Elements of Photonics, Volume II: For Fiber and Integrated Optics. Keigo Iizuka
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ELEMENTS OF PHOTONICS

Volume II

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For Fiber and Integrated Optics

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PREFACE

After visiting leading optics laboratories for the purpose of producing the educational video *Fiber Optic Labs from Around the World* for the Institute of Electrical and Electronics Engineers (IEEE), I soon realized there was a short supply of photonics textbooks to accommodate the growing demand for photonics engineers and evolving fiber-optic products. This textbook was written to help fill this need.

From my teaching experiences at Harvard University and the University of Toronto, I learned a great deal about what students want in a textbook. For instance, students hate messy mathematical expressions that hide the physical meaning. They want explanations that start from the very basics, yet maintain simplicity and succinctness. Most students do not have a lot of time to spend reading and looking up references, so they value a well-organized text with everything at their fingertips. Furthermore, a textbook with a generous allotment of numerical examples helps them better understand the material and gives them greater confidence in tackling challenging problem sets. This book was written with the student in mind.

The book amalgamates fundamentals with applications and is appropriate as a text for a fourth year undergraduate course or first year graduate course. Students need not have a previous knowledge of optics, but college physics and mathematics are prerequisites.

Elements of Photonics is comprised of two volumes. Even though cohesiveness between the two volumes is maintained, each volume can be used as a stand-alone textbook.

Volume I is devoted to topics that apply to propagation in free space and special media such as anisotropic crystals. Chapter 1 begins with a description of Fourier optics, which is used throughout the book, followed by applications of Fourier optics such as the properties of lenses, optical image processing, and holography.

Chapter 2 deals with evanescent waves, which are the basis of diffraction unlimited optical microscopes whose power of resolution is far shorter than a wavelength of light.

Chapter 3 covers the Gaussian beam, which is the mode of propagation in free-space optical communication. Topics include Bessel beams characterized by an unusually long focal length, optical tweezers useful for manipulating microbiological objects like DNA, and laser cooling leading to noise-free spectroscopy.

Chapter 4 explains how light propagates in anisotropic media. Such a study is important because many electrooptic and acoustooptic crystals used for integrated optics are anisotropic. Only through this knowledge can one properly design integrated optics devices.

Chapter 5 comprehensively treats external field effects, such as the electrooptic effect, elastooptic effect, magnetooptic effect, and photorefractive effect. The treatment includes solid as well as liquid crystals and explains how these effects are applied to such integrated optics devices as switches, modulators, deflectors, tunable filters, tunable resonators, optical amplifiers, spatial light modulators, and liquid crystal television.

Chapter 6 deals with the state of polarization of light. Basic optical phenomena such as reflection, refraction, and deflection all depend on the state of polarization of the light. Ways of converting light to the desired state of polarization from an arbitrary state of polarization are explained.

Chapter 7 explains methods of constructing and using the Poincaré sphere. The Poincaré sphere is an elegant tool for describing and solving polarization problems in the optics laboratory.

Chapter 8 covers the phase conjugate wave. The major application is for optical image processing. For example, the phase conjugate wave can correct the phasefront distorted during propagation through a disturbing medium such as the atmosphere. It can also be used for reshaping the light pulse distorted due to a long transmission distance inside the optical fiber.

Volume II is devoted to topics that apply to fiber and integrated optics.

Chapter 9 explains how a lightwave propagates through a planar optical guide, which is the foundation of integrated optics. The concept of propagation modes is fully explored. Cases for multilayer optical guides are also included.

Chapter 10 is an extension of Chapter 9 and describes how to design a rectangular optical guide that confines the light two dimensionally in the x and y directions. Various types of rectangular optical guides used for integrated optics are compared. Electrode configurations needed for applying the electric field in the desired direction are also summarized.

Chapter 11 presents optical fibers, which are the key components in optical communication systems. Important considerations in the choice of optical fibers are attenuation during transmission and dispersion causing distortion of the light pulse. Such special-purpose optical fibers as the dispersion-shifted fiber, polarization-preserving fiber, diffraction grating imprinted fiber, and dual-mode fiber are described. Methods of cabling, splicing, and connecting multifiber cables are also touched on.

Chapter 12 contains a description of light detectors for laboratory as well as communication uses. Mechanisms for converting the information conveyed by photons into their electronic counterparts are introduced. Various detectors, such as the photomultiplier tube, the photodiode, and the avalanche photodiode, and various detection methods, such as direct detection, coherent detection, homodyne detection, and detection by stimulated Brillouin scattering, are described and their performance is compared for the proper choice in a given situation.

Chapter 13 begins with a brief review of relevant topics in quantum electronics, followed by an in-depth look at optical amplifiers. The optical amplifier has revolutionized the process of pulse regeneration in fiber-optic communication systems. The chapter compares two types of optical amplifier: the semiconductor optical amplifier and the erbium-doped fiber amplifier. Knowledge gained from the operation of a single fiber amplifier is applied to the analysis of concatenated fiber amplifiers.

Chapter 14 is devoted to lasers, which is a natural extension of the preceding chapter on optical amplifiers. The chapter begins with an overview of different types of lasers, followed by an in-depth treatment of semiconductor lasers, which are the preferred light sources for most fiber-optic communication systems. The basic relationship among the laser structure, materials, and operational characteristics are clarified. The ability to tune the laser wavelength, which is indispensible to the wavelength division multiplexing of the communication system, is addressed. The quantum well, quantum wire, and quantum dot laser diodes that have low threshold current and hence a high upper limit on the modulation frequency are also included. The erbium-doped or Raman fiber lasers that are simple in structure and easy to install in an optical fiber system are also explained.

In Chapter 15, an introduction to the nonlinear (Kerr) effect is presented. Optical devices based on the Kerr effect are controlled by photons and can respond much faster than those controlled by electrons. The chapter also provides the mechanism of formation of a soliton wave. A light pulse that propagates in an optical fiber spreads due to the dispersion effect of the fiber, but as the intensity of the pulse is increased, the nonlinear effect of the fiber starts to generate a movement directed toward the center of the light pulse. When these two counteracting movements are balanced, a soliton wave pulse that can propagate distortion-free over thousands of kilometers is formed. The attraction of distortion-free pulse propagation is that it can greatly reduce, or even eliminate, the need for pulse regenerators (repeaters) in long-haul fiber-optic communication systems.

Chapter 16 interweaves the design skills developed throughout the book with realistic problems in fiber-optic communication systems.

The problems at the end of each chapter are an integral part of the book and supplement the explanations in the text.

As a photonics textbook, each volume would be sufficient for a two-semester course. If time is really limited, Chapter 16 alone can serve as a crash course in fiber-optic communication systems and will give the student a good initiation to the subject.

For those who would like to specialize in optics, I highly recommend reading through each volume, carefully and repeatedly. Each chapter will widen your horizon of optics that much more. You will be amazed to discover how many new applications are born by adding a touch of imagination to a fundamental concept.

This two-volume work has been a long time in the making. I applaud Beatrice Shube, and George Telecki and Rosalyn Farkas of John Wiley & Sons for their superhuman patience. Sections of the manuscript went through several iterations of being written, erased, and then rewritten. As painstaking as this process was, the quality of the manuscript steadily improved with each rewrite.

I am very grateful to Professor Joseph W. Goodman of Stanford University who first suggested I publish my rough lecture notes in book form.

I am indebted especially to Mary Jean Giliberto, who spent countless hours proofreading the text, smoothing the grammatical glitches, and checking equations and numerical examples for completeness and accuracy. I greatly valued her comments and perspective during our many marathon discussions. This book was very much a partnership, in which she played a key role.

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