Analysis of Integrated Optical Corner Reflectors Using a Finite-Difference Beam Propagation Method

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Abstract—**Integrated optical corner reflectors in III-V semiconductors are analyzed employing a finite-difference beam propagation method and propagating the beam in parallel with the etched semiconductor-air interface. For this choice of propagation direction, the effects of mirror roughness, rotation, and displacement of the mirror surface from its ideal position can be assessed very easily. The integrated reflector whose mode size is larger shows less dependence on the mirror displacement error. The loss due to mirror surface roughness depends weakly on the mode size and strongly on the mode polarization, being larger for the quasi-TE polarization. The loss due to rotational errors of the mirror surface is not a strong function of polarization, but increases as the waveguide width increases. However, for a rotation error smaller than 0.1°, which should be achieved easily, the excess loss is smaller than 0.2 dB at 1.3 μm regardless of the waveguide width.**

Introduction

For the practical realization of compact photonic integrated circuits one often needs to change the direction of optical propagation in a short distance. To achieve this goal, there have been several different approaches. The feasibility of the curved waveguides with small radii of curvatures has been studied, and it has been shown both theoretically and experimentally that quite small radii of curvatures can be realized using strongly guiding waveguides [1], [2]. However, for compatibility with single mode optical fibers, weakly guiding single mode waveguides with large mode sizes are more desirable than strongly guiding waveguides. For a weakly guiding waveguide, a fairly large radius of curvature is required for an acceptable radiation loss. The most appropriate method for steering the optical propagation abruptly in a weakly guiding waveguide is to use an integrated optical corner reflector which takes advantage of total internal reflection at an etched interface between semiconductor and air. Even though several experimental [3]–[5] and theoretical studies [4], [6] on such structures were reported, a careful characterization of their performance as a function of practical fabrication tolerances is still lacking. A bidirectional beam propagation method (BPM) has already been applied to the analysis of a 90° corner reflector by propagating the beam in a direction perpendicular to the etched semiconductor-air (or mirror) interface. At the mirror interface the reflected part of each plane wave component was calculated and then propagated backwards [6]. However, in this approach it is difficult to take into account the roughness of the etched semiconductor-air interface which will inevitably occur in the fabrication. This difficulty can be circumvented by propagating the beam in a direction parallel to the etched semiconductor-air interface (or mirror surface). In the present work, this approach is used together with a finite-difference BPM which has been confirmed to be very accurate and efficient for waveguides with strong discontinuities in the refractive index profile [7].

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Method of Analysis

In the paraxial limit, two-dimensional wave equations both for the TE and TM modes of a dielectric slab waveguide are given as follows: For TE modes,

$$2jk_0 n_r \frac{\partial E_y}{\partial z} = \left(\frac{\partial^2}{\partial x^2} + k_0^2 (n^2(x,z) - n_r^2) \right) E_y, \quad (1)$$

and for TM modes,

$$2jk_0 n_r \frac{\partial H_y}{\partial z} = \left(n^2(x,z) \frac{\partial}{\partial x} \left(\frac{1}{n^2(x,z)} \right) \frac{\partial}{\partial x} + k_0^2 (n^2(x,z) - n_r^2) \right) H_y \quad (2)$$

where n_r the reference refractive index and k_0 is the plane-wave k-vector for a vacuum. If one approximates the partial derivatives in these equations using a finite-difference algorithm employing the Crank-Nicholson scheme [9], one can relate the optical fields of both modes at $z + \Delta z$ to the optical fields at z through a tridiagonal set of linear equations [7]. Therefore, propagating a beam at every step requires the solution of a tridiagonal set of linear equations, which can be done very efficiently [10]. Furthermore, this algorithm is unconditionally stable and it is shown to be much more efficient compared to conventional BPM which utilizes the fast Fourier transform [7]. Enhanced efficiency becomes very valuable especially for structures with large refractive index discontinuities such as corner reflectors.

The structure under consideration is a 90° semiconductor rib waveguide corner reflector. The cross-sectional profile of the rib waveguides is shown in the inset of Fig. 1. Using effective index approximation, the rib guides are reduced to slab guides, and the geometry of Fig. 1 represents the corner reflector. In the analysis it is assumed that the optical beam is propagating in the z direction, which is parallel to the ideal mirror interface. For accurate beam propagation in a titled waveguide geometry, a proper value for the reference refractive index, n_r, should be chosen. Recently it was pointed out that the most appropriate value for n_r in the paraxial approximation is $\beta \sin \theta / k_0$ [8] where β is the propagation constant of the eigenmode of the slab waveguide and θ is the angle of incidence. To estimate the validity of this approach, the transmission error through a uniform waveguide tilted 45° with respect to the assumed beam

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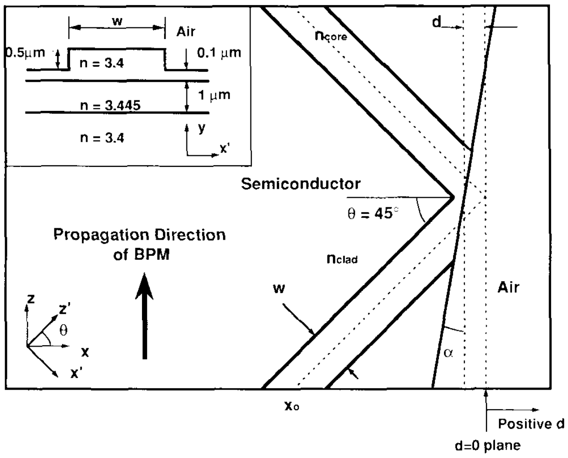

Fig. 1. Integrated optical corner reflector studied in this work. The inset shows the cross-sectional profile of rib waveguide. The slab waveguide in the corner reflector is obtained from the shown rib waveguide using the effective index approximation.

propagation direction is evaluated. At the input plane, i.e., $z = 0$, the following optical field distribution [8] is launched:

$$E_y(x, z) = \Psi_0((x - x_0 - z\cot\theta)) \cdot \exp(-j\beta(x - x_0 - z\cot\theta)\cos\theta) \quad (3)$$

where $\Psi_0(x - x_0)$ is the eigenmode of the slab waveguide which is represented by the index profile $n(x, z = 0)$ and β is the propagation constant of this eigenmode. As the input optical field is propagated in z direction, the overlap integral of the propagated beam with the field distribution given by (3) is evaluated at constant z planes. In the calculations, the computational window size is 100 μm and the number of mesh points in the x direction is 10 000. The propagation step size is taken as $\Delta z = 0.1$ μm and the wavelength is 1.3 μm. The waveguide widths considered are 3, 9, and 15 μm. After propagating the beams up to 40 μm, the calculated transmission loss is less than 0.006 dB for all waveguide widths. This result indicates that this approach can be used to analyze practical corner reflectors very accurately.

Analysis of Integrated Optical Corner Reflectors

Once the accuracy of the tilted propagation is established, the corner reflector in Fig. 1 is analyzed for both quasi-TE and quasi-TM modes of the rib waveguide shown in the inset of Fig. 1. The quasi-TE and quasi-TM modes of the rib waveguide correspond to the TM and TE modes, respectively, of the effective slab guide. In the calculations, the wavelength is 1.3 μm, the computational window size and the number of mesh points in the x direction are 50 μm and 5000, respectively, and the propagation step size in the z direction is 0.1 μm. The total propagation length in the positive z direction is 40 μm. The overlap integral of the propagated beam with the eigenmode of the waveguide is carried out at the end of total propagation length to get the transmission through the corner reflector. The transmission curves as a function of the displacement of the mirror from its ideal position, d, for both quasi-TE and -TM polarizations are generated, and the results are found to be in good agreement with the bidirectional BPM results on the same structure [6]. When $d = 1$ μm, the losses for quasi-TE modes are 0.3, 0.6, and 2.3 dB for $w = 15$, 9, and 3 μm, respectively. The optimum mirror position for the quasi-TM and quasi-TE modes are $d = -0.14$ μm and $d = -0.02$ μm, respectively. The corresponding values obtained using the bidirectional BPM are -0.12 μm and -0.02 μm, respectively [6]. In the calculations, various numbers of mesh points varying from 5000 to 15 000 are tried and it is found that the optimum displacement of the mirror plane varies between -0.14 μm and -0.11 μm for quasi-TM modes, between -0.02 μm and 0 μm for quasi-TE modes. At this point, it is concluded that the accuracy obtained is sufficient for the interpretation of the experimental results.

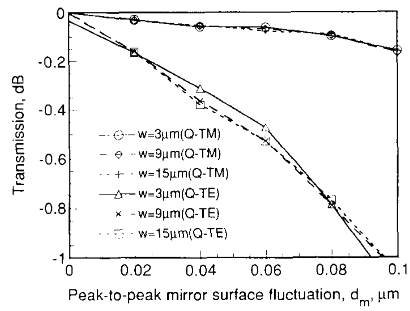

Fig. 2. Transmission as a function of the mirror surface roughness both for quasi-TE (Q-TE) and for quasi-TM (Q-TM) modes.

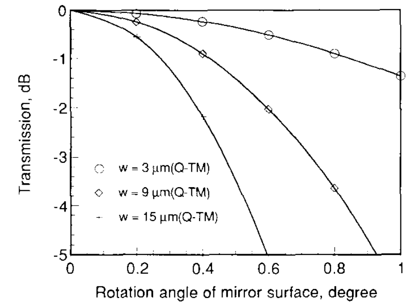

Fig. 3. Transmission as a function of the mirror rotational error for quasi-TM (Q-TM) modes.

Having established the accuracy of the present approach, the effect of the mirror roughness on the performance of the corner reflector is studied. The mirror surface variation along the propagation direction is assumed to be

$$d(z) = d_0 + d_m \mathrm{Random}(z) \quad (4)$$

where Random(z) is a random number generation function which generates random numbers between -0.5 and 0.5, and d_0 is chosen to be -0.14 μm for quasi-TM modes and -0.02 μm for quasi-TE modes. Fig. 2 shows the transmission characteristics of the reflector for different mirror roughness, i.e., different values of d_m. The transmission difference between 15 μm and 3 μm wide waveguide reflectors is less than 0.05 dB which suggests that the effect of mirror roughness is almost independent of the waveguide width, i.e., the size of the optical mode. The performance for quasi-TE mode drastically degrades while the transmission for the quasi-TM mode degrades slowly as the roughness increases. This can be understood by noting that for all the angles of incidence the reflectivity of the semiconductor–air interface for TE polarization is always larger than that for TM polarization. In addition, we study the effect of the rotation of the mirror from its ideal position. The transmission characteristics for varying tilt angles, α, are plotted in Fig. 3.

The results for quasi-TE modes are almost the same as those for quasi-TM modes. The wider waveguide reflectors are much more influenced by the rotation especially when the rotation angle is larger than 0.1°. However, for the rotation angles smaller than 0.1°, the excess loss due to rotation error is smaller than 0.2 dB for all the waveguide widths. In fact, 0.1° rotation error corresponds to 3.5 μm position error at the end of 2 mm long line; hence, the rotation error smaller than 0.1° should be easily achieved. This suggests that the rotation error should not impose limitation to the performance of the corner reflectors.

Conclusions

The finite-difference beam propagation method (FD-BPM) is applied to analyze the integrated optical 90° corner reflector in III–V compound semiconductor materials. In the analysis, the beam is propagated in the direction parallel to the etched semiconductor–air interface. Using this approach the effect of the mirror displacement is analyzed and it is found that the results are almost the same as the results calculated using the bidirectional BPM. The wider waveguide reflector is affected less by the mirror displacement. The loss due to the mirror roughness is found to be an insensitive function of waveguide width, i.e., the mode size. However, there is a strong polarization dependence and the loss for the quasi-TE mode increases very fast as the roughness becomes larger while the loss for the quasi-TM mode increases slowly as the roughness increases. The excess loss is less than 0.2 dB for the rotational error of the mirror surface less than 0.1°. For larger angles, loss of reflector for wider waveguides is influenced more by the rotation error. But, since alignment of rotation with an accuracy of 0.1° can be easily achieved, for improved corner reflector design, more attention must be paid to reducing the displacement error and the mirror surface roughness, and to the control of proper polarization.

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