Photonic Devices

Photonic devices lie at the heart of the communications revolution, and have become a large and important part of the electronic engineering field, so much so that many colleges now treat this as a subject in its own right. With this in mind, the author has put together a unique textbook covering every major photonic device, and striking a careful balance between theoretical and practical concepts. The book assumes a basic knowledge of optics, semiconductors, and electromagnetic waves; many of the key background concepts are reviewed in the first chapter. Devices covered include optical fibers, couplers, electro-optic devices, magneto-optic devices, acousto-optic devices, nonlinear optical devices, optical amplifiers, lasers, light-emitting diodes, and photodetectors. Problems are included at the end of each chapter and a solutions set is available. The book is ideal for senior undergraduate and graduate courses, but being device-driven it is also an excellent reference for engineers.

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To my family

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Preface

Over the past two decades, photonics, the use of photons for engineering applications, has gradually become established as a well-defined engineering discipline. Photonics has developed from studies in crystal optics, guided-wave optics, nonlinear optics, lasers, and semiconductor optoelectronics. Though many excellent books exist on each of these subjects, and several have been written specifically to address photonics, it is still difficult to find one book where the diverse core subjects that are central to the study of photonic devices are presented with a good balance of breadth and depth of coverage. Through my teaching of undergraduate courses, I have found it very effective to introduce the field of photonics to undergraduate students using the rigorous, systematic approach of this book. Through my experience of working with graduate students in research, I have found that such a book is very much needed to prepare a solid foundation for graduate students who intend to major, or minor, in photonics. Through my teaching experience, I have found it highly desirable and beneficial for both instructors and students to have ample examples and problems that are well thought out and fully integrated with the subjects covered in the text. This book is written to address these needs.

I began this project in early 1994 after many years of teaching undergraduate and graduate courses in lasers, nonlinear optics, quantum electronics, and quantum mechanics. Though I had already accumulated a large collection of classnotes and problem sets when I started this project, it still took me exactly nine years to finish writing this book, with fully one-third of that time devoted to the work on examples and problems. Then, it took another year to prepare the figures. My students, both those in my classes and those in my research group, have been highly collaborative with the writing of this book. Throughout this process, I have taught various parts in different undergraduate and graduate courses to several hundred students. These students range from junior undergraduates to second-year graduates majoring in the diverse fields of photonics, solid-state electronics, electromagnetics, materials engineering, mechanical engineering, bioengineering, physics, chemistry, and many other disciplines. Many of their suggestions and feedback have been incorporated. All of the equations, examples, and problem solutions have been checked by several highly capable students. All of the figures were produced, originally, by my graduate students. The manuscript underwent three major and numerous minor revisions before the book was finalized.

Objectives

This book is written for advanced undergraduate students and new graduate students who are interested in studying photonics as an engineering subject. A novice graduate student who plans to major in photonics can study this book thoroughly over a one-year period to lay a very solid foundation. It is also intended for practicing engineers and scientists who wish to broaden or deepen their knowledge in the principles of photonic devices. The objectives of this book are for a student (1) to obtain a good understanding of the core theory of photonic devices through coherent coverage of the subject, (2) to develop a deep physical insight into the principles of photonic devices through descriptive and illustrative approaches, (3) to gain realistic concepts of the functions of practical devices through numerical examples and discussions, and (4) to lay a solid foundation for further study and research in the photonics field through rigorous analytical treatment of the subject.

Guiding principles

To fulfill the objectives through a consistent approach, I followed several guidelines that I laid down for myself at the beginning of this project:

1. To address the subject at the device level, as the book title suggests. The physics and principles of devices are treated in depth, but the fabrication and processing of devices are not touched. The functions and characteristics of devices are also emphasized, but specific applications in subsystems and systems are not discussed for the reason that they are too diverse and vary quickly as time goes on.
2. To cover both bulk and guided-wave devices, with sufficient emphasis on guided-wave devices to reflect the development of photonics into integrated photonics.
3. To use a macroscopic treatment with two central approaches: (a) to treat the optical properties of materials through reference to the susceptibility tensor, χ, and permittivity tensor, ϵ; and (b) to treat the interaction of optical waves using coupled-wave theory for bulk devices and coupled-mode theory for guided-wave devices. With these approaches, it is possible to treat the majority of devices in great depth without ever touching quantum mechanics. For topics that necessitate an understanding of quantum concepts, I have adopted an approach that requires as little quantum mechanics background from the students as possible.

4. To balance both physics and engineering aspects with descriptive and analytical approaches to a significant, and consistent, depth throughout the entire book.
5. To concentrate on selected key topics and address them with sufficient rigor and thoroughness. On the one hand, analytical formulations and results that can be used at the level of practical applications and research are obtained. On the other, detailed and tedious mathematical derivations are avoided in favor of developing physical insight through an emphasis on the physical meanings of the analytical results.
6. To make the tables and figures useful and informative by using real data if possible while avoiding tedious details. Thus, the majority of the figures depicted in the book can be generated by the reader with realistic data using the analytical formulations obtained in the text.
7. To develop the concepts and data of working devices into realistic examples and problems.

Scope and structure

Photonics is a diverse field that can be addressed at various levels from many different perspectives. The scope and structure of this book are basically set by the guiding principles delineated above. This book focuses on the core topics of photonics at the device level covering both bulk and guided-wave devices. The entire book, as well as each chapter, is highly structured. Except for the general prerequisites described below, this book is written to be self-contained. General background and formulations that are needed for more than one chapter are provided in a few properly located individual chapters. Specific background needed only for the topics addressed within a particular chapter is provided at the start of each chapter. This arrangement allows the chapters and sections covering advanced topics to be treated as modules that can be added or dropped independently in a course or a study plan. Thus a minimum number of prerequisites are needed of the reader to begin studying any part of this book.

This book is divided into five parts. The first part consists of only one chapter that provides the relevant background in electromagnetics and optics for the entire book. This part also introduces χ and ϵ as the central concept for describing optical properties of materials. Part II covers four chapters on waveguides and couplers and lays the foundation for guided-wave devices. This part also develops coupled-wave and coupled-mode theories, which are used to formulate optical interactions throughout the entire book. Part III consists of four chapters covering devices based on electro-optics, magneto-optics, acousto-optics, and nonlinear optics. The fourth part contains two chapters on general discussions of laser amplifiers and laser oscillators. Fiber amplifiers and fiber lasers are specifically discussed in depth. Part V covers optoelectronic devices in three chapters. One chapter, i.e., Chapter 12, provides the background on semiconductors relevant to optoelectronics. The other two chapters in Part V cover semiconductor lasers, LEDs, and photodetectors.

All chapters are organized in a consistent manner that mirrors the structure of the book. Basically, each begins with a general introduction of the underlying fundamental physics of the topics covered in the chapter, followed by general formulations of the physical effects. The principles and functions of bulk devices are then discussed. In the final section, or sections, of a chapter, guided-wave devices are addressed.

Symbols and units

Consistent symbols and notations are used throughout the entire book. The symbols and notations are chosen based on two criteria: (1) they are the same as those commonly used in the literature, whenever possible; and (2) they are intuitive to recognize and easy to distinguish. I also choose not to use many special fonts; thus, *script* is the only special font used. However, in a book like this that covers a diverse range of topics, it is inevitable that one quickly runs into a situation that a particular symbol is commonly used in the literature to represent two or more different meanings on different occasions. Whenever there is no confusion, I still choose to use the common symbol for different meanings. Otherwise, I choose to use subscripts and superscripts to clarify the meaning of the symbols. The system of symbols and notations followed throughout this book is described in Appendix A, and a partial list of symbols is presented later among these preliminary pages.

The SI metric system, which is summarized in Appendix C, is used. The values of some important fundamental physical constants in SI units are listed in Appendix D. Values of all the parameters listed in the tables throughout the chapters in this book are commonly given in SI units. On some rare occasions when the value of a parameter is not quoted in an SI unit, a conversion to the SI unit is given in the text.

Examples and problems

There are a total of 164 examples and more than 600 problems in the book. The examples and problems justly take up about one-third of the volume of this book as they took me about one-third of the time spent on this entire project. All examples and problems are originally generated and they are evenly distributed across the entire book. To illustrate the concepts developed in the text, most examples are realistic numerical problems based on working devices. Problems are tied closely to the text and examples. There are four types of problems: (1) qualitative questions on general concepts, (2) analytical steps leading to important results presented in the text because filling such steps by the reader enhances understanding, (3) further development of certain concepts covered in the text into an advanced level beyond the general depth of the text, and (4) practical numerical problems reduced from realistic working devices. The problems are collected at the end of each chapter and are identified with the relevant section. They are not grouped by type, but are arranged in an order that parallels the presentation of the text. This arrangement, though not what I prefer, facilitates adding or dropping a particular topic module in a course syllabus or study plan.

Bibliography and reading lists

Though this book is intended to be self-contained, a reader always gains a deeper understanding and a different perspective of a topic by reading other books and journal articles. To maintain the coherence of the presentation in the text and to avoid unnecessarily distracting a reader, references and footnotes are rarely used. Instead, a bibliography containing reference books and a list of useful journal articles for advanced reading are placed at the end of each chapter. The reference books in a bibliography are meant to help a reader obtain a different perspective or further information on a particular topic. The journal articles listed in a reading list are meant for a reader to go beyond the level of the presentation in this book. The bibliographies and reading lists are rather extensive, but are carefully selected to limit their sizes to a manageable level.

Prerequisites and use of the book

The prerequisites of this book include background knowledge in optics covered in a college-level general physics course, a foundation in electromagnetic waves preferably in an electromagnetics course, and some background in semiconductors and quantum physics obtained in an introductory solid-state electronics course. In my experience, it is possible for a student who has only minimal background in these areas to succeed in an undergraduate course using this book if the background chapters of this book are studied thoroughly. Within the book, the prerequisites of each section are listed in a table in Appendix B.

This book can be used in a one-year undergraduate course by dropping advanced sections, and thus cutting about one-third of the material in the book, while covering every chapter. It can also be used in a one-year intensive graduate course covering all sections. I also envision this book as being used at different levels in different courses, including one-quarter or one-semester courses, depending on the interest and emphasis of a particular curriculum. The modular structure of this book and the table of prerequisites given in Appendix B make it very easy for an instructor to put together a specific course syllabus and for an independent reader to make up a study plan.

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Before acknowledging the many people who have made direct contributions to this project, I would like to pay tribute first to Professor Nicolaas Bloembergen, who brought me into the fields of nonlinear optics and lasers and guided me through my graduate studies, which began 26 years ago. I would like to express my gratitude to Erich P. Ippen, Chi Hsiang Lee, Thomas B. Simpson, and Jeffery Y. Tsao for their friendship, support, and intellectual illumination over more than 20 years. I also thank my colleagues Tatsuo Itoh and Kung Yao for their encouragement during the course of writing this book.

At the end of this long project, I want to give my deepest appreciation to my wife, Vida, and my daughter, Janelle, for their support, patience, and sacrifices throughout the past ten years while I indulged myself in this most expensive and time-consuming hobby. My editors, Philip Meyler, who convinced me to start this project, and Eric Willner, who helped me to finish it, at Cambridge University Press deserve my special thanks not only for their input and assistance but particularly for their patience and understanding when this project dragged on longer than originally expected.

Many students have contributed to this project. Numerous students in my classes have given me valuable input and feedback. Two overlapping groups of graduate students have made direct contributions to this project. Andrew K. Newman, Juan C. Garcia, Kevin Geary, and Sze-Chun Chan formed a study group to read the text, check the equations, and check my solutions of the examples and problems. How-Foo Chen, Sheng-Kwang Hwang, Shuo Tang, Fan-Yi Lin, Sze-Chun Chan, Margaret C. Chiang, and Tyan-Lin Wang shared the efforts to produce all of the electronic files for the figures from my drafts. They applied their research abilities and skills to generate many original plots based on real data of materials and devices. Two of them, Sze-Chun Chan and Margaret C. Chiang, made the extraordinary efforts of finalizing all figures uniformly. I am truly blessed with these highly capable and supporting students. Their crucial contributions to the completion of this project are most appreciated. Thanks are also due to my copy editor, Lesley Thomas, and production editor, Joseph Bottrill, for their numerous valuable suggestions and professional efforts at the final stage of this project.