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Characterization of interlayer directional coupler in layered silica-based planar lightwave circuit

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***Abstract*—We characterize interlayer directional couplers in a layered silica-based PLC, and demonstrate a core width tuning method to reduce imperfect coupling and polarization dependence. We achieved almost 100 % coupling between layers without polarization dependence.**

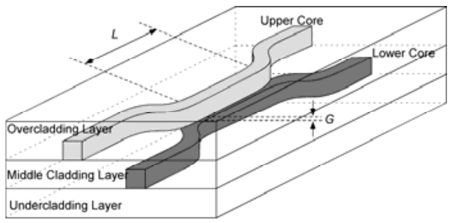
I. INTRODUCTION

SILICA-BASED planar lightwave circuits (PLCs) play an important role in optical communications systems, because they offer excellent optical characteristics, cost effectiveness and high reliability. Several approaches have been proposed for the large-scale integration of circuit components, including high contrast waveguides [1] and waveguide stacking on a single wafer [2-4]. The latter is attractive because it is capable of offering a novel function by using a 3-dimensional circuit topology with interlayer directional couplers. In this paper, we report the characteristics of interlayer directional couplers in a monolithically layered silica-based PLC. The couplers initially exhibited imperfect coupling characteristics and a polarization dependent coupling ratio due to the stress induced index mismatch between the layers and polarizations. To eliminate these undesirable characteristics, we developed a core width tuning method that matches the internal stresses of waveguides between layers.

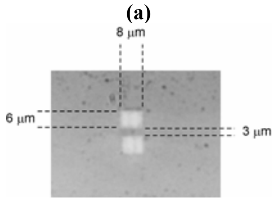
II. INTERLAYER DIRECTIONAL COUPLER

Figure 1 shows the schematic configuration and a microscope image of a cross-section of our interlayer directional coupler. The upper and lower waveguides, which are first separated at the input region to avoid optical coupling, converge in the horizontal direction and remain close together for a certain length L. They then diverge with sufficient separation for us to disregard the optical coupling.

The interlayer directional coupler is fabricated as follows. First, the lower layer of a layered PLC is fabricated by the conventional PLC fabrication technique using flame hydrolysis deposition (FHD) and reactive ion etching (RIE). Then, we polish the middle cladding layer to flatten it and adjust the gap between the upper and lower cores. Finally, we repeat the same procedure to fabricate the upper layer.



(a)



(b)

Figure 1 Schematic configuration and microscope image of the cross-section of an interlayer directional coupler.

The coupling ratio $C.R.$ of a [2x2] directional coupler is expressed as [5]

$$\begin{aligned} C.R. &= F\sin^2\left[q\left(L-L_0\right)\right] \\ F &= (\kappa/q)^2 \\ q &= \sqrt{\kappa^2+\delta^2} \\ \delta &= \frac{\beta_1-\beta_2}{2} \end{aligned} \quad . \qquad (1)$$

Here β_1, β_2, κ, L and L_0 show the propagation constants of the upper and lower waveguides, the coupling coefficient between the waveguides, the length of the straight waveguides, and the equivalent length of the curved waveguide, which contributes to optical coupling, respectively. It is clear that if the propagation constants of the two waveguides are different, the coupler exhibits imperfect coupling characteristics (i.e. F < 100 %). In other words, unless the two waveguides have the same propagation constant, the coupling ratio is less than unity for any straight length.

Here, it should be noted that the FHD process requires a high temperature, and the glass composition of each layer of the PLC must be different to avoid deformation of the lower layer core. In other words, the upper layer must be composed of a softer glass than the lower layer. This causes stress mismatches between the waveguide layers and between the polarizations, resulting in imperfect coupling and polarization dependence caused by the photo-elastic effect. Therefore, we investigated a method to tuning the core width to match the internal stress and refractive indices of the waveguides.

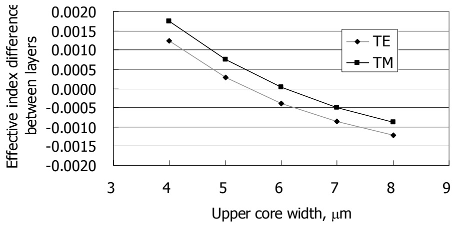


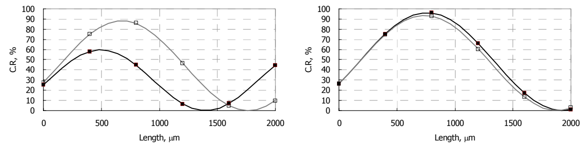
Figure 2. Calculated dependence of effective index difference between layers on the upper core width. The lower core width is fixed at 5.5 μm. The solid and dashed lines indicate the TM and TE polarization modes.

Figure 2 shows the dependence of the effective index difference between layers on the core width calculated by the finite element method (FEM). The lower core width is fixed at 5.5 μm and the upper width is varied from 4 to 8 μm. The difference is polarization dependent as a result of stress induced birefringence, and will result in polarization dependence and the imperfect coupling of the interlayer couplers. If the difference is zero or the propagation constants between the waveguides are the same, the coupler provides perfect coupling (F = 100 %). As shown in Fig. 2, the difference is almost zero when the upper core widths are around 5.5 and 6 μm for the TE and TM modes, respectively. This means that with the same core width of 5.5 μm, the coupler is not perfect for the TM mode, although it is for the TE mode. One way to relax the polarization dependence is to adjust the upper core width between 5.5 and 6 μm. In this case, although the coupler might be imperfect for both modes, the polarization dependence will be eliminated.

III. EXPERIMENT

Figure 3 shows typical characteristics of the fabricated interlayer directional couplers. We used 0.75 % refractive index contrast waveguides, and fixed the waveguide gap and core heights at 3 and 6 μm, respectively. Figures 3(a) and (b) show the coupling characteristics of couplers with a core width of 5.5 μm for both layers, and with a 6.0-μm upper core and a 5.5-μm lower core, respectively. Owing to the internal stress mismatch, the coupler with the same core width for both layers exhibits polarization dependence and imperfect coupling as shown in Fig. 3(a), while the coupler with a wider core for the upper layer exhibits little polarization dependence and almost perfect coupling characteristics.

Figure 4 summarizes the measured maximum coupling ratio for various combinations of core widths. It can be seen that better coupling is obtained when the width of the upper layer is wider than that of the lower layer. This agrees with reports stating that softer cladding provides a small birefringence [6] and a wider core width leads to a larger birefringence [7]. That is, with the same core width, the birefringence of the upper layer is smaller than that of the lower layer. An increase in the width of the upper core increases its birefringence. The condition seen in Fig. 3(b) is the best.



(a) **(b)**

Figure 3. Measured coupling characteristics of interlayer directional couplers, (a) with the same core width of 5.5 μm for both layers, and (b) with different core widths of 6.0 and 5.5 μm for the upper and lower cores, respectively. The solid and dashed lines show the characteristics of the TM and TE modes, respectively.

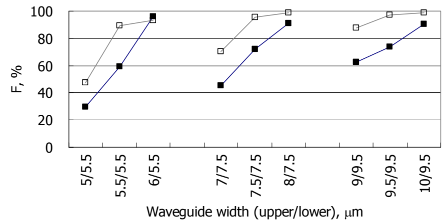


Figure 4. Measured maximum coupling ratio for various core widths. The solid and dashed lines show the TM and TE modes, respectively.

If we accept that there was a small error in the fabrication, the prediction in the previous section also agrees with the experiment. As predicted, for the same core width, the TE mode shows perfect characteristics while the TM mode does not. As the upper width increases, the effective index difference between layers for the TM mode approaches zero, and the optimum width for balancing both modes is between 5.5 and 6 μm.

IV. SUMMARY

We investigated interlayer directional couplers in a layered silica-based planar lightwave circuit. They exhibited inherent polarization dependence and imperfect coupling due to the stress mismatch induced by the photo-elastic effect. We demonstrated a core width tuning method as a countermeasure, and achieved almost 100 % coupling without polarization dependence. A layered silica-based PLC is a promising candidate for the greater integration of optical functional devices.

REFERENCES

[1] Y. Hibino, *IEEE J. Select. Topic. Quant. Electron,* vol. 8, no. 6, pp. 1090-1101, 2002.

[2] S. Suzuki, K. Shuto, and Y. Hibino, *IEEE Photon. Technol. Lett,* vol. 4, no. 11, pp. 1256-1258, 1992.

[3] P.P. Absil, J.V. Hryniewicz, B.E. Little, F.G. Johnson, K.J. Ritter, and P.T. Ho, *IEEE Photon. Technol. Lett*, vol. 13, no. 1, pp. 49-52, 2001.

[4] Y. Hatakeyama, T. Hanai, S. Suzuki, and Y. Kokubun, *IEEE Photon. Technol. Lett,* vol. 16, no. 2, pp. 473-475, 2004.

[5] K. Okamoto, Fundamentals of optical waveguides," Academic Press, 2000.

[6] S. Suzuki, S. Sumida, Y. Inoue, M. Ishii, and Y. Ohmori, *Electron. Lett,* vol. 33, no. 13, pp. 1173-1174, 1997.

[7] Y. Inoue, M. Itoh, H. Hashizume, Y. Hibino, A. Sugita, and A. Himeno, *Proc. OFC'01*, vol. 3, WB4, Anaheim, 2001.