Fundamentals of Guided-Wave Optoelectronic Devices

Optoelectronic guided-wave devices are used in a wide range of optical fiber communication and optoelectronic systems. In such networks, the electrical and the optical characteristics of guided-wave devices, and the interplay between them, have a profound effect on system design and overall performance.

Uniquely, this book combines both the optical and electrical behavior of guided-wave optoelectronic devices so that the interwoven properties, including interconnections to external components, are easily understood. It provides the key concepts and analytical techniques that readers can apply to current and future devices. It also presents the impact of material properties on guided-wave devices, and emphasizes the importance of time-dependent interactions between electrical and optical signals. The properties of the devices are presented and compared in terms of system requirements in applications. This is an ideal reference for graduate students and researchers in electrical engineering and applied physics departments, as well as practitioners in the optoelectronics industry.

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CAMBRIDGE
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University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314-321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre, New Delhi - 110025, India

103 Penang Road, #05-06/07, Visioncrest Commercial, Singapore 238467

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www.cambridge.org
Information on this title: www.cambridge.org/9780521868235

First published 2010

A catalogue record for this publication is available from the British Library

ISBN 978-0-521-86823-5 Hardback

Contents

Preface

Optoelectronic guided-wave devices are used in many optical fiber communication and optoelectronic systems. In these systems optical and electrical signals are transmitted, received, multiplexed and converted by means of a variety of procedures. In guided-wave optoelectronic devices, laser radiation propagates in a waveguide and energy can be coupled effectively to and from single mode optical fibers. The properties of materials used to fabricate the waveguides have a profound effect on the phase, amplitude or directional variations of the optical waves used for the generation, modulation, switching, conversion, multiplexing, and detection of optical signals. The small lateral dimensions of the waveguide structures provide for efficient control of their optical properties by means of electrical voltages or currents. On the other hand, optical signals are converted back into electrical signals via detectors. Therefore, the electrical characteristics of these devices are as important as their optical properties. Devices may potentially be monolithically integrated optically on the same chip. This is called photonic integration. Optical components may also be integrated, monolithically, with electronic devices on the same chip. This is called optoelectronic integration. In earlier times, these were called integrated optical devices, as opposed to integrated electronic devices.

The manner in which different material properties affect the electrical characteristics as well as the propagation of optical signals in optoelectronic devices is of great importance. Also of considerable importance is the process of back and forth conversion of the electrical signals and of the optical signals. Furthermore, because the electrical signals must be received or transmitted to external circuits, how the devices are interconnected or driven by other electrical systems is also of great importance. The electrical signals may propagate at microwave frequencies within the optoelectronic devices. Therefore their performances must be analyzed and evaluated in terms of time-dependent interactions of electrical and optical waves.

A large number of books are already available in the technical literature on the optical analysis of waveguides. There are also many books that analyze the specific properties of electrical devices and circuits. This book is intended for use as a graduate level reference or text book. It provides an analysis of guided-wave devices from both the optical and the electrical points of view so that the interwoven optical and electrical properties of the devices, including their optical and electrical interconnections to external components, can be represented clearly. When appropriate, the impact of material properties on guided-wave devices is presented and the importance of time-dependent interactions between electrical and optical signals is emphasized. The book emphasizes fundamental concepts and analytical techniques rather than giving a comprehensive coverage of different devices. The intention of the author is to illustrate these concepts and analytical techniques clearly so that they can be applied to all guided-wave optoelectronic devices, including many that are not covered in this book, or have not been investigated as yet.

Optical waveguides can be divided into planar waveguides (two-dimensional) and channel (three-dimensional) waveguides. The fabrication and analysis of optical waveguides constitute the most basic knowledge needed for understanding and designing guided-wave components. Chapter 1 begins with a discussion of the formation and the modal analysis of planar and channel optical waveguides. The optical analysis presented is similar to those in other books concerned with waveguides. Differently from other guided-wave books, a two-dimensional Green's function approach is presented which could be used to analyze propagation of planar guided waves in general. Also included is a description of the materials technologies employed for fabrication of optical waveguides.

The mathematical analysis of channel waveguide modes is already complicated because of the geometry of the boundaries of waveguides. Yet, in order to understand guided-wave devices, it is necessary to analyze the mutual interactions between optical waves in two or more channel waveguides. Therefore approximation techniques such as perturbation and coupled mode analyses are introduced in Chapter 2. They could be used to analyze the coupled waveguides and the interaction of optical waves with changes in material properties. Examples of waveguide components, such as the grating filter, the directional coupler and the Mach–Zehnder interferometer, are used as examples to illustrate these approximate analytical techniques. Another powerful technique useful for analysis of multiple waveguide components is the super mode analysis. It is introduced next in Chapter 2, after the coupled mode analysis. Additional insight into the properties of guided-wave devices such as the directional coupler, the Y-branch coupler and the interference coupler can be obtained from super mode analysis.

Optical amplification and photo-carrier generation are the basis of lasers and photodetectors and they are described in many other books. In this book, how changing the material properties affects the propagation and interaction of optical waves, thereby producing modulation, switching, beam scanning, etc. in optoelectronic components is treated in detail. Electro-optical effects such as the linear electro-optic effect, the electro-absorption effect and the electro-refraction effect are discussed in Chapter 3.

In optoelectronic applications, electrical fields are created by time varying electrical voltages applied to electrode structures of the components. Analytical techniques for dealing with the time varying electrical properties of optoelectronic guided-wave structures are reviewed in Chapter 4. These techniques include the analyses of electrical fields produced by time varying voltages, the electro-optical effects produced by the electric fields, and the representation of the parameters of electro-optic devices by lumped circuit elements at lower frequencies and by traveling wave transmission lines at higher frequencies. Discussion in this chapter includes issues related to impedance matching such devices to microwave sources. Note that the frequency response and the electrical behavior of the device, in turn, place additional demands on the design of electrode and waveguide configurations.

Chapters 5 and 6 provide a description of guided-wave devices using planar and channel waveguides. The analyses of these devices utilize all the optical and electrical analytical tools, material properties and electro-optical effects described in Chapters 1 to 4. The optical and electrical performances of such devices are evaluated from the application point of view and the properties of different devices designed for the same application are compared to each other.

In planar waveguides, optical guided waves can propagate in any direction, following the contour of the waveguide layer. Summations of planar guided waves form divergent, converging, diffracted and deflected waves. Therefore, how to harness the refraction, diffraction and reflection of planar guided waves by planar waveguide devices is also the focus of Chapter 5. However, most of the applications will involve channel waveguide devices because of the ease of coupling to optical fibers, the superior electro-optical performance derived from the small lateral dimension of channel waveguides, and the advantage of small electrical capacitance of the device at high electrical frequencies. Devices that perform the same practical functions such as power division, wavelength filtering, resonance filtering, signal time delay, switching, multiplexing, and modulation are described, analyzed, and compared together. Their time-dependent characteristics are derived from combined microwave and optical analyses. Device performances are evaluated in terms of the systems requirements in applications. This is an unusual feature of the book.

Acknowledgement

The author is indebted to Professors H. H. Wieder and Paul K. L. Yu at the University of California, San Diego for reviewing the manuscript. Our mission as a university is to explain the basic principles of guided-wave optoelectronics as best we can, and to continue to improve our explanations. The author welcomes any comments from readers. Comments can be sent directly to wchang@ucsd.edu.