ELECTROMAGNETIC WAVES PIER 11

Progress In Electromagnetics Research

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Methods for Modeling and Simulation of Guided-Wave Optoelectronic Devices:

Part II: Waves and Interactions

Editor: W. P. Huang

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METHODS FOR MODELING AND SIMULATION OF GUIDED-WAVE OPTOELECTRONIC DEVICES: PART II: WAVES AND INTERACTIONS

PREFACE

Optoelectronics is an emerging technology that melds the capability of photonics and microelectronics and has produced a variety of novel and useful devices for telecommunications, interconnections and signal processings. There has been tremendous progress in materials, fabrication technologies, packaging and integration, as well as system applications of optoelectronic devices. For example, modern epitaxial growth and lithography techniques allow precise control and engineering of material and geometrical properties. As a result, high-performance devices such as strained-layer multiple-quantum-well lasers and modulators have been demonstrated. So far, most of the these devices are still in the research and development stage and wide-spread applications of sophisticated optoelectronic devices are yet to be realized.

One of the difficulties for engineering, manufacturing as well as research and development of optoelectronic devices for system applications is the lack of powerful computerized design tools based on modeling and simulation. Up to now, development and engineering of optoelectronic devices still follow a pattern of design, fabrication, characterization and re-design process. Such an approach, though fruitful in the early research stage in discovering and verifying new ideas, is no longer adequate for optimization and timely engineering of sophisticated optoelectronic devices to specifications. The situation becomes even more acute for the advanced optoelectronic devices in which the number of adjustable material and geometrical parameters is large. In this respect, computer-aided modeling and simulation may be used to gain useful insight beyond intuition, to assist in detailed device characterization and optimization, and to increase efficiency and reduce cost. Therefore, it is imperative to develop powerful computer-aided modeling and simulation tools that are accurate, efficient, robust and user-friendly.

The objectives of PIER 10 and 11 are to report on the state-of-the-art methods being employed and/or developed for modeling and analysis of guided-wave optoelectronic devices. The focus is on the mathematical (both analytical and numerical) techniques that are adapted and applied to the waves and fields as described by Maxwell's equations with approximations suitable for optical guided-wave devices. Physical ideas and device concepts of guided-wave optoelectronics will be disussed in conjunction with the modeling and analysis methods, but will not be the central concern. The book will serve as a reference book for the research workers and graduate students who are interested in optoelectronics. In particular, it will allow those who have been in the field of optoelectronics to familiarize the various approaches to the modeling and analysis. In addition, it will be helpful for those who wish to enter the field to understand the features and the subtleties pertinent to the electromagnetic waves in optoelectronics.

PIER 11, Part II of the two-volume series entitled ``Methods for modeling and simulation of guided-wave optoelectronic devices", deals with physical models and mathematical algorithms for simulation of electromagnetic wave propagation in and interaction with optical waveguide structures of arbitrary index distributions and geometrical shapes. The main focus of the methods presented in this volume is to simulate wave propagation and interaction with media in longitudinally nonuniform structures. Different from the techniques presented in PIER 10, Part I: Modes and Couplings, the methods in this volume belong to the full-wave approach and is therefore more rigorous. Most of these methods may be used to calculate the guided modes. More importantly, they are also capable of simulating radiative fields in addition to the propagation and coupling of the guided modes.

Chapter 1 by Xu and Huang describes the finite-difference beam propagation method (FD-BPM) and its applications in guided-wave optics. The beam propagation method (BPM) was first introduced to guided-wave optics by Feit and Fleck in late seventies [1] and became popular in late eighties. The original BPM utilizes a FFT algorithm and solves paraxial scalar wave equation. New algorithms such as finite-difference (FD) schemes have been used and the FD-BPM is shown to be superior to the conventional FFT-BPM in terms of efficiency (i.e., the computation counts are in proportion to N rather than N*ln*(N) where N is the number of mesh points) and flexibility (e.g., use of transparent boundary conditions and nonuniform meshes, etc.). In addition, the finite-difference schemes have been successfully applied to the solutions of semi and full-vectorial and/or wide-angle and Helmholtz wave equations. In Chapter 1, a systematic derivation for the mathematical formulations of vectorial, semi-vectorial as well as scalar waves under one-way, wide-angle and paraxial conditions is presented. An implicit weighted finite-difference scheme to solve the governing equations is discussed in great detail. The applications of the FD-BPM are illustrated by way of examples. A comparison between several existing FD schemes is also given. Recently, there has been a series of new developments in the finite-difference beam propagation methods. New finite-differencing schemes have been proposed [2-4], new boundary conditions introduced [5,6]. Also, a number of methods to treat wide-angle propagation and reflections by either solving the Helmholtz equations in frequency domain [7-11] or the time-dependent wave equations [12,13] have been developed and reported.

A special finite-difference beam propagation method called the method of lines based beam propagation method (MOL-BPM) is discussed by Pregla in Chapter 2. The method-of-line based beam propagation method (MOL-BPM) is especially suitable for simulation of wave propagation in multi-layered waveguide structures. Unlike the finite-difference beam propagation method (FD-BPM), the MOL-BPM usually does not discretize the governing equations in the entire three-dimensional space. Rather, it discretizes only along one or two dimensions and seeks analytical solutions along the lines of discretization. For the optical rib waveguide, for instance, the MOL-BPM utilizes the analytical expressions for guided and radiation modes in the multi-layer slab waveguides and discretizes only along the lateral and the longitudinal directions if necessary. Several features of the MOL-BPM are discussed in Chapter 2, including a two-step algorithm, the absorbing boundary conditions, the reflecting schemes, and the algorithms for vector waves.

One of the difficulties associated with the finite-difference methods is that one has to diagonalize matrix equations whose orders are equal to total number of discretization points. For the one-way FD-BPM in three-dimension, the number of mesh points over the transverse cross-section may be large and the problem becomes much more acute for the reflecting and time-domain BPM. This problem may be solved by using the alternative-direction implicit (ADI) algorithms [3,11] or the explicit schemes [4,8,10]. Another approach to overcome this difficulty is presented by Fleck, Jr. in Chapter 3. By applying a well-known Lanczos reduction algorithm, propagation of a field over a limited distance may be approximated accurately by a set of orthogonal vectors. These Lanczos vectors form a subspace in which the matrix representation of the propagating operator is of low order and diagonalization trivial. Another advantage of the Lanczos reduction scheme is that it is directly applicable to solutions of one-way Helmholtz equation in terms of a square-root operator. Applications of the Lanczos scheme to longitudinally invariant waveguide structures have been very successful in terms of accuracy and efficiency, whereas some concerns arise when it is used for the longitudinally variant structures as mentioned in Chapter 3.

Another method -- the collocation method -- is discussed by Sharma in Chapter 4. The idea of the collocation method is to seek solutions of the wave equations in the form of a linear expansion of orthogonal functions. The expansion coefficients are obtained by imposing the condition that the trial solution satisfies the governing equation exactly at certain discrete points on the independent variable plane or the collocation points. By applying the collocation method, the partial differential equation is reduced to a finite set of ordinary differential equations. As such, paraxial and one-way Helmholtz equations may be treated similarly. Several key issues such as the stability of the collocation method, the choice of base functions as well as the applications of the method to different waveguide structures are discussed in detail in this chapter.

In Chapter 5, Safavi-Naeini and Chow present an analytical method based on physical optics for analysis of waveguide junctions. The junction problem represents one of the fundamental structures which serve as building-blocks for many guided-wave optoelectronic devices. Although several analytical (such as the mode-matching transfer matrix method) and numerical (such as the method of lines based beam propagation method and the finite-difference time-domain technique) methods can be used to simulate the junction problem, a rigorous analysis including both guided and radiative fields is complicated and time-consuming. In this respect, the physical optics method provides an attractive alternative which is simpler and more efficient. Physical optics (PO) is an approximate technique for finding the scattering field by an object from the knowledge of the field on its surface. By physical optics estimation of the fields over a dielectric interface, the junction problem may be formulated in terms of the junction interface fields and analytical expressions for the transmitted, reflected and radiative fields may be derived. As demonstrated in Chapter 5, the physical optics method produces results that are in excellent agreement with the rigorous methods such as the finite-difference time-domain (FDTD) method. The applications of the PO method to waveguide bends and branches are also discussed in Chapter 5. Other areas of applications for the PO method may be the planner optical waveguide structures such as optical star couplers, array-waveguide demultiplexers and diffractive grating reflectors. Due to the sizes of these structures, a full-wave simulation by the existing numerical techniques appears to be difficult. Use of the physical optics method is more accurate than the simple geometrical optics (GO) method often used for these structures and more efficient than the full-wave numerical methods.

The finite-difference time-domain method (FDTD) is discussed by Chu and Chaudhuri in Chapter 6. The finite-difference time-domain method solves the Maxwell's equations or reduced semi-vectorial and scalar wave equations in time-domain by an explicit finite-difference scheme. It was introduced to guided-wave optics in late 80s and became increasingly popular due to its attractive features such as ease of implementation, full-wave simulation of multiple reflections and radiations as well as wave propagation in time-domain. A detailed description of the FDTD algorithms is given and important issues such as the stability criterion, numerical error analysis, absorbing boundary conditions, source excitations, etc., are discussed. The applications of the FDTD to a traveling wave Mach-Zehnder modulator and a distributed Bragg reflector are presented to illustrate the salient features of the method. Recently, the FDTD technique has been applied to simulation of dispersive and nonlinear media [14-17].

In the previous chapters, the primary concern is on how an optical wave propagation is affected by the waveguiding structures or media. The reaction of the medium to the wave field is ignored except for some nonlinear waveguide problems. In Chapter 7 by Li, however, the focus is on the strong interaction between the optical fields and the carriers in a semiconductor laser. A self-consistent model that considers the optical modal fields in the waveguide, the reflection of the optical waves at the facets, the carrier transport, as well as the material properties of a multiple quantum-well (MQW) semiconductor laser is described. The governing equations are solved using a finite-element technique and the static characteristics of the device are simulated. This chapter, to some extent, reflects the complexity in modeling and simulation of practical optoelectronic devices such as the semiconductor lasers. The similar approach may be applied to modeling and simulation for other types of semiconductor optoelectronic devices such as tunable optical wavelength filters [18] and electro-optic modulators [19].

I would like to express my sincere thanks to all the contributors to this volume; without their enthusiasm, commitment and effort, a book like this would not be possible. Also, I would like to thank Prof. J. A. Kong, the chief editor of PIER series and the members of PIER 10 Editorial Board, for their encouragement and support. Staff members at EMW Publishing are also acknowledged for their prompt processing of the manuscripts.

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