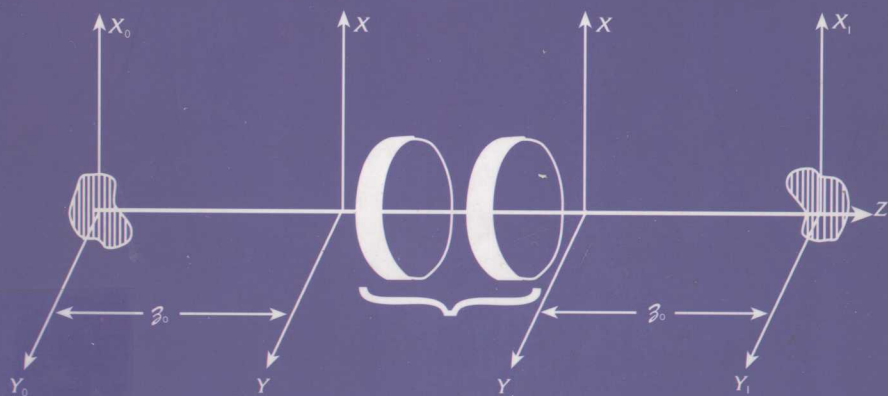


# Classical Optics and its Applications

## 经典光学及其应用

Masud Mansuripur



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# CLASSICAL OPTICS AND ITS APPLICATIONS

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## CLASSICAL OPTICS AND ITS APPLICATIONS

This book covers a broad range of the major topics of classical optics, in the form of 37 self-contained chapters. The chapters in the first half of the book deal primarily with the basic concepts of optics, while those in the second half describe how these concepts can be used in a variety of technological applications.

In each chapter, Professor Mansuripur introduces and develops a specialized topic in a comprehensive, clear and pedagogical style. The mathematical content is kept to a minimum as the book aims to provide the reader with insightful discussions of optical phenomena, at a level which is both accessible and interesting. This is aided by the numerous illustrations throughout in the form of diagrams, graphs and powerful computer simulation images. Topics covered include classical diffraction theory, optics of crystals, peculiarities of polarized light, thin-film multilayer stacks and coatings, geometrical optics and ray-tracing, various forms of optical microscopy, interferometry, coherence, holography, and nonlinear optics.

As such, this book will constitute the ideal companion text for graduate-level courses in optics, providing supplementary reading material for teachers and students alike. Industrial scientists and engineers developing modern optical systems will also find it an invaluable resource.

MASUD MANSURIPUR received a Bachelor of Science degree in Electrical Engineering from Arya-Mehr University of Technology in Tehran, Iran (1977), a Master of Science in Electrical Engineering from Stanford University (1978), a Master of Science in Mathematics from Stanford University (1980), and a Ph.D. in Electrical Engineering from Stanford University (1981). He has been Professor of Optical Sciences at the University of Arizona since 1988. His areas of research include: optical data storage, optical signal processing, magneto-optical properties of thin magnetic films, and the optical and thermal characterization of thin films and stacks. A Fellow of the Optical Society of America, he has published more than 200 papers in various technical journals, holds four patents, has given numerous invited talks at international scientific conferences, and is a contributing editor of *Optics & Photonics News*, the magazine of the Optical Society of America. Professor Mansuripur's published books include *Introduction to Information Theory* (1987), and *The Physical Principles of Magneto-optical Recording* (1995).

To Annegret, Kaveh, and Tobias

## Preface

I started writing the Engineering column of *Optics & Photonics News (OPN)* in early 1997. Since then nearly forty articles have appeared, covering a broad range of topics in classical optical physics and engineering. My original goal was to introduce students and practising engineers to some of the most fascinating topics in classical optics. This I planned to achieve with minimal usage of the mathematical language that pervades the literature of the field. I had met many bright students and practitioners who either did not know or did not fully appreciate some of the major concepts of classical optics such as the Talbot effect, Abbe's sine condition, the Goos-Hänchen effect, Hamilton's internal and external conical refraction, Zernike's method of phase contrast, Michelson's stellar interferometer, and so on. My columns were going to have little mathematics but an abundance of pictures and pedagogical arguments, to bring forth the essence of the physics involved in each phenomenon. In the process, I hoped, the readers would appreciate the beauty of the subject and, if they found it interesting, would dig deeper by searching the cited literature.

A unique tool available to me for this purpose was the computer programs **DIFFRACT<sup>TM</sup>**, **MULTILAYER<sup>TM</sup>**, and **TEMPROFILE<sup>TM</sup>**, which I have developed in the course of my research over the past 20 years. The first of these programs simulates the propagation of light through optical systems consisting of discrete elements such as lasers, lenses, mirrors, prisms, phase/amplitude masks, gratings, polarizers, wave-plates, multilayer stacks, birefringent crystals, diffraction gratings, and optically active materials. The other two programs simulate the optical and thermal behavior of multilayer stacks. I have used these programs to generate graphs and pictures to explain the various phenomena in ways that would promote a better understanding.

The articles have been successful beyond my wildest dreams. While I had hoped that a few readers would find something useful in this series, I have

received notes, e-mails, and verbal comments from distinguished scholars around the world who have found the columns stimulating and helpful. Some teachers informed me that they use the articles for their classroom teaching, and I have heard of several readers who collect the articles for future reference. All in all, I have been pleasantly surprised by the positive reaction of the *OPN* readers to these columns.

*Optics & Photonics News* is not an archival journal and, therefore, will not be widely available to future students. Thus I believe that collecting the articles here in one book, which provides for ease of cross-referencing, will be useful. Moreover, the book contains additional explanations of topics that were originally curtailed for lack of space in *OPN*; it includes corrections to errors discovered afterwards and incorporates some comments and criticisms made by *OPN* readers as well as my answers to these criticisms.

This book covers a broad range of topics: classical diffraction theory, the optics of crystals, the peculiarities of polarized light, thin-film multilayer stacks and coatings, geometrical optics and ray-tracing, various forms of optical microscopy, interferometry, coherence, holography, nonlinear optics, etc. It could serve as a companion to the principal text used in a number of academic courses in physics, engineering, and optics; it should be useful for university teachers as a guide to selecting topics for a graduate-level course; it should be useful also for self-study by graduate students. It could be used fruitfully by engineers who develop optical systems such as laser printers, scanners, cameras, displays, image-processing equipment, lasers and laser-based systems, telescopes, optical storage and communication systems, spectrometers, etc. I believe anyone working in the field of optics could benefit from this book, by being exposed to some of the major concepts and ideas (developed over the last three centuries) that shape our modern understanding of optics.

Some of the original *OPN* columns were written jointly with colleagues and students; these are identified in the footnotes and the corresponding co-authors acknowledged. I thank Ewan Wright and Rongguang Liang of the Optical Sciences Center, Lifeng Li of Tsinghua University, Mahmoud Fallahi of Nortel Co., and Wei-Hung Yeh of Maxoptix Co. for their collaboration as well as for giving permission to publish our joint papers in this collection. I also would like to acknowledge the late Peter Franken, Pierre Meystre, Yung-Chieh Hsieh, Dennis Howe, Glenn Sincerbox, Harrison Barrett, Roland Shack, José Sasian, Michael Descour, Arvind Marathay, Ray Chiao, James Wyant, Marc Levenson, Ronald Gerber, James Burge, Ferry Zijp and Dror Sarid, who shared their valuable insights with me and/or criticized the drafts of several articles prior to publication. Needless to say,



I am solely responsible for any remaining errors and inaccuracies. For their help with graphics and word processing, I am grateful to our administrative assistants Patricia Gransie, Nonie Veccia, Marylou Myers, and Amanda Palma.

Last but not least, I am grateful to my wife, Annegret, who has tolerated me with love and patience over the past four years while this book was being written. It is to her and to our children, Kaveh and Tobias, that this book is dedicated.

Masud Mansuripur  
Tucson, December 2000

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# Introduction

The common threads that run through this book are the classical phenomena of diffraction, interference, and polarization. Although the reader is expected to be generally familiar with these electromagnetic phenomena, the book does cover some of the principles of classical optics in the early chapters. The basic ideas of diffraction and Fourier optics are introduced in chapters 1 through 4; this introduction is followed by a detailed discussion of spatial and temporal coherence and of partial polarization in chapters 5 through 8. These concepts are then used throughout the book to explain phenomena that are either of technological import or significant in their own right as natural occurrences that deserve attention.

Each chapter is concerned with a single topic (e.g., surface plasmons, diffraction gratings, evanescent coupling, photolithography) and attempts to develop an understanding of this subject through the use of pictures, examples, numerical simulations, and logical argument. The reader already familiar with a particular topic is likely to learn more about its applications, to appreciate better the physics behind some of the formulas he or she may have previously encountered, and perhaps even learn a thing or two about the nuances of the subject. For the reader who is new to the field, our presentation is aimed to provide an introduction, an intuitive feel for the physical and/or technological issues involved, and, hopefully, motivation for digging deeper by consulting the cited references. For the most part, this book avoids repeating what is already in the open literature, aiming instead to expose concepts and ideas, ask critical questions, and provide answers by appealing to the reader's intuition rather than to his or her mathematical skills.

Some of the chapters address fundamental problems that historically have been crucial to our modern understanding of optics; conical refraction, the Talbot effect, the principle of holography, and the Ewald–Oseen extinction

theorem are representatives of this class. Other chapters introduce devices and phenomena of great scientific and technological importance; Fabry–Pérot etalons, the magneto-optical Faraday and Kerr effects, and the phenomenon of total internal reflection fall into this second category. Many of the remaining chapters single out a tool or an instrument that not only is of immense technological value but also has its unique principles of operation, worthy of detailed understanding; examples include various microscopes and telescopes, lithographic systems, ellipsometers, and so on. Occasionally a theoretical concept or a numerical method is found that has a wide range of applications; we have devoted a few chapters to these topics, such as the method of Fox and Li, the beam propagation method, and the concept of reciprocity in classical optics.

The majority of the computer simulations reported in this book were performed with the software packages DIFFRACT<sup>TM</sup>, MULTILAYER<sup>TM</sup>, and TEMPROFILE<sup>TM</sup>, which I have written in the course of the past twenty years and which are now commercially available. These programs in turn are based on theoretical methods and numerical algorithms that are fully documented in several of my publications.<sup>1–6</sup> In a few chapters, I have collaborated with Professor Lifeng Li (now at the Tsinghua University in China). Here, we have used Professor Li's program DELTA<sup>TM</sup>, also commercially available, for calculations pertaining to diffraction gratings. The theoretical foundations of DELTA<sup>TM</sup> are described in Professor Li's publications.<sup>7</sup>

Throughout the book, black-and-white pictures will be used to display the various properties of an optical beam; these include cross-sectional distributions of intensity, phase, polarization, and the Poynting vector. A unified scheme for the gray-scale encoding of real-valued functions of two variables is used in all the chapters, and it is helpful to review these methods at the outset. In the convention adopted the beam always propagates along the  $Z$ -axis, and its cross-sectional plane is  $XY$ . The Cartesian  $XYZ$  coordinate system is right-handed, the polar angles are measured from the positive  $Z$ -axis, and the azimuthal angles are measured from the positive  $X$ -axis towards the positive  $Y$ -axis. In general, the beam has three components of polarization along the  $X$ -,  $Y$ -, and  $Z$ -axes of the coordinate system, that is, its electric field  $E$  has components  $E_x(x, y)$ ,  $E_y(x, y)$ , and  $E_z(x, y)$  at any given cross-sectional plane, say, at  $z = z_0$ . Since the  $E$ -field components are complex-valued, their complete specification requires two distributions for each component, namely, amplitude and phase. The following paragraphs describe in some detail the encoding

scheme used for displaying different cross-sectional properties of the beam and also provide a few examples.

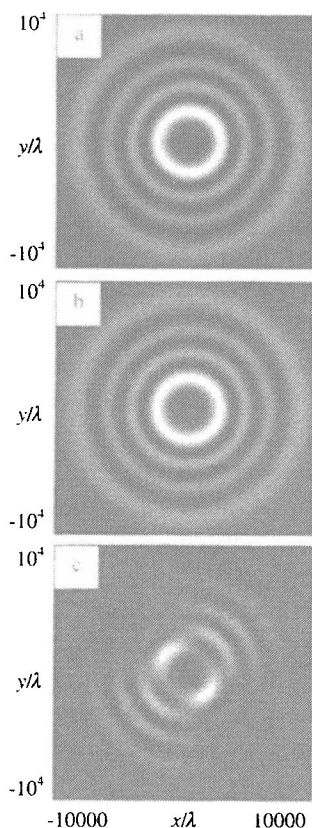
### Plots of intensity distribution

The electric-field intensity is the square of the field amplitude at any given location in space. Thus, for example, the intensity distribution in the cross-sectional  $XY$ -plane for the  $E$ -field component along the  $X$ -axis is denoted by  $I_x(x, y) = |E_x(x, y)|^2$ . Figure 0.1 shows plots of intensity distribution for the three components of polarization of a Laguerre–Gaussian beam propagating along the  $Z$ -axis. The black pixels represent locations where the intensity is at its minimum (zero in the present case), the white pixels correspond to the locations of maximum intensity within the corresponding frame, and the gray pixels linearly interpolate between these minimum and maximum values. In the case of Figure 0.1, the beam was taken to be linearly polarized at  $45^\circ$  to the  $X$ -axis, leading to identical distributions for the  $X$ - and  $Y$ -components of polarization.

The much weaker  $Z$ -component is computed to ensure that the Maxwell equations will be satisfied for the assumed distributions of the  $X$ - and  $Y$ -polarization components. In general, one may assume arbitrary distributions for  $E_x$  and  $E_y$  within a given cross-sectional  $XY$ -plane. To determine  $E_z$  in a self-consistent manner, one must break up the  $E_x$  and  $E_y$  distributions into their plane-wave constituents and proceed to determine  $E_z$  for each plane wave that propagates along the unit vector  $\sigma = (\sigma_x, \sigma_y, \sigma_z)$  by requiring the inner product of  $E$  and  $\sigma$  to vanish (i.e.,  $E_x\sigma_x + E_y\sigma_y + E_z\sigma_z = 0$ ). One must then superimpose the  $Z$ -components of all the plane waves thus obtained to arrive at the total distribution of  $E_z$ . In Figure 0.1 the peak intensities in the three frames are in the ratios  $I_x : I_y : I_z = 1.0 : 1.0 : 1.47 \times 10^{-7}$ .

### Logarithmic plots of intensity distribution

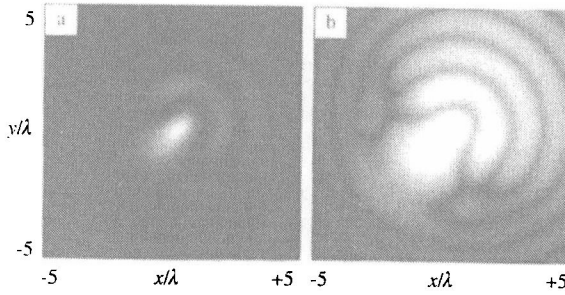
In order to emphasize the weaker regions of an intensity distribution, we will show on numerous occasions the distribution of the logarithm of the intensity. First, the intensity distribution is normalized by its peak value, then the base-10 logarithm of the normalized intensity is computed and all values below some cutoff point are truncated. For instance, if the cutoff is set to  $-\alpha$  then all values of the normalized intensity below  $10^{-\alpha}$  are reset to  $10^{-\alpha}$ ; the range of the logarithm of normalized intensity thus becomes  $(-\alpha, 0)$ . The continuum of gray levels from black to bright-white is then mapped linearly



**Figure 0.1** Plots of intensity distribution in the cross-sectional plane of a Laguerre–Gaussian beam for the three components of the  $E$ -field. In each frame the black pixels represent locations of zero intensity, while the white pixels represent locations of maximum intensity in the corresponding frame. The beam is assumed to propagate along the  $Z$ -axis, linearly polarized at  $45^\circ$  to the  $X$ -axis. (a) Intensity of the component of polarization along the  $X$ -axis,  $I_x(x, y) = |E_x(x, y)|^2$ , (b)  $I_y(x, y) = |E_y(x, y)|^2$ , (c)  $I_z(x, y) = |E_z(x, y)|^2$ . The peak intensities in (a), (b), (c) are in the ratios  $1.0 : 1.0 : 1.47 \times 10^{-7}$ , respectively.

onto this interval and used to display plots of normalized intensity on the logarithmic scale. When it is deemed useful or necessary, the corresponding value of  $\alpha$  will be indicated in a figure's caption.

Figure 0.2 shows two plots of the same intensity distribution at the focal plane of a comatic lens. In (a) the distribution is linearly mapped onto the gray-scale, whereas in (b) the logarithm of intensity with a cutoff at  $\alpha = 4$  is displayed. The latter is similar to what would be obtained by over-exposing a photographic plate placed at the focal plane of the lens.



**Figure 0.2** (a) Intensity distribution in the focal plane of a  $0.5NA$  lens having  $1.5\lambda$  of third-order coma (Seidel aberration). The uniformly distributed incident beam is assumed to be circularly polarized. In the focal plane, the  $X$ -,  $Y$ -, and  $Z$ - components of the electric field vector are added together to yield the total  $E$ -field intensity. (b) Same as (a) but on a logarithmic scale with  $\alpha = 4$  (see text).

### Plots of phase distribution

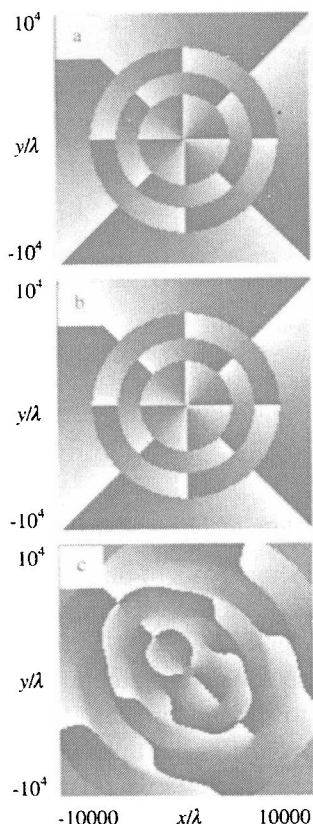
In several chapters we will show plots of phase distribution in a beam's cross-sectional plane. The phase, a modulo- $2\pi$  entity, will always be limited to a range less than or equal to  $360^\circ$ . We typically divide the range of phase values for a given distribution into equal sub-intervals, assigning black to the minimum value, bright-white to the maximum value, and various gray levels to the values in between. A sharp discontinuity (from black to white or vice versa) appearing in these phase plots would be of no physical significance, since it merely indicates a  $360^\circ$  phase jump.

Figure 0.3 is a cross-sectional plot of the phase distribution for the Laguerre–Gaussian beam whose intensity distribution was given in Figure 0.1. The three frames of Figure 0.3 correspond to the components of polarization along the  $X$ -,  $Y$ -, and  $Z$ - axes. The black pixels represent the minimum phase,  $-180^\circ$ , and the white pixels correspond to the maximum phase,  $+180^\circ$ ; the gray pixels cover the continuous range of values in between.

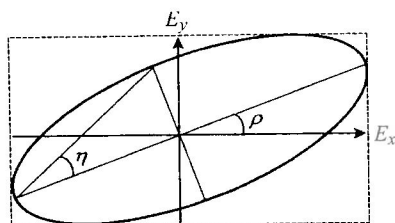
### Ellipse of polarization

Consider a collimated beam of light propagating along the  $Z$ -axis. In general, the state of polarization of the beam at any given point is elliptical, as shown in Figure 0.4. So long as the electric-field vector  $E$  may be assumed to be confined to the  $XY$ -plane, it may be resolved into two orthogonal components, along the  $X$ - and  $Y$ - axes say. If  $E_x$  and  $E_y$  happen to be in phase, the polarization will be linear along some direction specified by the angle  $\rho$ . If, on the other hand, the phase difference between  $E_x$  and  $E_y$  is  $\pm 90^\circ$  then the





**Figure 0.3** Plots of phase distribution in the cross-sectional plane of the Laguerre–Gaussian beam depicted in Figure 0.1. Frames (a), (b), and (c) correspond, respectively, to the components of the  $E$ -field along the  $X$ -,  $Y$ -, and  $Z$ - coordinate axes. In each frame the black pixels represent a phase of  $-180^\circ$  and the white pixels correspond to a phase of  $+180^\circ$ ; the gray pixels linearly interpolate between these two extreme values.



**Figure 0.4** The ellipse of polarization is uniquely specified by  $E_x$  and  $E_y$ , the complex-valued electric field components along the  $X$ - and  $Y$ - axes. The major axis of the ellipse makes an angle  $\rho$  with the  $X$ -direction, and the angle  $\eta$  facing the minor axis represents the polarization ellipticity.