A Rigorous 2D Approximation Technique for 3D Waveguide Structures for BPM Calculations

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ABSTRACT—We propose a rigorous 2D approximation technique for the 3D waveguide structures; it can minimize the well-known approximation errors of the commonly used effective index method. The main concept of the proposed technique is to compensate for the effective cladding index in the equivalent slab model of the original channel waveguide from the modal effective index calculated by the nonuniform 2D finite difference method. With simulations, we used the proposed technique to calculate the coupling characteristics of a directional coupler by the 2D beam propagation method, and the results were almost exactly the same as the results calculated by the 3D beam propagation method.

Keywords—Effective index method, beam propagation method, directional coupler, modified EIM, BPM.

I. Introduction

Accurate simulations of waveguide structures, such as splitters, switches, AWGs, and directional couplers, are indispensable to modeling and designing planar lightwave circuits (PLC). One of the most commonly used simulation techniques is the beam propagation method (BPM). Generally it is more desirable that the 3D waveguide structures be simulated with the 3D beam propagation method (3DBPM), but this requires extensive computer memory and computational time [1]. Therefore to insure computational efficiency, the 2D cross sectional index profile is usually transformed to the one dimensional index profile by using the effective index method (EIM) [1]. In the EIM approach, the eigenvalue of the equivalent slab waveguide is an approximate index value of the original waveguide. Although the EIM approach provides a good approximation, it still suffers from errors in the vicinity of the cutoff [2]-[4]. An improvement on the EIM approach is the modified effective index method (MEIM) [5]. The MEIM gives a modified effective cladding index for the cladding regions of the equivalent slab waveguide, but there still remain some errors. M. Munowitz reported other numerical procedures for constructing a more accurate equivalent slab waveguide; they vary the effective core and cladding index to obtain the best agreement between the one dimensional field of the equivalent slab waveguide and the square root of the integrated intensity distribution of the 2D rib waveguide [6]. This technique was very accurate and provided a good starting point for subsequent BPM calculations.

In this letter, as a relatively simple alternative to the approach of M. Munowitz, we propose a rigorous 2D approximation technique for constructing the equivalent slab waveguide with minimized approximation errors. In our technique, the effective cladding index was compensated for to achieve the best agreement between the effective index of the equivalent slab waveguide and the modal effective index of the original waveguide calculated by the nonuniform 2D finite difference method (2DFDM) [7]. We used the proposed technique to calculate the coupling characteristics of a directional coupler by 2DBPM simulations and the results were compared with 3DBPM simulations.

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II. Numerical Results

The equivalent slab waveguide of the rectangular channel waveguide was modeled for the 2DBPM simulations. In the EIM, the effective index concept is applied only in the core region of the equivalent slab waveguide as shown in Fig. 1(c). In the proposed technique, we additionally compensated for the effective cladding index (N_{clad}) (Fig. 1(d)) by a sequence of procedures as follows: i) the modal effective index (N_{ch}) of the original structure (Fig. 1(a)) is calculated by the nonuniform 2DFDM [7]; ii) an eigenvalue for the slab (Fig. 1(b)) is computed as the effective core index (N_{core}) by the well-known bisection method, and then the equivalent slab is defined with this effective core index (N_{core}) and the cladding refractive index (n_{clad}) (Fig. 1(c)); iii) the effective cladding index (N_{clad}) is repeatedly modified by using the bisection method until the effective index (N_{slab}) of the equivalent slab waveguide coincides with the previously determined modal effective index (N_{ch}) of the channel waveguide. In this way, we can easily find the effective cladding index without the overlap integral of optical fields, and the proposed technique is simpler than the procedures proposed by M. Munowitz [6].

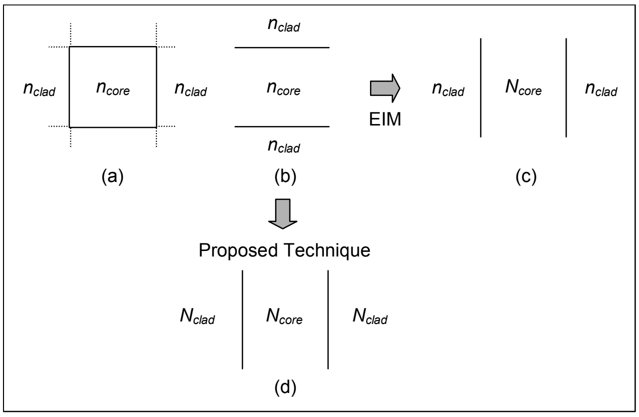

Fig. 1. Equivalent slab model of rectangular channel waveguide: (a) channel structure, (b) slab waveguide approximation for the core region, (c) the equivalent slab waveguide by the EIM, and (d) the equivalent slab waveguide by the proposed technique.

Figure 2 shows the schematic illustrations of the directional coupler with a step index profile. The rectangular channel waveguide in Fig. 2 has a width of $W = 6$ μm, a height of $H = 6$ μm, a relative index difference of $\Delta n = 0.75\%$, a separation of $S = 4$ μm between waveguides, and a pitch of $D = 250$ μm in the input/output sections. The bends have a radius of 6000 μm and were optimized with an offset of 0.3 μm. The refractive index of core regions n_{core} and that of cladding regions n_{clad} at a wavelength of 1550 nm are 1.45493563 and 1.44402362, respectively.

Table 1 shows the modal effective index (N_{ch}) of the channel waveguide depicted in Fig. 2 and the effective core (N_{core}) and cladding index (N_{clad}) of the equivalent slab model obtained by the above procedures. These results are for the transverse magnetic (TM) and fundamental mode at a wavelength of 1550 nm. The modal effective index (N_{ch}) was solved under a condition of nonuniform discretization with minimum grid spacings of $dx = dy = 0.15$ μm. The effective cladding index (N_{chad}) obtained by the proposed technique was smaller than the value of 1.44402362 obtained by the EIM and larger than that of 1.44143734 obtained by the MEIM [5]. From these results, we expected that the coupling characteristics would be different in each method.

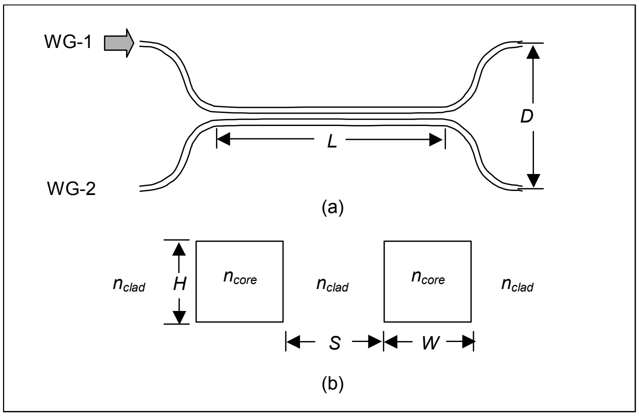

Fig. 2. Schematic illustrations of the directional coupler: (a) layout of the directional coupler, (b) cross sectional view in the coupling region.

Table 1. Effective indices of the equivalent slab model.

N_{ch}	N_{core}	N_{clad}		
		EIM	MEIM	Proposed
1.44981942	1.45232679	1.44402362	1.44143734	1.44279512

The commercially available BeamPROP simulator is able to carry out both 2D and 3D BPM simulations very efficiently. First the 3D finite difference semivectorial beam propagation method (FD-SVBPM) simulations were performed for the TM mode by the BeamPROP simulator. The directional coupler was uniformly discretized with grid spacings of $dx = dy = 0.1$ μm in the cross sectional direction and $dz = 0.25$ μm in the propagating direction. BeamPROP software was also used to calculate the input field and reference index of the TM mode for the BPM simulations. The simulation result showed that the input beam to a waveguide (WG-1) was almost perfectly coupled back to the same waveguide (WG-1) at a wavelength of 1550 nm when the interaction length (*L*) was 5600 μm and showed a crosstalk value of about –32 dB. After the equivalent slab waveguide was constructed with the values in Table 1, 2D FD-SVBPM simulations were performed for the transverse electric (TE) mode with all other conditions identical.

Figure 3 shows the change of optical power coupled into the other waveguide (WG-2) from the input waveguide (WG-1) in the propagating direction. The results calculated by the proposed technique were compared with those obtained by the 3DBPM simulations and showed almost exactly the same results. There were slight differences around the input/output waveguide sections (Fig. 3), which we believed came from the previously calculated modal effective index. Accordingly, a more accurate modal effective index is needed for higher accuracy of the proposed technique.

From the comparison with the 2DBPM simulations, we could see that there were fairly big errors in the EI and MEI-2DBPM. For example, the interaction lengths (*L*) calculated by the EI and MEI-2DBPM were 4800 μm and 6700 μm, respectively. The values were the lengths for perfect coupling of optical power from the input waveguide (WG-1) to the same waveguide (WG-1) and showed a crosstalk value of around –32 dB. They were largely different from the accurate result (*L* = 5600 μm) calculated by the 3DBPM. The results computed by the EI-2DBPM showed strong coupling due to the weak confinement in the equivalent slab waveguide. On the contrary, weak coupling appeared in the MEI-2DBPM, meaning that the effective cladding index was overcompensated for in the equivalent slab waveguide.

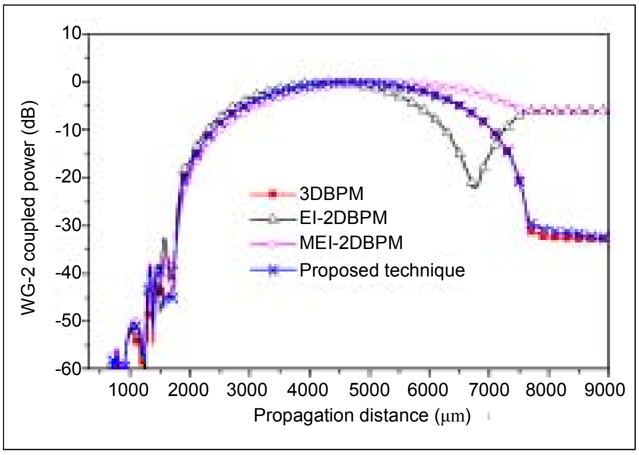

Fig. 3. Coupling characteristics of the directional coupler (TM mode, $dx = dy = 0.1$ μm in the cross sectional direction, $dz = 0.25$ μm in the propagating direction, and $L = 5600$ μm).

As the simulation results show, the proposed technique was very accurate for the BPM simulations. The proposed technique uses the previously calculated modal effective index to compensate for the effective cladding index in the equivalent slab waveguide. Thus, it would be very accurate and efficient in simulations of waveguide devices, such as directional couplers, MZ interferometers, and AWGs, where an accurate modal effective index is a key factor of designing.

III. Conclusions

We proposed a rigorous 2D approximation technique for 3D waveguide structures for BPM calculations; our technique can minimize the well-known approximation errors of the commonly used effective index method. In the proposed technique, we compensated for the effective cladding index in the equivalent slab model so as to get the best fit of the effective index calculated from the equivalent slab with the modal effective index of the original waveguide. The coupling characteristics of the directional coupler obtained by the proposed technique were almost exactly the same as the result obtained by the 3DBPM. This technique will be very accurate and efficient in designs and simulations for devices such as directional couplers, MZ interferometers, and AWGs where the accurate modal effective index is a key factor of designing.

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