CONTEMPORARY OPTICS
FOR
SCIENTISTS AND ENGINEERS

ALLEN NUSSBAUM

RICHARD A. PHILLIPS

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PREFACE

During the last decade, revolutionary changes have taken place in the field of optics. Foremost among these has been the development of the laser and the widespread application of lasers in many areas of science and engineering. Everyone who has made predictions of the future has concluded that the existing applications are only a beginning and that the greatest growth of this field lies ahead. The laser has made applications possible which had previously only been conjectured.

Two entirely new areas exploiting the unique properties of laser light have emerged: these are holography (three-dimensional photography) and nonlinear optics (frequency shifting and modulation of laser light). Other developments are the filtering of optical images to enhance selected features and character recognitition. Advances in detectors and detection techniques have made the infrared region more accessible.

Geometrical optics has undergone a similar advance during the decade. Matrix methods have greatly simplified the design of lens and optical systems. The use of computers in the interactive mode has made possible a great improvement in the design of optical systems and the tailoring of a system to a particular job. Further, it permits the elimination of a large amount of the tedious algebra associated with geometric optics.

All of these factors have indicated to us that a new and modern treatment of optics would serve a definite need. This book aims at a fairly broad coverage in both its subject matter and its audience, and it has been written using the modular approach. Each major topic is introduced separately and is self-contained. This permits different portions to be combined to serve different course needs. There is more material than can be incorporated in a one semester course, so that the instructor should choose the topics for his particular course. Traditionally, optics has been taught in physics departments. The pedagogical function of the optics course was to familiarize students with wave phenomena using light waves that they would see. This need is met in this book by the sections on interference, diffraction, and polarization. The modern aspects of these topics (coherence, spatial filtering, holography, and nonlinear optics) have been woven into the treatment. The initial development of each topic has been made as simple mathematically as possible. This provides a discussion of the fundamental aspects of the phenomena. The treatment of each topic is extended using more advanced mathematical techniques. Students preparing for graduate school can pursue the treatments in greater depth while others will still obtain a sound knowledge of phenomena. An example of this is the section on nonlinear optics. Each effect is first described simply, then a more advanced treatment using eigenvalues and eigenvectors is presented. Another example is our treatment of Fraunhofer diffraction, which is based on Huyghens' principle. Diffraction patterns for simple objects are calculated. Then a more advanced treatment leading to the optical transfer function is developed.

Recently, physics departments have renewed their interest in applied areas of physics, and the need to train physicists in applied areas is now widely recognized. At the same time, engineering departments are developing optics courses because of engineering applications of optics. The sections on holography, optical data processing, sources (including laser theory), detectors, crystal optics, and electro-optics meet this need.

Engineers are also particularly concerned with geometrical optics and systems design. The sections on matrix methods, the optical transfer function, sources, and detectors are well suited for this.

The following table contains suggestions for three different courses:

Geometrical Optics	Physical Optics	Applied or Engineering Optics
Matrix Methods	Introduction to Waves	Introduction to Waves
Introduction to Waves	Interference	Interference
Diffraction	Diffraction	Diffraction
Spatial Filtering	Holography	Holography
Optical Transfer Function	Absorption and Dispersion	Absorption and Dispersion
Sources	Crystal Optics	Crystal Optics
Detectors	Polarization	Polarization
	Nonlinear Optics (full treatment)	Nonlinear Optics (introductory parts)

The material in this book has been presented by the authors in regular courses, short intensive courses, and over television. We wish to express our gratitude for comments, from students and colleagues, that have improved our treatment. In addition, the material on the extension of matrix methods to non-paraxial optics (Chapters 2 and 3) was originally worked out under the auspices of an NSF Curriculum Development Grant, for which we are grateful.

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PART

I

ELEMENTARY AND ADVANCED GEOMETRICAL OPTICS

The first four chapters of this book provide a fairly detailed introduction to geometrical optics. Chapter 1, which describes the matrix approach used by many teachers of optics, covers the material generally presented in an introductory physics course. This, plus some of the discussion of aberrations in the next two chapters, is all the background needed to understand the effect of lenses on light waves, as considered in Chapter 10. On the other hand, readers interested in the functioning or design of optical instruments such as cameras, telescopes, and spectroscopes should go through Chapters 1–3 thoroughly and select those parts of Chapter 4 which are appropriate. It will be noted that geometrical optics involves fairly extensive use of a computer or a scientific electronic calculator; it is the combination of matrix and numerical methods which takes what was once a very tedious and complicated discipline and makes it both simple and interesting.

1

PARAXIAL MATRIX OPTICS

1-1 The Newton and Gauss Lens Equations

Our ultimate purpose is to learn to calculate exactly how very complicated optical systems affect the light rays passing through them, but we shall start our approach to geometric optics in a very intuitive fashion. In Fig. 1-1, we show a simple magnifier—a double convex lens—used as a burning glass. The sun's rays, assumed to be traveling parallel to the axis of the lens, meet at the *focal point* or *focus F*, producing a small, intense spot of light capable of igniting paper. The lens is symmetric and if the sun's rays came from the opposite direction there would be another such point F' on the other side of the lens at an equal distance from the corresponding surface.

Next, let us use this lens to magnify. We find that when we view an object located a few centimeters away, it is enlarged significantly (Fig. 1-2(a)), but if the lens is brought closer to the object, the magnification is not very great (Fig. 1-2(b)). In fact, if the lens is placed very close to the print, the magnification is only perceptibly greater than unity. (The reader should try this with an ordinary magnifier.) This leads us to suspect that there is a position of the object, perhaps touching the lens, which would actually give an image of identical size and oriented in the same way. Denoting the object position for this situation by H and the image position by H', Fig. 1-3 shows how

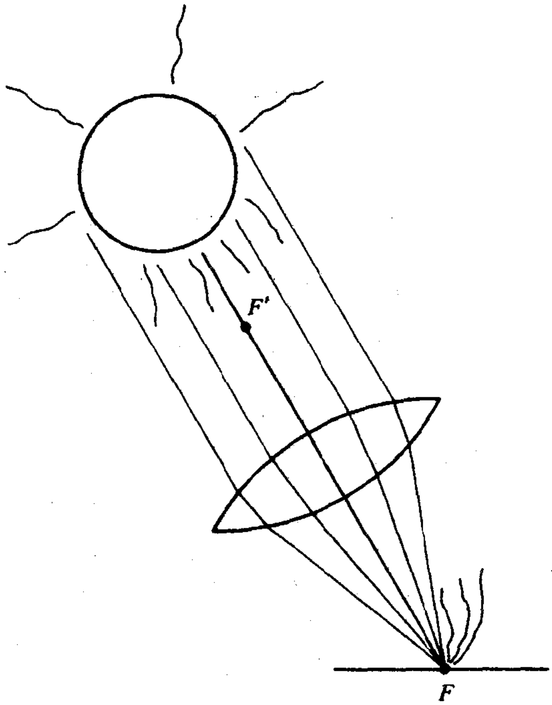

Figure 1-1

object and image might be related. (Actually, Fig. 1-3 is not quite a true representation of this one-to-one relation, for reasons we shall consider shortly.) The points H and H' are called the *unit* or *principal points* of the lens. We shall use the former term since it is self-explanatory. The four points F, F', H, and H' are collectively known as *cardinal points*, and the planes through these points normal to the axis are the *cardinal planes*.

Let us now place an object of height x at a distance s to the left of the symmetrical convex lens of Fig. 1-4. The axis of the lens is AA' and the cardinal points F, H, H', and F' lie on the axis in the order given, since the unit points are fairly close to the lens and the focal points are a little farther out. We consider a ray PQ which is parallel to AA'. Such a ray does not actually pass through the lens, so we cannot trace it from Q to R'. However, if the lens were larger or the object smaller, then this ray would emerge from the lens in such a way that it would cross the unit plane determined by H' at a distance $\overline{H'R'} = x$ from the axis. This follows from the fact that $\overline{HQ} = x$ and its image $\overline{H'R'}$ must be identical in size and orientation. Further, the ray which leaves P and passes through Q and R' must also pass through the focal point F'. This is a consequence of the focusing property discussed in connection with Fig. 1-1.