

Full-vectorial Characterisation of Optoelectronic Guided Wave Devices using the Finite Element Method

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Abstract

A review of the characterisation of optoelectronic guided wave devices using the modal solution, junction analysis and beam propagation method based on the numerically efficient finite element method is presented. Numerically simulated results for mode propagation in optical waveguides and the characterization of various photonic devices such as optical modulators, spot-size converters, polarization rotators, and nonlinear photonic switches are presented.

Keywords: optoelectronics, finite element method

1. INTRODUCTION

With the advent of semiconductor lasers and low-loss optical fibres, the progress of optical technology has been significant in the field of optical communication, sensing, and signal processing. As optical technology has reached maturity, the associated devices have themselves become more complex. The optimization of such advanced devices requires accurate characterisation of their lightwave propagation characteristics and its dependence on their fabrication parameters.

Unfortunately, analytical techniques are not adequate to model lightwave devices without significant approximations. Even the simplest homogeneous optical waveguide, with a step-index difference and infinite cladding, cannot be analyzed in closed form. Therefore, the optimization of existing realistic designs or the evaluation of new designs for optoelectronic devices has created great interest in the development and use of effective numerical methods, as lightwave systems do not lend themselves well to the application of analytical methods. Hence, there is a significant need for the use of methods, usually numerical, to simulate

complex structures in order to optimize existing designs and evaluate novel devices, either prior to or instead of fabrication and experimental testing. This has been a stimulus for the high degree of interest seen in the development and use of effective theoretical methods, and in particular computer-aided design techniques. Among these methods, the method of Marcanti [1], the effective index method [2], the spectral index method [3], the matrix method [4], the finite difference method [5], the finite element method [6] and the beam propagation method [7] can be mentioned.

2. THE FINITE ELEMENT METHOD

Of the different numerical approaches considered so far, the finite element method (FEM) has been established as one of the most powerful and versatile methods in many branches of engineering, being used to model complicated structural, fluid flow, thermal, and electromagnetic problems [8]. Over the last two decades this method has been used to model optical waveguides [9], devices based on directional couplers [10], or multimode interference couplers [11], electrooptic modulators [12], second

harmonic generators [13], and semiconductor lasers [14], for example. In the finite element approach, the problem domain is suitably divided into a patchwork of finite number of subregions called elements. Each element can have a different shape and size and using many elements a complex problem can be accurately represented. A wide range of optical devices can be modeled as each element can be considered to have different optical parameters such as refractive index, anisotropic tensors, nonlinearity, and loss or gain factors.

3. MODAL SOLUTION OF OPTICAL WAVEGUIDES

The optical waveguide is the basic building block of all guided wave optical systems. The finite element method (FEM) has been used to characterize accurately lightwave propagation through a wide range of waveguides, such as semiconductor ridge, titanium diffused LiNbO_3 , and ion exchanged glass waveguides. This method is particularly advantageous because of its applicability to waveguides with arbitrary shapes and arbitrary refractive index profiles. The finite element formulation, using accurate vector $\mathbf{H}$ -field formulation which is "exact-in-the-limit", is also valid for anisotropic materials. A review paper by one of the author s[6] discusses the application of the FEM to optical waveguides.

Optical fibres are the most widely used optical waveguides and modern high-birefringence fibres, which can maintain the same state of polarization over a long distance, are desirable for use in coherent optical communications and fibre-optic sensing systems. The FEM has been used to model such polarization maintaining fibres [15]. Taking this as an example, first the tensor stress components are calculated using the finite element method to obtain the tensor refractive index change due to the elasto-optic effect. Then vector finite element program [15] is used to obtain the propagation constant difference for two

orthogonal polarizations to calculate the modal birefringence. Similarly, the FEM is also equally successful as a method to model another class of highly anisotropic optical waveguide [10], such as the titanium diffused lithium niobate crystal waveguide, widely used for electrooptic modulators or parametric oscillators.

Another class of optical waveguide, particularly important for integrated optics, is the semiconductor rib waveguide, important for integration with semiconductor lasers and detectors. The FEM has also been shown to provide the benchmark accuracy to characterise such waveguides [16]. Semiconductor quantum well and super-lattice structures with physical dimensions comparable to the de Broglie wavelength are gaining importance in many photonic devices. The novel features (such as enhanced nonlinearity and absorption) involved with multiple quantum well (MQW) structures makes them attractive for use in advanced semiconductor lasers and all-optical switching and signal processing devices. The major benefit brought about by using the MQW region in semiconductor lasers is the greatly reduced threshold current, improved temperature stability, narrower line widths and wavelength tuning. Recently, the FEM has also been used to characterize lightwave propagation through optical waveguides incorporating sub-micron MQW regions. Figure 1 shows the dispersion curves of a semiconductor laser [17] incorporating 70 periods of InGaAs quantum well sandwiched between InP barrier layers with their individual layer heights of 4 nm and 10 nm respectively. The dispersion curves, given as a function of the rib width, W , for the H_{11}^y and H_{12}^y (quasi-TE) modes, are shown. It can be seen that for a rib width of up to 6.5 μm , only a single lateral mode is possible.

The vectorial approach is necessary to identify the polarization dependent behaviour of optical waveguides and photonic devices. Modes in optical

waveguides with two-dimensional confinement are hybrid in nature, where all the six components of the electric and magnetic fields, $\mathbf{E}$ and $\mathbf{H}$, respectively are present. For the quasi-TE mode, its E_x and H_y components are dominant and the E_y and the H_x components are nondominant. Similarly, for the quasi-TM modes, E_y and H_x components are dominant. To design polarization rotators or to identify possible polarization crosstalk, it is necessary to calculate the modal 'hybridness' of a mode, which can be defined as the ratio of the non-dominant to the dominant components of the electromagnetic fields. It has been identified that when the waveguide sidewalls are not perfectly vertical, the modal hybridness is enhanced considerably [18]. The spatial profile of the nondominant, $H_x(x,y)$ field, for a highly hybrid TE mode in a waveguide with 52° slanted wall is shown in Figure 2.

4. COUPLED OPTICAL WAVEGUIDES

The optical directional couplers also play a major role in optical systems and they may be used as power dividers, power combiners, modulators, switches and filters. The isolated and supermodes of such coupled waveguides, their propagation constants and field profiles can be easily obtained by using the finite element method. The coupling length of the system can be calculated [10] from the difference between the propagation constants of the two supermodes. Figure 3 shows the variation of the coupling length for two nonidentical coupled optical waveguides [19] in the design of an optical filter.

5. JUNCTION ANALYSIS

Many important photonic devices, such as optical modulators, filters, polarization splitters, polarization rotators, power splitters, etc may be fabricated by combining several butt-coupled uniform waveguide sections. To design and analyse such photonic devices, it is important to use a junction analysis program in association with

a modal analysis program. One of the simplest junction analysis approaches is potentially the Overlap Integral approach. However, in this approach, the effects of the radiation modes cannot be included as these modes with a continuous spectrum are not orthogonal to the guided modes, so the usual superposition theorem is no longer applicable. One of the most rigorous approach, the least squares boundary residual (LSBR) method [20] has been developed by some of the authors. In this approach the continuity of the tangential electric and magnetic fields are imposed globally over the interface to obtain the scattering coefficients at the junction. Recently, a combination of the LSBR and the finite element methods has also been used to obtain the power transfer efficiency and the cross-talk between optical waveguides. The power transfer efficiency between nonidentical waveguides has also been studied, a parameter whose knowledge is useful in the design of optical filters [19] and optical modulators [21].

6. OPTICAL MODULATORS

The finite element program has also been developed to model electrooptic devices such as titanium diffused LiNbO_3 or GaAs modulators or switches [12, 21]. The Laplace equation is solved by using the FEM to obtain the two transverse components of the modulating electric field (vector), which is subsequently used to calculate the electrooptic contribution to the tensor refractive indices. Then the vector $\mathbf{H}$ -field based FEM can be used to model the electrooptic modulators more accurately. For a directional coupler-based electrooptic modulator, with the increase of the modulating voltage, the refractive index of one of the guides increases and for the other it decreases. As the guides lose their phase matching with increased modulating signal, two supermodes become highly asymmetrical. The dominant field profiles of the even- and odd-like supermodes are

shown in Figure 4. The overall power transfer efficiency with the induced refractive index change, Δn , is shown in Figure 5.

7. SPOT-SIZE CONVERTERS

In most cases, when a photonic device is butt coupled to a standard single mode fibre (SMF) nearly 80 to 90% power is lost at the interface due to their highly unequal spot-sizes. Only recently, the approach of designing a monolithically integrated spot-size converter is gaining considerable interest as the coupling efficiency can be significantly increased without deteriorating the alignment tolerances. However, instead of traditional tapered spot-size converters (SSC), a novel approach [22] has been developed, where two uniform coupled waveguides with nonidentical spot-size but with identical propagation constants, are considered. The schematic diagram of the SSC is shown in Figure 6. The numerically simulated results are shown in Figure 7 which illustrate more than 9 dB coupling efficiency improvement along with a relaxed vertical alignment tolerances, Δy .

8. POLARIZATION ROTATORS

The polarization state in a SMF cannot be maintained as the waveguide is circularly symmetric and the two orthogonal modes degenerate. On the other hand many optoelectronic devices, such as modulators, or detectors are polarization sensitive. Other devices such as a polarization controller can be used to compensate polarization mode dispersion, and polarization modulators can be used to prevent polarization hole burning in long transoceanic systems with concatenated erbium doped fibre amplifiers, where passive or electronic control of the polarization state is a key issue. To analyse the polarization rotator, a full vectorial approach would be necessary as even a semi-vectorial approach would be inadequate. Earlier work by the authors shows [18] that a compact 320 μm long single section

polarization rotator can be designed with very small insertion loss. Figure 8 shows the evolution of the polarized power along the axial direction of such a passive semiconductor polarizer using waveguide with slanted side wall.

9. BRAGG GRATINGS

Bragg gratings are important components for many optical communications and sensing applications. The coupled mode approach (CMA) is often adequate for the analysis of fibre Bragg gratings as refractive index change due to UV exposure is quite small. However, in integrated optical semiconductor structures, the discontinuity could be significantly larger and thus the CMA may not offer the accuracy required for the design of such structures. Devices with strong gratings, such as photonic crystals, could be analysed effectively by using a combination of the FEM, the LSBR and the transfer matrix method (TMM) [23]. The numerically simulated reflection spectrum of a multi-wavelength apodised narrow-band filter is shown in Figure 9.

10. BEAM PROPAGATION METHOD

Recently, to simulate the propagation of optical waves through a z -dependent linear or nonlinear structure, finite element-based beam propagation method (BPM) has been developed [24] using a fully vectorial approach with a difference scheme along the axial directions. Such an approach is particularly useful in the characterization of tapered sections, Y and X junctions and nonlinear optical devices. Being fully vectorial, this approach can be used to calculate polarization conversion along a periodically loaded semiconductor optical waveguides. Figure 10 shows the evolution of TM polarized power in a seven-section cascaded polarization rotator.

It is also known [18] that when the axial symmetry of a waveguide is absent,

modal hybridness is enhanced significantly. It has also been observed that considerable polarization conversion can take place in a curved waveguide. It has been reported [26] by the authors that significant polarization conversion in a compact curved waveguide with a slanted side wall. Figure 11 show the evolution of TM polarized power in such a structure [26].

11. NONLINEAR DIRECTIONAL COUPLERS

Recently, research in the areas of nonlinear optics has attracted much attention due to its potential application in the generation of optical solitons, photonic switching and all-optical signal processing. The modal solution for nonlinear optical waveguides can be obtained by a semi-analytical approach for some carefully chosen examples in planar structures, but it has been shown that the BPM is more suitable to characterize general nonlinear optical devices. The FEM-based BPM has been used to obtain beam evolutionary solutions for nonlinear optical waveguides with two-dimensional confinement [27]. Figure 12 shows the occurrence of fast photonic switching by using a nonlinear directional coupler.

12. CONCLUSIONS

The finite element method is a powerful and versatile method suitable to model accurately optical, thermal, elasto-optic, electro-optic, and electronic effects in passive or active opto-electronic devices. Some examples of computer aided characterization of optoelectronic devices are presented here and all these calculations were carried out using a SUN Sparcstation. Characterisation of important optical devices and the identification of important fabrication parameters by performing numerical experiments are invaluable in the optimization of such advanced photonic devices.

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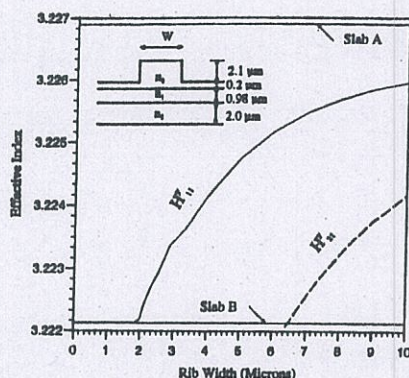


Figure 1 Dispersion curves of a MQW semiconductor laser.

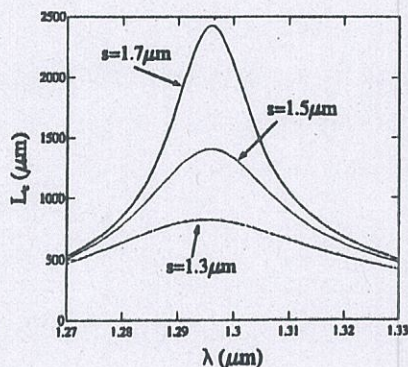


Figure 3 Variation of the coupling length for two coupled nonidentical waveguides.

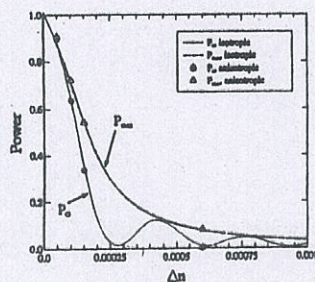


Figure 5 Power transfer efficiency with the change of the electrooptic index, Δn .

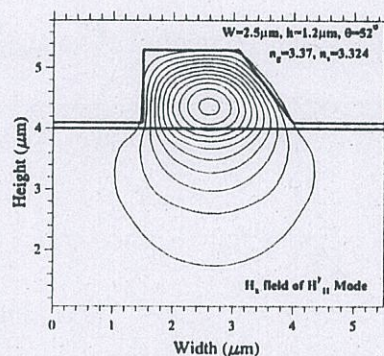


Figure 2 Modal field profile for a semiconductor waveguide with slanted side.

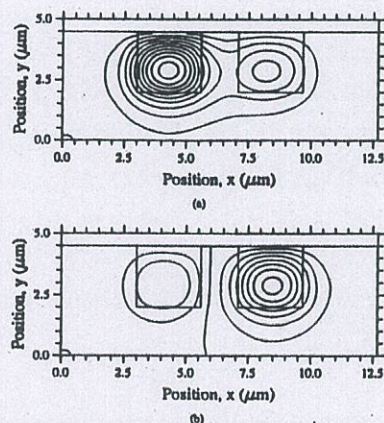


Figure 4 Even- and odd-like supermodes for nonidentical coupled waveguides.

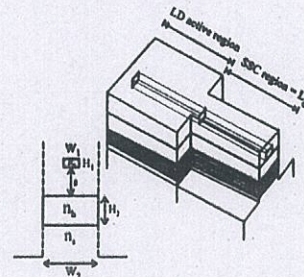


Figure 6 Schematic of a compact spot-size converter.

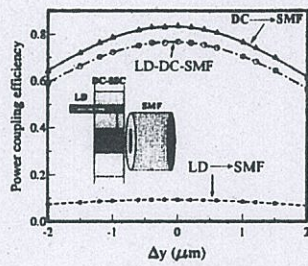


Figure 7 Variation of the coupling efficiency with the alignment tolerance, Δy .

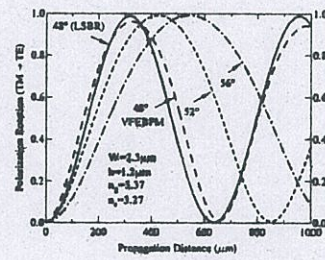


Figure 8 Evolution of TE power along the length of a polarization rotator.

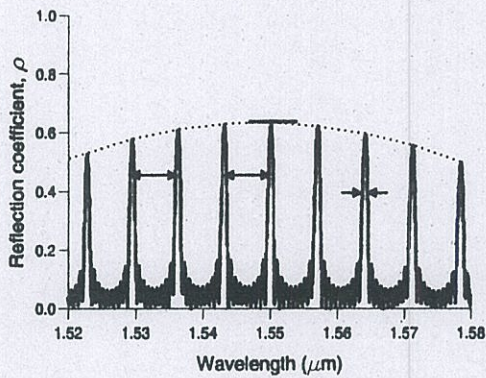


Figure 9 Reflection spectrum of a strong Bragg gratings in semiconductor waveguide.

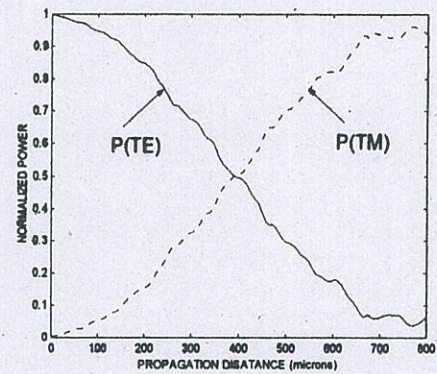


Figure 10 Evolution of polarization rotation in a periodically loaded waveguide.

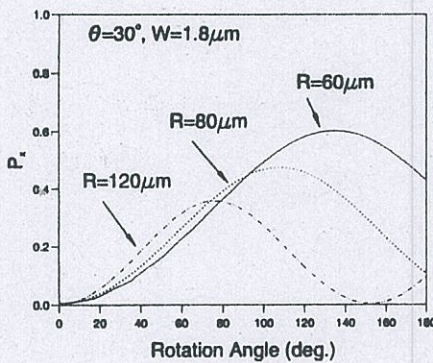


Figure 11 Polarisation conversion in a curved waveguide with a slanted side wall.

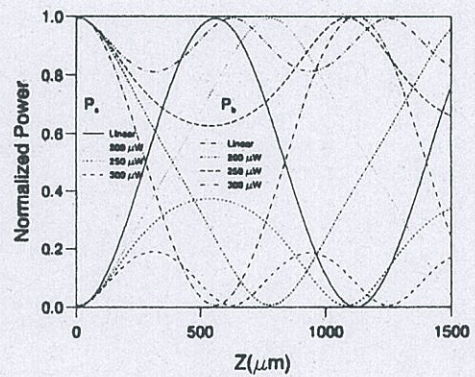


Figure 12 Variation of the optical power in bar and cross ports with the total power.