Design and Fabrication of

Diffractive Optical Elements with MATLAB®

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To the Lord God Almighty—for being my strength
To my beloved mother Jacintha—for showing me the meaning of love and sacrifice
To my dearest wife and best friend Arthi—for loving me unconditionally
To all of my teachers—for guiding me through various journeys in my life

–Vijay

To my husband, Subbu:
Note: An empty day with clan is better handled with you! (2, 4, 6)

–Shanti

Introduction to the Series

Since its inception in 1989, the Tutorial Texts (TT) series has grown to cover many diverse fields of science and engineering. The initial idea for the series was to make material presented in SPIE short courses available to those who could not attend and to provide a reference text for those who could. Thus, many of the texts in this series are generated by augmenting course notes with descriptive text that further illuminates the subject. In this way, the TT becomes an excellent stand-alone reference that finds a much wider audience than only short course attendees.

Tutorial Texts have grown in popularity and in the scope of material covered since 1989. They no longer necessarily stem from short courses; rather, they are often generated independently by experts in the field. They are popular because they provide a ready reference to those wishing to learn about emerging technologies or the latest information within their field. The topics within the series have grown from the initial areas of geometrical optics, optical detectors, and image processing to include the emerging fields of nanotechnology, biomedical optics, fiber optics, and laser technologies. Authors contributing to the TT series are instructed to provide introductory material so that those new to the field may use the book as a starting point to get a basic grasp of the material. It is hoped that some readers may develop sufficient interest to take a short course by the author or pursue further research in more advanced books to delve deeper into the subject.

The books in this series are distinguished from other technical monographs and textbooks in the way in which the material is presented. In keeping with the tutorial nature of the series, there is an emphasis on the use of graphical and illustrative material to better elucidate basic and advanced concepts. There is also heavy use of tabular reference data and numerous examples to further explain the concepts presented. The publishing time for the books is kept to a minimum so that the books will be as timely and up-to-date as possible. Furthermore, these introductory books are competitively priced compared to more traditional books on the same subject.

When a proposal for a text is received, each proposal is evaluated to determine the relevance of the proposed topic. This initial reviewing process has been very helpful to authors in identifying, early in the writing process, the need for additional material or other changes in approach that would serve to strengthen the text. Once a manuscript is completed, it is peer reviewed to ensure that chapters communicate accurately the essential ingredients of the science and technologies under discussion.

It is my goal to maintain the style and quality of books in the series and to further expand the topic areas to include new emerging fields as they become of interest to our reading audience.

James A. Harrington
Rutgers University

Contents

Foreword

Light sustains life. It enthralls, captivates, and provides immense pleasure. It connects cultures and establishes vocal and visual communication among different life forms. We admire the beauty of flowers, of butterflies, and of the feathers of a peacock. There is something mystical about light, with even the ancients speculating on its nature. Although we now accept its dual nature, we continue to explore its other hidden features.

Diffractive optical elements (DOEs) essentially function due to the interplay of the phenomena of diffraction and interference that often display vivid colors. Diffraction of light takes place when a wavefront is limited in space; the limitation may be imposed either by the mountings of the optics or by the apertures. Therefore, diffraction of light always takes place, and its effects become significant when an aperture allows only a tiny portion of the wavefront to pass. Grimaldi (1618–1663) carried out extensive experimental investigations on diffraction, although the term *diffraction* is attributed to Leonardo da Vinci (1452–1519). In 1818 Fresnel (1788–1827) wrote a memoir on diffraction that is fundamental to the theory of diffraction of light. While making a presentation to the French Academy of Sciences, Fresnel showed the appearance of a bright spot in the shadow of a round object. Not believing the theory, Arago rushed to the laboratory and indeed found that it is true, and the spot became known as an Arago spot. Kirchhoff (1824–1887) put the theory of diffraction of light on sound mathematical footing. Thereafter, it became known that light could be bent either by reflection, refraction, or diffraction; hence, devices based on diffraction—like those based on reflection and refraction—could be conceived. Fresnel indeed showed that an interesting planar artifact, when properly fabricated, would act as a positive lens, a negative lens, and a plate; this artifact is known as a Fresnel zone plate.

DOEs can have both scientific and nonscientific applications. Nonscientific applications include security holograms and elements for amusement. These are used on bank notes and on products as a sign of authenticity. This particular application has, in fact, spread to many marketable products.

Scientific applications of DOEs lie in beam manipulation and the miniaturization of instruments for imaging and sensing. Gratings were the earliest DOEs and were painstakingly fabricating by drawing lines with a diamond tip on speculum metal. With the invention of holography by Gabor (1900–1979), gratings could be made with considerable ease: the gratings were the record of the interference pattern between two plane waves or between a spherical wave and a plane wave on a light-sensitive material. With an understanding of the holographic principle in place, methods to record amplitude and phase of the light reflected/transmitted by works of art were developed. The phase detour method attributed to Lohmann (1926–2013) was used to record both the amplitude and phase of an object wave in the artwork created by the computer-controlled plotter. These computer-generated holograms (CGHs) were used as filters for optical processing in photoreduction, making it much easier to draw line artwork, i.e., by skeletonizing the interferogram. These same elements were used for testing optical surfaces and systems. Following the work of Wyant, in 1976 I made the CGH for testing a planoconvex lens. One of authors (SB in 1996) of this tutorial made a checker grating on a desktop-controlled plotter for splitting the wavefront into a large number of spots. After photoreduction and on illumination, the checker grating produced spots that were surprisingly of almost equal intensities. Many different types of elements, all of them line elements, were made on this plotter for several other applications. It is worth mentioning that all CGHs are DOEs. On the contrary, all DOEs are not CGHs.

Coming to this book, the authors present the art and technology of making DOEs using MATLAB® and have simulated the results. They successfully explain the transition from 3D optics to 2D optics, taking the example of a Fresnel lens used even today in lighthouses. The transition from 3D to 2D is important in understanding the functioning of DOEs. The authors develop the topic by starting with a 1D binary grating. In order to direct diffracted light into a single order, usually the first order, the grating is blazed. The book moves to a discussion of 2D elements, such as the Fresnel zone plate. Methods to improve efficiency are also discussed. For example, multilevel zone plates provide high diffraction efficiency. An array of such zone plates constitutes the Hartman sensor used in adaptive optics applications. Other 2D diffractive optical elements include circular gratings or axicons, axilenses, spiral phase plates, cross binary gratings, and their combinations. These elements and their combinations having interesting, multifunctional properties are all discussed in the book. The design of DOEs in Fresnel and Fraunhofer regions is explained separately. These designs are based on the scalar theory of diffraction, and a ray-tracing approach is followed. Because the DOEs are written on refracting surfaces in order to compensate for certain aberrations, MATLAB codes for the aberration evaluation are also provided.

CGHs are the interference record between a reference and object wave; a reference wave is usually a plane wave, while the object wave at the plane of recording is obtained by use of a Fresnel propagator. In some cases, Fourier/

Fraunhofer holograms are also recorded. The transmittance of the hologram is usually linearly related to the intensity distribution in the interference pattern. When illuminated with the reference wave, the CGH generates the desired object wave. A CGH with a mathematically defined wavefront or a picture as input can be designed.

This book provides MATLAB codes for almost all of the examples described, be they DOEs or CGHs. It is therefore a 'must-have' book for a person intent on carrying out DOE design for research or economic reasons. Because detailed theory of the functioning of these elements is not provided, the Ph.D. thesis* by one of the authors (VK) is also a 'must read.' The fabrication procedures of these DOEs/CGHs using electron beam lithography, ion beam lithography, and photolithography are described. The exercises provided at the end of the chapters add value in the way of beneficial practice afforded to the readers.

Needless to say, this tutorial will be useful to students, teachers, and optical designers. Diffraction patterns of complex apertures can be visualized using the knowledge acquired by attempting the codes provided in the book.

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Preface

Diffractive optics, if not yet a household word, is certainly a household phenomenon. Many systems encountered in our everyday world contain or use diffractive optics. A good example is DVD players or barcode scanners. Elements that work on the principles of diffraction, or diffractive optical elements (DOEs), can successfully replace refractive elements used in different systems. This is because DOEs are capable of manipulating light in ways not possible by conventional refractive optical elements. In addition, DOEs are light in weight and compact compared to their refractive counterparts. The development of this technology will encourage the conversion of bulky refractive optical systems into highly compact, lightweight diffractive optical systems. It is our belief that fabrication of diffractive optics needs to be further developed and simplified so that more diffractive elements replace refractive elements in the future. We hope that this book will ease this transition.

Several excellent books* already exist that explain the basics and important concepts in the field of DOEs. This book does not intend to replace them. Rather, the idea is to supplement the available information with a text that will equip one with the skills required to start designing, simulating, and even fabricating diffractive optics. Given the many different applications and uses of diffractive optics, the importance of this field cannot be underestimated. Surprisingly, there are only a few books that provide a hands-on approach to the field. The lacuna of such information from a single source motivated us to create a resource based on our practical experience. In this book, learning occurs with assistive MATLAB® codes that enable visualization of the ideas presented and a better understanding of the parameters controlling different aspects of light. We believe that this manner of treatment will enable a new graduate student to quickly grasp the fundamentals of diffractive optics, beginning with the design of simple DOEs and moving to more complex ones.

We hope the reader will benefit from this practical approach to designing and fabricating diffractive optical elements. Experimentalists will be able to design appropriate structures that can be used in many different applications such as

*See Chapter 1, Refs. 6, 33, and 57–59.

spectroscopy, optical trapping, or beam shaping. The design of DOEs is presented with simple equations and step-by-step procedures for simulation—from the simplest 1D grating to the more-complex multifunctional DOEs—along with analysis of their diffraction patterns using MATLAB. The fundamentals of fabrication techniques such as photolithography, electron beam lithography, and focused ion beam lithography with basic instructions for the beginner are presented. Basic error analysis and error-correction techniques for a few cases are also discussed. It must be noted that this book will focus only on passive DOEs; SLMs are not required for demonstration. However, the MATLAB codes provided can be used for displaying DOE designs on SLMs as well. Thus, we hope that this book will help not only new students but also scientists in the industry to quickly learn techniques to help with the design, simulation, and testing of DOEs.

The book consists of eight chapters. A brief summary of the content of each chapter is as follows:

Chapter 1 introduces the fundamentals of diffractive optics and compares diffractive and refractive optics. A quick review of the theoretical formulation of diffraction are presented, along with different theoretical approximations and their validity regimes.

Chapter 2 presents the fundamentals of design and far-field analysis of simple binary DOEs such as 1D and 2D gratings, axicons, and Fresnel zone plates (FZPs). It shows the beginner how to make simple calculations to extract the intensity values and spacing between the different diffraction maxima.

Chapter 3 discusses the design, simulation aspects, and far-field analysis of multilevel and blazed DOEs such as multilevel gratings, diffractive axicons, blazed FZPs, axilenses, spiral phase plates, etc. It also discusses the basic algorithms for designing DOEs to obtain any desired intensity profile.

Chapter 4 describes the design and analysis of DOEs in the Fresnel diffraction regime to simulate diffraction patterns at different planes in the propagation direction. It also discusses some interesting phenomena such as the Talbot effect.

Chapter 5 presents the basic aberration correction techniques used to reduce and avoid errors while designing DOEs.

Chapter 6 introduces the art of creating different advanced multifunctional DOEs, along with their design, simulation, and analysis. The important properties of multifunctional DOEs are also discussed.

Chapter 7 describes the design and analysis of holographic optical elements for different applications. Computer-generated Fourier and Fresnel holography techniques are also discussed.

Chapter 8 presents the fundamentals of designing lithography files and the fabrication of DOEs using photolithography, electron beam lithography, and focused ion beam lithography, with basic fabrication recipes provided.

The content of the chapters is supported throughout by clearly commented MATLAB codes, making this book useful even to a novice programmer.

Happy Diffracting!

A. Vijayakumar and Shanti Bhattacharya
November 2016

Acknowledgments

As with any project, this book began with one small step or rather one seemingly small suggestion. Vijay (Vijayakumar), who was then my doctoral student in the finishing stages of his work, proposed that we record the basics of what we had done over the last few years in the form of a book. He felt that although a number of books on diffractive optics exist, they did not cover the hands-on knowledge required to actually start designing and fabricating such elements. Over the next few days, we discussed his proposal, and in one of those coincidences that seem to happen uncannily often, an email from SPIE Press popped into both of our email boxes, encouraging researchers to publish. It seemed that the time was right to create this book. The rest, as they say, is history.

The first person to thank, therefore, is my fellow author Vijay, for his enthusiasm and hard work. This book would not exist if it were not for him. Many of the examples and results presented were developed over the course of Vijay's Ph.D. work, and we both thank Prof. Enakshi Bhattacharya, Prof. Harishankar Ramachandran, Dr. Deepa Venkitesh, and Dr. Balaji Srinivasan of the Department of Electrical Engineering, IIT Madras, for their invaluable suggestions during that period and Dr. Bijoy Krishna Das, from the same department, for lending us his fiber-coupled sources with which to test our elements.

All of the electron beam lithography (EBL) work presented in this book was carried out at the Centre for NEMS and Nanophotonics, IIT Madras. We thank the Ministry of Communications and Information Technology for funding this Centre and our research work. The EBL work would not have been possible without help from several staff members associated with the EBL system, and we thank them and the students who have helped with the running of the machine or preparation of the samples. In particular, we are deeply indebted to Dr. Manu Jaiswal, Department of Physics, IIT Madras, for his support and help when the RAITH electron beam lithography system was being set up and to the ever-helpful, ever-present staff of the Centre, namely, Mr. Rajendran, Mr. Prakash, Mr. Joseph, and Mr. Sridhar. We also thank Mr. Karthick Raj, EBL operator (2013–2014), Centre for NEMS and Nanophotonics, IIT Madras, for his help relating to the work described in Section 8.3.4.

The focused ion beam (FIB) work was carried out at two institutions. At IIT Madras, the Quanta 3D FEG FIB system located in the Nano-Functional Materials Technology Centre (NFMTC), IIT Madras, was used for all of the initial FIB work. We are grateful to the NFMTC faculty in charge for giving us access to the tool. The FIB work on fibers was carried out at the Max Planck Institute (MPI) for Intelligent Systems, Stuttgart, Germany. We thank Dr. Michael Hirscher and Prof. Joachim P. Spatz, MPI, for offering the use of their FIB system to us any time we needed it. We are also grateful for their helpful suggestions and discussions. Several of the results presented in Chapter 8 arose from collaborative work between Dr. Shanti Bhattacharya and Dr. Pramitha Vayalamkuzhi, Inspire Faculty, IIT Madras, and Ms. Ulrike Eigenthaler and Dr. Kahraman Kesinbora, MPI. Figures 8.52, 8.54, 8.56, 8.57, 8.58, and 8.59 were taken with the FIB system made available to us at MPI. We gratefully acknowledge their permission to use these results in this book. We thank Mr. Jayavel, staff member, and Ms. Gayathri, M.S. doctoral student, Department of Electrical Engineering, IIT Madras, for their suggestions and help in handling and preparing fibers for diffractive optic fabrication with the FIB system. Dr. Pramitha is specially thanked for her many contributions to Chapter 8.

We would be remiss if we did not acknowledge Prof. S. S. Bhattacharya and Dr. Deepa Venkitesh for reviewing the initial chapters of this book. Their suggestions greatly enhanced the clarity of those chapters. Vijay also thanks his friend and former colleague, Mr. Vinoth, for his suggestions while writing this book.

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Writing a book requires two kinds of support: that relating to the book itself and that provided by the network of family and friends who surround us. We hope that we have thanked everyone connected with the former and apologize if, by oversight, we have left someone out.

We reserve the final part of this acknowledgment to the people who made the task of writing easy just by being part of our lives. We truly appreciate the constant encouragement and support extended to us by our families during this book project.

Shanti thanks her friend Anu for their weekly runs that helped keep her sane and her daughter Sumi for all the fun they share. As for her husband Subbu, who once commented, “One day, I will get you to put in writing how you cannot manage without me,” he may consider that day as having arrived! Shanti would also like to use this opportunity to thank her Ph.D. advisor, Prof. R. S. Sirohi for starting her out on this journey with light.

We hope that readers find this book useful and encourage them to contact the authors with questions, comments, or suggestions at physics.vijay@gmail.com or shantib@iitm.ac.in.

Symbols and Notation

A	Aperture function
d	Distance
d	Lateral feature
D_m	Fourier coefficients of order m
E	Optical field (complex amplitude)
f	Focal length
f_0	Focal length of axilens
f_x	Spatial frequency along x direction
fx	Focal length along x direction
f_y	Spatial frequency along y direction
fy	Focal length along y direction
g	Number of levels
I_m	Relative intensity for diffraction order m with respect to incident intensity
I_0	On-axis intensity
k	Wave vector $(2\pi/\lambda)$
$k\psi(\bar{u})$	Phase of beam
L	Topological charge
m	Order of diffraction
m_x	Order of diffraction along x direction
m_x	Order of diffraction along y direction
M	Magnification
M_r	Radial magnification
n	Order of zones of FZP/mesh
n	Refractive index
n_1	Number of rings in mesh
n_g	Refractive index of glass medium
n_r	Refractive index of resist
N	Number of sampling points
P_r	Power in a circle of radius r
P_{TOT}	Power over the entire beam
r_n	Radius of n^{th} zone
R	Radius of diffractive optical element

t	Thickness/height of resist/substrate
T	Transmittance value
u	Object distance
v	Image distance
w_0	Waist of the Gaussian beam
z_T	Talbot distance
α	Base angle of prism
β	Deviation/diffraction angle
Δ	Sampling period
Δf	Focal depth
λ	Wavelength
Λ	Period of the grating
Λ_x	Period of the grating along x direction
Λ_y	Period of the grating along y direction
Φ	Phase
Φ_{1D}	Phase of 1D binary phase grating
Φ_{2D}	Phase of 2D binary phase grating
Φ_A	Phase aberration
$\Phi_{Axilens}$	Phase of axilens
Φ_{FZP}	Phase of Fresnel zone plate
Φ_G	Phase of grating
Φ_{in}	Phase of input wave
Φ_m	Phase of multifunctional diffractive optical element
Φ_{out}	Phase of output wave
Φ_R	Phase of reference wave
$\Phi_{Ring\ lens}$	Phase of ring lens
Φ_{SPP}	Phase of spiral phase plate
ψ	Complex amplitude of a wave
$\nabla\psi$	Gradient of a wavefront

Acronyms and Abbreviations

1D	One-dimensional
2D	Two-dimensional
3D	Three-dimensional
BPSE	Beam path steering element
CAD	Computer-aided design
CCD	Charge-coupled device
CGH	Computer-generated hologram
CIF	Caltech Intermediate Format
DFT	Discretized Fourier transform
DI	De-ionized
DOE	Diffractive optical element
DXF™	Drawing Exchange Format
EBL	Electron beam lithography
FBMS	Fixed-beam moving stage
FF	Fill factor
FFT	Fast Fourier transform
FIB	Focused ion beam
FT	Fourier transform
FZA	Fresnel zone axilens
FZP	Fresnel zone plate
GDS	Graphic Data System
HF	Hydrofluoric acid
HMDS	Hexamethyldisilizane
HOBB	Higher-order Bessel beam
HOE	Holographic optical element
ICP	Inductively coupled plasma
IFTA	Iterative Fourier transform algorithm
IPA	Isopropyl alcohol
ITO	Indium tin oxide
KOH	Potassium hydroxide
MEMS	Micro-electromechanical system
MIBK	Methyl isobutyl ketone
NDF	Neutral density filter

PMMA	Poly methyl methacrylate
RCWA	Rigorous coupled-wave analysis
ROE	Refractive optical element
SEM	Scanning electron microscope
SLM	Spatial light modulator
SMF	Single-mode fiber
SPP	Spiral phase plate
STL	STereoLithography
UV	Ultraviolet
X-OR	Exclusive OR