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Semivectorial Mode Analysis of a Rib Waveguide by an Imaginary-Distance Beam-Propagation Method Based on the Generalized Douglas Scheme

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SUMMARY The field profile and effective index of a rib waveguide are calculated using an improved semivectorial beam-propagation method using the imaginary-distance procedure. Convergence behavior of the effective index is compared with that obtained by the conventional Crank-Nicholson scheme and with that derived from a Bierwirth-type formula, demonstrating the effectiveness of the present method. Field discontinuities at the interface between different materials are clearly displayed.
key words: *finite-difference methods, mode solver, optical waveguides*

1. Introduction

The beam-propagation method (BPM) is known to be the most popular method for the simulation of propagating beams in optical waveguides. The BPM can also be used as an eigenmode solver by taking a purely imaginary propagation step [1]–[3]. Recently, the authors have formulated an improved finite-difference beam-propagation method (IFD-BPM) [4] based on the generalized Douglas (GD) scheme for the semivectorial mode analysis [5]. The formulation was made using Stern's formula [6]. The field profile and effective index were determined by the imaginary distance procedure. An eigenmode solver based on the BPM has the advantage that it can be directly employed for the propagating beam analysis by simply changing the propagation axis to the real one. In Ref. [5] we treated a two-dimensional step-index waveguide and a three-dimensional graded-index waveguide to demonstrate the effectiveness of the GD scheme. We are also interested in investigating the extent to which the GD scheme is effective for the analysis of a three-dimensional waveguide with a large refractive-index discontinuity. In this article, the IFD-BPM is applied to the eigenmode analysis of a rib waveguide frequently used as a benchmark test. The effective index is compared with that obtained by the conventional Crank-Nicholson (CN) scheme and with that derived using a Bierwirth-type formula [7], [8].

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2. Configuration and Numerical Method

The geometry of a rib waveguide to be considered here [7], [8] is shown in Fig. 1. The configuration parameters are $n_f = 3.44$, $n_s = 3.34$, rib width $W = 2.0\,\mu$m, central rib height $H = 1.3\,\mu$m, and lateral height $T = 0.2\,\mu$m. A wavelength of $\lambda = 1.55\,\mu$m is used.

The field profile is determined by the imaginary distance IFD-BPM based on the GD scheme, and the effective index is calculated by the growth in the field amplitude. Since the numerical method has been described in Refs. [4], [5] and [9] in detail, we do not repeat here. The analysis is made using symmetry with respect to the y axis, so that the computational domain is approximately chosen to be $0 \leqq x \leqq 3.3\,\mu$m and $-3.7 \leqq y \leqq 1.8\,\mu$m, which is almost the same as that used in Ref. [7]. In the present method, Stern's formula is used, in which the discontinuity lines of different materials are located midway between sampling points. This is in contrast with the Bierwirth-type formula, in which the discontinuity lines are just on sampling points [10].

As the input field, we choose a step function as

$$\phi(x,y,0) = \begin{cases} 1 & \text{for } 0 \leqq x \leqq 1.0\,\mu\text{m and} \\ & \qquad 0 \leqq y \leqq 1.3\,\mu\text{m} \\ 0 & \text{otherwise} \end{cases}$$

A transparent boundary condition often used in a propagating beam analysis is not necessarily needed for this analysis, since the fields other than the fundamental

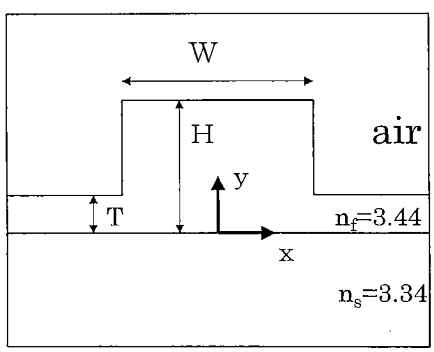

Fig. 1 Rib waveguide geometry.

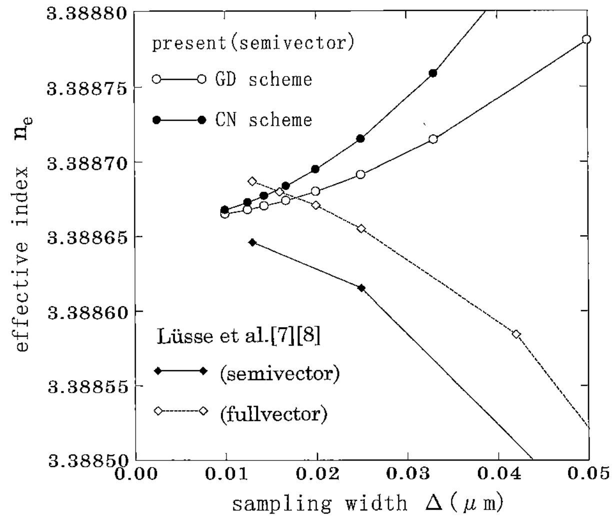

Fig. 2 Convergence behavior of effective index n_e as a function of transverse sampling width.

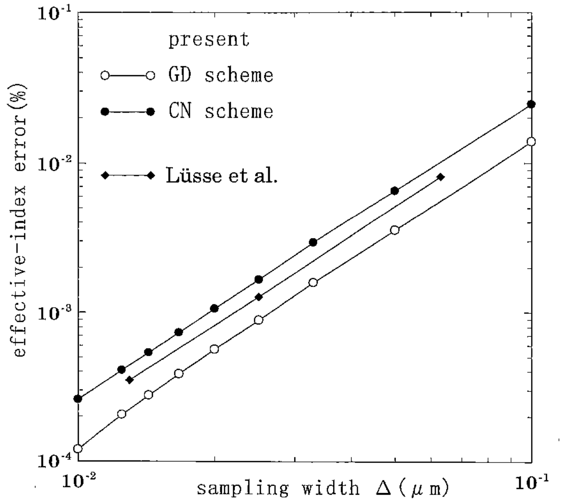

Fig. 3 Effective-index error as a function of transverse sampling width.

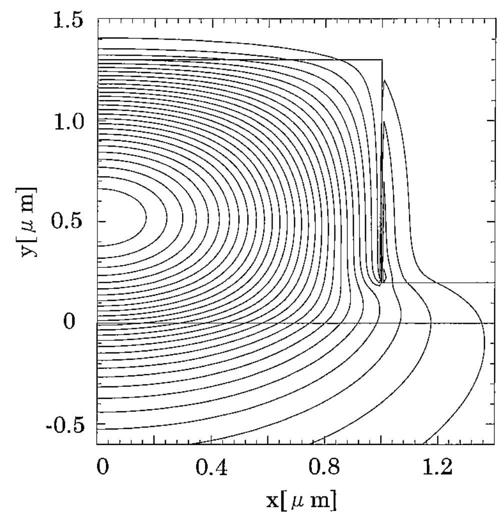

Fig. 4 Field profile for the quasi-TE mode.

mode decay rapidly as they propagate along the imaginary axis. Hence, no special boundary condition is imposed at the edge of the computational window, i.e., zero boundary terms are used instead of a transparent boundary condition.

3. Results

Figure 2 shows the convergence behavior of the effective index n_e for the quasi-TE mode as a function of transverse sampling width $\Delta(=\Delta x=\Delta y)$. The data is obtained at a propagation distance of $\tau(=-jz)=100\,\mu$m with $\Delta\tau=0.1\,\mu$m. For comparison, the data obtained from the CN scheme and derived by Lüsse et al. [8] using the Bierwirth-type formula are also presented. The present results are found to show faster convergence than the CN scheme (The CPU time for the GD scheme is increased by 5%). It is interesting to note that the convergence behavior of the present method contrasts with that of Lüsse et al. due to the difference in a discretization scheme. For further reference, the data for the fullvectorial case derived by Lüsse et al. [7] are also shown. It is noted that the semivectorial results indicate slightly smaller n_e than the fullvectorial results.

Since the convergence is not complete, we determine a more precise effective index using an extrapolation technique. Assuming that $n_e(\Delta)=n_e(\Delta=0)+\alpha\Delta^2$, we can readily determine $n_e(\Delta=0)$ and α from data at two different Δ's. The extrapolated values for all the semivectorial results are the same in six-digit values: $n_e(\Delta=0)=3.38866$. Figure 3 shows the effective-index error in which the extrapolated value is assumed to be exact: $[n_e(\Delta=0)-n_e(\Delta)]/n_e(\Delta=0)\times 100[\%]$. We can confirm the second-order accuracy of each scheme, and higher accuracy of the GD scheme. Note that the GD scheme also shows the second-order accuracy. This is due to the fact that the main source of error is related to the interface discretization, in which Stern's formula is approximately employed.

A typical field profile is plotted in Fig. 4. Discontinuities of the field are clearly visible at the vertical interface with air.

4. Conclusions

The imaginary-distance beam-propagation method based on generalized Douglas scheme has been applied to the semivectorial mode analysis of a rib waveguide. The present method achieves faster convergence in the effective index than the conventional schemes. The field profile for the quasi-TE mode clearly shows discontinuities at the interface with air.

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