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An improved effective index method for planar multimode waveguide design on an silicon-on-insulator (SOI) platform

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In this paper, an improved effective index method (EIM) for designing planar multimode waveguides on the silicon-on-insulator (SOI) platform is presented. The proposed method predicts the evolution of the fields more accurately than the conventional effective index method. This improved method is particularly suited to the design of multimode interference (MMI) couplers.

Keywords: multimode interference (MMI), silicon-on-insulator (SOI), effective index method (EIM).

1. Introduction

The effective index method (EIM) [1, 2] is one of the most well-known semi-analytical methods for solving the wave equation in optical waveguides. This technique replaces a 3D waveguide structure with an equivalent 2D structure having effective indices. The EIM is well-suited for analyzing 3D waveguide structures having low-index contrast [3]. It has also been applied to devices using silicon-on-insulator (SOI) rib waveguides [4]. However, the conventional EIM is not suitable for structures based on SOI channel waveguides due to the limitations of its accuracy [3, 5].

An improved effective index method (IEIM) for designing optical planar directional couplers for the silica technology has been presented by QIAN WANG *et al.* [3]. The aim of the method was to find an optimized value of the cladding refractive index in the 2D model so that the coupling length of the directional coupler in the 2D model equaled the coupling length in the 3D model. However, that approach can only be applied to directional couplers using single-mode waveguides based on low-index contrast material systems.

Recently, the high-index contrast SOI platform has attracted much interest due to its potential for miniaturization, improved performance, and compatibility with existing CMOS technology [6]. For directional couplers silicon waveguides, accurate fabrication of the gap requires very tight control of the fabrication process. Moreover, additional loss due to mode conversion loss has been found to be a problem [7].

Therefore, multimode interference (MMI) couplers have been used in many optical devices to overcome the above mentioned issues. MMI devices use the principle of self-imaging within multimode optical waveguides to produce single or multiple images, of an input field, at periodic distances along the waveguide [6]. Such MMI couplers have the desirable advantages of low-loss, compactness and good fabrication tolerances.

In this paper, an IEIM is proposed for the design of optical devices including MMI devices using SOI channel waveguides.

2. Theory

The MMI coupler consists of a multimode optical waveguide that can support a number of modes. In order to launch and extract light from the multimode region, a number of single-mode access waveguides are placed at the input and output planes. If there are N input waveguides and M output waveguides, then the device is called an $N\times M$ MMI coupler.

The operation of an optical MMI coupler is based on the self-imaging principle [6, 8]. Self-imaging is a property of a multimode waveguide by which an input field is reproduced in single or multiple images at periodic intervals along the propagation direction of the waveguide. The central structure of the MMI filter is formed by a waveguide designed to support a large number of modes. In the MMI section, the 2D scalar Helmholtz wave equation is defined as

$$\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} + \left[\frac{2\pi n(x, y)}{\lambda}\right]^2 \psi = \beta^2 \psi$$

where

$$\psi(x, y, z) = \sum_{\nu = 0}^{P-1} c_\nu \psi_\nu(x, y) \exp\left[j(\omega t - \beta_\nu z)\right]$$

and x is the lateral dimension, y is the transverse dimension, z is the propagation direction, c_ν is the filed excitation coefficient, $\psi_\nu(x, y)$ is the modal field distribution, $n(x, y)$ is refractive index profile, $\nu = 0, 1, \ldots, P-1$ are the mode numbers of the waveguide supporting P modes, λ is the optical wavelength and β_ν is the propagation constant.

In this study, the proposed new effective index method uses the beat length L_π as the invariant. The beat length L_π of a multimode waveguide can be defined as $L_\pi = \pi/(\beta_0 - \beta_1)$, where β_0 and β_1 are the propagation constants of the fundamental and first order modes, respectively. Beat length is an important parameter of an MMI structure.

Figure 1 shows a 3D SOI channel waveguide and a 2D equivalent slab waveguide. The parameters used in the designs are as follows: the waveguide has a standard silicon thickness of $h_{co} = 220$ nm. The refractive index of the silicon core is $n_{Si} = 3.45$

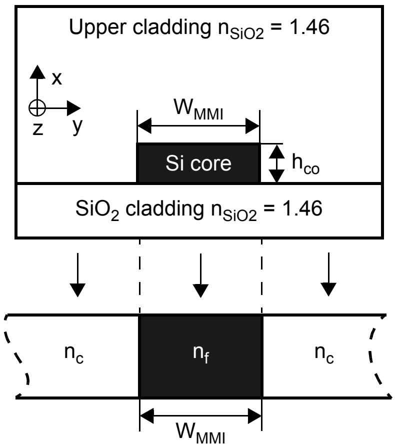

Fig. 1. 3D waveguide structure and its decomposition into planar waveguides (n_f and n_c are the effective refractive indices of the core and cladding region).

at the operating wavelength λ = 1550 nm and SiO_2 (n_{SiO2} = 1.46) is used as the upper and lower cladding material. The aim of the improved method is to determine appropriate effective indices n_f and n_c of the core and cladding, respectively, for the equivalent 2D waveguide that will yield the same beat length as that of the original 3D waveguide. A numerical technique, such as the film mode matching method [9] or finite difference method [10], can be used to calculate the beat length L_π of the 3D structure, to high accuracy.

In the proposed method, the effective index of the core region is assumed to have the same value as that calculated for the conventional EIM and is found by solving the relevant transverse electric (TE) or transverse magnetic (TM) dispersion equation [11]. By varying the value of the cladding refractive index in the 2D model, it is possible to find an effective cladding index that produces the same beat length as that calculated using the 3D numerical method. This is the key concept in the proposed effective index method.

The advantage of using the IEIM is that a full 3D solution is only required once for the purpose of establishing the matching cladding index. Then, the IEIM can be used to compute the propagating fields in the whole MMI structure quickly, with little further computational effort. The proposed method is also suitable for modeling strip waveguides where the upper cladding has a different refractive index to that of the substrate. In this latter case, the effective cladding index is not well defined in the conventional EIM.

3. Numerical simulations and discussions

In order to illustrate and verify the proposed IEIM, an 1×1 MMI coupler of width W_{MMI} = 3 μm and having the structure shown in Fig. 1 will be designed. The beat length calculated using the film mode matching method is $L_\pi(3D)$ = 24 μm. Using a first step of the conventional EIM (solving the slab waveguide in the vertical direction), the TE effective index of the core region is found to be $n_f = 2.8156$.

By repeated solution of the TM dispersion equation of the equivalent horizontal slab waveguide (Fig. 1) for β_0 and β_1, the beat length L_π(2D) can be found as a function of the cladding index n_c, as illustrated in Fig. 2. The value of n_c which produces the same beat length in both models is found to be $n_c = 2.13$.

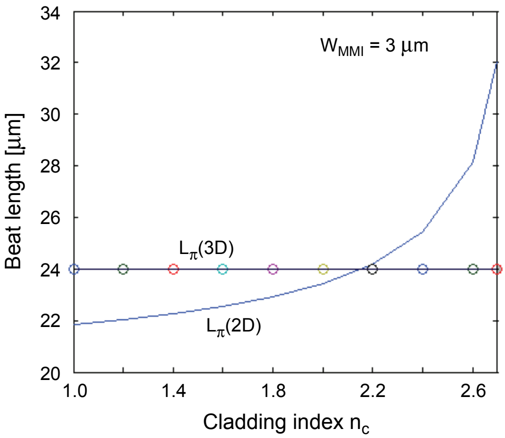

Fig. 2. Determination of the cladding index n_c that produces the same beat length L_π in both the 3D and the equivalent 2D model of an SOI MMI coupler of width 3 µm.

Using the same approach to the MMI structure having different widths, the optimal cladding index at different widths of the MMI region can be found as shown in Fig. 3. It is shown that the optimal refractive index of the cladding region increases in the increase of the width of the MMI structure.

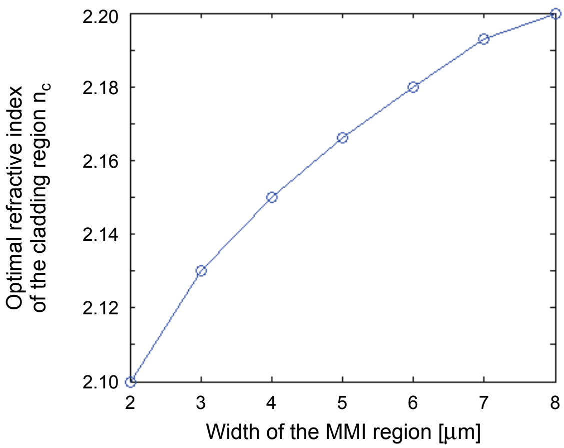

Fig. 3. The optimal cladding index n_c at different widths of the MMI region.

Next, the beam propagation method (BPM) is used to simulate the whole MMI coupler. It is well-known that the finite-difference time-domain (FDTD) method is a general method to solve Maxwell's partial differential equations numerically in the time-domain. Simulation results for devices on the SOI channel waveguide using the 3D-FDTD method can achieve a very high accuracy. However, due to the limitation of computer resources and memory requirements, it is difficult to apply the 3D-FDTD method to the modeling of large devices on the SOI channel waveguide. Meanwhile, the 3D-BPM was shown to be a quite suitable method that has sufficient accuracy for simulating devices based on SOI channel waveguides [12, 13]. Therefore, the design for devices on the SOI platform will now be performed using the 3D-BPM [14].

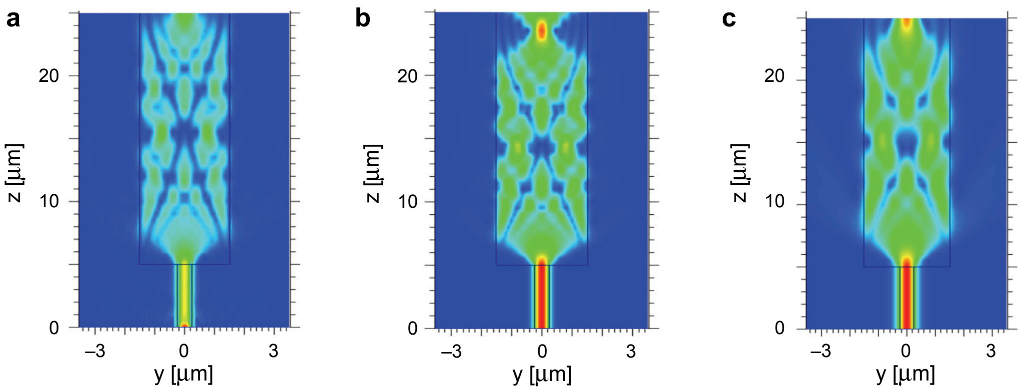

Fig. 4. Power distributions within a 1×1 MMI coupler 3D-BPM simulation for actual 3D structure (**a**), and 2D-BPM simulations of equivalent 2D structures resulting from EIM (**b**) and IEIM (**c**).

The 3D-BPM simulation result for the 3D structure and 2D-BPM simulations for the equivalent 2D structure using the conventional EIM and the IEIM are shown in Figs. 4**a**, 4**b**, and 4**c**, respectively. The simulations show that the IEIM more accurately predicts the field evolution inside multimode waveguides than does the conventional EIM. The optimal lengths of the 1×1 MMI coupler found by using 3D-BPM and IEIM are nearly 20 μm; while the optimal length of the MMI coupler calculated by using the conventional EIM is to be 17.5 μm. Using the 3D-BPM and 2D-BPM simulations for the MMI couplers at different widths after using the EIM and IEIM, it is shown that the conventional EIM underestimates the imaging length and is therefore of limited use.

Figure 5 shows the normalized output powers of the 1×1 MMI coupler at different MMI lengths. The simulation results were implemented by using the BPM for the actual 3D device structure, the equivalent coupler based on the conventional EIM (CEIM) and the equivalent coupler based on the IEIM. The normalized output powers calculated by using the 3D-BPM and IEIM are 0.85 at the MMI length of 20 μm, while the normalized output power calculated by using the CEIM at the optimal length of the 1×1 MMI coupler is 0.8. Therefore, the improved EIM predicts more accurately

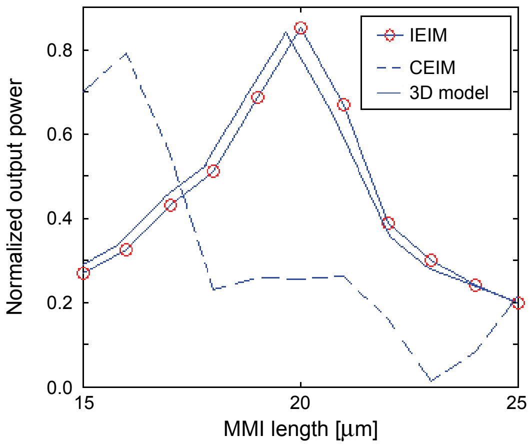

Fig. 5. Comparison of normalized output powers calculated by the 2D-BPM at different MMI lengths for the device using the conventional EIM and improved EIM with the 3D-BPM result.

the normalized output power and the length of the MMI coupler than does the conventional EIM.

It should be noted that the proposed method gives only an approximation to the actual fields which are hybrid (not pure TE or TM) in nature. The proposed method may also be applied to the design of more complex MMI structures on the SOI platform such as MMI couplers with arbitrary shapes or MMI couplers having higher number of ports.

4. Conclusions

We have proposed an improved effective index method for designing multimode waveguide devices on the SOI platform. The method is computationally efficient and easy to apply. BPM simulations have shown that the proposed method predicts the field propagation more accurately than does the conventional effective index method. The proposed method is particularly suited for the rapid calculation of the evolution of the fields in MMI couplers.

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