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Leakage Loss and Phase Variation of a Buried Directional Coupler on a Silicon Substrate

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***Abstract*—Effects of the presence of a silicon substrate on the leakage loss and phase variation of silica-based parallel waveguides are investigated using the imaginary-distance beam-propagation method. The leakage loss is evaluated as a function of the distance between the core and the substrate. Calculation shows that the loss of the directional coupler can be estimated using the single waveguide with the same cross section. It is also found that the beat length becomes longer than that without the substrate except the case where the core is extremely close to the substrate. In terms of the loss reduction, the insertion of a SiO_2 film with a 1-μm thickness corresponds to an increase in the distance between the core and the substrate without the SiO_2 film by about 2 μm.**

***Index Terms*—Beam-propagation method (BPM), leakage loss, leaky modes, polarization dependence, silicon substrate.**

I. INTRODUCTION

SILICA-ON-SILICON buried waveguides are most popular in fabricating arrayed waveguide gratings [1], wavelength-division-multiplexing modules [2], and other functional devices. Since silicon has a higher refractive index than the core and cladding silica-based materials, the light propagating in the core will leak into the silicon substrate. Therefore, considerable attention has been paid to evaluation of the leakage loss of a silica-on-silicon buried waveguide. Analytical methods have been proposed with the aid of a perturbation method for a two-dimensional structure [3], [4]. Recently, He *et al.* presented a simple analytical method for a three-dimensional structure with the extension of the well-known Marcatilli approach [5]. Meanwhile, the beam-propagation method (BPM) has been used to evaluate the leakage loss [6].

Note, however, that no previous work treats a directional coupler fabricated on a silicon substrate. Since the directional coupler is one of the fundamental components in the lightwave circuit using the silica-on-silicon waveguide, it is important to estimate the effects of the silicon substrate on the waveguiding properties. In this study, we investigate not only the leakage loss but also the phase variation of silica-on-silicon parallel waveguides. Simulation based on the imaginary-distance BPM shows that the beat length of a directional coupler tends to increase due to the presence of the silicon substrate. Further consideration reveals that in terms of the loss reduction, the insertion of a SiO_2 film with a 1-μm thickness [7] corresponds to an increase in the distance between the core and the substrate without the SiO_2 film by about 2 μm.

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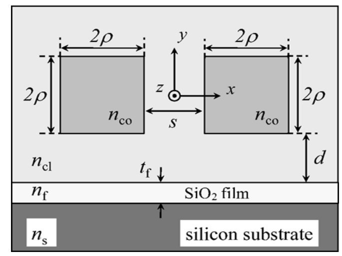

Fig. 1. Cross section of a buried directional coupler on a silicon substrate ($2\rho = 6$ μm).

II. CONFIGURATION AND NUMERICAL METHOD

Fig. 1 illustrates the cross section of a buried directional coupler on a silicon substrate whose refractive index is taken to be $n_s = 3.4$. We study silica waveguides with a square cross section ($2\rho = 6$ μm). The refractive indexes of the core and cladding are $n_{co} = 1.4675$ and $n_{cl} = 1.46$, respectively. The spacing between the two waveguides and the distance between the core and the SiO_2 film are, respectively, designated as s and d. Note that d is defined by the distance between the core and the substrate when the SiO_2 film is not inserted. We typically investigate the case for $s = 3$ μm, with d being changed. Throughout this letter, the wavelength is chosen to be $\lambda = 1.55$ μm.

To evaluate the field and complex propagation constant of the directional coupler, we employ the imaginary-distance semivectorial BPM together with the improved finite difference formulas, which take into account the boundary conditions at the interface of different refractive index [8]. The semivectorial treatment is sufficient, since the structure is symmetric with respect to the $y - z$ plane and the waveguides are weakly guiding. The transverse sampling widths are taken to be $\Delta x = \Delta y = 0.1$ μm. The longitudinal sampling width is determined by the so-called amplification factor so as to accelerate the numerical convergence [9]. The computational window size is taken to be 20 μm$\times$ 40 μm using the symmetry of the structure. The perfectly matched layers are placed at the edge of the computational window.

It should be noted that the multifrontal method [10] is employed for inverting sparse matrices, rather than the alternating-direction implicit (ADI) method. This is because the amplification factor cannot be strictly determined due to the splitting error in the ADI process [11]. It is known that the multifrontal method based on the sparse LU decomposition technique is an

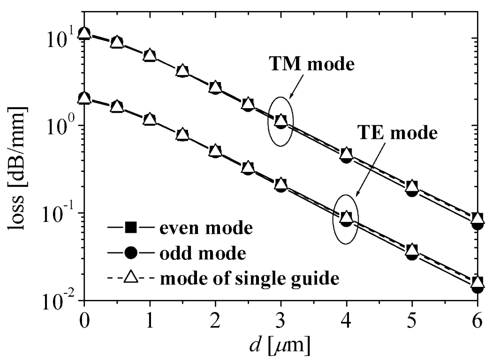

Fig. 2. Leakage loss as a function of d.

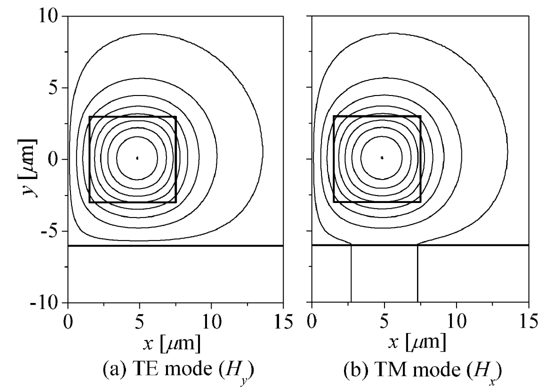

Fig. 3. Field distributions (odd mode, $d = 3\ \mu$m).

efficient direct method, which can be used for the case where an iterative method is unstable, although the more memory is required than the iterative method. The multifrontal method has already been used for electromagnetic problems [12]–[14]. We adopted the software developed by Visual Integration & Numerical Analysis Systems Co. Ltd: Super Matrix Solver-MF Version 2.1 [15].

To compare the present method with that previously published, we have also calculated the propagation constant of the single waveguide by the analytical method presented by He *et al.* [5]. As a result, we find a good correlation between the two methods. For example, the difference in phase constant (real part of the propagation constant) between the two methods was less than 0.004% and that in loss was 3% for $d = 3\ \mu$m in the quasi-TE mode. Since the analytical method is not simple to extend to the case where a SiO_2 film is inserted in the coupler structure shown in Fig. 1, we only present the data obtained with the imaginary-distance BPM in the following sections.

III. Directional Coupler Without an Insertion Film

We now investigate the leakage loss of the directional coupler without an insertion film, i.e., corresponding to the case where t_f is zero in Fig. 1. The leakage losses of odd and even supermodes are shown for both quasi-TE and quasi-TM modes in Fig. 2. As expected, the losses for both modes decrease as d is increased. Fig. 2 also shows that the quasi-TM mode has a higher loss than the quasi-TE mode. This is because the field of the quasi-TM mode extends more to the silicon substrate than that of the quasi-TE mode, as will be shown in Fig. 3. For reference, the losses of the fundamental modes of a single waveguide are also presented. It is observed that the losses for the single waveguide are almost the same as those of the supermodes, although the phase constant of the single waveguide lies almost midway between those of the two supermodes. In other words, the loss of the directional coupler can be estimated using the single waveguide with the same cross section.

Typical field distributions are shown in Fig. 3, where the field of the odd supermode is illustrated. Note that only half the field is displayed due to the configuration symmetry. As mentioned in Fig. 2, the field of the quasi-TM mode in Fig. 3(b) more extends to the silicon substrate than that of the quasi-TE mode in Fig. 3(a).

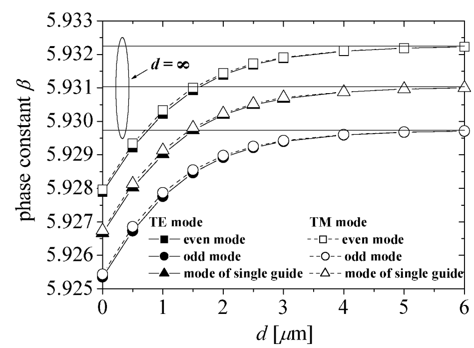

Fig. 4. Phase constants as a function of d.

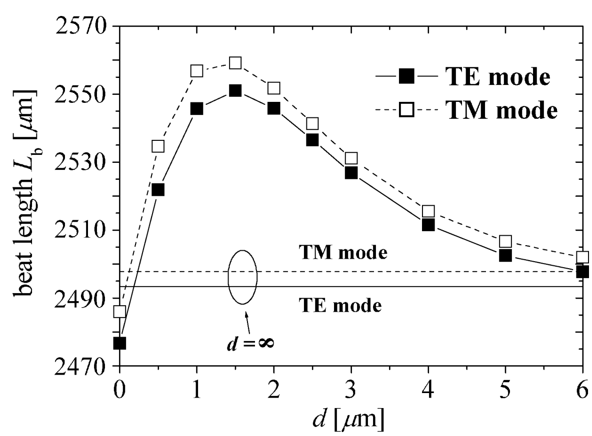

Fig. 5. Beat length as a function of d.

Fig. 4 shows the phase constants for both supermodes as a function of d. As expected, when d is sufficiently large, the phase constants ($\beta_{\rm even}$ and $\beta_{\rm odd}$) are almost the same as those observed without the silicon substrate ($d = \infty$). As d is decreased, the phase constants decrease. This is due to the fact that the field tends to extend toward the upper region as d is decreased.

Note that the beat length is determined by the difference between the phase constants of the supermodes. Fig. 5 shows the beat length $L_b (= 2\pi/(\beta_{\rm even} - \beta_{\rm odd}))$ as a function of d. An appreciable change in the beat length is observed when d is small. In general, the beat length becomes longer than that without the silicon substrate except the case where the core is extremely

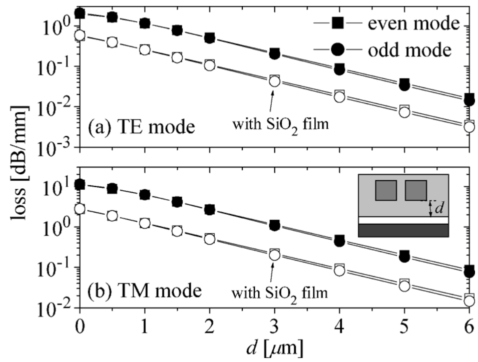

Fig. 6. Leakage loss as a function of d.

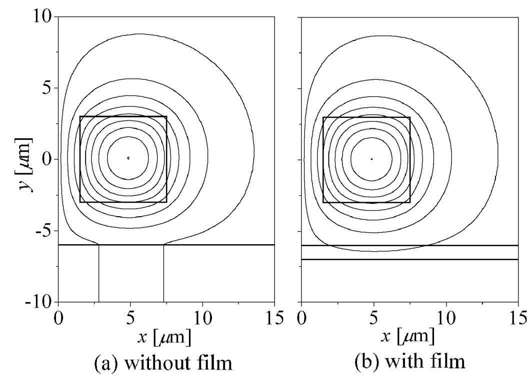

Fig. 7. Field distributions for the quasi-TM mode (H_x) (odd mode, $d = 3$ μm).

close to the substrate, i.e., $d \simeq 0$ μm. It is also found that a slight difference exists in the beat length between the quasi-TE and quasi-TM modes.

IV. Effects of Inserting a SiO_2 Film

To prevent the lightwave from leaking into the high-index substrate, a low-index film, such as SiO_2, is often inserted between the substrate and the cladding [7]. However, the effects of an insertion film have never been studied quantitatively. In this section, we consider the case for a film thickness of $t_f = 1$ μm. The refractive index of the film is chosen to be $n_f = 1.44$.

Fig. 6 shows the leakage loss as a function of d. The data obtained without the insertion film are again plotted for comparison. It is found that the losses for both modes decrease due to the addition of the film. In terms of the loss reduction, the insertion of the SiO_2 film corresponds to an increase in the distance between the core and the substrate without the film by about 2 μm. This leads to the possibility of height matching between the silica waveguide and other optical devices such as a photodiode and laser diode, with the loss being acceptable.

The odd supermode fields with and without the SiO_2 film are illustrated in Fig. 7. As a typical example, the quasi-TM fields are shown for $d = 3$ μm. It is clear that the field leaking toward the substrate is satisfactorily suppressed by the insertion of the film. Further calculation shows that no significant effects are observed for the phase variation caused by the insertion of the film, so that the beat length is almost the same as that shown in Fig. 5.

V. Conclusion

The leakage loss and the beat length of a buried directional coupler on a silicon substrate have been investigated using the imaginary-distance BPM. After showing the leakage loss as a function of the distance d between the core and the substrate, we find that the quasi-TM mode has higher loss than the quasi-TE mode, with almost the same loss as the single guide with the same cross section. It is found that the presence of the silicon substrate causes the beat length to be longer. The insertion of a SiO_2 film with a 1-μm thickness serves to reduce the loss, corresponding to the effects of increasing the distance d without the SiO_2 film by about 2 μm.

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