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Improved Extinction Ratio in Ultra Short Directional Couplers Using Asymmetric Structures

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Various means of increasing the extinction ratio in ultra short directional couplers using slight asymmetry in the coupled waveguide structure are investigated. It is shown that couplers with 10–200 μm coupling length and with high extinction ratios larger than 30 dB can be achieved. Shorter asymmetric couplers have an extinction ratio that is more fabrication tolerant.

KEYWORDS: directional coupler, coupled mode theory, extinction ratio, asymmetric couplers, vertical couplers

1. Introduction

Directional couplers are critical components in photonic integrated circuits used in optical communication systems. The conventional directional couplers with laterally arranged waveguides can not achieve very short coupling lengths due to extreme sensitivity to fabrication variations and limitations to produce uniformly very narrow gap layers.[1] Vertical directional couplers, however, can obtain a short coupling length that is smaller than 100 μm.[2] The difficulty of separating the two vertically coupled waveguides into two distinct inputs and outputs limits the application of these devices.[3] Recently, a novel fused vertical coupler (FVC) with a very short coupling length of 62 μm was demonstrated, that can solve this problem.[4] To use FVC in large switching fabrics, it should have a low crosstalk. Ultra short directional couplers have an inherent limitation in their extinction ratio due to non-orthogonality of individual waveguide modes.[5] In this paper, we analyze various means to improve the extinction ratio using slight asymmetry in the structure. We also study the fabrication tolerance needed to maintain these improved characteriatics. Since vertical coupling through the ridge structure defined by etch-stopping techniques is much less sensitive to the ridge waveguide width and sidewall smoothness than the planar waveguide couplers,[6] it is expected that these slight asymmetric structures can be better realized in fused vertical coupler configuration.

2. Model Used in the Analysis

Figure 1(a) shows the FVC with separated input and output waveguides. Since the two waveguides are brought together with an air gap except the interaction region, we could minimize unwanted couplings for the separation of the output of the FVC. The two-dimensional index profile of the FVC is reduced to one dimension using effective index method. The schematic diagram of one dimension index profile in the straight coupling region is shown in Fig. 1(b). The structure is composed of two waveguides A and B with effective indices n_a and n_b, and thicknesses d_a and d_b, separated by an inner cladding region, index n_{ci} and thickness t. The outer cladding regions have indices n_{ca} and n_{cb}. Since the two waveguides are strongly coupled ($t = 0.2$–1 μm separation), an improved coupled mode theory (ICMT) is used to model accurately the crosstalk. This theory takes into account explicitly the finite

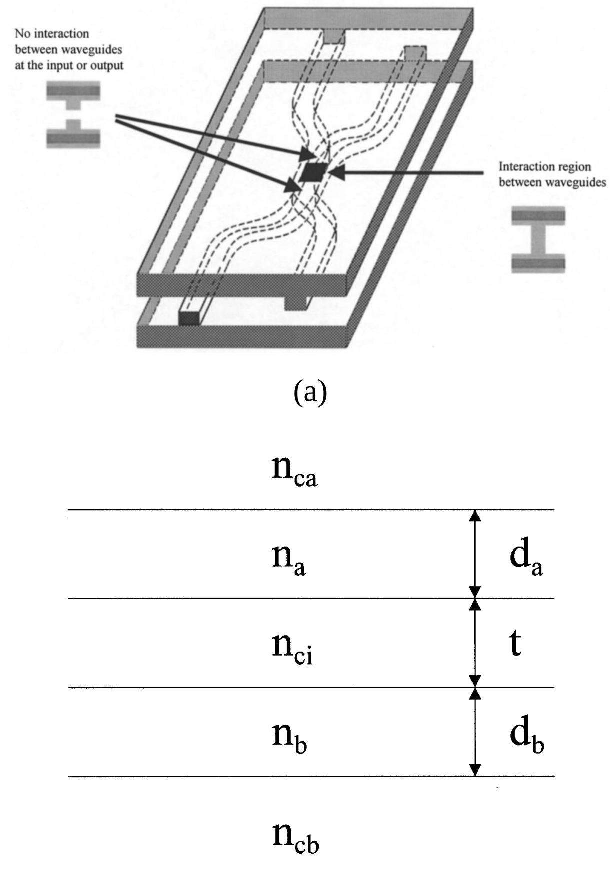

Fig. 1. (a) Fused vertical coupler with separated input and output waveguides. (b) Schematic diagram of one dimension index profile in the straight interaction region.

overlap integral between modes of individual waveguides.[7–9] Assuming that the power is incident into the waveguide A, without the loss of generality, the extinction ratio after a distance equal to the coupling length is defined as p_b/p_a where p_a and p_b are the guided mode powers in waveguides A and B respectively. The wavelength used in the calculation is 1.55 μm.

3. Results

Figures 2 and 3 show the extinction ratio and coupling length of TE and TM modes as a function of the refractive index of waveguide A using ICMT and also 2D finite difference beam propagation method (BPM). The parameter values used in the calculation are $n_b = 3.37$, $n_{ca} = n_{cb} = n_{ci} = 3.17$, $d_a = d_b = 0.5$ μm, and $t = 0.6$ μm. We can see that the data

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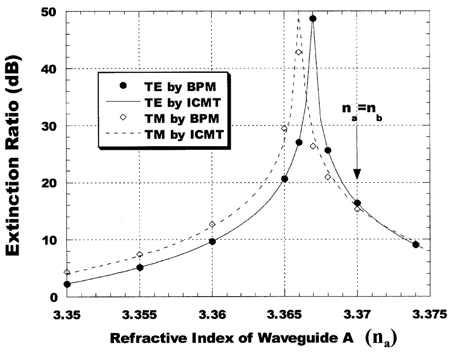

Fig. 2. Extinction ratio for TE and TM modes as a function of the index of waveguide A calculated using ICMT and BPM.

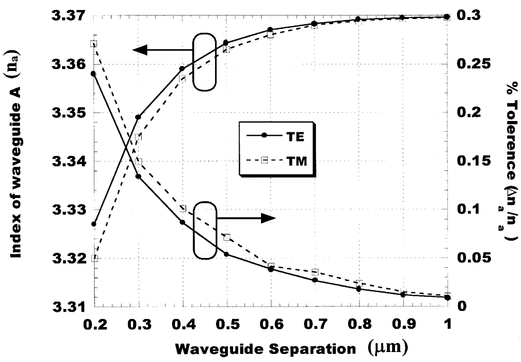

Fig. 4. Index of waveguide A for maximum extinction ratio and tolerance to achieve larger than 30 dB extinction ratio as a function of waveguide separation.

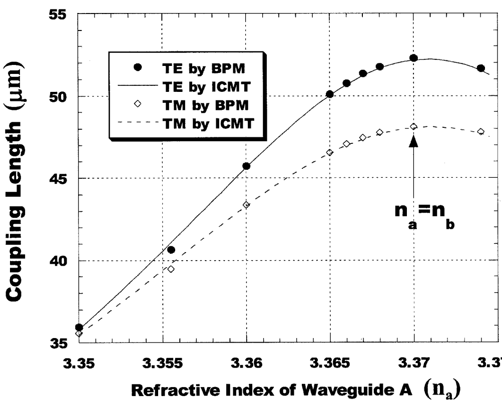

Fig. 3. Coupling length for TE and TM modes as a function of the index of waveguide A calculated using ICMT and BPM.

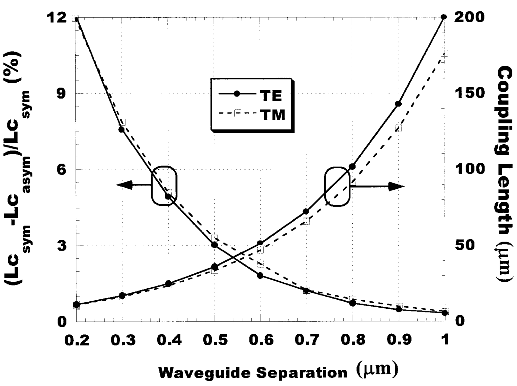

Fig. 5. Coupling length of the asymmetric coupler for the different values of n_a corresponding to Fig. 4 and its percent difference with respect to the symmetric case as a function of waveguide separation.

calculated by ICMT agrees very well to that by BPM. The extinction ratio larger than 50 dB for TE (TM) mode occurs at $n_a = 3.367$ ($n_a = 3.366$) and the coupling length in this case is 51 μm (47 μm). The extinction ratio and the coupling length in the symmetric case for TE (TM) mode are 16.4 dB (15.7 dB) and 52 μm (48 μm) respectively. We can see that the extinction ratio is increased considerably at the expense of having less than 100% power tranfer to the waveguide B by slight detuning of the two waveguide eigenmodes as Chuang showed in ref. 10. The coupling length is not significantly affected by making the waveguides asymmetric.

Figure 4 shows the optimum asymmetry in the index of waveguide A (n_a) for TE and TM modes as a function of waveguide separation with the parameters used in Figs. 2 and 3. It also displays the percent tolerance ($\Delta n_a/n_a$) to obtain an extinction ratio larger than 30 dB. One can see that the optimum value of n_a for TE mode is larger than that of TM mode, while the percent tolerance of TM mode is larger than that of TE mode. When the waveguides are separated by 0.6 μm, the asymmetry defined by $n_b - n_a$ required to achieve the highest extinction ratio for TE (TM) mode is 0.003 (0.004). Having index of waveguide A within $\pm$ 0.019 % ($\pm$ 0.021 %) of the optimum value for TE (TM) mode, one can achieve the extinction ratio larger than 30 dB. As the separation between the two waveguides decreases, more asymmetry is needed but the tolerance to obtain an extinction ratio larger than 30 dB increases to 0.24 % (0.27%). This means that the peak in extinction ratio in Fig. 2 becomes broader as the coupling length decreases. This facilitates the fabrication of passive ultra short asymmetric couplers or setting the voltage or current in active components.

Figure 5 shows the coupling length of the optimum asymmetric coupler for the different values of n_a corresponding to Fig. 4 and its percent difference with respect to the the symmetric case as a function of waveguide separation. The coupling length decreases and the percent difference increases as the separation decreases. One can see that, as expected, the coupling length of TM mode is shorter than that of TE mode. By making the waveguides very close to each other (< 0.4 μm) one can achieve ultra short coupling lengths less than 30 μm and at the same time maintain the extinction ratio larger than 30 dB.

In the case of symmetric couplers, even though the coupling lengths are comparable to those of asymmetric ones (see Fig. 5), the extinction ratios are severely deteriorated to less than 15 dB when the separation between the two waveguides is less than 0.55 μm (see Fig. 6).

To confirm that the effect of the asymmetry on the extinction ratio comes from the slight difference in the shapes of the two waveguide eigenmodes, the extinction ratio and coupling length of TE and TM modes as a function of the width

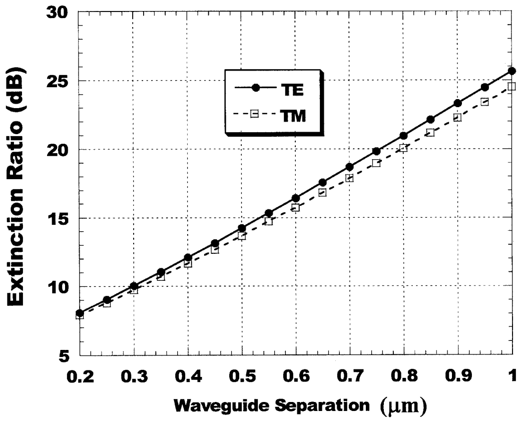

Fig. 6. Extinction ratio for TE and TM modes for the symmetric coupler as a function of waveguide separation.

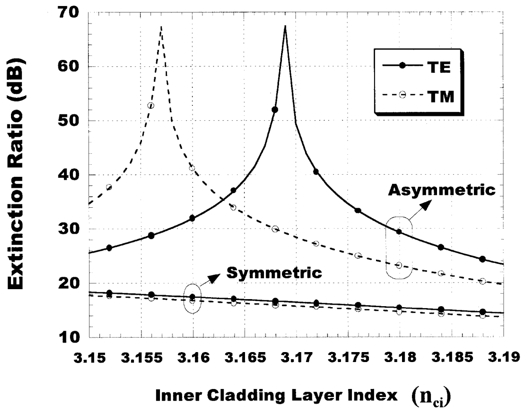

Fig. 7. Extinction ratio for TE and TM modes for the asymmetric and symmetric structures as a function of refractive index of inner cladding layer.

of waveguide A rather than its refractive index are calculated with the parameter values $n_a = n_b = 3.37$, $n_{ca} = n_{cb} = n_{ci} = 3.17$, $d_b = 0.5\ \mu$m, and $t = 0.6\ \mu$m. An extinction ratio larger than 42 dB for TE (TM) mode occurs at $d_a = 0.486\ \mu$m (0.484 μm) while the extinction ratio in the symmetric case was around 16 dB. The effect of inner cladding layer on the characteristics of the coupler is also studied. Figure 7 shows the extinction ratio of TE and TM modes as a function of the refractive index of inner cladding layer for the symmetric and asymmetric structures. The parameter values used in the calculation are $n_b = 3.37$, $n_{ca} = n_{cb} = 3.17$, $d_a = d_b = 0.5\ \mu$m, $t = 0.6\ \mu$m, $n_a = 3.367$ for the asymmetric structure and $n_a = 3.37$ for the symmetric one. The extinction ratio for the symmetric structure does not change much as a function of the refractive index of the inner cladding layer. It increases slightly as the inner cladding layer index decreases due to smaller overlap integral between two individual waveguide modes. For the asymmetric structure, the extinction ratio changes considerably ($>$ 40dB) as a function of the inner cladding layer index. The highest extinction ratio occurs at $n_{ci} = 3.169$ for TE mode and at $n_{ci} = 3.157$ for TM mode. A slight asymmetry can equalize the overlap integral of one of the waveguide modes with the symmetric and antisymmetric supermodes of the coupler and thus increase the extinction ratio.[5)]

4. Conclusions

We have shown that one can achieve ultra short vertical directional couplers (coupling length 10–200 μm) while maintaining a high extinction ratio larger than 30 dB with slight asymmetry in the coupled waveguide structure. Shorter asymmetric couplers have an extinction ratio that is more fabrication tolerant. Also, we confirmed that the high extinction ratio of asymmetric stuctures comes from the slight difference in the shapes of the two waveguide eigenmodes by changing the refractive index of inner cladding layer and the width of one of the waveguides.

Acknowledgment

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