where 4 is the relative phase between the two point sources. Separation of the correlation (or convolution) terms from the uninteresting on-axis terms requires adequate separation of the two inputs at the start. 6.2.1 The Amplitude Wansfer Function Our analysis of coherent systems has yielded a space-invariant form of the amplitude mapping, as evidenced by the convolution equation (6-13). For example, rather than trying to distinguish between several possible known patterns, we may wish simply to detect the presence or absence of a single known object in a larger image. However, there are two different regimes within which the acousto-optic interaction exhibits different properties, the Raman-Nath regime and the Bragg regime. CHASER 8 Analog Optical Information Processing 237 FIGURE 8.12 Reachable regions of the frequency plane for (a) a purely absorbing filter, (b) an absorbing filter and binary phase control, (c) a pure phase filter, and (d) a filter that achieves arbitary distributions of absorbtion and phase control. 8-1). Let the function A(aIA, P I A ; z) represent the angular spectrum of U (x , y, z) ; that is, Now if the relation between A(aIA, P I A ; 0) and A(aIA, PlA; z) can be found, then the effects of wave propagation on the angular spectrum of the disturbance will be evident. With these two pieces of data in hand, we begin the algorithm. I found this a very handy way to grab photos of my nieces and nephews that my siblings share on Facebook. Find the form of the general result of Eq. (5-57) under the following limiting conditions: (a) zl + (b) zl + and d + 0. This viewpoint is illustrated in Fig. Beginning with the term involving the variables of integration (x, y) first, note that the presence of a quadratic phase factor in what otherwise would be a Fourier transform relationship will generally have the effect of broadening the impulse response. More generally, when aberrations of any kind are severe, the geometrical optics predictions of the intensity point-spread function may be Fourier-transformed to yield a good approximation to the OTF of the system. 4.2 THE FRESNEL APPROXIMATION To reduce the Huygens-Fresnel principle to a more simple and usable expression, we introduce approximations for the distance rol between P I and Po.The approximations are based on the binomial expansion of the square root in Eq. (4-10). (4- 1) The proportionality constant R is called the responsivity of the detector and is given by where qqe is the quantum efJiciency of the photodetector (the average number of electron-hole pairs released by the absorption of a photon, a quantity that is less than or equal to unity in the absence of internal gain), q is the electronic charge (1.602 x 10- l9 coulombs), h is Planck's constant (6.626196 X joule-second), and v is the optical frequency. Since each plane-wave component propagates at a different angle, each travels a different distance between two parallel planes, and relative phase delays are thus introduced. [136]. f (c) transparency or on the lens. To lend further physical insight into the OTF, consider the ways in which a sinusoidal component of intensity at a particular frequency pair (fx, fy) can be generated in the image. In the material that follows, we shall be concerned primarily, though not exclusively, with a restricted class of systems that are said to be lineal: The assumption of linearity will be found to yield simple and physically meaningful representations of such systems; it will also allow useful relations between inputs and outputs to be developed. 1678. [284], pp. In the case of the ferroelectric liquid crystal cell, the molecules can be shown to have a permanent electric dipole (with an orientation normal to the long dimension of the molecules), which enhances their interaction with the applied fields, and leads to only two allowable orientation states, one for each possible direction of the applied field. E curve and with proper processing, this component of amplitude transmittance can be written The second transparency is exposed in the linear region of the H&D curve and processed with a photographic y equal to 2. Letting p k , represent the correlation between gk and g,, we see that CHAPTER 8 Analog Optical Information Processing 257 Now by considering all N members of the training set, we establish a total set of N linear equations in the N unknowns an,each similar to Eq. (8-47), but for a different value of k. The directions of orientation between layers form a helical spiral. Once the state of the device has been set by the applied optical beams, it is possible to read out that state nondestructively and pass it on to a subsequent S-SEED pair. It is important to realize that the Huygens-Fresnel principle, as expressed by Eq. (3-51), is nothing more than a superposition integral of the type discussed in Chapter 2. The difficulties are in general much less severe in the space domain, for the impulse responses required are often simple, and the necessary masks can be constructed by conventional photographic techniques. Certain postulates underlie this method of recording a filter. When used in Eq. (6-9), the result is obtained. 6-4. There are three different general classes (or phases) of liquid crystals that are of general interest in optics: (1) nematic, (2) smectic, and (3) cholesteric. Prove the following Fourier transform theorems: (a) 3F{g(x, y)) = 3-'3-1{g(x, y)) , (c) . Densities as high as 4 can seldom be achieved in practice, and even a density of 3 requires some special effort. Let Eqs. The intensity impulse response of an aberrated incoherent system is, of course, the squared magnitude of the amplitude impulse response. As an additional point of interest, the bias point at which maximum dynamic range is obtained is found to lie in the toe of the H&D curve. Such plates could be ruled on a substrate, much as diffraction gratings are ruled, or deposited on a flat plate using thin-film coating techniques. To begin, note that in the monochromatic case we obtain the phasor representation of the field by suppressing the positive-frequency component of the cosinusoidal field, and doubling the remaining negative frequency component. The lenses need not be thin in the sense defined earlier. Thus the pupil sharply limits the range of Fourier components passed by the system. Attention is now restricted to the case of a purely monochromatic wave, with the generalization to polychromatic waves being deferred to Section 3.8. For a monochromatic wave, the scalar field may be written explicitly as where A(P) and $(P) are the amplitude and phase, respectively, of the wave at position P, while v is the optical frequency. The light passes through a transparent conducting electrode and is detected by a photoconductor, which in the most common version of the device is cadmium sulfide (CdS). File Transfer Protocol is the old-school way of moving data around, but these days it is more focused on the business side of things. By properly scaling 72 this scaling factor can be removed and a true convolution can be obtained. The propagation velocity in the first medium, having refractive index n l , is vl = clnl, c being the vacuum velocity of light. The interested reader can consult Ref. (The object is a transparency illuminated through a diffuser.) limit of an optical system, the speckle effect can be quite bothersome if coherent light is used. There also exist optical methods for coordinate distortion that can be used for this task [42]. Consider a cell with the long molecular axis (the "slow" axis) aligned parallel to the y axis throughout the cell. An example of this effect will be seen in the section that follows. One of the most successful early applications of coherent filtering in the radar realm has been to the processing of data collected by synthetic aperture radar systems [74], a subject that will be briefly treated in Section 8.9. A survey of the literature from the mid-1960s shows application of coherent processing techniques in such widely diverse fields as, for example, Fourier spectroscopy [276] and seismicwave analysis [153]. Note that at frequencies where the signal-to-noise ratio is high (@,, I), it reduces to a strongly attenuating matched filter, 8For a detailed discussion of the concept of power spectral density, see [123], Section 3.3. 260 Introduction to Fourier Optics FIGURE 8.21 Magnitudes of the transfer function of a Wiener filter. They found the Kirchhoff solution and the two Rayleigh-Sommerfeld solutions to be essentially the same provided the aperture diameter is much greater than a wavelength. Synthesis of nine separate impulse responses in a single mask was demonstrated by VanderLugt at an early date (see Ref. It was not until 1963, with the invention of the interferometrically recorded filter, that this serious limitation was largely overcome, extending the domain of complex filters that could be realized to those with simple impulse responses. Goldberg, who was granted a U.S. patent in 1931 [I 181, fully recognized the potential application of his invention to the field of character recognition. After the first passage through the cell, the incident linear polarization has been converted to circular polarization. 238 Introduction to Fourier Optics FIGURE 8.13 L1 P1 L2 Recording the frequency-plane mask for a VanderLugt filter. The image is assumed to have been blurred by a point-spread function consisting of a circular disk of radius w. Here are a few tricks for reducing the size of huge files that will make them easier to transfer and save you a lot of hassle—without sacrificing the quality of the file itself. Now the expansion can be applied to the expression for U(y;t). The inverse filter takes no account of the fact that there is inevitably noise present in the detected image, along with the desired signal. The second lens, L2, is also placed in this plane, and images the input onto the output plane P3 with unity magnification. The Kirchhoff theory was also modified by Sommerfeld, who eliminated one of the aforementioned assumptions concerning the light amplitude at the boundary by making use of the theory of Green's functions. Impulse response synthesis with a misfocused system Direct synthesis of a desired impulse is possible, within the confines of geometrical optics, by means of the "misfocused" system illustrated in Fig. Assume unit-amplitude, normally incident plane-wave illumination. 4.16. CHAPTER 7 Wavefront Modulation 199 trates the geometry. If the aperture is illuminated by a unit-amplitude, normally incident, monochromatic plane wave, then the field distribution across the aperture is equal to the transmittance function t~. To find the desired relation, note that U can be written In addition, U must satisfy the Helmholtz equation, v2u+ k 2 u = 0 at all source-free points. A normally incident, unit-amplitude, monochromatic plane wave illuminates a converging lens of 5 cm diameter and 2 meters focal length (see Fig. If the distance z is allowed to approach zero, i.e. the observation point approaches the diffracting aperture, then the two-dimensional quadratic-phase function behaves in the limit like a delta function, producing a field U (x ,y) that is identical to the aperture field U ([, v) in the aperture. 5-16. Ample references are given for more detailed treatments of this material. For simplicity we assume that 71 and P' are each at distance 2f from the lens L2, thus yielding magnification unity in the proper image plane. These assumptions were later proved to be inconsistent with each other, by PoincarC in 1892 and by Sommerfeld in 1894.' As a consequence of these criticisms, Kirchhoff's formulation of the so-called Huygens-Fresnel principle must be regarded as a first approximation, although under most conditions it yields results that agree amazingly well with experiment. Finally, suppose that the two image intensities collected with the OTFs shown in parts (b) and (c) of the figure are subtracted, perhaps by an electronic system. Under each mirror element are two landing glectrodes, held at the bias voltage, so that when the mirror tip twists so far as to hit the utderlying landing electrode, there is no electrical discharge. The quadratic phase factor of concern is exactly canceled by this converging spherical wave. This theorem, which can be found in most texts on advanced calculus, can be stated as follows: Let U(P) and G(P) be any two complex-valued functions of position, and let S be a closed surface surrounding a volume V. We know that the object was space-limited, so we simply truncate the image to the spatial bound of the object (i.e. multiply it by a rectangle function of the appropriate width). One state of the device will then be entirely off, and the other will be partially on. 158 Introduction to Fourier Optics -2 -1 I 1 2 FIGURE 6.19 Image intensities for two equally bright coherent point sources separated by the Rayleigh resolution distance, with the phase difference between the two sources as a parameter. Figure 7.22 shows the structures for a membrane device and for a cantilever beam device. In all cases the imaging system is assumed to be diffractionlimited. The effective exposure distribution applied to the nonlinear portion of the film mapping may therefore be written E' = Eo + M(f)El cos 2~ f x. 120 Introduction to Fourier Optics The result presented in Eq. (5-57) can be shown to reduce to the results of the previous cases considered if 21, z2, and d are properly chosen to represent those cases (see Prob. 3-4) that the normal derivative of this function vanishes across the screen and aperture, leading to the second Rayleigh-Sommer3'eld solution, It can be shown that, on 2 and under the condition that rol >> A, G+ is twice the Kirchhoff Green's function G, This leads to an expression for U(Po) in terms of the Green's function used by Kirchhoff, 3.5.2 The Rayleigh-Sommerfeld Diffraction Formula Let the Green's function G- be substituted for G in Eq. (3-23). Note that the input amplitude transmittance t~ will also have a finite aperture associated with it; the effective aperture in the input space is therefore determined by the intersection of the true input aperture with the projected pupil function of the lens. 4.1.1 The Intensity of a Wave Field In the optical region of the spectrum, a photodetector responds directly to the optical power falling on its surface. [9]. For example, if an iris is placed in the focal plane and stopped down to pass only the on-axis Fourier component, then with a gradual expansion of the iris the Fourier synthesis of the mesh can be watched step by step. 8.2(b) is the full image of the original mesh. A convenient normalized version of this function, with value unity at the origin, is 2 F . Thus we have no universal quality criterion upon which to base our conclusions. The most frequently encountered function with circular symmetry is: circ(r) = "' r= 1 . We close with one final observation. Director, Carnegie Mellon University Circuits and Systems Communications and Signal Processing Computer Engineering Control Theory Electromagnetics Electronics and VLSI Circuits Introductory Power and Energy Radar and Antennas PREVIOUS CONSULTING EDITORS Ronald N. exposure (the tA-E curve) for a typical KI-Y'~ 180 Introduction to Fourier Optics FIGURE 7.6 E Typical amplitude transmittance vs. First, the bias coil must be driven with current such that it establishes a strong magnetic field in the direction of the desired magnetization. To illustrate a particular order-of-magnitude off,, suppose that w = 1 cm, zi = 10 cm, and h = cm. For additional examples the reader may consult the problems (see Probs. 8-13. The recording geometry is that of a VanderLugt filter, exactly as illustrated previously in Fig. Wiener filter A superior approach to realizing an image restoration filter is one that generates a Wiener filter, and does so with considerably more dynamic range than the previous 262 Introduction to Fourier Optics method afforded. - f - FIGURE P5.9 5-10. squared moduli of the outputs Ivl 12, Iv2I2,. Let b be a number The binomial expansion of that is less than unity, and consider the expression the square root is given by Jl+b. However, rather than writing the angular spectra as functions of the direction cosines (a,p), it is now more convenient to leave the spectra as functions of spatial frequencies (fx, fy). Taking the magnitude of Ma and noting that the term la-j2"f = 1 proves that [Ma[is independent of scale size a. Marbchal regarded undesired defects in photographs as arising from corresponding defects in the optical transfer function of the incoherent imaging system that produced them. Subfolders for each of your connected services will automatically be created there, too. The length of this system remains 5f, as before. There are three different conditions under which this term can be neglected: 1 . 236 Introduction to Fourier Optics A linear array of one-dimensional filters may now be introduced in plane Pz.The lens pair L5, L6 again images in the y direction and Fourier transforms in the x direction, thus retaining the array structure but returning the original functions to the "space domain". 3-5. 2-9. This operator is represented by the usual symbol is defined by F and m n U (x) }= U (x)e - j 2 " f x dx. The image produced by a conventional microscope could be written, in our approximation, as where, to remain consistent with our approximation, the term has been replaced by zero, Zernike realized that the diffracted light arising from the phase structure is not observable in the image plane because it is in phase quadrature with the strong background, and that if this phase-quadrature relation could be modified, the two terms might interfere more directly to produce observable variations of image intensity. All of these functions are achieved at extremely low cost. Show that in the limit A + 0. The letters Q, W, and P are at different angles with respect to the reference point, and as a consequence, the crosscorrelations of Q, W, and P with the input character appear at different distances from the origin, as illustrated in Fig. Until now, our examples have involved only transmittance functions of the form 1 in the aperture 0 outside the aperture. How small must A be if the measured intensity distribution is to accurately represent the Fraunhofer diffraction pattern of the object? The method was applied to the bandwidth extrapolation problem first by Gerchberg [I161 and by Papoulis [228]. [182], Chapter 3. From this result we can see that again the general relation between intensity incident during exposure and intensity r after development is a nonlinear one, but in the specific case of an overall transmitted gamma equal to unity, the process becomes a linear one. Let the object be a cosinusoidal intensity distribution of finite extent, with a frequency that exceeds the incoherent cutoff frequency, as illustrated in Fig. The critical fact to keep in mind is that we have chosen our phasors to rotate in the clockwise direction, i.e. their time dependence is of the form exp(- j 2 ~ v t) For . FIGURE 4.8 The Fraunhofer diffraction pattern of a rectangular aperture (wxlwy = 2). Similarly, the inverse Fourier transform of a function G(fx, fy) will be represented by F 1 { G } and is defined as Note that as mathematical operations the transform and inverse transform are very similar, differing only in the sign of the exponent appearing in the integrand. The light incident on each Bixel is deflected in either of two directions by the mirror when it is activated, and is nqt deflected when it is not activated. Second, we consider only monochromatic illumination, a restriction implying that the imaging system is linear in complex field amplitude (see Prob. [220] and its associated references. the first negative lobe of 7-l by 180". The vertical lines show the locations of the two point sources. The optical frequency of the qth diffraction order can be determined from the Doppler-shift relation vq = (+3 v, 1 - sin eq = v, + q f,. In many cases there is considerable latitude of choice here, since for many possible shapes of the region R there are a multitude of transfer functions that will pass the (n = 0, m = 0) term of Gs and exclude all other terms. (5-1) The complex field U;(x,y) across a plane immediately behind the lens is then related to the complex field Ul(x, y) incident on a plane immediately in front of the lens by u;(x, Y) = t l h Y) Ul(x7 Y). The thickness variations are greatly exaggerated. The exposed photographic transparency is immersed in a chemical bath, the developer, which acts on silver specks containing more than the threshold number2 of silver atoms. If you want to find out more, we have a dedicated FTP article you should look into. How To Make Transferring Files Easier Many people make the mistake of sending files in their raw formats, but that only makes the task more difficult. Entrance Exit U Object "Black box" Image FIGURE 6.1 Generalized model of an imaging system. A paid service does offer a few benefits that might appeal to you, especially if you want to keep things simple. We turn now to the former of these problems, considering Kirchhoff's choice of an auxiliary function and the consequent integral theorem that follows. In this way, the spectral components beyond the diffraction limit are introduced and are gradually refined to be consistent with the known information. As we have seen in Chapter 6 and will continue to see in this chapter, the disciplines of optics and electrical engineering were to develop even closer ties in the years to follow. 2. On the other hand, in the presence of a sufficiently large applied voltage, the long axes of the molecules all rotate to alignment with the direction of the applied field, which coincides with the direction of propagation of the wave, eliminating the birefringence of the cell. We conclude that it is possible to perform a Mellin transform with an optical Fourier transforming system provided the input is introduced in a "stretched" coordinate system, in which the natural space variable is logarithmically stretched (x = - In 5). They will be used frequently, since they provide the basic tools for the manipulation of Fourier transforms and can save enormous amounts of work in the solution of Fourier analysis problems. A number of potential criteria might be considered (e.g., least-mean-square difference between the object and image intensities), but unfortunately the interaction of a human observer is so complex and so little understood that a truly meaningful criterion is difficult to specify. It can be shown (see Chapter 1 of [223] and [16]) that if G(x) is the solution to the same differential equation (3-16) when V(x) is replaced by the 2The reader may wish to verify that, for our choice of clockwise rotation of phasors, the description of an expanding wave should have a + sign in the exponential. In view of the linearity of the wave propagation phenomenon, we can in all cases express the field Uiby the following superposition integral: where h(u, v ; 6, q) is the field amplitude produced at coordinates (u, v) by a unitamplitude point source applied at object coordinates (5 , ~)Thus . Such applications rest on the ability to perform general linear transformations of input data. This approach provides a means for performing bandpass filtering using incoherent light for at least part of the processing operation. But as the structure on the input transparencies gets finer and finer, more and more of the light passing through them will be diffracted, with less and less of the light obeying the laws of geometrical optics. The velocity of propagation in the second medium is v2 = cln2. The first of these conditions rarely occurs in practice. When the address voltage is removed, the membrane moves upward to its original position. A variety of different materials can be used for the substrate of such elements including silicon and glass. Off-axis spots correspond to components directed at corresponding angles in the object plane. There is a broad categorization of SLMs into two classes that can be made at the start: (1) electrically written SLMs and (2) optically written SLMs. In the former case, electrical signals representing the information to be input to the system (perhaps in raster format) directly drive a device in such a way as to control its spatial distribution of absorption or phase shift. To make the nature of this function clearer, also plot W(0, x) for 1x1 5 1. (c) Find the relationship between the line-spread function and the step response of the system, i.e. the response to a unit step excitation oriented parallel to the x axis. To the memory of my Mothel; Doris Ryan Goodman, and my Fathel; Joseph Goodman, Jr: CONTENTS Preface 1 Introduction 1 . We could use the convolution form of the Fresnel diffraction equation, i.e. Eq. (4-14), or the Fourier transform form of Eq. (4-17). The resulting electron is in the conduction band, is mobile within the silver halide crystal, and eventually, with some probability, becomes trapped at a crystal dislocation. 210 Introduction to Fourier Optics Diffractive optics can be made to perform functions that would be difficult or impossible to achieve with more conventional optics (e.g., a single diffractive optical element can have several or many different focal points simultaneously). 5.9. In this case the spherical wave illumination results in the Fourier transform of the object appearing in the pupil plane of the lens. 232 Introduction to Fourier Optics 8.3 COHERENT OPTICAL INFORMATION PROCESSING SYSTEMS When coherent illumination is used, filtering operations can be synthesized by direct manipulation of the complex amplitude appearing in the back focal plane of a Fourier transforming lens. In the spectral domain, we know the object spectrum within the passband of the imaging system, for this data was actually measured. (Hint: The Fourier transform of the circularly symmetric function Jo(2.rrr) is the circularly symmetric spectrum & S(p - I).) CHAPTER 4 Fresnel and Fraunhofer Diffraction 95 4-21. For further development of this point, the reader is referred to Prob. We thus confirm that coherent object illumination yields an imaging system that is linear in complex amplitude. Note that the transparency 71 must be inserted in an inverted geometry to compensate for the inversion introduced by the imaging operation performed by L2. 5.5(b). In the former case, the information is generally of a temporal nature (e.g. a modulated voltage or current waveform), while in the latter case it is of a spatial nature (e.g. a light amplitude or intensity distribution over space), but from an abstract point of view, this difference is a rather superficial one. Both U and G satisfy the homogeneous scalar wave equation. 5.4 ANALYSIS OF COMPLEX COHERENT OPTICAL SYSTEMS In the previous sections we have analyzed several different optical systems. However, the monochromatic results are directly applicable themselves when the optical source has a sufficiently narrow spectrum. 2.2 LOCAL SPATIAL FREQUENCY AND SPACE-FREQUENCY LOCALIZATION Each Fourier component of a function is a complex exponential of a unique spatial frequency. + 4-6. 8.2 INCOHERENT OPTICAL INFORMATION PROCESSING SYSTEMS The use of spatially incoherent light in optical information processing provides certain advantages, but also certain disadvantages. Thus an intensity distribution similar to Eq. (8-15) is again produced at the recording plane. Kirchhoff showed that such properties are a natural consequence of the wave nature of light. It is therefore important to use some caution when approaching the analysis of the properties of diffractive optical elements. 3.5. Note that the "outward normal to the composite surface points outward in the conventional sense on S, but inward (towards Po) on S,. Over the portion of Sl that lies in the geometrical shadow of the screen, the field distribution U and its derivative dUldn are identically zero. Naturally the introduction of absorbing material in the pupil diminishes the light that reaches the image, but the normalization of the OTF suppresses this fact. Therefore it is not possible to associate a spatial location with a particular spatial frequency. Finally, a cholesteric liquid crystal is a distorted form of a smectic liquid crystal in which, from layer to layer, the alignment of molecules undergoes helical rotation about an axis. 3.10.3 Effects of a Diffracting Aperture on the Angular Spectrum Suppose that an infinite opaque screen containing a diffracting structure is introduced in the plane z = 0.We now consider the effects of that diffracting screen on the 6Notethat evanescent waves are predicted only under the very same conditions for which the use of the scalar theory is suspect. To that end we Fourier transform the amplitude transmittance above, yielding Now the above transfer function has value unity at the origin, and when evaluated at frequencies (fx, fu) = (k 0) yields i, Thus after propagation over distance z behind the grating, the Fourier transform of the field becomes Inverse transforming this spectrum we find the field at distance z from the grating to be given by which can be simplified to Finally, the intensity distribution is given by I(x, y) = I 4 [1 + 2- cos I)?(($) (F) + COG cos m2 (4-52) We now consider three special cases of this result that have interesting interpretations. Show that the intensity image of a step-object (edge along the 77 axis) formed by a coherent imaging system having a square pupil (width 2w) with edges parallel to and orthogonal to the direction of the step can be expressed as where Si(z) is defined by CHAPTER 6 Frequency Analysis of Optical Imaging Systems 171 and c is a constant. The problem is evident if we consider only the second filter, which was recorded in the linear region of the H&D curve. Diffraction, rather than absorption, is used to attenuate frequency components. In this treatment, the field behind a diffracting obstacle is found by the principles of geometrical optics, modified by the inclusion of "diffracted rays" that originate at certain points on the obstacle itself.) y2) + H * (- 2- G2 - - (I? Alternatively, if N is not too large, it is possible to synthesize the entire bank of filters on a single frequency-plane filter. Note that while our derivation of this expression assumed the specific lens shape shown in Fig. As a final example which has merit (but by no means the only other system geometry possible), consider the system shown in part (c) of the figure. A simplified electrical model [14] for the device is shown in Fig. (b) Show that for a line source oriented along the x axis, the (ID) Fourier transform of the line-spread function is equal to a slice through the (2D) Fourier transform of the point-spread function, the slice being along the f y axis. Since the complex amplitude of the transmitted light is, from both viewpoints, the important quantity in a coherent system, it is necessary to describe a transparency in terms of its complex amplitude transmittance t~ [187]. Using such a bleach it is possible, for example, to make an approximately sinusoidal relief grating, which will exhibit diffraction efficiencies typical of sinusoidal phase gratings, considerably higher than those of sinusoidal amplitude gratings. (~ Such "functions", being infinite at the origin and zero elsewhere, have an infinite discontinuity and therefore fail to satisfy existence condition 3. The corresponding image, seen in Fig. When only small angles are involved in the diffraction problem, it is easy to show that all three solutions are identical. CHAPTER6 Frequency Analysis of Optical Imaging Systems 157 6.5.2 Two-Point Resolution A second possible comparison criterion rests on the ability of the respective systems to resolve two closely spaced point sources. 2-2). This can be done by frequency-multiplexing, or recording the various frequency-plane filters with different carrier frequencies on a single transparency. The phase of the quadratic phase factor changes by an amount that is only a small fraction of a radian within the region of the object that contributes significantly to the field at the particular image point (u, v). (a) Find the Wigner distribution function of the infinite-length chirp function by inserting g(x) = exp(j.rrpx2)in the definition of W (f,x). Along with these several advantages comes one significant difficulty with diffractive optical components: because they are based on diffraction, they are highly dispersive (i-e. Sketch the fx and fycross sections of the optical transfer function of an incoherent imaging system having as a pupil function the aperture shown in Fig. The most recent versions have used mirror elements with two points of support, which twist under the application of an applied field. However, an extra flexibility has been obtained in the present configuration; namely, the scale of the Fourier transform is under the control of the experimenter. When the system is out of focus, a gradual attenuation of contrast and a number of contrast reversals are obtained for increasing spatial frequency, as illustrated in Fig. The first is fairly simple, consisting of two spherical lenses, each with the same focal length f , with a separation off between them, as shown in Fig. If you have fast internet, you can upload large files quickly without artificial bottlenecks placed by the service to conserve bandwidth. pCloud also provides multiple features that make it even more appealing, like the ability to spread your files across multiple services to keep them safe. 3.4 THE KIRCHHOFF FORMULATION OF DIFFRACTION BY A PLANAR SCREEN Consider now the problem of diffraction of light by an aperture in an infinite opaque screen. Leger, P. 8.18, it would be possible to synthesize N separate VanderLugt filters, applying the input to each filter sequentially. Erteza and M. Gibbons, Willis W. 3.4.3 The Fresnel-Kirchhoff Diffraction Formula A further simplification of the expression for U(Po) is obtained by noting that the distance rol from the aperture to the observation point is usually many optical wavelengths, and therefore, since k >> llroI,Eq. (3-20) becomes Substituting this approximation and the expression (3-15) for G in Eq. (3-24), we find Now suppose that the aperture is illuminated by a single spherical wave, arising from a point source at P2, a distance r2l from P1 (see Fig. Consider the addition of a strong desired field of amplitude A with a weak undesired field of amplitude a. In fact it is often possible to modify (mismatch) all the filters in such a way that the discrimination between characters is improved. 7-7. FIGURE P4.7 4-8. 2-11. In addition, for coherent optical information processing systems we require the ability to modify and manipulate the complex optical fields transmitted through the focal plane of a lens, for through such manipulation we are able to filter the input data in various desired ways. 8.10(a) optically Fourier transforms U2. The output of the H&D curve is a density D', which is itself subjected to linear spreading and blur by the chemical diffusion process to produce a final density D. Eq. (3-36)) and for the second Rayleigh-Sommerfeld solution (cf. -3 -2 -1 1 2 3 hz FIGURE 4.7 Cross section of the Fraunhofer diffraction pattern of a rectangular aperture. However, by properly selecting the material to be covered, the needs of any of a number of different audiences can be met. The range of frequencies over which significant frequency response is obtained varies widely from emulsion to emulsion, depending on grain size, emulsion thickness, and other factors.

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