Book Review

Fundamentals of Photonics, Second Edition

Bahaa E. A. Saleh and Malvin Carl Teich, 1177 pages +xix, 978-0-471-35832-9, illus., index, John Wiley & Sons, Hoboken, New Jersey (2007), $140.00, hardcover.

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Photonics is an active field that is a hybrid of physical theories and engineering principles. Research and development in photonics has produced many of our modern technologies, and these advances impact the research published in the *Journal of Biomedical Optics*. Modern applications of interest to the readers of this journal include: diagnostic sensing and imaging systems, from DNA arrays to molecular and microsensing devices, new light sources such as LEDs and lasers, two-dimensional displays and detectors, optical low-coherence tomography (OCT), single-molecule imagers, nonlinear optical imagers, and new types of endoscopes. With such a disparate mix of various branches of physics and engineering (in particular electrical engineering and materials) and the wide range of their resulting technologies and applications, the problem is how to teach these materials to seniors or first year graduate students. Furthermore, professors often ponder which textbook is preferred for the students in a class on photonics. I now present a solution to these problems: *Fundamentals of Photonics*, hereafter called *Photonics*.

The first edition of *Photonics* was published in 1991, and it quickly became a classic success. Bahaa Saleh and Malvin Teich, in their full-color second edition, have succeeded in their ambitious task to update all the chapters in the first edition and write new chapters on photonic-crystal optics (multilayer and periodic media, waveguides, and resonators), ultrafast optics (femtosecond optical pulses, ultrafast nonlinear optics), optical interconnects and switches, and optical fiber communication; yet, they maintained the size of the book. The authors have augmented the chapters of the first edition by presenting many new and important topics: near-field imaging, plasmonics, doubly negative metamaterials, polarization mode dispersion, optical coherence tomography, free-electron lasers, superluminescent diodes, organic and white-light LEDs, photon-crystal lasers, low-noise APDs, quasi-phase matching devices, THz generation, chirp pulse amplification, and supercontinuum light generation.

The authors wrote the second edition for their intended audience of senior undergraduate or first-year graduate students in electrical engineering or applied physics. They recommend that the reader be familiar with the following prerequisites: modern physics, electricity and magnetism, wave motion, linear systems, and elementary quantum mechanics.

What is the scope of the book? The authors have determined what topics are to be included in a book that describes the fundamentals of photonics; of course, different authors may make different lists of topics. There is the implicit assumption that if a student masters the fundamentals of the subject then she will have the necessary background to approach and comprehend the more advanced topics. The authors generalize the content to include the following broad topics: the physical theories, the instruments, and the technologies that are associated with the generation, the transmission, the modulation, the amplification and frequency conversion, and the detection of light. *Photonics* provides the reader with a balanced approach that includes physical theory, mathematical description, and numerous examples of real photonic devices.

What are the components of their pedagogical approach? The authors appropriately begin their book with a discussion of light: its generation, transmission in free space and in matter, the modulation of light, and the detection of light. One result from a careful reading of *Photonics* is a questioning of our concept of the nature of light. What is light in free space? What is light inside of matter? How does polychromatic light differ from monochromatic light? What is a femtosecond pulse of light? The authors presentation is elegant, clear, and progressively more difficult. First, they describe light as rays, then they present scalar waves, then electromagnetic waves, and finally they present light in the avatar of photons. Each type of description serves a delimited regime that can explain specific phenomena; for example, to explain polarization and dispersion it is necessary to invoke electromagnetic theory, and to explain light matter interactions it is necessary to invoke photons and quantum optics. The authors explain that the wavefront normals of the wave optics model are equivalent to the rays of the ray optic model. It is important for the reader to realize that the phenomenon we denote as light is a physical reality; which theory we employ to explain the particular observation or measurement is often a matter of mathematical convenience.

An advantage of a textbook that is written by one or two authors, as compared to a book that contains contributions from several authors, is a uniform style of presentation, a single definition of terms, and a standard format for mathematical expressions. This pedagogical consistency is further enhanced in the second edition of the book by the use of a uniform color and symbol chart that is faithfully implemented throughout the book. The authors use special symbols and colors to indicate optical rays, beams, waves, materials (glass, dielectric waveguides, fibers, semiconductors, and metals), and both energy levels and photonic bandgaps. The text is associated with copious full-color illustrations; furthermore, each figure is associated with exceptionally clear and self-contained figure legends that permit the reader to understand the figures without searching the surrounding text for explanations. All of the illustrations are sharp and the selective use of color enhances the readers comprehension.

As an illustration of the chapter-to-chapter consistency, I present some of the common features. The chapters begin with the photograph or drawing of a person or persons who made major contributions to the materials described in the chapter. First, the authors provide the reader with a concise introduction to the content of the chapter, and then there is a segment labeled “This Chapter” that places the material in context with other chapters in the book. Key equations are placed within a box and given a name or description and a unique number. Within each section, when appropriate, there is a “Summary” box that restates the critical physics and the associated mathematical descriptions. Each chapter contains exercises that serve to stimulate further thinking and exploration by the reader. At the end of each chapter there is a “Reading List” that contains suggested books and articles (some as recent as 2006). Finally, the authors provide well-designed problems that extend beyond the materials that are covered in each chapter. Problems of a more advanced nature are so indicated.

The superb expertise of the authors as educators is immediately apparent to the reader: the authors integrate physics and mathematics so that the reader understands the physical basis of the phenomena and grasps the analytical techniques required to calculate and model the phenomena. Throughout the book each physical term, mathematical symbol, and expression is clearly defined, and the key physical and mathematical equations are readily found in the index. At the end of the book there is a useful section named “Symbols and Units” that defines the Roman symbols, the acronyms, the Greek symbols, and the mathematical symbols. When a specific symbol is used in multiple contexts, each definition is provided. Finally, the inside back cover contains a list of useful constants and prefixes for units, and graphics relate the pulse width, pulse length, and spectral width of optical pulses, and free-space conversions of photon wavelength, frequency, and energy.

It is a difficult task to judge the required amount of mathematical detail that must be presented with an equation that describes the physics; the limits range from a full derivation from first principles to stating the final equation. The authors cite the sources that contain the full mathematical derivations and stress the physics and the mathematics that are useful descriptors of the phenomena. I found that their approach works very well and is suited to a book on the fundamentals of photonics. The sections that are deemed advanced are indicated by asterisks and may be omitted from course materials. The authors have provided course content that is appropriate for several courses that may use this book; for each type of course the authors suggest different groups of chapters for the syllabus.

What are the other special features of the book? Several detailed appendices contain materials that are used throughout the book. Because of their general applicability to many topics in the book, these supplementary reviews serve as a rapid reference to the mathematical details. Some of the topics that are developed in the appendices include: one-dimensional Fourier transforms, convolution, correlation, Parsevals theorem, time duration and spectral width (bandwidth), two-dimensional Fourier transforms, one-dimensional linear transforms, transfer functions, Hilbert transform, Kramers-Kronig relations, two-dimensional linear systems, modes of linear systems, the eigenvalue problem, discrete and continuous linear systems, and modes of a field/wave in a homogeneous medium or in a periodic medium.

The first part of the book is the presentation of these various models of light; the emphasis is on the propagation of light in free space in a homogeneous medium and the interaction of light and matter. The second part is devoted to light sources and light detectors. The third part of the book describes the modulation of light, and nonlinear and ultrafast optics and closes with chapters on integrated optics (interconnects and switches) and the important field of optical communications.

I now review some examples from individual chapters. The authors provide an integrated approach to the study of optics. They follow the typical order (based on the historical sequence of developments) of presentation: ray optics, wave optics, electromagnetic optics, and quantum optics. Each specific model is first presented as a set of postulates and many experimental phenomena and measurements are deduced from the unproved postulates. As the exposition proceeds from the simple to the more complicated models it becomes clear that a given model of light is actually a special case (valid only under specific conditions) of the next more complex model. For some phenomena, ray optics may provide quantitative predictions, for others scalar approaches (light as a single scalar wavefunction) serve to predict the phenomena, and yet other optical phenomena require the use of vector approaches or quantum mechanical theory to explain the observations. The authors provide a clear section on the relation between wave optics and ray optics that should be read carefully. Ray optics will not explain interference effects.

Following a careful reading of *Photonics* the reader will better appreciate the integrative view of light as a composite theory with several subsets. Clearly, there are optical phenomena that can only be explained with quantum theory; the classical theory fails to explain the measurements. The shaping of Gaussian beams (Carl Friedrich Gauss and Lord Rayleigh) are carefully developed in an entire chapter where they are shown to be a subset of a more general class of Hermite-Gaussian beams. Gaussian beams satisfy the paraxial Helmholtz equation and occur in many optical resonators (the natural modes of spherical resonators) and lasers. In this chapter, the reader will also learn of types of beams with unique properties: Laguerre-Gaussian beams that carry angular momentum and can cause a torque in the illuminated object, and Bessel-Gaussian beams that do not diverge.

The presentation of Fourier optics (optical Fourier transforms, Fraunhofer diffraction, Fresnel diffraction, image formation with a lens and a 4-f imaging system, near field imaging, and the theory of holography) is an example of the exceedingly clear exposition of these important topics. Throughout *Photonics* the high quality of the presentation is remarkably maintained.

The chapter on electromagnetic optics (a vector theory, while wave optics is a scalar theory) begins with a photograph of James Clerk Maxwell (1831–1879). Although he is famous for the Maxwell equations that predict the propagation of electromagnetic waves, he was also one of the worlds great scientists and worked in fields such as statistical mechanics, kinetic theory of gases, color vision, and the stability of Saturns rings. His original equations (about 30) contained some twenty variables, used the Gaussian system of units, and were written in Cartesian coordinate forms. Nevertheless, these equations summarized all that was known at the time about electric and magnetic phenomena and their interaction. While Maxwell followed the mechanical model building of Faraday, and postulated the propagation of electromagnetic waves via an elastic medium that was an incompressible and massless fluid (the ether), the solution of the derived wave equation indicated that the waves are transverse waves (vibration orthogonal to the direction of propagation) and their velocity is almost identical to the measured velocity of light in vacuum. Therefore, it became understood that light is a transverse electromagnetic wave. Twenty years later Heinrich Hertz demonstrated the existence of electromagnetic waves and measured their properties of reflection, refraction, and polarization. It was Oliver Heaviside (1850–1925) who in 1886 reformulated the multitude of Maxwell equations into the four vector equations that we know today. These electromagnetic vector equations were also simultaneously and independently derived by Hertz. It is of note that Einstein, in his papers, referred to these equations as the Maxwell-Hertz equations.

The authors clearly explain the interaction of electromagnetic waves with various types of media: linear, nondispersive, homogeneous, and isotropic, and then they present similar equations for nonlinear, dispersive, and inhomogeneous or anisotropic media. From that discussion they derive the important equations of dispersion and absorption. The reader is also introduced to the classical Drude model of how light interacts with matter. Much of the phenomena that is described in the next chapters on polarization, photon-crystal optics, guided-wave optics, fiber optics, and resonator optics involves the solution of the wave equation for specific sets of boundary values.

The work of Emil Wolf was responsible for the development of the field of coherence theory in optics. In *Photonics* the authors provide a clear description of both spatial and temporal coherence and describe the propagation of partially coherent light in free space and in different optical systems. The reader is shown the physics and the mathematical definition of coherence time, coherence length, and power spectral density. The generation of interference is the experimental measure of coherence. Optical coherence tomography (actually optical low-coherence tomography) is based on a partially coherent (low coherence) light source with a short coherence length.

The chapter on photon optics rightly begins with the images of Max Planck (1858–1947) and Albert Einstein (1879–1955); the former predicted the quantized emission and absorption of light by matter, the latter predicted that light is composed of quanta of energy. While the authors do not formally derive the equations of quantum electrodynamics, they instead choose to teach photon optics within the framework of electromagnetic optics with some of the principles taken from quantum electrodynamics (QED). Many of these topics are critical to the understanding of detectors.

The modern scientist has a variety of photodetectors in the laboratory; *Photonics* presents a detailed discussion of the detectors and the physical principles that they are based on. Many organisms contain light detectors and the human eye is an example of a visible light intensity detector that can detect a single photon. It has a dynamic range (after dark adaptation) of several log units. What is the history of photocells or photoelectric detectors that are based in photovoltaic, photoconductive, or photoemissive properties? Edmond Becquerel discovered, in 1839, that light incident on a photosensitive surface such as selenium produces an electromotive force (voltage). In 1887, Heinrich Hertz published the paper, "On an effect of ultraviolet light on the electrical discharge." Hertz investigated the effect of light on spark discharges of a resonant circuit. In 1869, Hertz used the spectroscope of Bunsen and Kirchhoff to show that the maximum effect is caused by the ultraviolet region of the spectrum. Hertz also derived the Maxwell equations in a modern form and was thus responsible for disseminating Maxwells theory to the physics community in Europe. Philipp Lenard, a student of Hertz, continued the research on the photoelectric effect and was awarded the Nobel Prize in 1905 for his work on cathode rays. In 1888 Wilhelm Hallwachs showed that ultravioloet light removed negative charge from a zinc plate. One year later, Julius Elster and Hans Gritel showed that the photoelectric effect could be used for photometry. The quantum nature of the physics behind the photoelectric effect was finally understood, and in 1921 Albert Einstein was awarded the Nobel Prize for his discovery of the law of the photoelectric effect.

In subsequent years, many crude photodetectors based on the photoelectric effect were used with telescopes and replaced photographic methods. The Radio Corporation of America (RCA) was involved in the development of photomultiplier tubes during and after the second world war. In 1943 RCA manufactured the 1P21 photomultiplier tube that showed a low dark current and a high sensitivity. In 1946 it was used as the detector in telescope photometers. This tube was probably the most widely used photomultiplier tube by spectroscopists for many decades. In 1970, Willard Boyle and George Smith, working at Bell laboratories, published a paper in which they described the first charge-coupled device (CCD): a two-dimensional chip of doped silicon in which the photoemissive charges could be stored in potential wells. In the readout mode, the accumulated charges could be shifted from one potential well to another. It was suggested that this device could have applications in imaging. Today, CCD imagers are ubiquitous in research laboratories as well as on telescopes and satellites.

In the next chapters of *Photonics* we are taught how photons and atoms interact. Quantum mechanics is required to calculate the energy levels of atoms. Einsteins theory on absorption and emission from a two-level system, especially the concept of stimulated emission, and the associated rate equations provides the basis for the subsequent chapters on lasers. The discussion on the theory and rate equations of laser amplifiers and the technical descriptions of various lasers and light-emitting diodes (LEDs) is both comprehensive and readily understandable due to the clarity of the exposition.

A recurring theme in many branches of photonics is the behavior of electromagnetic waves in two and three-dimensional resonators. The authors point out that light inside a resonator is completely characterized by the electromagnetic field that can be expressed by a superposition of discrete orthogonal modes of different spatial distributions, different frequencies, and different polarizations. While the expansion functions of the field are not unique, it is often convenient to choose a set of three-dimensional standing waves to express the field. That was the approach of Dirac in 1927 that was so elegantly utilized in the doctoral thesis of Maria Göppert-Mayer in which she predicted the phenomena of two-photon absorption and emission. The calculation of the density of modes is analogous to the calculation of the allowed quantum states of confined electrons. The physical principles and the derived mathematical expressions explain the properties of the photonic devices that are described in the textbook.

In summary, based on a careful reading of this textbook, I find the physical explanations together with the analytical expressions to be exceptionally lucid. I think that the pedagogical approach of the authors is appropriate for the intended audience of their textbook. *Photonics* is comprehensive in exposition, well illustrated, and it promises to become another classic. I highly recommend this perspicuous book.