WILEY

FUNDAMENTALS OF
PHOTONICS

Second Edition

B. E. A. Saleh
M. C. Teich

Wiley Series in Pure and Applied Optics • Bahaa E. A. Saleh, Series Editor

FUNDAMENTALS OF PHOTONICS

SECOND EDITION

BAHAA E. A. SALEH
Boston University

MALVIN CARL TEICH
Boston University
Columbia University

BICENTENNIAL 1807 WILEY 2007 BICENTENNIAL

WILEY-INTERSCIENCE
A John Wiley & Sons, Inc., Publication

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic format. For information about Wiley products, visit our web site at www.wiley.com.

Wiley Bicentennial Logo: Richard J. Pacifico

Library of Congress Cataloging-in-Publication Data is available.

ISBN: 978-0-471-35832-9

Printed in the United States of America.

10 9 8 7 6 5 4 3 2

PREFACE TO THE SECOND EDITION

Since the publication of the *First Edition* in 1991, *Fundamentals of Photonics* has been reprinted some 20 times, translated into Czech and Japanese, and used worldwide as a textbook and reference. During this period, major developments in photonics have continued apace, and have enabled technologies such as telecommunications and applications in industry and medicine. The *Second Edition* reports some of these developments, while maintaining the size of this single-volume tome within practical limits.

In its new organization, *Fundamentals of Photonics* continues to serve as a self-contained and up-to-date introductory-level textbook, featuring a logical blend of theory and applications. Many readers of the *First Edition* have been pleased with its abundant and well-illustrated figures. This feature has been enhanced in the *Second Edition* by the introduction of full color throughout the book, offering improved clarity and readability.

While each of the 22 chapters of the *First Edition* has been thoroughly updated, the principal feature of the *Second Edition* is the addition of two new chapters: one on photonic-crystal optics and another on ultrafast optics. These deal with developments that have had a substantial and growing impact on photonics over the past decade.

The new chapter on **photonic-crystal optics** provides a foundation for understanding the optics of layered media, including Bragg gratings, with the help of a matrix approach. Propagation of light in one-dimensional periodic media is examined using Bloch modes with matrix and Fourier methods. The concept of the photonic bandgap is introduced. Light propagation in two- and three-dimensional photonic crystals, and the associated dispersion relations and bandgap structures, are developed. Sections on photonic-crystal waveguides, holey fibers, and photonic-crystal resonators have also been added at appropriate locations in other chapters.

The new chapter on **ultrafast optics** contains sections on picosecond and femtosecond optical pulses and their characterization, shaping, and compression, as well as their propagation in optical fibers, in the domain of linear optics. Sections on ultrafast nonlinear optics include pulsed parametric interactions and optical solitons. Methods for the detection of ultrafast optical pulses using available detectors, which are relatively slow, are reviewed.

In addition to these two new chapters, the chapter on **optical interconnects and switches** has been completely rewritten and supplemented with topics such as wavelength and time routing and switching, FBGs, WGRs, SOAs, TOADs, and packet switches. The chapter on **optical fiber communications** has also been significantly updated and supplemented with material on WDM networks; it now offers concise descriptions of topics such as dispersion compensation and management, optical amplifiers, and soliton optical communications.

Continuing advances in device-fabrication technology have stimulated the emergence of **nanophotonics**, which deals with optical processes that take place over subwavelength (nanometer) spatial scales. Nanophotonic devices and systems include quantum-confined structures, such as quantum dots, nanoparticles, and nanoscale periodic structures used to synthesize *metamaterials* with exotic optical properties such as negative refractive index. They also include configurations in which light (or its interaction with matter) is confined to nanometer-size (rather than micrometer-size) regions near boundaries, as in *surface plasmon* optics. Evanescent fields, such as those produced at a surface where total internal reflection occurs, also exhibit such confinement. Evanescent fields are present in the immediate vicinity of sub-wavelength-size apertures, such as the open tip of a tapered optical fiber. Their use allows imaging with resolution beyond the diffraction limit and forms the basis of *near-field optics*. Many of these emerging areas are described at suitable locations in the *Second Edition*.

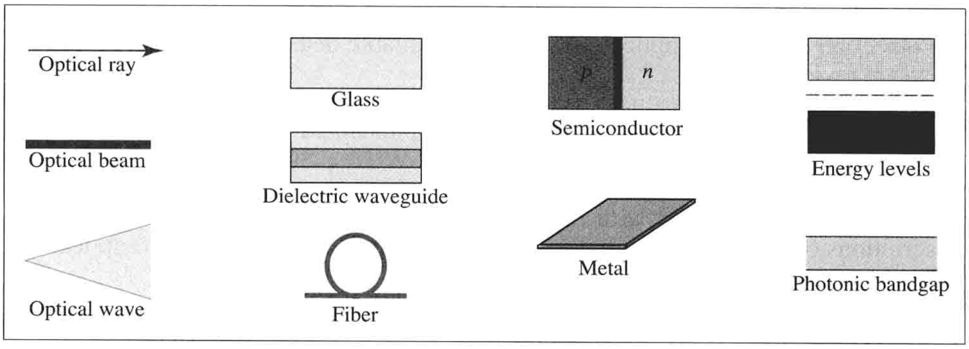
New sections have been added in the process of updating the various chapters. New topics introduced in the early chapters include: Laguerre–Gaussian beams; near-field imaging; the Sellmeier equation; fast and slow light; optics of conductive media and plasmonics; doubly negative metamaterials; the Poincaré sphere and Stokes parameters; polarization mode dispersion; whispering-gallery modes; microresonators; optical coherence tomography; and photon orbital angular momentum.

In the chapters on laser optics, new topics include: rare-earth and Raman fiber amplifiers and lasers; EUV, X-ray, and free-electron lasers; and chemical and random lasers. In the area of optoelectronics, new topics include: gallium nitride-based structures and devices; superluminescent diodes; organic and white-light LEDs; quantum-confined lasers; quantum-cascade lasers; microcavity lasers; photonic-crystal lasers; array detectors; low-noise APDs; SPADs; and QWIPs.

The chapter on nonlinear optics has been supplemented with material on parametric-interaction tuning curves; quasi-phase-matching devices; two-wave mixing and cross-phase modulation; THz generation; and other nonlinear optical phenomena associated with narrow optical pulses, including chirp pulse amplification and supercontinuum light generation. The chapter on electro-optics now includes a discussion of electroabsorption modulators.

Appendix C on **modes of linear systems** has been expanded and now offers an overview of the concept of modes as they appear in numerous locations within the book. Finally, additional exercises and problems have been provided, and these are now numbered disjointly to avoid confusion.

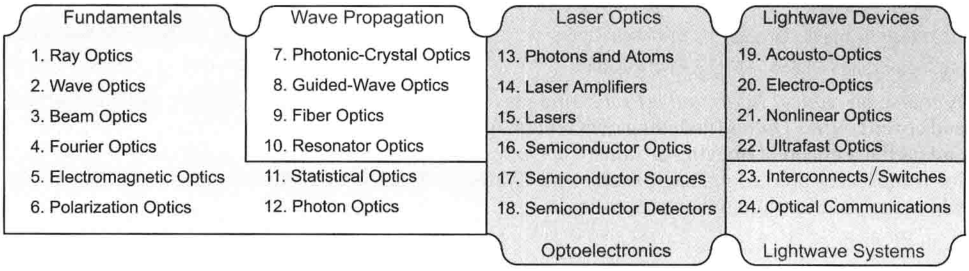
In this full-color edition, we have used the color code illustrated in the following chart for most of the illustrations. Light beams and field distributions are colored red (except when light beams of multiple colors are involved, as in nonlinear optics). Glass and glass fibers are depicted in light blue. Semiconductors are cast in green, with various shades representing different doping levels, and metal is indicated by the color of copper. Energy diagrams are marked in blue and forbidden photonic bandgaps in pink, as indicated.



Color chart

Organization

In its new incarnation, *Fundamentals of Photonics* comprises 24 chapters compartmentalized into six parts, as depicted in the diagram below. The form of the book is modular so that it can be used by readers with different needs; it also provides instructors an opportunity to select topics for different courses. Essential material from one chapter is often briefly summarized in another to make each chapter as self-contained as possible. For example, at the beginning of Chapter 24 (Optical Fiber Communications), relevant material from earlier chapters that describe fibers, light sources, detectors, and amplifiers is briefly reviewed. This places the important features of the various components at the disposal of the reader before the chapter proceeds with a discussion of the design and performance of the overall communication system that makes use of these components.



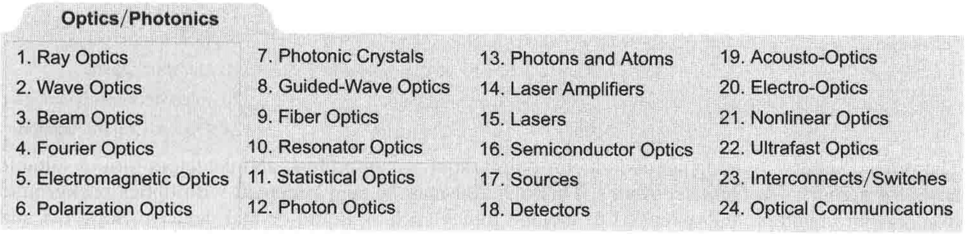
Recognizing the different degrees of mathematical sophistication of the intended readership, we have endeavored to present difficult concepts in two steps: at an introductory level providing physical insight and motivation, followed by a more advanced analysis. This approach is exemplified by the treatment in Chapter 20 (Electro-Optics), in which the subject is first presented using scalar notation and then treated again using tensor notation.

Commonly accepted notation and symbols have been used wherever possible. Because of the broad spectrum of topics covered, however, there are a good number of symbols that have multiple meanings; a list of **symbols and units** is provided at the end of the book to clarify symbol usage. Throughout the book, important equations are highlighted by boxes to facilitate future retrieval. Sections dealing with material of a more advanced nature are indicated by asterisks and may be omitted if desired. Summaries are provided throughout at points where a recapitulation is deemed useful because of the involved nature of the material.

Each chapter also contains exercises, problem sets, and updated selected reading lists. Examples of real systems are included to emphasize the concepts governing applications of current interest, and appendixes summarize the properties of one- and two-dimensional Fourier transforms, linear-systems theory, and modes of linear systems.

Representative Courses

The chapters of this book may be combined in various ways for use in semester or quarter courses. Representative examples of such courses are provided below. Some of these courses may be offered as part of a sequence. Other selections may be made to suit the particular objectives of instructors and students.



The first six chapters of the book are suitable for an introductory course on *Optics* or *Photonics*. These may be supplemented by Chapter 11, *Statistical Optics*, to introduce incoherent and partially coherent light, or by the introductory sections of Chapters 8 and 9, *Guided-Wave Optics* and *Fiber Optics*, which offer applications.

Optical Information Processing

1. Ray Optics	7. Photonic Crystals	13. Photons and Atoms	19. Acousto-Optics
2. Wave Optics	8. Guided-Wave Optics	14. Laser Amplifiers	20. Electro-Optics
3. Beam Optics	9. Fiber Optics	15. Lasers	21. Nonlinear Optics
4. Fourier Optics	10. Resonator Optics	16. Semiconductor Optics	22. Ultrafast Optics
5. Electromagnetic Optics	11. Statistical Optics	17. Sources	23. Interconnects/Switches
6. Polarization Optics	12. Photon Optics	18. Detectors	24. Optical Communications

A course on *Optical Information Processing* may begin with a background of wave and beam optics, and cover *Fourier Optics* (including coherent image formation and processing), along with incoherent and partially coherent imaging in *Statistical Optics*. This may be followed by material on devices used for analog data processing, such as *Acousto-Optics*, and end with switches and gates (Chapter 23), which are used for digital data processing.

Guided-Wave Optics

1. Ray Optics	7. Photonic Crystals	13. Photons and Atoms	19. Acousto-Optics
2. Wave Optics	8. Guided-Wave Optics	14. Laser Amplifiers	20. Electro-Optics
3. Beam Optics	9. Fiber Optics	15. Lasers	21. Nonlinear Optics
4. Fourier Optics	10. Resonator Optics	16. Semiconductor Optics	22. Ultrafast Optics
5. Electromagnetic Optics	11. Statistical Optics	17. Sources	23. Interconnects/Switches
6. Polarization Optics	12. Photon Optics	18. Detectors	24. Optical Communications

A course on *Guided-Wave Optics* may begin with an introduction to wave propagation in layered and periodic media (Chapter 7, *Photonic-Crystal Optics*) and follow with the chapters on *Guided-Wave Optics*, *Fiber Optics*, and *Resonator Optics*. Additional topics may include *Electro-Optics* and *Optical Interconnects and Switches*.

Lasers

1. Ray Optics	7. Photonic Crystals	13. Photons and Atoms	19. Acousto-Optics
2. Wave Optics	8. Guided-Wave Optics	14. Laser Amplifiers	20. Electro-Optics
3. Beam Optics	9. Fiber Optics	15. Lasers	21. Nonlinear Optics
4. Fourier Optics	10. Resonator Optics	16. Semiconductor Optics	22. Ultrafast Optics
5. Electromagnetic Optics	11. Statistical Optics	17. Sources	23. Interconnects/Switches
6. Polarization Optics	12. Photon Optics	18. Detectors	24. Optical Communications

A course on *Lasers* could begin with *Beam Optics* and *Resonator Optics*, and follow with the theory of interaction of light with matter (Chapter 13) and laser amplification and oscillation (Chapters 14 and 15), and include semiconductor LEDs and lasers (Chapters 16 and 17). An introduction to femtosecond lasers can be provided by including appropriate sections from *Ultrafast Optics*.

Optoelectronics

1. Ray Optics	7. Photonic Crystals	13. Photons and Atoms	19. Acousto-Optics
2. Wave Optics	8. Guided-Wave Optics	14. Laser Amplifiers	20. Electro-Optics
3. Beam Optics	9. Fiber Optics	15. Lasers	21. Nonlinear Optics
4. Fourier Optics	10. Resonator Optics	16. Semiconductor Optics	22. Ultrafast Optics
5. Electromagnetic Optics	11. Statistical Optics	17. Sources	23. Interconnects/Switches
6. Polarization Optics	12. Photon Optics	18. Detectors	24. Optical Communications

The three chapters covering semiconductor optics, sources/amplifiers, and detectors form a suitable basis for a course on *Optoelectronics*. This material may be supplemented with optics background from earlier chapters, and extended to include topics such as liquid-crystal devices (Secs. 6.5 and

20.3), semiconductor electroabsorption modulators (Sec. 20.5), and an introduction to the use of photonic devices for switching and/or communications (Chapters 23 and 24, respectively).

Photonic Devices

1. Ray Optics	7. Photonic Crystals	13. Photons and Atoms	19. Acousto-Optics
2. Wave Optics	8. Guided-Wave Optics	14. Laser Amplifiers	20. Electro-Optics
3. Beam Optics	9. Fiber Optics	15. Lasers	21. Nonlinear Optics
4. Fourier Optics	10. Resonator Optics	16. Semiconductor Optics	22. Ultrafast Optics
5. Electromagnetic Optics	11. Statistical Optics	17. Sources	23. Interconnects/Switches
6. Polarization Optics	12. Photon Optics	18. Detectors	24. Optical Communications

Photonic Devices is another possible topic for a course that combines photonic-crystal and guided-wave devices with electro-optic, acousto-optic, and nonlinear optical devices, and includes ultrafast optics and optical interconnects/switches.

Fiber-Optic Communications

1. Ray Optics	7. Photonic Crystals	13. Photons and Atoms	19. Acousto-Optics
2. Wave Optics	8. Guided-Wave Optics	14. Laser Amplifiers	20. Electro-Optics
3. Beam Optics	9. Fiber Optics	15. Lasers	21. Nonlinear Optics
4. Fourier Optics	10. Resonator Optics	16. Semiconductor Optics	22. Ultrafast Optics
5. Electromagnetic Optics	11. Statistical Optics	17. Sources	23. Interconnects/Switches
6. Polarization Optics	12. Photon Optics	18. Detectors	24. Optical Communications

A course on *Fiber-Optic Communications* could include optical waveguides and fibers, semiconductor sources and amplifiers (possibly also Secs. 14.3C and 14.3D on optical-fiber and Raman-fiber amplifiers), as background material for the chapter on *Optical Fiber Communications* (Chapter 24). If fiber-optic networks are to be emphasized, Sec. 23.3 on photonic switches may also be included.

Acknowledgments

We are grateful to many colleagues for providing us with valuable comments about draft chapters for the *Second Edition* and for drawing our attention to errors in the *First Edition*: Mete Atatüre, Michael Bär, Silvia Carrasco, Thomas Daly, Gianni Di Giuseppe, Adel El-Nadi, John Fourkas, Majeed Hayat, Tony Heinz, Erich Ippen, Martin Jaspan, Gerd Keiser, Jonathan Kane, Paul Kelley, Ted Moustakas, Magued Nasr, Roy Olivier, Roberto Paiella, Alexander Sergienko, Peter W. E. Smith, Stephen P. Smith, Kenneth Suslick, and Tommaso Toffoli.

We extend our special thanks to those colleagues who graciously provided us with in-depth critiques of various chapters: Ayman Abouraddy, Luca Dal Negro, and Paul Prucnal.

We are indebted to the legions of students and postdoctoral associates who have posed so many excellent questions that helped us hone our presentation. In particular, many improvements were initiated by suggestions from Mark Booth, Jasper Cabalu, Michael Cunha, Darryl Goode, Chris LaFratta, Rui Li, Eric Lynch, Nan Ma, Nishant Mohan, Julie Praino, Yunjie Tong, and Ranjith Zachariah. We are especially grateful to Mohammed Saleh, who diligently read much of the manuscript and provided us with excellent suggestions for improvement throughout.

Wai Yan (Eliza) Wong provided logistical support and a great deal of assistance in crafting diagrams and figures. Many at Wiley, including George Telecki, our Editor, and Rachel Witmer have been most helpful, patient, and encouraging. We appreciate the attentiveness and thoroughness that Melissa Yanuzzi brought to the production process. Don DeLand of the Integre Technical Publishing Company provided invaluable assistance in setting up the Latex style files.

We are most appreciative of the financial support provided by the National Science Foundation (NSF), in particular the Center for Subsurface Sensing and Imaging

Systems (CenSSIS), an NSF-supported Engineering Research Center; the Defense Advanced Research Projects Agency (DARPA); the National Reconnaisance Office (NRO); the U.S. Army Research Office (ARO); the David & Lucile Packard Foundation; the Boston University College of Engineering; and the Boston University Photonics Center.

Photo Credits. Most of the portraits were carried forward from the First Edition with the benefit of permissions provided for all editions. Additional credits are: Godfrey Kneller 1689 portrait (Newton); Siegfried Bendixen 1828 lithograph (Gauss); Engraving in the Small Portraits Collection, History of Science Collections, University of Oklahoma Libraries (Fraunhofer); Stanford University, Courtesy AIP Emilio Segrè Visual Archives (Bloch); Eli Yablonovitch (Yablonovitch); Sajeev John (John); Charles Kao (Kao); Philip St John Russell (Russell); Ecole Polytechnique (Fabry); Observatoire des Sciences de l'Univers (Perot); AIP Emilio Segrè Visual Archives (Born); Lagrelius & Westphal 1920 portrait (Bohr); AIP Emilio Segrè Visual Archives, Weber Collection (W. L. Bragg); Linn F. Mollenauer (Mollenauer); Roger H. Stolen (Stolen); and James P. Gordon (Gordon). In Chapter 23, the Bell Symbol was reproduced with the permission of BellSouth Intellectual Property Marketing Corporation, the AT&T logo is displayed with the permission of AT&T, and Lucent Technologies permitted us use of their logo. Stephen G. Eick kindly provided the image used at the beginning of Chapter 24. The photographs of Saleh and Teich were provided courtesy of Boston University.

BAHAA E. A. SALEH

MALVIN CARL TEICH

Boston, Massachusetts
December 19, 2006

PREFACE TO THE FIRST EDITION

Optics is an old and venerable subject involving the generation, propagation, and detection of light. Three major developments, which have been achieved in the last thirty years, are responsible for the rejuvenation of optics and for its increasing importance in modern technology: the invention of the laser, the fabrication of low-loss optical fibers, and the introduction of semiconductor optical devices. As a result of these developments, new disciplines have emerged and new terms describing these disciplines have come into use: **electro-optics**, **optoelectronics**, **quantum electronics**, **quantum optics**, and **lightwave technology**. Although there is a lack of complete agreement about the precise usages of these terms, there is a general consensus regarding their meanings.

Photonics

Electro-optics is generally reserved for optical devices in which electrical effects play a role (lasers, and electro-optic modulators and switches, for example). *Optoelectronics*, on the other hand, typically refers to devices and systems that are essentially electronic in nature but involve light (examples are light-emitting diodes, liquid-crystal display devices, and array photodetectors). The term *quantum electronics* is used in connection with devices and systems that rely principally on the interaction of light with matter (lasers and nonlinear optical devices used for optical amplification and wave mixing serve as examples). Studies of the quantum and coherence properties of light lie within the realm of *quantum optics*. The term *lightwave technology* has been used to describe devices and systems that are used in optical communications and optical signal processing.

In recent years, the term **photonics** has come into use. This term, which was coined in analogy with electronics, reflects the growing tie between optics and electronics forged by the increasing role that semiconductor materials and devices play in optical systems. *Electronics* involves the control of electric-charge flow (in vacuum or in matter); *photonics* involves the control of photons (in free space or in matter). The two disciplines clearly overlap since electrons often control the flow of photons and, conversely, photons control the flow of electrons. The term *photonics* also reflects the importance of the photon nature of light in describing the operation of many optical devices.

Scope

This book provides an introduction to the fundamentals of photonics. The term *photonics* is used broadly to encompass all of the aforementioned areas, including the following:

- The *generation* of coherent light by lasers, and incoherent light by luminescence sources such as light-emitting diodes.
- The *transmission* of light in free space, through conventional optical components such as lenses, apertures, and imaging systems, and through waveguides such as optical fibers.
- The *modulation*, switching, and scanning of light by the use of electrically, acoustically, or optically controlled devices.
- The *amplification* and *frequency conversion* of light by the use of wave interactions in nonlinear materials.
- The *detection* of light.

These areas have found ever-increasing applications in optical communications, signal processing, computing, sensing, display, printing, and energy transport.

Approach and Presentation

The underpinnings of photonics are provided in a number of chapters that offer concise introductions to:

- The four theories of light (each successively more advanced than the preceding): ray optics, wave optics, electromagnetic optics, and photon optics.
- The theory of interaction of light with matter.
- The theory of semiconductor materials and their optical properties.

These chapters serve as basic building blocks that are used in other chapters to describe the *generation* of light (by lasers and light-emitting diodes); the *transmission* of light (by optical beams, diffraction, imaging, optical waveguides, and optical fibers); the *modulation* and switching of light (by the use of electro-optic, acousto-optic, and nonlinear-optic devices); and the *detection* of light (by means of photodetectors). Many applications and examples of real systems are provided so that the book is a blend theory and practice. The final chapter is devoted to the study of fiber-optic communications, which provides an especially rich example in which the generation, transmission, modulation, and detection of light are all part of a single photonic system used for the transmission of information.

The theories of light are presented at progressively increasing levels of difficulty. Thus light is described first as rays, then scalar waves, then electromagnetic waves, and finally, photons. Each of these descriptions has its domain of applicability. Our approach is to draw from the simplest theory that adequately describes the phenomenon or intended application. Ray optics is therefore used to describe imaging systems and the confinement of light in waveguides and optical resonators. Scalar wave theory provides a description of optical beams, which are essential for the understanding of lasers, and of Fourier optics, which is useful for describing coherent optical systems and holography. Electromagnetic theory provides the basis for the polarization and dispersion of light, and the optics of guided waves, fibers, and resonators. Photon optics serves to describe the interactions of light with matter, explaining such processes as light generation and detection, and light mixing in nonlinear media.

Intended Audience

Fundamentals of Photonics is meant to serve as:

- An introductory textbook for students in electrical engineering or applied physics at the senior or first-year graduate level.
- A self-contained work for self-study.
- A text for programs of continuing professional development offered by industry, universities, and professional societies.

The reader is assumed to have a background in engineering or applied physics, including courses in modern physics, electricity and magnetism, and wave motion. Some knowledge of linear systems and elementary quantum mechanics is helpful but not essential. Our intent has been to provide an introduction to photonics that emphasizes the concepts governing applications of current interest. The book should, therefore, not be considered as a compendium that encompasses all photonic devices and systems. Indeed, some areas of photonics are not included at all, and many of the individual chapters could easily have been expanded into separate monographs.

Problems, Reading Lists, and Appendices

A set of problems is provided at the end of each chapter. Problems are numbered in accordance with the chapter sections to which they apply. Quite often, problems deal with ideas or applications not mentioned in the text, analytical derivations, and numerical computations designed to illustrate the magnitudes of important quantities. Problems marked with asterisks are of a more advanced nature. A number of exercises also appear within the text of each chapter to help the reader develop a better understanding of (or to introduce an extension of) the material.

Appendices summarize the properties of one- and two-dimensional Fourier transforms, linear-systems theory, and modes of linear systems (which are important in polarization devices, optical waveguides, and resonators); these are called upon at appropriate points throughout the book. Each chapter ends with a reading list that includes a selection of important books, review articles, and a few classic papers of special significance.

Acknowledgments

We are grateful to many colleagues for reading portions of the text and providing helpful comments: Govind P. Agrawal, David H. Auston, Rasheed Azzam, Nikolai G. Basov, Franco Cerrina, Emmanuel Desurvire, Paul Diament, Eric Fossum, Robert J. Keyes, Robert H. Kingston, Rodney Loudon, Leonard Mandel, Leon McCaughan, Richard M. Osgood, Jan Peřina, Robert H. Rediker, Arthur L. Schawlow, S. R. Seshadri, Henry Stark, Ferrel G. Stremler, John A. Tataronis, Charles H. Townes, Patrick R. Trischitta, Wen I. Wang, and Edward S. Yang.

We are especially indebted to John Whinnery and Emil Wolf for providing us with many suggestions that greatly improved the presentation.

Several colleagues used portions of the notes in their classes and provided us with invaluable feedback. These include Etan Bourkoff at Johns Hopkins University (now at the University of South Carolina), Mark O. Freeman at the University of Colorado, George C. Papen at the University of Illinois, and Paul R. Prucnal at Princeton University.

Many of our students and former students contributed to this material in various ways over the years and we owe them a great debt of thanks: Gaetano L. Aiello, Mohamad Asi, Richard Campos, Buddy Christyono, Andrew H. Cordes, Andrew David, Ernesto Fontenla, Evan Goldstein, Matthew E. Hansen, Dean U. Hekel, Conor Heneghan, Adam Heyman, Bradley M. Jost, David A. Landgraf, Kanghua Lu, Ben Nathanson, Winslow L. Sargeant, Michael T. Schmidt, Raul E. Sequeira, David Small, Kraisin Songwatana, Nikola S. Subotic, Jeffrey A. Tobin, and Emily M. True. Our thanks also go to the legions of unnamed students who, through a combination of vigilance and the desire to understand the material, found countless errors.

We particularly appreciate the many contributions and help of those students who were intimately involved with the preparation of this book at its various stages of completion: Niraj Agrawal, Suzanne Keilson, Todd Larchuk, Guifang Li, and Philip Tham.

We are grateful for the assistance given to us by a number of colleagues in the course of collecting the photographs used at the beginnings of the chapters: E. Scott Barr, Nicolaas Bloembergen, Martin Carey, Marjorie Graham, Margaret Harrison, Ann Kottner, G. Thomas Holmes, John Howard, Theodore H. Maiman, Edward Palik, Martin Parker, Aleksandr M. Prokhorov, Jarus Quinn, Lesley M. Richmond, Claudia Schüler, Patrick R. Trischitta, J. Michael Vaughan, and Emil Wolf. Specific photo credits are as follows: AIP Meggers Gallery of Nobel Laureates (Gabor, Townes, Basov, Prokhorov, W. L. Bragg); AIP Niels Bohr Library (Rayleigh, Fraunhofer, Maxwell, Planck, Bohr, Einstein in Chapter 12, W. H. Bragg); Archives de l'Académie des Sciences de Paris (Fabry); The Astrophysical Journal (Perot); AT&T Bell Laboratories (Shockley, Brattain, Bardeen); Bettmann Archives (Young, Gauss, Tyndall); Bibliothèque Nationale de Paris (Fermat, Fourier, Poisson); Burndy Library (Newton, Huygens); Deutsches Museum (Hertz); ETH Bibliothek (Einstein in Chapter 11); Bruce Fritz (Saleh); Harvard University (Bloembergen); Heidelberg University (Pockels); Kelvin Museum of the University of Glasgow (Kerr); Theodore H. Maiman (Maiman); Princeton University (von Neumann); Smithsonian Institution (Fresnel); Stanford University (Schawlow); Emil Wolf (Born, Wolf). Corning Incorporated kindly provided the photograph used at the beginning of Chapter 8. We are grateful to GE for the use of their logotype, which is a registered trademark of the General Electric Company, at the beginning of Chapter 16. The IBM logo at the beginning of Chapter 16 is being used with special permission from IBM. The right-most logotype at the beginning of Chapter 16 was supplied courtesy of Lincoln Laboratory, Massachusetts Institute of Technology. AT&T Bell Laboratories kindly permitted us use of the diagram at the beginning of Chapter 22.

We greatly appreciate the continued support provided to us by the National Science Foundation, the Center for Telecommunications Research, and the Joint Services Electronics Program through the Columbia Radiation Laboratory.

Finally, we extend our sincere thanks to our editors, George Telecki and Bea Shube, for their guidance and suggestions throughout the course of preparation of this book.

BAHAA E. A. SALEH

Madison, Wisconsin

MALVIN CARL TEICH

New York, New York
April 3, 1991

CONTENTS