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国外物理名著系列 7

（影印版）

Optics and Lasers
Including Fibers and Optical Waveguides
(5th Edition)

光学与激光
——光纤和光波导
（第五版）

M. Young

科学出版社
www.sciencep.com

图字:01-2007-1094

M. Young: Optics and Lasers: Including Fibers and Optical Waveguides (5th Edition)

图书在版编目(CIP)数据

光学与激光:光纤和光波导:第5版=Optical and Lasers: Including Fibers and Optical Waveguides: 5th Edition:英文/(美)杨(Young, M.)编著.—影印本.—北京:科学出版社,2007

(国外物理名著系列;7)

ISBN 978-7-03-018787-1

Ⅰ.光… Ⅱ.杨… Ⅲ.①光学-英文②激光技术-英文 Ⅳ.O43 TN24

中国版本图书馆 CIP 数据核字(2007)第042391号

责任编辑:胡凯 鄢德平/责任印制:赵德静/封面设计:陈敬

科学出版社 出版

北京东黄城根北街16号

邮政编码:100717

http://www.sciencep.com

中国科学院印刷厂 印刷

科学出版社发行 各地新华书店经销

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2007年4月第 一 版 开本:B5(720×1000)

2007年4月第一次印刷 印张:32 1/2

印数:1—3 000 字数:610 000

定价:79.00元

(如有印装质量问题,我社负责调换(科印))

《国外物理名著系列》(影印版)专家委员会名单

国外物理名著(影印版)系列序言

对于国内的物理学工作者和青年学生来讲，研读国外优秀的物理学著作是系统掌握物理学知识的一个重要手段。但是，在国内并不能及时、方便地买到国外的图书，且国外图书不菲的价格往往令国内的读者却步，因此，把国外的优秀物理原著引进到国内，让国内的读者能够方便地以较低的价格购买是一项意义深远的工作，将有助于国内物理学工作者和青年学生掌握国际物理学的前沿知识，进而推动我国物理学科研和教学的发展。

为了满足国内读者对国外优秀物理学著作的需求，科学出版社启动了引进国外优秀著作的工作，出版社的这一举措得到了国内物理学界的积极响应和支持，很快成立了专家委员会，开展了选题的推荐和筛选工作，在出版社初选的书单基础上确定了第一批引进的项目，这些图书几乎涉及了近代物理学的所有领域，既有阐述学科基本理论的经典名著，也有反映某一学科专题前沿的专著。在选择图书时，专家委员会遵循了以下原则：基础理论方面的图书强调“经典”，选择了那些经得起时间检验、对物理学的发展产生重要影响、现在还不“过时”的著作（如：狄拉克的《量子力学原理》）。反映物理学某一领域进展的著作强调“前沿”和“热点”，根据国内物理学研究发展的实际情况，选择了能够体现相关学科最新进展，对有关方向的科研人员和研究生有重要参考价值的图书。这些图书都是最新版的，多数图书都是 2000 年以后出版的，还有相当一部分是 2006 年出版的新书。因此，这套丛书具有权威性、前瞻性和应用性强的特点。由于国外出版社的要求，科学出版社对部分图书进行了少量的翻译和注释（主要是目录标题和练习题），但这并不会影响图书“原汁原味”的感觉，可能还会方便国内读者的阅读和理解。

“他山之石，可以攻玉”，希望这套丛书的出版能够为国内物理学工作者和青年学生的工作和学习提供参考，也希望国内更多专家参与到这一工作中来，推荐更多的好书。

杨国桢

中国科学院院士

中国物理学会理事长

2007 年 3 月 20 日

For my father,
Professor Arthur K. Young,
from whom I am
still learning the art
of clear thinking

And God said: "Let there be light." And there was light.
And God saw the light, that it was good;
and God divided the light from the darkness.
THE TORAH

And the light is sweet, and a pleasant
thing it is for the eyes to behold the sun.
KOHELETH (ECCLESIASTES)

But soft! what light through yonder window breaks?
It is the east, and Juliet is the sun!
SHAKESPEARE

Light breaks where no sun shines.
DYLAN THOMAS

Sadness flies on the wings of morning and
out of the heart of darkness comes light.
GIRAUDOUX

Let us bathe in this crystalline light!
POE

... On a river of crystal light,
Into a sea of dew.
EUGENE FIELD

I see a black light.
VICTOR HUGO (last words)

Do not go gentle into that good night ...
Rage, rage against the dying of the light.
DYLAN THOMAS

Preface

This is the fifth edition of a book that first appeared in 1977, when it was half its present length. In the twenty-odd years since that first edition was published, optical communications has burgeoned, computers have become ubiquitous, and video techniques have supplemented classical optics. Hence, the book now includes sections on optical fibers and integrated optics, video microscopes and digital image processing, holography and coherent optical processing, and scanning confocal microscopy. Thus, whereas much of the book is devoted to classical optics, the denouement is the coverage of modern optics, lasers, and optical waveguides. Nevertheless, the sections on classical optics include material, such as those on coherence and resolution, that is not readily found in texts at similar levels.

The fourth edition included over 100 problems; many are designed to display important results that are not discussed in the text. I have therefore added to this edition the solutions to all the problems. I hope that the inclusion of the solutions will make the book more amenable to self-study, but also that the solutions will enhance the usefulness of the book in the classroom. Finally, I think that optics has a lot of terms that are sometimes not easily understood or whose technical meanings differ from their colloquial meanings; "focal point", "grain", "intensity", and even "light" are examples. I have therefore added a glossary to the book.

Optics has been changing greatly for over 40 years, since the invention of the laser. Partly because of the applied or engineering nature of much of modern optics, there has been a need for a practical text that surveys the entire field. Such a book should not be a classical-optics text but, rather, should be strong on principles, applications, and instrumentation; on lasers, holography, and coherent light; and on optical-fiber waveguides and integrated optics. On the other hand, it should concern itself relatively little with such admittedly interesting topics as the formation of the rainbow or the precise determination of the speed of light.

My purpose, therefore, has been to write an up-to-date textbook that surveys applied or engineering optics, including lasers, optical processing, optical waveguides, and other areas that might be called modern optics. I have attempted to treat each topic in enough depth to give it considerable practical value, while keeping it as free from mathematical detail as possible. Because I have surveyed applied optics in a very general way (including much more than I would attempt to incorporate into a single, one-semester college course), this book should also be a useful handbook for the practicing physicist or engineer who works from time to time with optics. Any of the material is appropriate to an introductory undergraduate course in optics; the work as a whole will be useful to the graduate student or applied physicist with scant background in optics.

The book originated in class notes for several one-semester courses that I offered in the Electrical Engineering Curriculum at Rensselaer Polytechnic Institute and in the Physics Department of the University of Waterloo (Canada), before I joined the Optoelectronics Division of the National Institute of Standards and Technology. Most of the courses were at the second- and fourth-year level, but I have drawn much additional material from graduate courses I have offered in lasers and related areas. I have also used the book as a textbook for courses in the Electrical and Computer Engineering Department of the University of Colorado and in the Electronics Department of the Weizmann Institute of Science. To make the book as useful to as large an audience as possible, I have included short reviews of such subjects as complex-exponential notation, superposition of waves, and atomic energy levels.

Nearly all the references are to books or reviews and are chosen to allow the reader to explore any topic in greater detail. The problems are designed to help increase the reader's understanding and, sometimes, to derive a useful result. Certain portions of the text are largely descriptive; there I have used comparatively few problems.

It is my very great pleasure to acknowledge the invaluable assistance of the first editor of this book, David MacAdam, whose guidance and comments have led to a clearer, more readable, and more complete work. My former officemate at Rensselaer Polytechnic Institute, William Jennings, read the early versions with great care, offered excellent suggestions, and occasionally made me rewrite the same passage several times with very salutary results. Helmut Lotsch of Springer-Verlag ably supervised the production of the early editions of the book and adhered only to the highest standards.

I also acknowledge my debt to my former professors and fellow students at the Institute of Optics of the University of Rochester. My closest advisers there were Michael Hercher and Albert Gold; I also have warm memories of Philip Baumeister, Parker Givens, and others. My first optics course was Rudolf Kingslake's introductory optical-engineering course, and I still occasionally refer to his duplicated course notes.

I have been working, on and off, with optical-fiber communications since about 1972; the number of people I have learned from is, as a practical matter, nondenumerable. However, I want to single out for acknowledgement my former colleagues and co-editors of the Optical Waveguide Communications Glossary and, in particular, Robert Gallawa and Gordon Day of NIST in

Boulder. Neither of these able scientists ever lets me get away with anything, and Bob Gallawa has offered many pithy comments on the chapters on optical waveguides. I am equally grateful to Ernest Kim for his critical reading of the entire third edition. Kevin Malone and Steven Mechels formerly of NIST, suggested many worthwhile improvements, while Paule Hale of NIST reviewed the material on noise in detectors with great care. Roberto Forneris and Yara Forneris of the University of Sao Paulo, Brazil, and Burton Brody of Bard College pointed out a number of errors and made many helpful suggestions.

Additionally, I thank Tim Ohno of the Colorado School of Mines for suggesting the glossary and Reuben Collins of the Colorado School of Mines for a tutorial on near-field scanning microscopy. Theodor Tamir, the editor of the second edition, offered dozens of helpful suggestions. I also acknowledge my very good fortune to have been a Visiting Scientist at the Weizmann Institute of Science. A course I taught there gave me the impetus to organize, edit, and supplement my problems and led to their inclusion in this volume.

Finally, I thank Hans Jürgen Koelsch of Springer for giving me the opportunity to revise and publish this fifth edition, and Torsten Baade, Kristina Uhlendorf, and Barbara Luedge of the Friederich-Schiller University of Jena for carefully weeding the errors from the text and, in particular, from the problem solutions. Any errors that persist, like the weeds in my lawn, are mine alone.

Boulder, Colorado, June 2000 M. Young

Contents

1. Introduction

This is an applied optics book. It is written for physics or engineering students who will incorporate optical instruments into practical devices or who will use optical components in their laboratories or their experiments. My aim is to present as complete a picture of modern applied optics as possible, while going into as much depth as possible, yet using a minimum of advanced mathematics.

In much of the book, we will consider a beam of light as a collection of rays. When it is necessary to understand interference and diffraction, we will, in effect, add a wave motion to the rays. Less often, we will use the particle nature of light and, in effect, consider the rays as if they were streams of particles. If you like, you can call this the *triplicity* of light – rays, waves, particles. We will use the wave and particle natures of light without justification and without philosophical foundation: that is, as heuristic devices that enable us to understand certain kinds of phenomena in as much depth as we require for designing and understanding optical instruments and systems.

Deeper understanding of the wave and particle natures of light is presented in courses in quantum electrodynamics. Here, let me just say, without apology, that sometimes it is convenient to consider light as a wave motion and sometimes as a stream of particles, depending on the kind of experiment we are performing. Still, there is something mysterious about performing an experiment, like the double-slit experiment (Chap. 5), in which the light propagates and exhibits interference precisely as if it were a wave, and yet detecting the interference pattern with a quantum detector (Chap. 4), which interacts with the light as if it were a series of particles. The most common explanation, that particles in the subatomic world behave in a way that we do not find intuitive, is not very satisfying and gets us back where we began: we must, to some extent, consider the light as a wave when it propagates, but as a particle when it is absorbed by matter. When the wave motion is not important, as in many simple lens instruments, we ignore it and use a formalism based on rays.

The book begins with two chapters based on geometrical, or ray, optics. In Chap. 2, I treat as much ray optics as I find necessary for a complete understanding of the optical instruments introduced in Chap. 3. In particular, Chap. 2 derives the *lens equation*, which allows calculation of object and