Handbook of Optical Systems

Edited by
Herbert Gross

Volume 2: Physical Image Formation

Wolfgang Singer, Michael Totzeck, Herbert Gross

WILEY-VCH Verlag GmbH & Co. KGaA

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Volume 1: Fundamentals of Technical Optics
Volume 2: Physical Image Formation
Volume 3: Aberration Theory and Correction of Optical Systems
Volume 4: Survey of Optical Instruments
Volume 5: Metrology of Optical Components and Systems
Volume 6: Advanced Physical Optics

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Introduction

Physical image formation – no other subject is quite as closely connected with the name of Ernst Abbe. Ernst Abbe derived the first comprehensive theoretical description of optical image formation, he never published his work apart from a few remarks, which he made in 1873. Ernst Abbe died in 1905. It is therefore a privilege to dedicate this second volume of the Handbook of Optical Systems to the 100th anniversary of his death.

Abbe discovered the optical image as an interference phenomenon. The image intensity is interpreted by the interference of the coherent waves, which are formed by emission or diffraction at the object, and transmitted and transformed by the optical imaging system. In order to achieve an image that is similar to the object, the properties of the transformation need to follow certain rules, the first of which is the Abbe sine condition. In the case of non-self-luminous objects, the physical optical description of imaging also includes consideration of the illumination and coherence properties of the light source. In order to consider polarization and vector diffraction effects at the object, a complete vector theory is required. These theoretical descriptions have been developed or adapted from other disciplines of optics, sometimes triggered by the question of image formation. In this volume, we cover the most important topics within optical image formation.

Since the time of Abbe, the complexity of optical systems has increased considerably and the level of knowledge about them has improved a great deal. In modern systems, the use of laser light sources makes it necessary to consider the questions of coherence. Imaging at high numerical apertures, or the use of crystal materials, generates polarization effects. Digital image detection with pixellated solid-state sensors involves the consideration of sampled images. Modern image formation methods are frequently scanning methods, such as confocal imaging, where each object point is individually illuminated and imaged. The resulting image is obtained electronically, and further non-linear processes, such as digital filtering, are frequently applied. Here in Volume 2 we will concentrate on the physical effects involved in image formation, but computerized methods of imaging will be discussed in later volumes.

The general physical imaging problem is electromagnetic in its nature. The image is formed as an interference pattern of waves or a wave front, transmitted by an optical imaging system. For non-self-luminous objects, the waves that finally form the image originate from diffraction at the object. Diffraction and interference can be conveniently described by wave optics. In a rather abstract way, the task of developing an optical system is to find a distribution of refractive indices and boundaries of the imaging system between the source and the detector that produce in the detector plane a wave field that is, as far as possible, like the object field. A purely geometrical formulation of the system description is not able to cover all the effects that take place. However, a full wave optical treatment of physical image formation is rarely possible. The dimensions and the complexity of optical systems typically do not allow for a rigorous solution of Maxwell's equations. Therefore, the solution is typically separated into different steps. The nature of the physical effects involved in image formation can be split into two different groups, and the steps are selected in accordance with the dominating physical effect, which might be either:

- the propagation of a wave field, i.e., through free space or optical systems, or
- an interaction, either with diffracting objects, detectors or the superposition of wave-fields to form interference patterns.

For each step, there are certain levels of approximate solutions, each of which can be solved by an appropriate solution for propagation or interaction, depending on the required accuracy. For example, there are several powerful methods, which are used in the calculation of field transport and propagation problems as numerical solutions to the wave equation. The remaining difficulties are mostly given by the interfaces between the different sections of the description. In the simplest case, different sampling grids have to be adapted by interpolation or re-sampling. In general, however, the transition is more complicated. While a transfer from ray optics to wave optics is straightforward, for example, transfer from wave to ray optics, generally requires further restrictions and is usually limited to coherent wave fronts. Here in Volume 2 of the Handbook series we will concentrate our description on the most relevant steps for optical imaging, such as diffraction at the object, consideration of partial coherence and vector effects. The standard description of optical imaging systems is shown in figure I-1.

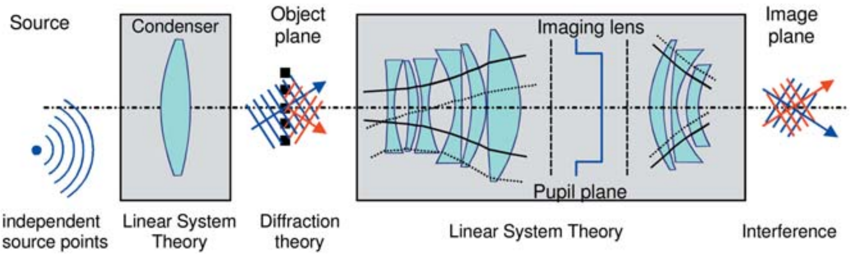

Figure I-1: Physical model for the description of optical imaging.

The physical model of optical imaging aims, whenever possible, to provide a linear system description. In the most convenient description, the effective light source is described by incoherent source points and the object is illuminated by an assembly of incoherent plane waves. Diffraction is often taken into account by the Thin

Element Approximation (TEA), which is equivalent to Fourier-transforming the object transmission function. Imaging is considered, in general, by a complex transfer function and the image intensity is formed by squaring the linearly transmitted amplitudes. The standard procedure is shown in table I-1.

Table I-1: Standard physical model of optical image formation

Step	Physical Principle	Preferred Methods of Solution	Simplification
Source	Linear decomposition	• Source points • Laser modes	• Coherence properties
Condenser	Propagation	• Linear system theory	• Fourier transformation of effective light source
Object	Interaction – Diffraction theory	• Thin element approximation • Scalar diffraction theory • Vector Diffraction theory	• Decomposition of illumination into plane waves
Imaging lens	Propagation and filtering	• Linear System theory	• Complex transfer function by ray-tracing
Image formation	Interference	• Intensity–square • Incoherent superposition	• Time average

In the following the contents and also the limits of Volume 2 are outlined.

i) Coherence and Illumination

The amplitude spectrum in image space and the image intensity for coherent image formation, together with the diffraction spectrum of the object, are all obtained by a linear system approach. The only remaining question is how to consider the coherence properties of the light source. With coherent illumination of, e.g., a grating, the light propagation cancels out in certain directions, while it is constructively superposed in others. The image is formed as an interference phenomenon of the coherent diffracted waves. Illumination conditions, however, are typically not coherent, and in fact, coherent conditions usually have an adverse effect on image formation. The role of coherence is introduced in section 19.

The coherence properties of optical imaging are generally given by the properties of the light source and the illumination system. As will be shown in sections 21–24, the optical image is predominantly influenced by the physical properties of the illumination conditions. The description of the illumination in optical image formation is conveniently reduced to an effective light source. The illumination system will be considered as an optical system, with the effective light source being provided by a physical light source such as a laser beam. Inside the illumination system, the use of components with micro-structured surfaces eventually makes it necessary to calculate the interaction of the light propagation and the light transfer using non-geometrical models, and then the transition between wave and ray optics is more complicated. The illumination systems and the physical effects involved will be discussed in Volume 4. The discussion of physical image formation in Volume 2 is – as usual – limited to the effective light source model.

ii) Diffraction – Coherent Interaction of Light and Matter

One of the consequences of Abbe's theory is that the information contained in the image is restricted to the information which is contained in the light scattered by the object. For most applications, a scalar description of scattering is sufficient, but further approximations may be applied for convenience. Diffraction, however, can be considered in physical optical imaging in two ways. On the one hand, as far as non self-luminous objects are concerned, diffraction theory is required for the treatment of the interaction of light with the object to be imaged. On the other hand, diffraction at the aperture stop of an imaging lens causes a diffraction-limited spot size. In general the task is to compute the diffraction field of either object or aperture stop, depending on the incident light amplitude distribution. There are several methods used for physically modelling the interaction of light with objects and the method of choice has to be decided upon depending on the appropriate conditions for numerical solution. Possible algorithms are, for example, the Kirchhoff integral, the Fresnel paraxial approximation or the Fraunhofer far-field approximation.

Light is a transverse electromagnetic wave – in the classical limit – and obeys Maxwell's equations. For this reason it can be polarized. Polarization has an impact on optical imaging because the contrast of the interference depends on the mutual polarization of the contributing waves. Furthermore, polarization effects can be used to generate an image contrast as in polarization microscopy and some projection devices. The mathematical description of polarization states and their change due to various optical components is the subject of section 26, while polarization optical imaging is discussed in chapter 28.

If either the level of accuracy required to describe the diffraction at the object becomes extraordinarily high or if the structure sizes become comparable to the wavelength, then scalar approximation theories are no longer sufficient. Some frequently-used rigorous methods that solve Maxwell's equations in object space are treated in chapter 27. However, apart from some examples, it is beyond the scope of this volume to consider near-field effects of the interaction of light with small structures in detail, as is required, for instance, in the interpretation of the images in near-field optical microscopy. Some common near-field optical measurement methods will be discussed in Volume 6.

iii) Propagation of Coherent Light in Optical Systems

If the propagators are chosen in an appropriate way and the sampling conditions are considered properly, the field propagation through nearly every real system can be calculated to an acceptable accuracy. To illustrate the complexity of the propagation problem, a simple example of an optical system is considered. Propagation through optical systems, including interfaces, is frequently simplified by a geometrical optical description, without the need to sacrifice accuracy. Refraction or reflection follows well-known laws, but dielectric coatings might influence the amplitude and the phase, for example. The complex transmission and reflection coefficients generally require a wave optical treatment. These wave optical effects have to be included in the geometrical optical description by, e.g., reference tables or functional descriptions of the coefficients. The consideration of coefficients alone might not be sufficient since, e.g., for multi-layer coatings with a thickness of several wavelengths the position of the reflection of refraction of a ray is not clear. This simple example shows that the level of detail involved in the steps might be quite complex. A full description of all details is beyond the scope of Volume 2. In section 20, however, the formal transition from geometrical optics to wave optics is discussed for the example of imaging systems.

For a wave optical treatment, the effect of the phase elements such as thin lenses or phase filters of an optical system can be considered as for complex filters. The thin phase element is considered by a simple projection of the phase shift of the element. The role of the z-dimension is neglected and the output wave is obtained from the incident wave by multiplication with a complex transfer function, given by the amplitude transmission A of the element and the phase shift Φ, which is added to the phase of the incident wave. In general, however, the complex transmission function depends on the angle of incidence. It should be noted that this TEA, although called a thin-element approximation, is really a small-angle approximation. The TEA is frequently applied in so-called Fourier Optics, which is a simplified wave optical treatment of image formation and optical filter techniques. Within the scope of this approximation, compound optical systems may be treated using the paraxial Collins integral, based on the Fresnel approximation and then by applying the matrix approach of first-order optics. Separated parts of an optical system with nearly-perfect correction can be described as paraxial lens groups. The characterization of the subsystem is possible by a simple paraxial ABCD matrix. An extension of the approximation is possible for small residual aberrations of the optical system. This approach, based on Fresnel's integral, is outlined in section 18. The paraxial formulation of Fourier Optics, however, frequently leads to the incorrect assumption that the application of optical imaging theory – and Fourier Optics in general – is restricted to the paraxial regime. In this volume we will concentrate on general optical imaging theory with no lack of approximations. Fortunately, wave-optical propagators by optical imaging systems are not necessary, since the treatment using geometrical optical approximation produces results with a very high accuracy. The application of wave optical propagators is restricted to special applications and will not be considered further in Volume 2.

In addition, the design and analysis of optical imaging systems is frequently also based on ray tracing and the geometrical optical description. The advantages of ray tracing are many: it is powerful, fast, flexible and applicable over large scales, and there are a variety of commercially available software packages in existence. With certain approximations and, e.g., statistical methods, it is possible to consider even scattering or diffractive optical elements. However, for a comprehensive treatment of optical design, simulated by ray tracing, the reader is referred to Volume 3.

iv) Conversion between Rays and Waves

For a description of physical image formation it is necessary to achieve the transfer between geometrical ray optics and wave optics. As will be shown in section 20, conversion from rays to waves and vice versa is generally only possible for coherent wave fields obeying the law of Malus – a property called orthotomy. Both forms of description are then equivalent and can be converted into each other. The conditions can be summarized as:

1. A wave front must exist. This wave front must be continuous, and there should be no phase singularities.
2. The conversion is generally not possible in the region of a caustic, where wave fronts cannot be defined.

Having defined a coherent wave field $U(x,y,z)$ by a complex amplitude distribution with the phase $\Phi(x,y,z)$ and amplitude distribution $A(x,y,z)$, the local direction of light rays is directly given by the Eikonal equation (see sections 17 and 20). As a second condition, the transfer between the two forms of description has to satisfy the conservation of energy. For this purpose, a ray is either characterized by a weighting coefficient g or – in a statistical approach – the ray density is selected in accordance with the amplitude A. For a more general treatment of the transfer from ray optics to wave optics and vice versa we refer you to a later volume of this Handbook of Optical Systems.

Ultimately the wave optical treatment of propagation through imaging systems is preferred or sometimes even necessary. For micro-optical systems, numerical methods may be applied, such as finite differences for small distances and gradient index media, or mode-expansion methods inside light-guiding structures, such as waveguides. In Volume 6, we address beam-propagation methods in order to model the propagation of light in guiding structures and more complex environments, and also the description of laser light.

The image formed as an interference phenomenon is considered by a wave optical description, either in the space domain by a superposition of, e.g., plane waves; or in the spatial frequency domain by the spatial frequency spectrum representation of the wave field in the image plane. For an introduction, see the wave optical description which is outlined in section 17.

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