Fundamentals of Photonics
Bahaa E. A. Saleh, Malvin Carl Teich

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PREFACE

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 of 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.

Organization

The book consists of four parts: **Optics and Fiber Optics** (Chapters 1 to 10), **Quantum Electronics** (Chapters 11 to 14), **Optoelectronics** (Chapters 15 to 17), and **Electro-Optics and Lightwave Technology** (Chapters 18 to 22). 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 22 (Fiber-Optic Communications), relevant material from earlier chapters that describe fibers, light sources, and detectors 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 18 (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 is provided at the end of the book to help clarify symbol usage. Important equations are highlighted by boxes to simplify 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 the chapters at points where a recapitulation is deemed useful because of the involved nature of the material.

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 also be made to suit the particular objectives of instructors and students.

Optics

Background: Chapter 1 (Ray Optics) and Chapter 2 (Wave Optics)
Chapter 3 (Beam Optics)
Chapter 4 (Fourier Optics)
Chapter 5 (Electromagnetic Optics)
Chapter 6 (Polarization and Crystal Optics)
Chapter 7 (Guided-Wave Optics)
Chapter 10 (Statistical Optics)

Optical Information Processing

Background: Chapter 1 (Ray Optics) and Chapter 2 (Wave Optics)
Chapter 4 (Fourier Optics)
Chapter 10 (Statistical Optics)
Chapter 18 (Electro-Optics)
Chapter 20 (Acousto-Optics)
Chapter 21 (Photonic Switching and Computing)

Lasers* or *Quantum Electronics

Background: Chapter 1 (Ray Optics); Chapter 2 (Wave Optics); and Chapter 15 (Photons in Semiconductors, Section 15.1)
Chapter 3 (Beam Optics)
Chapter 9 (Resonator Optics)
Chapter 11 (Photon Optics)
Chapter 12 (Photons and Atoms)
Chapter 13 (Laser Amplifiers)
Chapter 14 (Lasers)
Chapter 15 (Photons in Semiconductors, Section 15.2)
Chapter 16 (Semiconductor Photon Sources, Sections 16.2 and 16.3)

Optoelectronics

Background: Chapter 6 (Polarization and Crystal Optics); Chapter 11 (Photon Optics, Sections 11.1A and 11.2); Chapter 12 (Photons and Atoms, Sections 12.1 and 12.2); Chapter 13 (Laser Amplifiers, Section 13.1); Chapter 14 (Lasers, Sections 14.1 and 14.2); and Chapter 15 (Photons in Semiconductors, Section 15.1)
Chapter 15 (Photons in Semiconductors, Section 15.2)
Chapter 16 (Semiconductor Photon Sources)
Chapter 17 (Semiconductor Photon Detectors)
Chapter 18 (Electro-Optics)
Chapter 21 (Photonic Switching and Computing, Sections 21.1 to 21.3)
Chapter 22 (Fiber-Optic Communications)

Optical Electronics and Communications

Background: Chapter 1 (Ray Optics); Chapter 2 (Wave Optics); and Chapter 15 (Photons in Semiconductors, Section 15.1)
Chapter 9 (Resonator Optics, Section 9.1)
Chapter 11 (Photon Optics, Sections 11.1 and 11.2)

Chapter 12 (Photons and Atoms)
Chapter 13 (Laser Amplifiers)
Chapter 14 (Lasers, Sections 14.1 and 14.2)
Chapter 15 (Photons in Semiconductors, Section 15.2)
Chapter 16 (Semiconductor Photon Sources)
Chapter 17 (Semiconductor Photon Detectors)
Chapter 22 (Fiber-Optic Communications)

Lightwave Devices

Background: Chapter 5 (Electromagnetic Optics); Chapter 9 (Resonator Optics, Section 9.1); Chapter 11 (Photon Optics, Sections 11.1A and 11.2); Chapter 12 (Photons and Atoms, Sections 12.1 and 12.2); and Chapter 15 (Photons in Semiconductors)
Chapter 6 (Polarization and Crystal Optics)
Chapter 7 (Guided-Wave Optics)
Chapter 8 (Fiber Optics)
Chapter 16 (Semiconductor Photon Sources)
Chapter 17 (Semiconductor Photon Detectors)
Chapter 18 (Electro-Optics)
Chapter 19 (Nonlinear Optics)
Chapter 20 (Acousto-Optics)

Fiber-Optic Communications* or *Lightwave Systems

Background: Chapter 5 (Electromagnetic Optics); Chapter 6 (Polarization and Crystal Optics); Chapter 9 (Resonator Optics, Section 9.1); Chapter 11 (Photon Optics, Sections 11.1A and 11.2); and Chapter 12 (Photons and Atoms, Sections 12.1 and 12.2)
Chapter 7 (Guided-Wave Optics)
Chapter 8 (Fiber Optics)
Chapter 15 (Photons in Semiconductors, Section 15.2)
Chapter 16 (Semiconductor Photon Sources)
Chapter 17 (Semiconductor Photon Detectors)
Chapter 21 (Photonic Switching and Computing, Sections 21.1 to 21.3)
Chapter 22 (Fiber-Optic Communications)

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.

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