Fundamentals of Optical Waveguides

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Second Edition

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To Kuniko, Hiroaki and Masaaki

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Preface to the First Edition

This book is intended to describe the theoretical basis of optical waveguides with particular emphasis on the transmission theory. In order to investigate and develop optical fiber communication systems and planar lightwave circuits thorough understanding of the principle of lightwave propagation and its application to the design of practical optical devices are required. To answer these purposes, the book explains important knowledge and analysis methods in detail.

The book consists of ten chapters. In Chapter 1 fundamental wave theories of optical waveguides, which are necessary to understand the lightwave propagation phenomena in the waveguides, are described. Chapters 2 and 3 deal with the transmission characteristics in planar optical waveguides and optical fibers, respectively. The analytical treatments in Chapters 2 and 3 are quite important to understand the basic subjects of waveguides such as (1) mode concepts and electromagnetic field distributions, (2) dispersion equation and propagation constants, and (3) chromatic dispersion and transmission bandwidths. Directional couplers and Bragg gratings are indispensable to construct practical lightwave circuits. In Chapter 4 coupled mode theory to deal with these devices is explained in detail and concrete derivation techniques of the coupling coefficients for several practical devices are presented. Chapter 5 treats nonlinear optical effects in optical fibers such as optical solitons, stimulated Raman scattering, stimulated Brillouin scattering and second-harmonic generation. Though the nonlinearity of silica-based fiber is quite small, several nonlinear optical effects manifest themselves conspicuously owing to the high power density and long interaction length in fibers. Generally nonlinear optical effects are thought to be harmful to communication systems. But, if we fully understand nonlinear optical effects and make good use of them we can construct much more versatile communication systems and information processing devices. From Chapter 6 to 8 various numerical analysis methods are presented; they are, the finite element method (FEM) waveguide and stress analyses, beam propagation methods (BPM) based on the fast Fourier transform (FFT) and finite difference methods (FDM), and the staircase concatenation method. In the analysis and design of practical lightwave circuits, we often encounter problems to which analytical methods cannot be applied due to the complex waveguide structure and insufficient accuracy in the results. We should rely on numerical techniques in such cases. The finite element method is suitable for the mode analysis and stress analysis of optical waveguides having arbitrary and complicated cross-sectional geometries.

The beam propagation method is the most powerful technique for investigating linear and nonlinear lightwave propagation phenomena in axially varying waveguides such as curvilinear directional couplers, branching and combining waveguides and tapered waveguides. BPM is also quite important for the analysis of ultrashort light pulse propagation in optical fibers. Since FEM and BPM are general-purpose numerical methods they will become indispensable tools for the research and development of optical fiber communication systems and planar lightwave circuits. In Chapters 6 to 8, many examples of numerical analyses are presented for practically important waveguide devices. The staircase concatenation method is a classical technique for the analysis of axially varying waveguides. Although FEM and BPM are suitable for the majority of cases and the staircase concatenation method is not widely used in lightwave problems, the author believes it is important to understand the basic concepts of these numerical methods. In Chapter 9, various important planar lightwave circuit (PLC) devices are described in detail. Arrayed-waveguide grating multiplexers (AWGs) are quite important wavelength filters for wavelength division multiplexing (WDM) systems. Therefore the basic operational principles, design procedures of AWGs, as well as their performances and applications, are extensively explained. Finally Chapter 10 serves to describe several important theorems and formulas which are the bases for the derivation of various equations throughout the book.

A large number of individuals have contributed, either directly or indirectly, to the completion of this book. Thanks are expressed particularly to the late Professor Takanori Okoshi of the University of Tokyo for his continuous encouragement and support. I also owe a great deal of technical support to my colleagues in NTT Photonics Laboratories. I am thankful to Professor Un-Chul Paek of Kwangju Institute of Science & Technology, Korea, and Dr. Ivan P. Kaminow of Bell Labs, Lucent Technologies, who gave me the opportunity to publish this book. I would like to express my gratitude to Prof. Gambling of City University of Hong Kong who reviewed most of the theoretical sections and made extensive suggestions. I am also thankful to Professor Ryouichi Itoh of the University of Tokyo, who suggested writing the original Japanese edition of this book.

May 1999
Katsunari Okamoto

Preface to the Second Edition

Since the publication of the first edition of this book in 1999, dramatic advancement has occurred in the field of optical fibers and planar lightwave circuits (PLCs). Photonic crystal fibers (PCFs) or holey fibers (HFs) are a completely new class of fibers. Light confinement to the core is achieved by the Bragg reflection in a hollow-core PCF. To the contrary, light is confined to the core by the effective refractive-index difference between the solid core and holey cladding in the solid-core HF. One of the most striking features of PCFs is that zero-dispersion wavelength can be shifted down to visible wavelength region. This makes it possible to generate coherent and broadband supercontinuum light from visible wavelength to near infrared wavelength region. Coherent and ultra broadband light is very important not only to telecommunications but also to applications such as optical coherence tomography and frequency metrology.

The research on PLCs has been done for more than 30 years. However, PLC and arrayed-waveguide grating (AWG) began to be practically used in optical fiber systems from the middle of 1990s. Therefore, PLCs and AWGs were in their progress when the first edition of this book was published. Performances and functionalities of AWGs have advanced dramatically after the first edition. As an example, 4200-ch AWG with 5-GHz channel spacing has been fabricated in the laboratory. Narrow-channel and large channel-count AWGs will be important not only in telecommunications but also in spectroscopy.

Based on these rapid advances in optical waveguide devices over the last six years, the publisher and I deemed it necessary to bring out this second edition in order to continue to provide a comprehensive knowledge to the readers.

New subjects have been brought into Chapters 2, 3, 5, 6, 7 and 9. Multimode interference (MMI) devices, which have been added to Chapter 2, are very important integrated optical components which can perform unique splitting and combining functions. In Chapter 3, detailed discussion of the polarization mode dispersion (PMD) and dispersion control in single-mode fibers are added together with the comprehensive treatment of the PCFs. Four-wave mixing (FWM) that has been added to Chapter 5 is an important nonlinear effect especially in wavelength division multiplexing (WDM) systems.

High-index contrast PLCs such as Silicon-on-Insulator (SOI) waveguides are becoming increasingly important to construct optoelectronics integrated circuits. In order to deal with high-index contrast waveguides, semi-vector analysis becomes prerequisite. In Chapters 6 and 7, semi-vector finite element method

(FEM) analysis and beam propagation method (BPM) analysis have been newly added. Moreover, comprehensive treatment of the finite difference time domain (FDTD) method is introduced in Chapter 7.

Almost all of the material in Chapter 9 is new because of recent advances in PLCs and AWGs. Readers will acquire comprehensive understanding of the operational principles in various kinds of flat spectral-response AWGs. Origin of crosstalk and dispersion in AWGs are described thoroughly. Various kinds of optical-layer signal processing devices, such as reconfigurable optical add/drop multiplexers (ROADM), dispersion slope equalizers, PMD equalizers, etc., have been described.

I am indebted to a large number of people for the work on which this second edition of the book is based. First, I should like to thank the late Professor Takanori Okoshi of the University of Tokyo for his continuous encouragement and support. I owe a great deal of technical support to my colleagues in NTT Photonics Laboratories. I am thankful to Professor Un-Chul Paek of Gwangju Institute of Science and Technology, Korea, and Dr Ivan P. Kaminow of Kaminow Lightwave Technology, USA, who gave me the opportunity to publish the book. I am also grateful to Prof. Gambling of LTK Industries Ltd, Hong Kong, who made extensive suggestions to the first edition of the book.

Finally, I wish to express my hearty thanks to my wife, Kuniko, and my sons, Hiroaki and Masaaki, for their warm support in completing the book.

June 2005
Katsunari Okamoto