Optical Information Processing

Fundamentals

Edited by S. H. Lee

With Contributions by
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With 197 Figures

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Preface

Optical information processing is an advancing field which has received much attention since the nineteen sixties. It involves processing a two-dimensional array of information using light. The attractive feature of optical processing is the parallel processing capability, which offers great potentials in processing capacity and speed. Optical processing is especially useful if the information to be processed is in optical form. When good electrical to optical interface devices are available, optical processing will also be useful for electrical information.

To enter and then participate in new developments in the advancing field of optical processing, it will be necessary to be familiar with its fundamental principles. Basic knowledge about realtime interface devices and hybrid electronic/optical system will prove to be very useful to comprehend much of the current developmental efforts in the field. This volume covers these important basics, although attempts are made to keep these discussions as concise as possible so that sufficient space remains available to discuss subjects of current research interest such as space variant and nonlinear processing. Therefore, this volume can serve as a good text for new graduate students or undergraduates with advanced standing, and as a good reference for those researchers who are already working in certain sub-areas of the field but wish to be more familiar with other sub-areas. Applications are included in such a manner as to illustrate the usefulness of certain processing principles. For more extensive coverage, the companion Topics in Applied Physics Vol. 23 is highly recommended.

June 1981 *Sing H. Lee*

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1. Basic Principles

S. H. Lee

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1.1 Historical Overview

To comprehend the development in the advancing field of optical information processing, we shall begin this chapter with a brief summary of its history. Main discussions in the remaining chapters are the simple, scalar diffraction theory of light, the important Fourier transform and imaging properties of lenses. Since the Fourier transform properties require coherent light and the imaging properties are affected by the degree of coherency of the light used, the subject of coherence is also considered. This is followed by discussions on the usefulness of the transfer function concept in further understanding the basic properties of diffraction and lens, and by discussions on several topics of practical interest concerning these basic properties.

Historically, optical processing dates from 1859, when *Foucault* first described the knife-edge test in which the direct image light was removed and the scattered or diffracted light was kept [1.1]. In 1873, *Abbe* advanced a theory in which diffraction plays an important role in coherent image formation [1.2]. In 1906, *Porter* demonstrated *Abbe*'s theory experimentally [1.3]. *Zernike* developed the Nobel prize-winning concepts of phase contrast microscopy in 1935 [1.4]. In 1946 *Duffieux* published his important study on the use of the Fourier integral in optical problems [1.5]. In the fifties, *Elias* and co-workers provided the initial exchange between the disciplines of optics and communication theory [1.6, 7]. Later *O'Neill* contributed a great deal to reconciling the two viewpoints by presenting a unified theory [1.8]. *Maréchal* motivated future expansion of interest in the optical processing field by successfully applying coherent spatial-filtering techniques to improve the quality of photographs [1.9].

In the 1960's, optical processing activities reached a new height with its successful application to synthetic-aperture radar [1.10, 11]. The inventions of the holographic spatial filter by *Vander Lugt* [1.12] and of the computer generated spatial filter by *Lohmann* and *Brown* [1.13] also form the important cornerstones of applying optical processing to the lucrative field of pattern recognition. Much research has also been carried out in developing realtime interface devices to be used between electronic or incoherent optic and coherent optic systems (Chap. 4).

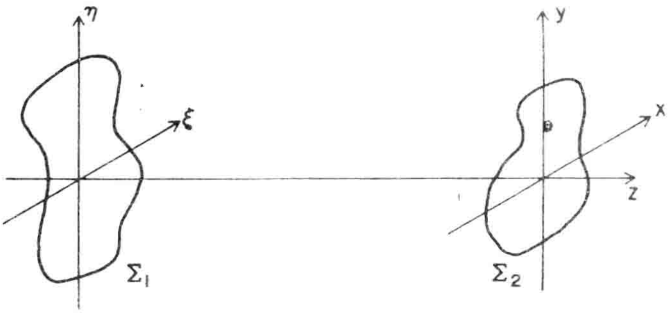


Fig. 1.1. Diffraction

In the seventies, the importance of combining electronic digital computers with optical analog processors to form hybrid processors was established (Chap. 5). Much attention has also been given to extending the flexibility of optical processors beyond the linear, space invariant regime (Chaps. 6, 7).

1.2 Diffraction Phenomena

In optical processing, the information to be processed is often obtained by illuminating a photographic transparency with a laser beam or modulating a coherent wave front by an optical interface device, or from a self-illuminating object. In any case, to design optical systems for processing the information it is important to understand the basic physical phenomena of diffraction.

The term *diffraction* has been conveniently defined by *Sommerfeld* [1.14] as "any deviation of light rays from rectilinear paths which cannot be interpreted as reflection or refraction". The diffraction of monochromatic light (of wavelength λ) by a finite aperture Σ_1 in an infinite opaque screen, as indicated in Fig. 1.1, is described mathematically by the Huygens-Fresnel superposition integral

$$u_2(x,y)=\iint_{\Sigma_1} h(x,y;\xi,\eta)u_1(\xi,\eta)d\xi d\eta\,, \tag{1.1}$$

where $u_1(\xi,\eta)$ and $u_2(x,y)$ are the field amplitudes at points (ξ,η) and (x,y), respectively. and $h(x,y;\xi,\eta)$ is the impulse response

$$h(x,y;\xi,\eta)=(1/\mathrm{j}\lambda r)\exp(\mathrm{j}kr)\cos(\boldsymbol{n},\boldsymbol{r})\,. \tag{1.2}$$

In (1.2), k is $(2\pi/\lambda)$ and the angle $(\boldsymbol{n},\boldsymbol{r})$ is that between vectors $\boldsymbol{n}$ and $\boldsymbol{r}$ [$\boldsymbol{n}$ being normal to the plane containing aperture Σ_1]. The limit associated with the superposition integral can be extended to infinity, if it is understood that $u_1(\xi,\eta)$ is identical to zero outside the aperture Σ_1.

Since the common situations of interest in optical processing problems involves the distance z between aperture and observation planes greater than the maximum linear dimensions of the aperture Σ_1 and the observation region Σ_2, the obliquity factor $\cos(\boldsymbol{n}, \boldsymbol{r})$ can readily be approximated by

$$\cos(\boldsymbol{n}, \boldsymbol{r}) \simeq 1, \tag{1.3a}$$

where the accuracy is to within 5% if the angle $(\boldsymbol{n}, \boldsymbol{r})$ does not exceed 18°. Under similar conditions, r in the denominator of (1.2) will not differ significantly from z, allowing the impulse response function $h(x, y; \xi, \eta)$ to be approximated as

$$h(x, y; \xi, \eta) \simeq (1/\mathrm{j}\lambda z) \exp(\mathrm{j}kr). \tag{1.3b}$$

a) The Fresnel Diffraction

Further simplification suggested by Fresnel was to apply a binomial expansion to the square root associated with r in the exponent of (1.3b):

$$\begin{aligned} r &= [z^2 + (x-\xi)^2 + (y-\eta)^2]^{1/2} \\ &\simeq z[1 + (x-\xi)^2/2z^2 + (y-\eta)^2/2z^2]. \end{aligned} \tag{1.3c}$$

Substituting the approximations expressed in (1.3a–c) into the superposition integral of (1.1), the following convolution relationship is obtained:

$$\begin{aligned} u_2(x, y) &= (1/\mathrm{j}\lambda z) \exp(\mathrm{j}kz) \iint u_1(\xi, \eta) \exp\{\mathrm{j}(k/2z)[(x-\xi)^2 + (y-\eta)^2]\} d\xi d\eta \\ &= u_1(x, y) * h(x, y), \end{aligned} \tag{1.4a}$$

where

$$h(x, y) = (1/\mathrm{j}\lambda z) \exp(\mathrm{j}kz) \exp[(\mathrm{j}k/2z)(x^2 + y^2)]$$

and the symbol $*$ stands for convolution.

Alternatively, the quadratic terms in the exponent may be expanded to yield

$$\begin{aligned} u_2(x, y) = (1/\mathrm{j}\lambda z) \exp[\mathrm{j}kz + \mathrm{j}k(x^2 + y^2)/2z] \iint u_1(\xi, \eta) \exp[\mathrm{j}k(\xi^2 + \eta^2)/2z] \\ \cdot \exp[-\mathrm{j}2\pi(x\xi + y\eta)/\lambda z] d\xi d\eta. \end{aligned} \tag{1.4b}$$

Thus, aside from multiplicative amplitude and phase factors of $(1/\mathrm{j}\lambda z) \exp[\mathrm{j}kz + \mathrm{j}k(x^2 + y^2)/2z]$ which are independent of (ξ, η), the function $u_2(x, y)$ may be found from a Fourier transform of $u_1(\xi, \eta) \exp[(\mathrm{j}k/2z)(\xi^2 + \eta^2)]$, where the transform must be evaluated at spatial frequencies $(\nu_x = x/\lambda z$, $\nu_y = y/\lambda z)$ to assure the correct space scaling in the observation plane. Figures

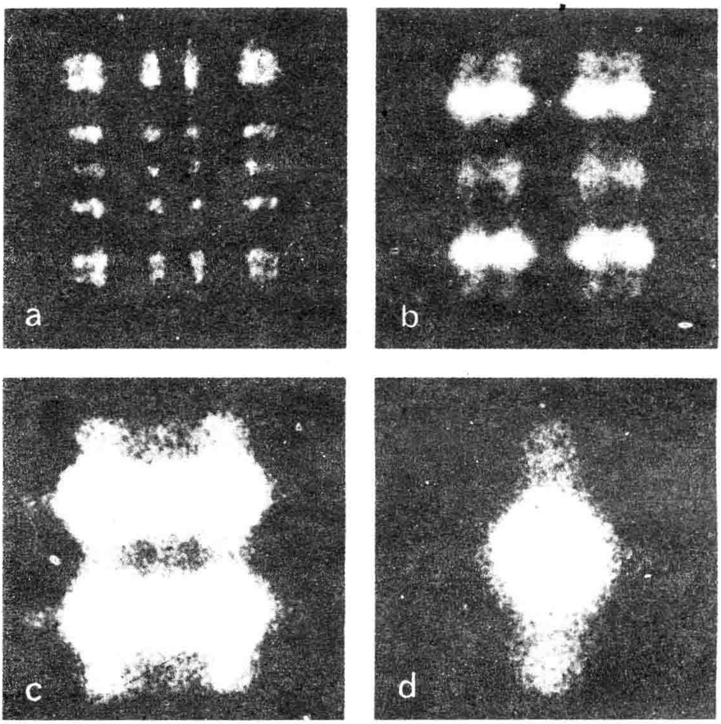


Fig. 1.2a–d. Some typical Fresnel diffraction patterns associated with a rectangular aperture, Σ_1. In (a) Σ_2 is closest to the aperture and the remaining photographs were taken at increasing distances from the aperture [Ref. 1.22, p. 30]

1.2, 3 show some typical Fresnel diffraction patterns associated with rectangular and circular apertures respectively.

The convolution nature of (1.4a) suggests that perhaps some additional insight can be gained by examining the Fresnel diffraction in the spatial frequency domain. Hence, the Fourier transform of (1.4a) is taken to give

$$\hat{u}_2(x/\lambda z, y/\lambda z) = \hat{u}_1(x/\lambda z, y/\lambda z)\hat{h}(x/\lambda z, y/\lambda z), \tag{1.4c}$$

where

$$\hat{h}(x/\lambda z, y/\lambda z) = \exp(jkz)\exp\{-j\pi\lambda z[(x/\lambda z)^2 + (y/\lambda z)^2]\}.$$

The effect of propagating a distance z in the Fresnel diffraction region therefore consists of two parts: the first exponential factor represents an overall phase retardation experienced by any component of the angular spectrum, and the second exponential factor represents a phase dispersion with quadratic spatial frequency dependence.

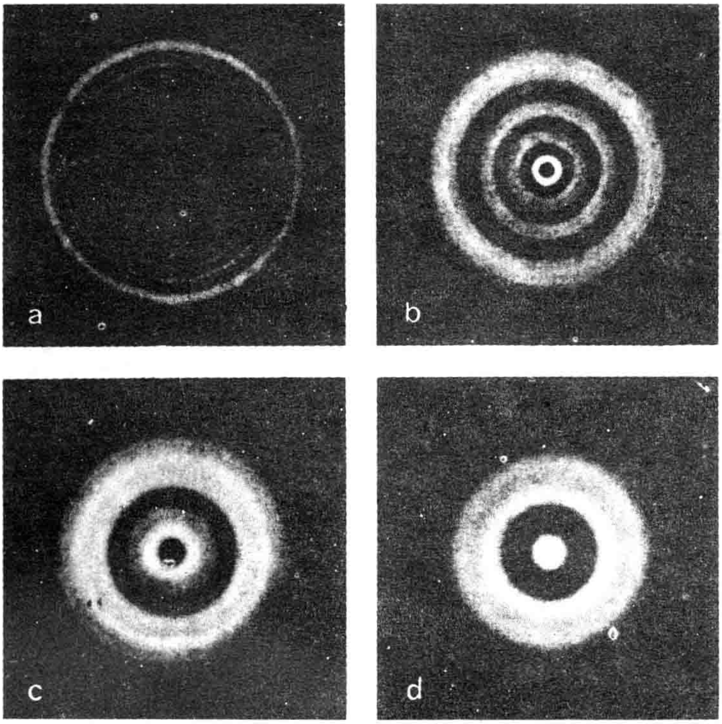


Fig. 1.3a–d. Some typical Fresnel diffraction patterns associated with a circular aperture, Σ_1. In (a) Σ_2 is closest to the aperture and the remaining photographs were taken at increasing distances from the aperture [Ref. 1.22, p. 30]

b) The Fraunhofer Diffraction

Diffraction pattern calculations can be further simplified if restrictions more stringent than those used in the Fresnel approximation are adopted. If the stronger (Fraunhofer) assumption

$$z \gg (k/2)(\xi^2+\eta^2)_{\max}$$

is adopted, the quadratic phase factor $\exp[jk(\xi^2+\eta^2)/2z]$ inside the convolution integral of (1.4b) is approximately unity over the entire aperture, and the observed field distribution can be found directly from a Fourier transform of the aperture distribution itself. Thus in the region of Fraunhofer diffraction,

$$u_2(x,y)=(1/j\lambda z)\exp\{jkz[1+(x^2+y^2)/2z^2]\} \cdot \iint u_1(\xi,\eta)\exp[-j2\pi(x\xi+y\eta)/\lambda z]\,d\xi d\eta\,. \tag{1.5}$$

Figure 1.4 shows photographs of the Fraunhofer diffraction patterns of rectangular and circular apertures.

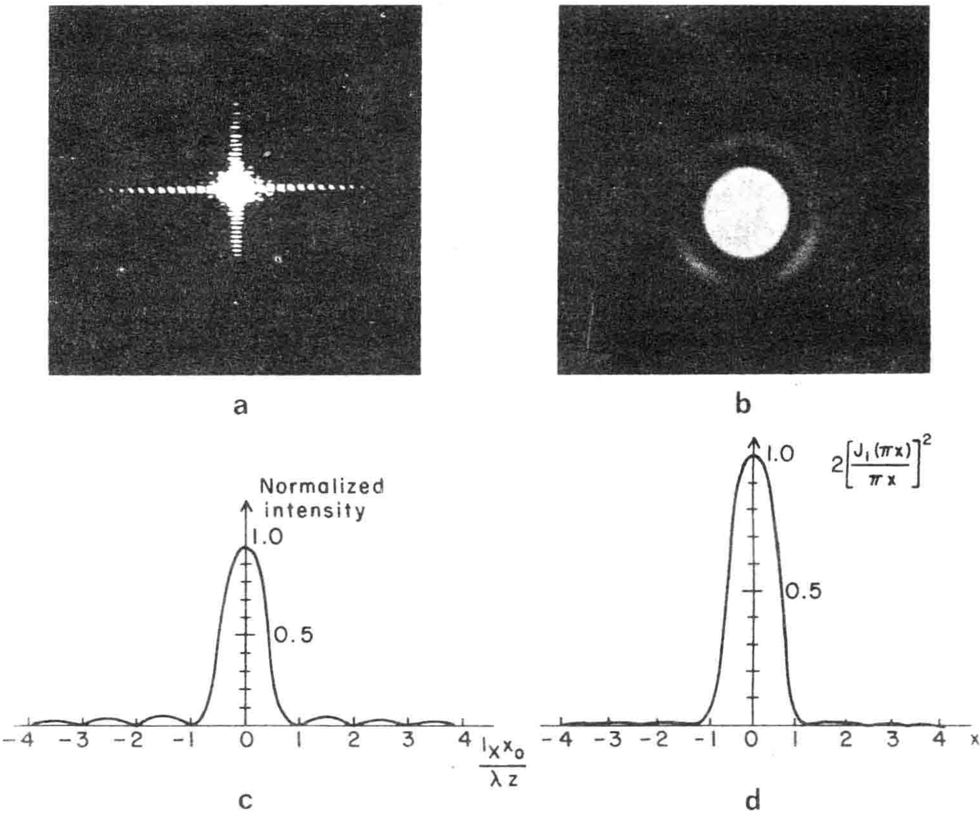


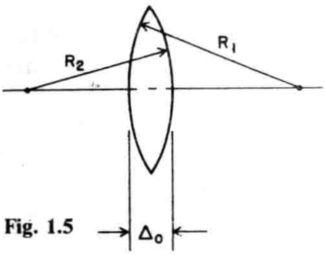
Fig. 1.4a–d. Photographs of the Fraunhofer diffraction patterns of uniformly illuminated (**a**) rectangular aperture, (**b**) circular aperture, (**c**) cross section of (**a**), and (**d**) cross section of (**b**) [Ref. 1.15, Figs. 4-2–5]

1.3 Fourier Transform Properties of Ideal Thin Lens

One of the most important components of optical information processing and optical imaging systems are lenses. A lens is composed of optically dense material, such as glass or fused quartz, in which the propagation velocity of an optical field is less than the velocity in air. A lens is said to be a *thin* lens if a ray entering at coordinates (x, y) on one face emerges at approximately the same coordinates on the opposite face, i.e., if there is negligible translation of the ray within the lens. Thus, a thin lens simply delays an incident wavefront by an amount proportional to the thickness of the lens at each point.

It can be shown that a plane wave passing through a thin lens experiences a phase delay factor of $t_l(x, y)$:

$$t_l(x, y) = \exp[jkn\Delta_0]\exp[-jk(x^2 + y^2)/2F], \tag{1.6a}$$



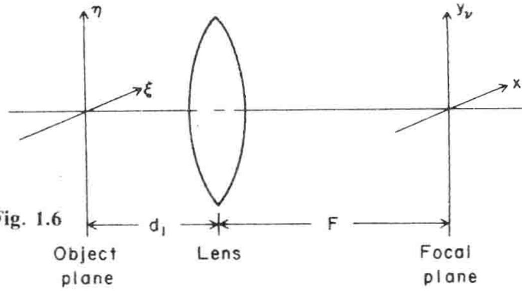


Fig. 1.5. Thin lens. As rays travel from left to right, each convex surface encountered is taken to have a *positive* radius of curvature R_1, while each concave surface is taken to have a negative radius of curvature (i.e., R_2 is negative)

Fig. 1.6. Fourier transforming with object placed in front of lens

where n is the index of refraction of the lens material, F is the focal length defined by

$$1/F=(n-1)(1/R_1-1/R_2), \tag{1.6b}$$

and Δ_0, R_1 and R_2 are shown in Fig. 1.5. Strictly speaking (1.6a) is valid only under the paraxial approximation [1.15, Sect. 5.1; 1.16, Sect. 5.1], i.e., only the portions of the wavefront that lie near the lens axis experience the phase delay of (1.6a). The first term $\exp(jkn\Delta_0)$ is simply a constant phase delay, while the second term $\exp[-jk(x^2+y^2)/2F]$ may be recognized as a quadratic phase factor associated with a spherical wave.

Next, let us see how a simple converging lens can be used to perform complex analog Fourier transformations in two dimensions. (The Fourier transform operation generally requires either complex and expensive electronic spectrum analyzers or a long computing time with a digital electronic computer; yet it can be performed with extreme simplicity in a coherent optical system.)

1.3.1 Object Placed Against the Lens

Recalling the two results that (a) the quadratic phase factor inside the convolution integral of (1.4b) is approximately unity in the Fraunhofer diffraction region providing the Fourier transform of the aperture distribution as the observed field distribution (see Sect. 1.2), and that (b) a thin lens introduces the phase delay factor of (1.6a) (see the earlier part of this section), we would like to show that the observed field distribution $u_v(x_v, y_v)$ at the back focal plane of a lens is Fourier transform related to the transmittance of an object $t_o(\xi, \eta)$ placed against the lens [Fig. 1.6, $d_1=0$].