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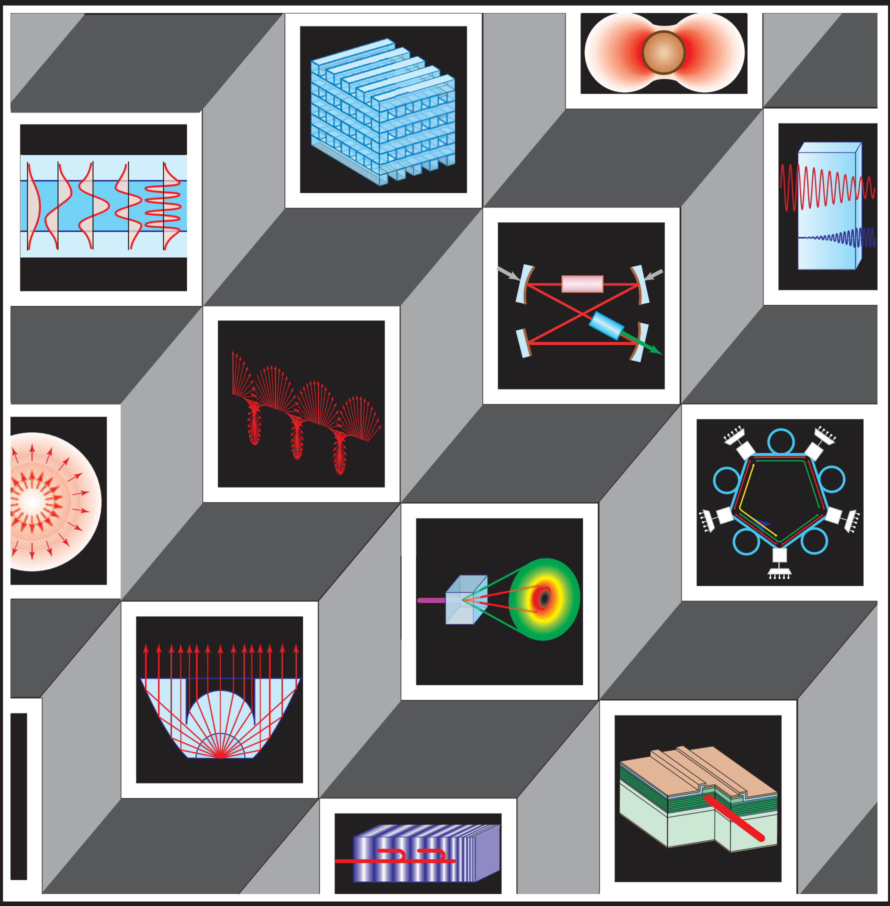
FUNDAMENTALS OF PHOTONICS



Third Edition

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WILEY

FUNDAMENTALS OF PHOTONICS

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THIRD EDITION

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PREFACE TO THE THIRD EDITION

Since the publication of the *Second Edition* in 2007, *Fundamentals of Photonics* has maintained its worldwide prominence as a self-contained, up-to-date, introductory-level textbook that features a blend of theory and applications. It has been reprinted dozens of times and been translated into German and Chinese, as well as Czech and Japanese. The Third Edition incorporates many of the scientific and technological developments in photonics that have taken place in the past decade and strives to be cutting-edge.

Optics and Photonics

Before usage of the term photonics became commonplace at the time of the *First Edition* in the early 1990s, the field was characterized by a collection of appellations that were not always clearly delineated. Terms such as quantum electronics, optoelectronics, electro-optics, and lightwave technology were widely used. Though there was a lack of agreement about the precise meanings of these terms, there was nevertheless a vague consensus regarding their usage. Most of these terms have since receded from general use, although some have retained their presence in the titles of technical journals and academic courses.

Now, more than 25 years later, the term *Optics* along with the term *Photonics*, as well as their combination *Optics & Photonics*, have prevailed. The distinction between optics and photonics remains somewhat fuzzy, however, and there is a degree of overlap between the two arenas. Hence, there is some arbitrariness in the manner in which the chapters of this book are allocated to its two volumes, *Part I: Optics* and *Part II: Photonics*. From a broad perspective, the term *Optics* is taken to signify free-space and guided-wave propagation, and to include topics such as interference, diffraction, imaging, statistical optics, and photon optics. The term *Photonics*, in contrast, is understood to include topics that rely on the interaction of light and matter, and is dedicated to the study of devices and systems. As the miniaturization of components and systems continues to progress and foster emerging technologies such as nanophotonics and biophotonics, the importance of photonics continues to advance.

Printed and Electronic Versions

The *Third Edition* appears in four versions:

1. A printed version.
2. An eBook in the form of an ePDF file that mimics the printed version.
3. An eBook in the form of a standard ePUB.
4. An eBook in the form of an enhanced ePUB with animations for selected figures.

In its *printed* form, the text consists of two volumes, each of which contains the Table of Contents and Index for both volumes along with the Appendices and List of Symbols:

- *Part I: Optics*, contains the first thirteen chapters.
- *Part II: Photonics*, contains the remaining twelve chapters.

The material in the eBook versions is identical to that in the printed version except that all 25 chapters reside in a single electronic file. The various *eBooks* enjoy the following features:

- Hyperlinked table of contents at the beginning of the text.

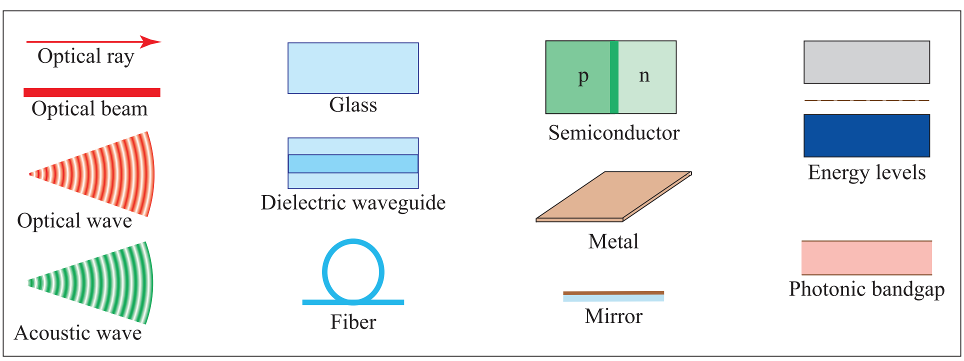
- Hyperlinked table of contents as an optional sidebar.
- Hyperlinked index.
- Hyperlinked section titles, equations, and figures throughout.
- Animations for selected figures in the enhanced ePUB.

Presentation

Exercises, examples, reading lists, and appendices. Each chapter of the *Third Edition* contains exercises, problem sets, and an extensive reading list. Examples are included throughout to emphasize the concepts governing applications of current interest. Appendices summarize the properties of one- and two-dimensional Fourier transforms, linear systems, and modes of linear systems. Important equations are highlighted by boxes and labels to facilitate retrieval.

Symbols, notation, units, and conventions. We make use of the symbols, notation, units, and conventions commonly used in the photonics literature. Because of the broad spectrum of topics covered, different fonts are often used to delineate the multiple meanings of various symbols; a list of symbols, units, abbreviations, and acronyms follows the appendices. We adhere to the International System of Units (SI units). This modern form of the metric system is based on the meter, kilogram, second, ampere, kelvin, candela, and mole, and is coupled with a collection of prefixes (specified on the inside back cover of the text) that indicate multiplication or division by various powers of ten. However, the reader is cautioned that photonics in the service of different areas of science can make use of different conventions and symbols. In Chapter 2, for example, we write the complex wavefunction for a monochromatic plane wave in a form commonly used in electrical engineering, which differs from that used in physics. Another example arises in Chapter 6, where the definitions we use for right (left) circularly polarized light are in accord with general usage in optics, but are opposite those generally used in engineering. These distinctions are often highlighted by *in situ* footnotes. Though the choice of a particular convention is manifested in the form assumed by various equations, it does not of course affect the results.

Color coding of illustrations. The color code used in illustrations is summarized in the chart presented below. Light beams and optical-field distributions are displayed in red (except when light beams of multiple wavelengths are involved, as is often the case in nonlinear optics). When optical fields are represented, white indicates negative values but when intensity is portrayed, white indicates zero. Acoustic beams and fields are similarly represented, but by with green rather than red. Glass and glass fibers are depicted in light blue; darker shades represent larger refractive indices. Semiconductors are cast in green, with various shades representing different doping levels. Metal and mirrors are indicated as copper. Semiconductor energy-band diagrams are portrayed in blue and gray whereas photonic bandgaps are illustrated in pink.



Color chart

Intended Audience

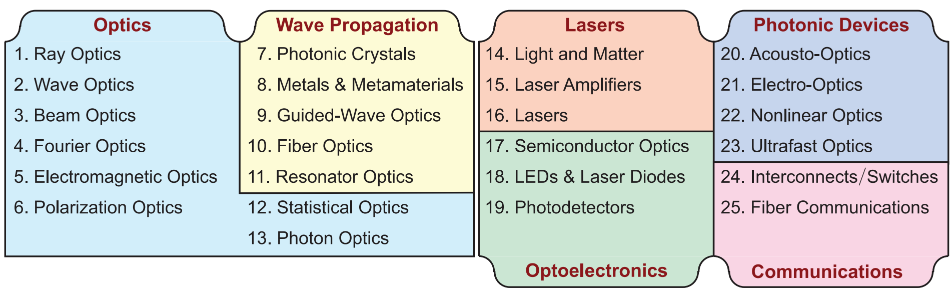
As with the previous editions, the *Third Edition* is meant to serve as:

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

The reader is assumed to have a background in engineering, physics, or optics, 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. The intent is to provide an introduction to optics and photonics that emphasizes the concepts that govern applications of current interest. The book should therefore not be considered as a compendium encompassing 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 free-standing monographs.

Organization

The *Third Edition* comprises 25 chapters compartmentalized into six divisions, as depicted in the diagram below.



In recognition of the different levels of mathematical sophistication of the intended audience, we have endeavored to present difficult concepts in two steps: at an introductory level that provides physical insight and motivation, followed by a more advanced analysis. This approach is exemplified by the treatment in Chapter 21 (*Electro-Optics*), in which the subject is first presented using scalar notation and then treated again using tensor notation. Sections dealing with material of a more advanced nature are indicated by asterisks and may be omitted if desired. Summaries are provided at points where recapitulation is deemed useful because of the involved nature of the material.

The form of the book is modular so that it can be used by readers with different needs; this 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. At the beginning of Chapter 25 (*Optical Fiber Communications*), for example, relevant material from earlier chapters describing optical fibers, light sources, optical amplifiers, photodetectors, and photonic integrated circuits is briefly reviewed. This places important information about the components of such systems at the disposal of the reader in advance of presenting system-design and performance considerations.

Contents

A principal feature of the *Third Edition* is a new chapter entitled *Metal and Metamaterial Optics*, an area that has had a substantial and increasing impact on photonics.

The new chapter comprises theory and applications for single- and double-negative media, metal optics, plasmonics, metamaterial optics, and transformation optics.

All chapters have been thoroughly vetted and updated. A chapter-by-chapter compilation of new material in the *Third Edition* is provided below.

- ***Chapter 1 (Ray Optics)***. Ray-optics descriptions for optical components such as biprisms, axicons, LED light collimators, and Fresnel lenses have been added. The connection between characterizing an arbitrary paraxial optical system by its ray-transfer matrix and its cardinal points has been established. A matrix-optics analysis for imaging with an arbitrary paraxial optical system has been included.
- ***Chapter 2 (Wave Optics)***. A wave-optics analysis of transmission through biprisms and axicons has been added. A treatment of the Fresnel zone plate from the perspective of interference has been introduced. An analysis of the Michelson–Fabry–Perot (LIGO) interferometer used for the detection of gravitational waves in the distant universe has been incorporated.
- ***Chapter 3 (Beam Optics)***. An enhanced description of Laguerre–Gaussian beams has been provided. The basic features of several additional optical beams have been introduced: optical vortex, Ince–Gaussian, nondiffracting Bessel, Bessel–Gaussian, and Airy.
- ***Chapter 4 (Fourier Optics)***. An analysis of Fresnel diffraction from a periodic aperture (Talbot effect) has been included. Nondiffracting waves and Bessel beams have been introduced from a Fourier-optics perspective. A discussion of computer-generated holography has been added.
- ***Chapter 5 (Electromagnetic Optics)***. A new section on the dipole wave, the basis of near-field optics, has been incorporated. A new section on scattering that includes Rayleigh and Mie scattering, along with attenuation in a medium with scatterers, has been added.
- ***Chapter 6 (Polarization Optics)***. The material dealing with the dispersion relation in anisotropic media has been reworked to simplify the presentation.
- ***Chapter 7 (Photonic-Crystal Optics)***. The behavior of the dielectric-slab beamsplitter has been elucidated. A discussion relating to fabrication methods for 3D photonic crystals has been incorporated.
- ***Chapter 8 (Metal and Metamaterial Optics)***. This new chapter, entitled Metal and Metamaterial Optics, provides a venue for the examination of single- and double-negative media, metal optics, plasmonics, metamaterial optics, and transformation optics. Topics considered include evanescent waves, surface plasmon polaritons, localized surface plasmons, nanoantennas, metasurfaces, subwavelength imaging, and optical cloaking.
- ***Chapter 9 (Guided-Wave Optics)***. A new section on waveguide arrays that details the mutual coupling of multiple waveguides and introduces the notion of supermodes has been inserted. A new section on plasmonic waveguides that includes metal–insulator–metal and metal-slab waveguides, along with periodic metal–dielectric arrays, has been incorporated.
- ***Chapter 10 (Fiber Optics)***. A discussion of multicore fibers, fiber couplers, and photonic lanterns has been added. A brief discussion of the applications of photonic-crystal fibers has been provided. A new section on multimaterial fibers, including conventional and hybrid mid-infrared fibers, specialty fibers, multimaterial fibers, and multifunctional fibers, has been introduced.
- ***Chapter 11 (Resonator Optics)***. A section on plasmonic resonators has been added.
- ***Chapter 12 (Statistical Optics)***. The sections on optical coherence tomography and unpolarized light have been reorganized.
- ***Chapter 13 (Photon Optics)***. A brief description of single-photon imaging has been added. The discussion of quadrature-squeezed and photon-number-squeezed

light has been enhanced and examples of the generation and applications of these forms of light have been provided. A section that describes two-photon light, entangled photons, two-photon optics, and the generation and applications thereof, has been incorporated. Examples of two-photon polarization, two-photon spatial optics, and two-beam optics have been appended.

- ***Chapter 14 (Light and Matter)***. The title of this chapter was changed from *Photons and Atoms* to *Light and Matter*. Brief descriptions of the Zeeman effect, Stark effect, and ionization energies have been added. The discussion of lanthanide-ion manifolds has been enhanced. Descriptions of Doppler cooling, optical molasses, optical tweezers, optical lattices, atom interferometry, and atom amplifiers have been incorporated into the section on laser cooling, laser trapping, and atom optics.
- ***Chapter 15 (Laser Amplifiers)***. Descriptions of quasi-three-level and in-band pumping have been added. The sections on representative laser amplifiers, including ruby, neodymium-doped glass, erbium-doped silica fiber, and Raman fiber devices, have been enhanced.
- ***Chapter 16 (Lasers)***. Descriptions of tandem pumping, transition-ion-doped zinc-chalcogenide lasers, silicon Raman lasers, and master-oscillator power-amplifiers (MOPAs) have been added. Descriptions of inner-shell photopumping and X-ray free-electron lasers have been incorporated. A new section on optical frequency combs has been provided.
- ***Chapter 17 (Semiconductor Optics)***. The section on organic semiconductors has been enhanced. A discussion of group-IV photonics, including graphene and 2D materials such as transition-metal dichalcogenides, has been added. A brief discussion of quantum-dot single-photon emitters has been incorporated.
- ***Chapter 18 (LEDs and Laser Diodes)***. The title of this chapter was changed from *Semiconductor Photon Sources* to *LEDs and Laser Diodes*. A new section on the essentials of LED lighting has been incorporated. Brief discussions of the following topics are now included: resonant-cavity LEDs, silicon-photonics light sources, quantum-dot semiconductor amplifiers, external-cavity wavelength-tunable laser diodes, broad-area laser diodes, and laser-diode bars and stacks. A discussion of the semiconductor-laser linewidth-enhancement factor has been added. A new section on nanolasers has been introduced.
- ***Chapter 19 (Photodetectors)***. The title of this chapter was changed from *Semiconductor Photon Detectors* to *Photodetectors*. Brief discussions of the following topics have been added: organic, plasmonic, group-IV-based, and graphene-enhanced photodetectors; edge vs. normal illumination; photon-trapping microstructures; SACM and superlattice APDs; multiplied dark current; and $1/f$ detector noise. New examples include multi-junction photovoltaic solar cells; Ge-on-Si photodiodes; graphene-Si Schottky-barrier photodiodes; and SAM, SACM, and staircase APDs. A new section on single-photon and photon-number-resolving detectors details the operation of SPADs, SiPMs, and TESs.
- ***Chapter 20 (Acousto-Optics)***. The identical forms of the photoelastic matrix in acousto-optics and the Kerr-effect matrix in electro-optics has been highlighted for cubic isotropic media.
- ***Chapter 21 (Electro-Optics)***. New sections on passive- and active-matrix liquid-crystal displays have been introduced and their operation has been elucidated. The performance of active-matrix liquid-crystal displays (AMLCDs) has been compared with that of active-matrix organic light-emitting displays (AMOLEDs).
- ***Chapter 22 (Nonlinear Optics)***. New material relating to guided-wave nonlinear optics has been introduced. Quasi-phase matching in periodically poled integrated optical waveguides, and the associated improvement in wave-mixing efficiency, is now considered. The section pertaining to Raman gain has been enhanced.
- ***Chapter 23 (Ultrafast Optics)***. New examples have been incorporated that con-

sider chirped pulse amplification in a petawatt laser and the generation of high-energy solitons in a photonic-crystal rod. A new section on high-harmonic generation and attosecond optics has been added. The section on pulse detection has been reorganized.

- ***Chapter 24 (Optical Interconnects and Switches)***. The role of optical interconnects at the inter-board, inter-chip, and intrachip scale of computer systems is delineated. All-optical switching now incorporates nonparametric and parametric photonic switches that operate on the basis of manifold nonlinear-optical effects. Photonic-crystal and plasmonic photonic switches are discussed. The treatment of photonic logic gates now includes an analysis of embedded bistable systems and examples of bistability in fiber-based-interferometric and microring laser systems.
- ***Chapter 25 (Optical Fiber Communications)***. The material on fiber-optic components has been updated and rewritten, and the role of photonic integrated circuits is delineated. A new section on space-division multiplexing in multicore and multimode fibers has been added. The section on coherent detection has been expanded and now emphasizes digital coherent receivers with spectrally efficient coding.

Representative Courses

The different chapters of the book may be combined in various ways for use in courses of semester or quarter duration. Representative examples of such courses are presented 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.

Optics

1. Ray Optics	8. Metals & Metamaterials	14. Light and Matter	20. Acousto-Optics
2. Wave Optics	9. Guided-Wave Optics	15. Laser Amplifiers	21. Electro-Optics
3. Beam Optics	10. Fiber Optics	16. Lasers	22. Nonlinear Optics
4. Fourier Optics	11. Resonator Optics	17. Semiconductor Optics	23. Ultrafast Optics
5. Electromagnetic Optics	12. Statistical Optics	18. LEDs & Laser Diodes	24. Interconnects/Switches
6. Polarization Optics	13. Photon Optics	19. Photodetectors	25. Fiber Communications
7. Photonic Crystals			

The first six chapters of the book are suitable for an introductory course on *Optics*. These may be supplemented by Chapter 12 (*Statistical Optics*) to introduce incoherent and partially coherent light, and by Chapter 13 (*Photon Optics*) to introduce the photon. The introductory sections of Chapters 9 and 10 (*Guided-Wave Optics* and *Fiber Optics*, respectively) may be added to cover some applications.

Guided-Wave Optics

1. Ray Optics	8. Metals & Metamaterials	14. Light and Matter	20. Acousto-Optics
2. Wave Optics	9. Guided-Wave Optics	15. Laser Amplifiers	21. Electro-Optics
3. Beam Optics	10. Fiber Optics	16. Lasers	22. Nonlinear Optics
4. Fourier Optics	11. Resonator Optics	17. Semiconductor Optics	23. Ultrafast Optics
5. Electromagnetic Optics	12. Statistical Optics	18. LEDs & Laser Diodes	24. Interconnects/Switches
6. Polarization Optics	13. Photon Optics	19. Photodetectors	25. Fiber Communications
7. Photonic Crystals			

A course on *Guided-Wave Optics* might begin with an introduction to wave propagation in layered and periodic media in Chapter 7 (*Photonic-Crystal Optics*), and could include Chapter 8 (*Metal and Metamaterial Optics*). This would be followed by Chapters 9, 10, and 11 (*Guided-Wave Optics*, *Fiber Optics*, and *Resonator Optics*, respectively). The introductory sections of Chapters 21 and 24 (*Electro-Optics* and *Optical Interconnects and Switches*) would provide additional material.

Lasers

1. Ray Optics	8. Metals & Metamaterials	14. Light and Matter	20. Acousto-Optics
2. Wave Optics	9. Guided-Wave Optics	15. Laser Amplifiers	21. Electro-Optics
3. Beam Optics	10. Fiber Optics	16. Lasers	22. Nonlinear Optics
4. Fourier Optics	11. Resonator Optics	17. Semiconductor Optics	23. Ultrafast Optics
5. Electromagnetic Optics	12. Statistical Optics	18. LEDs & Laser Diodes	24. Interconnects/Switches
6. Polarization Optics	13. Photon Optics	19. Photodetectors	25. Fiber Communications
7. Photonic Crystals			

A course on *Lasers* could begin with *Beam Optics* and *Resonator Optics* (Chapters 3 and 11, respectively), followed by *Light and Matter* (Chapter 14). The initial portion of *Photon Optics* (Chapter 13) could be assigned. The heart of the course would be the material contained in *Laser Amplifiers* and *Lasers* (Chapters 15 and 16, respectively). The course might also include material drawn from *Semiconductor Optics* and *LEDs and Laser Diodes* (Chapters 17 and 18, respectively). An introduction to femtosecond lasers could be extracted from some sections of *Ultrafast Optics* (Chapter 23).

Optoelectronics

1. Ray Optics	8. Metals & Metamaterials	14. Light and Matter	20. Acousto-Optics
2. Wave Optics	9. Guided-Wave Optics	15. Laser Amplifiers	21. Electro-Optics
3. Beam Optics	10. Fiber Optics	16. Lasers	22. Nonlinear Optics
4. Fourier Optics	11. Resonator Optics	17. Semiconductor Optics	23. Ultrafast Optics
5. Electromagnetic Optics	12. Statistical Optics	18. LEDs & Laser Diodes	24. Interconnects/Switches
6. Polarization Optics	13. Photon Optics	19. Photodetectors	25. Fiber Communications
7. Photonic Crystals			

The chapters on *Semiconductor Optics*, *LEDs and Laser Diodes*, and *Photodetectors* (Chapters 17, 18, and 19, respectively) form a suitable basis for a course on *Optoelectronics*. This material would be supplemented with optics background from earlier chapters and could include topics such as liquid-crystal devices (Secs. 6.5 and 21.3), electroabsorption modulators (Sec. 21.5), and an introduction to photonic devices used for switching and/or communications (Chapters 24 and 25, respectively).

Photonic Devices

1. Ray Optics	8. Metals & Metamaterials	14. Light and Matter	20. Acousto-Optics
2. Wave Optics	9. Guided-Wave Optics	15. Laser Amplifiers	21. Electro-Optics
3. Beam Optics	10. Fiber Optics	16. Lasers	22. Nonlinear Optics
4. Fourier Optics	11. Resonator Optics	17. Semiconductor Optics	23. Ultrafast Optics
5. Electromagnetic Optics	12. Statistical Optics	18. LEDs & Laser Diodes	24. Interconnects/Switches
6. Polarization Optics	13. Photon Optics	19. Photodetectors	25. Fiber Communications
7. Photonic Crystals			

Photonic Devices is a course that would consider the devices used in *Acousto-Optics*, *Electro-Optics*, and *Nonlinear Optics* (Chapters 20, 21, and 22, respectively). It might also include devices used in optical routing and switching, as discussed in *Optical Interconnects and Switches* (Chapter 24).

Nonlinear & Ultrafast Optics

1. Ray Optics	8. Metals & Metamaterials	14. Light and Matter	20. Acousto-Optics
2. Wave Optics	9. Guided-Wave Optics	15. Laser Amplifiers	21. Electro-Optics
3. Beam Optics	10. Fiber Optics	16. Lasers	22. Nonlinear Optics
4. Fourier Optics	11. Resonator Optics	17. Semiconductor Optics	23. Ultrafast Optics
5. Electromagnetic Optics	12. Statistical Optics	18. LEDs & Laser Diodes	24. Interconnects/Switches
6. Polarization Optics	13. Photon Optics	19. Photodetectors	25. Fiber Communications
7. Photonic Crystals			

The material contained in Chapters 21–23 (*Electro-Optics*, *Nonlinear Optics*, and *Ultrafast Optics*, respectively) is suitable for an in-depth course on *Nonlinear and Ultrafast Optics*. These chapters could be supplemented by the material pertaining to electro-optic and all-optical switching in Chapter 24 (*Optical Interconnects and Switches*).

Fiber-Optic Communications

1. Ray Optics	8. Metals & Metamaterials	14. Light and Matter	20. Acousto-Optics
2. Wave Optics	**9. Guided-Wave Optics**	15. Laser Amplifiers	21. Electro-Optics
3. Beam Optics	**10. Fiber Optics**	16. Lasers	22. Nonlinear Optics
4. Fourier Optics	11. Resonator Optics	17. Semiconductor Optics	23. Ultrafast Optics
5. Electromagnetic Optics	12. Statistical Optics	18. LEDs & Laser Diodes	**24. Interconnects/Switches**
6. Polarization Optics	13. Photon Optics	19. Photodetectors	**25. Fiber Communications**
7. Photonic Crystals			

The heart of a course on *Fiber-Optic Communications* would be the material contained in Chapter 25 (*Optical Fiber Communications*). Background for this course would comprise material drawn from Chapters 9, 10, 18, and 19 (*Guided-Wave Optics*, *Fiber Optics*, *LEDs and Laser Diodes*, and *Photodetectors*, respectively), along with material contained in Secs. 15.3C and 15.3D (doped-fiber and Raman fiber amplifiers, respectively). If fiber-optic networks were to be emphasized, Sec. 24.3 (photonic switches) would be a valuable adjunct.

Optical Information Processing

1. Ray Optics	8. Metals & Metamaterials	14. Light and Matter	**20. Acousto-Optics**
2. Wave Optics	9. Guided-Wave Optics	15. Laser Amplifiers	21. Electro-Optics
3. Beam Optics	10. Fiber Optics	16. Lasers	22. Nonlinear Optics
4. Fourier Optics	11. Resonator Optics	17. Semiconductor Optics	23. Ultrafast Optics
5. Electromagnetic Optics	**12. Statistical Optics**	18. LEDs & Laser Diodes	**24. Interconnects/Switches**
6. Polarization Optics	13. Photon Optics	19. Photodetectors	25. Fiber Communications
7. Photonic Crystals			

Background material for a course on *Optical Information Processing* would be drawn from *Wave Optics* and *Beam Optics* (Chapters 2 and 3, respectively). The course could cover coherent image formation and processing from *Fourier Optics* (Chapter 4) along with incoherent and partially coherent imaging from *Statistical Optics* (Chapter 12). The focus could then shift to devices used for analog data processing, such as those considered in *Acousto-Optics* (Chapter 20). The course could then finish with material on switches and gates used for digital data processing, such as those considered in *Optical Interconnects and Switches* (Chapter 24).

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June 4, 2018

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 subwavelength-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.

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, Robert Balahura, Silvia Carrasco, Stephen Chinn, 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, Allen Mullins, Magued Nasr, Roy Olivier, Roberto Paiella, Peter W. E. Smith, Stephen P. Smith, Kenneth Suslick, Anna Swan, Tristan Tayag, Tommaso Toffoli, and Brad Tousley.

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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.

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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 Reconnaissance 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.

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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.

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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

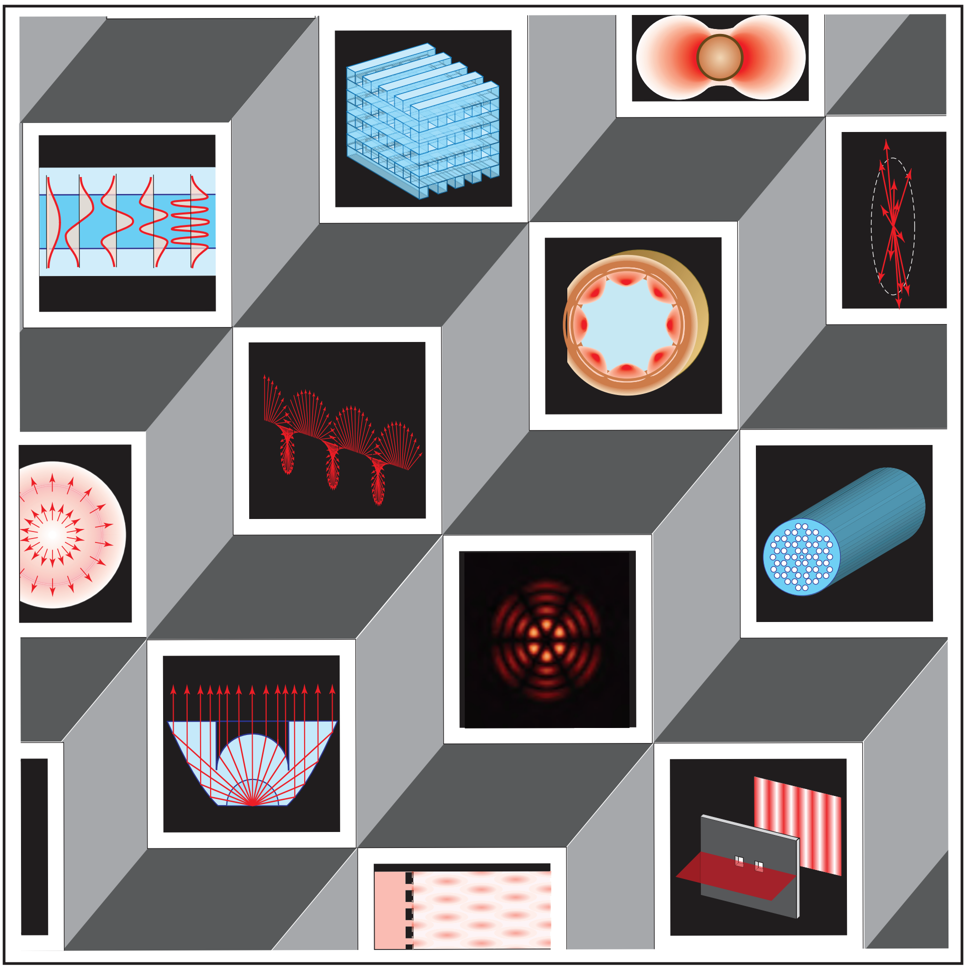
Madison, Wisconsin

MALVIN CARL TEICH

New York, New York
April 3, 1991

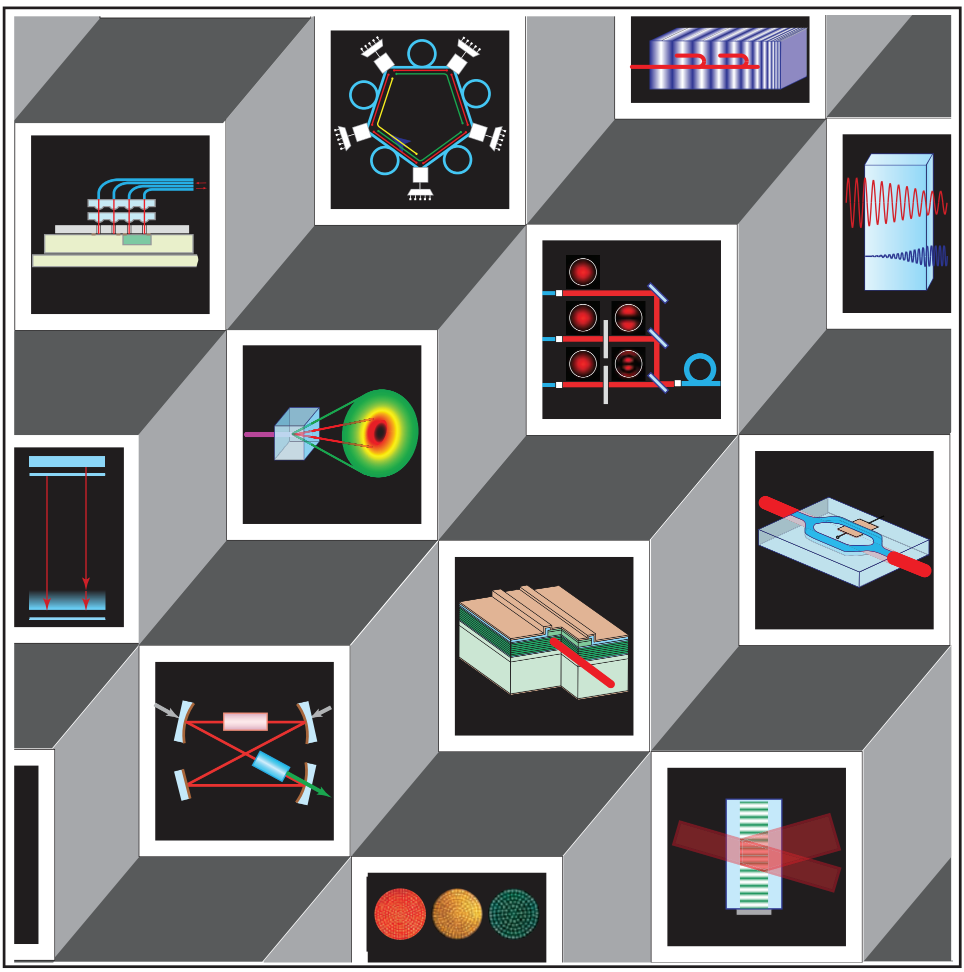
FUNDAMENTALS OF PHOTONICS

Part I: Optics
(Chapters 1–13)



FUNDAMENTALS OF PHOTONICS

Part II: Photonics
(Chapters 14–25)



AUTHORS

Bahaa E. A. Saleh has been Distinguished Professor and Dean of CREOL, The College of Optics and Photonics at the University of Central Florida, since 2009. He was at Boston University in 1994–2008, serving as Chair of the Department of Electrical and Computer Engineering (ECE) in 1994–2007, and becoming Professor Emeritus in 2008. He received the Ph.D. degree from the Johns Hopkins University in 1971 and was a faculty member at the University of Wisconsin-Madison from 1977 to 1994, serving as Chair of the ECE Department from 1990 to 1994. He held faculty and research positions at the University of Santa Catarina in Brazil, Kuwait University, the Max Planck Institute in Germany, the University of California-Berkeley, the European Molecular Biology Laboratory, Columbia University, and the University of Vienna.

His research contributions cover a broad spectrum of topics in optics and photonics including statistical optics, nonlinear optics, quantum optics, and image science. He is the author of *Photoelectron Statistics* (Springer-Verlag, 1978) and the co-author of *Fundamentals of Photonics* (Wiley, *First Edition* 1991, *Second Edition* 2007, *Third Edition* 2019) and *Introduction to Subsurface Imaging* (Cambridge University Press, 2011). He has published more than 600 papers in technical journals and conference proceedings. He holds nine patents.

Saleh served as the founding editor of the OSA journal *Advances in Optics and Photonics* (2008–2013), editor-in-chief of the *Journal of the Optical Society of America A* (1991–1997), and Chairman of the Board of Editors of OSA (1997–2001). He served as Vice President of the International Commission of Optics (ICO) (2000–2002), and as a member of the Board of Directors of the Laser Institute of America (2010–2011). He is a Fellow of the Institute of Electrical and Electronics Engineers (IEEE), the Optical Society of America (OSA), the International Society for Optics and Photonics (SPIE), the American Physical Society (APS), and the Guggenheim Foundation. He received the 1999 OSA Beller Medal for outstanding contributions to optical science and engineering education, the 2004 SPIE BACUS award for his contribution to photomask technology, the 2006 Kuwait Prize, the 2008 OSA Distinguished Service Award, and the 2013 OSA Mees Medal. He is a member of Phi Beta Kappa, Sigma Xi, and Tau Beta Pi.

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

Malvin Carl Teich received the S.B. degree in physics from the Massachusetts Institute of Technology in 1961, the M.S. degree in electrical engineering from Stanford University in 1962, and the Ph.D. degree from Cornell University in 1966. His first professional affiliation, in 1966, was with MIT Lincoln Laboratory. He joined the faculty at Columbia University in 1967, where he served as a member of the Electrical Engineering Department (as Chairman from 1978 to 1980), the Applied Physics and Applied Mathematics Department, the Columbia Radiation Laboratory in the Department of Physics, and the Fowler Memorial Laboratory at the Columbia College of Physicians & Surgeons. During his tenure at Columbia, he carried out research in the areas of photon statistics and point processes; quantum heterodyne detection; the generation of nonclassical light; noise in avalanche photodiodes and fiber-optic amplifiers; and information transmission in biological sensory systems. In 1996 he became Professor Emeritus at Columbia.

From 1995 to 2011, he served as a faculty member at Boston University in the Departments of Electrical & Computer Engineering, Biomedical Engineering, and Physics. He was the Director of the Quantum Photonics Laboratory and a Member of the Photonics Center, the Hearing Research Center, and the Graduate Program for Neuroscience. In 2011, he was appointed Professor Emeritus at Boston University.

Since 2011, Dr. Teich has been pursuing his research interests as Professor Emeritus at Columbia University and Boston University, and as a member of the Boston University Photonics Center. He is also a consultant to government and private industry and has served as an expert in numerous patent conflict cases. He is most widely known for his work in photonics and for his studies of fractal stochastic processes and information transmission in biological systems. His current efforts in photonics are directed toward the characterization of noise in photon streams. His work in fractals focuses on elucidating the information-carrying properties of sensory-system action-potential patterns and the nature of heart-rate variability in patients with coronary disorders. His efforts in neuroscience are directed toward auditory and visual perception, neural information transmission, and sensory detection. During periods of sabbatical leave, he served as a visiting faculty member at the University of Colorado at Boulder, the University of California at San Diego, and the University of Central Florida at Orlando.

Dr. Teich is a Life Fellow of the Institute of Electrical and Electronics Engineers (IEEE), and a Fellow of the Optical Society of America (OSA), the International Society for Optics and Photonics (SPIE), the American Physical Society (APS), the American Association for the Advancement of Science (AAAS), and the Acoustical Society of America (ASA). He is a member of Sigma Xi and Tau Beta Pi. In 1969 he received the IEEE Browder J. Thompson Memorial Prize for his paper "Infrared Heterodyne Detection." He was awarded a Guggenheim Fellowship in 1973. In 1992 he was honored with the Memorial Gold Medal of Palacký University in the Czech Republic, and in 1997 he received the IEEE Morris E. Leeds Award. In 2009, he was honored with the Distinguished Scholar Award of Boston University. He has authored or coauthored some 350 refereed journal articles/book chapters and some 550 conference presentations/lectures; he holds six patents. He is the co-author of *Fundamentals of Photonics* (Wiley, *First Edition* 1991, *Second Edition* 2007, *Third Edition* 2019) and of *Fractal-Based Point Processes* (Wiley, 2005, with S. B. Lowen).

INDEX

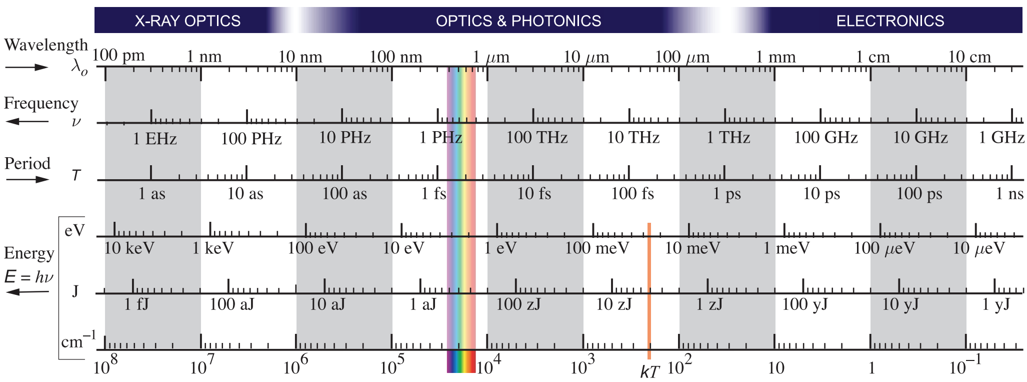
USEFUL CONSTANTS

Speed of light in free space	c_o	2.9979×10^{8}	m/s
Permittivity of free space	ϵ_o	8.8542×10^{-12}	F/m
Permeability of free space	μ_o	1.2566×10^{-6}	H/m
Impedance of free space	η_o	376.73	Ω
Planck's constant	h	6.6261×10^{-34}	J · s
Electron charge	e	1.6022×10^{-19}	C
Electron mass	m_0	9.1094×10^{-31}	kg
Boltzmann's constant	k	1.3807×10^{-23}	J/°K

PREFIXES FOR UNITS

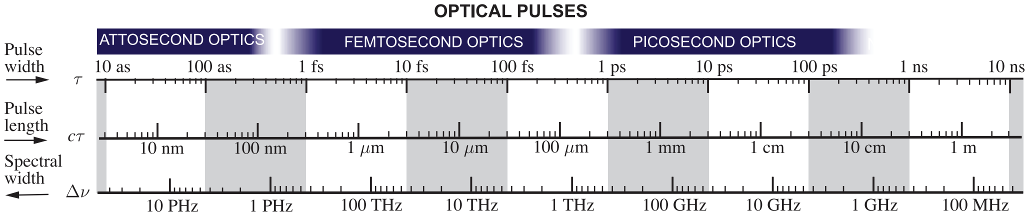
10^{-24}	10^{-21}	10^{-18}	10^{-15}	10^{-12}	10^{-9}	10^{-6}	10^{-3}	10^{0}	10^{3}	10^{6}	10^{9}	10^{12}	10^{15}	10^{18}	10^{21}	10^{24}
yocto (y)	zepto (z)	atto (a)	femto (f)	pico (p)	nano (n)	micro (μ)	milli (m)		kilo (k)	mega (M)	giga (G)	tera (T)	peta (P)	exa (E)	zetta (Z)	yotta (Y)

THE PHOTON

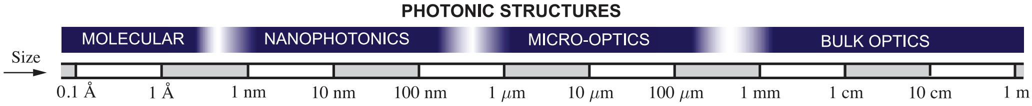


A photon of free-space wavelength $\lambda_o = 1\ \mu$m has frequency $\nu = 300$ THz, period $T = 3.33$ fs, and energy $E = 1.24$ eV $= 199$ zJ $= 10^4$ cm^{-1}. At room temperature ($T = 300^o$ K), the thermal energy $kT = 26$ meV $= 4.14$ zJ $= 209$ cm^{-1}.

OPTICAL PULSES



PHOTONIC STRUCTURES



Fundamentals of Photonics

A complete, thoroughly updated, full-color third edition

Fundamentals of Photonics, *Third Edition* is a self-contained and up-to-date introductory-level textbook that thoroughly surveys this rapidly expanding area of engineering and applied physics. Featuring a blend of theory and applications, coverage includes detailed accounts of the primary theories of light, including **ray optics**, **wave optics**, **electromagnetic optics**, and **photon optics**, as well as the **interaction of light with matter**. Presented at increasing levels of complexity, preliminary sections build toward more advanced topics, such as **Fourier optics and holography**, **photonic-crystal optics**, **fiber and guided-wave optics**, **LEDs and lasers**, **acousto-optic and electro-optic devices**, **nonlinear optical devices**, **ultrafast optics**, **optical interconnects and switches**, and **optical fiber communications**. The third edition features an entirely new chapter on the **optics of metals and plasmonic devices**. Each chapter contains highlighted equations, exercises, problems, summaries, and selected reading lists. Examples of real systems are included to emphasize the concepts governing applications of current interest. Each of the chapters of the second edition has been thoroughly updated.

BAHAA E. A. SALEH, PhD, has been Distinguished Professor and Dean of CREOL, The College of Optics and Photonics at the University of Central Florida, since 2009. He is also Professor Emeritus at Boston University. Saleh is the author of *Photoelectron Statistics* and *Introduction to Subsurface Imaging*, and is the Founding Editor of *Advances in Optics and Photonics*. He is a Fellow of APS, IEEE, OSA, and SPIE, and is the recipient of the OSA Beller Medal, the OSA Mees Medal, the SPIE BACUS Award, and the Kuwait Prize.

MALVIN CARL TEICH, PhD, is Professor Emeritus at Boston University and Columbia University, and a member of the Boston University Photonics Center. He is the coauthor of *Fractal-Based Point Processes* and is a Fellow of the IEEE, OSA, SPIE, APS, AAAS, and ASA. He is the recipient of the IEEE Browder J. Thompson Memorial Prize Award, the IEEE Morris E. Leeds Award, the Memorial Gold Medal of Palacký University, and the Distinguished Scholar Award of Boston University.

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