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Optical Waveguide Coupler Fabrication Based On Time Variation Ion-Exchange Technique

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Abstract – **Optical power transfer in a planar waveguide directional coupler is dependent on the geometry and refractive indices of the two waveguides. A method for fabricating optical directional couplers using ion-exchange $Ag^+/K^+/Ca^+$ processes is presented, where the time of ion-exchange process is used to control the ratio of output power at the two output ports at a fixed temperature of 300^0C. As far as the device geometry is still in single-mode regime, this method eliminates the need for high-resolution lithography for producing exact geometry of the device.**

I. INTRODUCTION

Directional couplers are used to divide the guided light at almost any desired ratio. The main draw back of this device which is based on the field coupling between closed waveguides is their high sensitivity to the fabrication process and device geometry, especially the spacing of the waveguides in the coupling region [1]. Due to this fact access to high resolution lithography is inevitable for successful fabrication of these devices based on conventional designs.

Optical planar and channel waveguides fabrication using ion-exchange process is very common due to low cost and simple technique. The process involves the exchange of sodium ions originally in the glass with other alkali ions of larger polarizability.

In this study, 5 samples of buried waveguides were fabricated using thermal ion exchange process, immersed in molten mixture of $AgNO_3$, KNO_3 and $NaNO_3$, at fixed temperature of 300^0C. As the ion exchange time increases, the embedded graded index waveguide formed by the diffusion of silver ions is getting deeper and wider. When the two waveguides in the coupling region become closer, the coupling becomes more easy and faster, and this allows the power ratio at output ports to vary. As the time is kept longer, larger size of the channel waveguides are obtained and effectively reducing the spacing. This effectively changes the coupling coefficients between the two waveguides and eventually their splitting ratio.

Therefore this method offers a simple way of getting directional couplers with different output or coupling ratio by using only a single set of lithography photomask.

II. DIRECTIONAL COUPLER DESIGN

A directional coupler is usually formed by two identical parallel dielectric waveguides separated from each other by a gap on the order of a wavelength. Consider when two waveguides are far enough from each other, two normal modes propagate independently on each waveguide with propagation constants β_a and β_b , and the field distributions are ψ_a and ψ_b respectively. When the separation of the waveguides is reduced, the two waveguide fields interact with each other and this allows the exchange of energy. Coupled mode theory can be used as a method to analyze this behavior [2]. When the separation decreases the coupling between the two waveguides become easier and the energy periodically exchanges along the coupling region. At a certain length L, the maximum transfer of power from one waveguide to another will take place. For a simple structure of two identical coupled waveguides, L is given by:

$$L = \pi / 2\beta_c \qquad (1)$$

where,

$$\beta_c = \sqrt{\kappa^2 + \Delta^2};$$

$$\Delta = \frac{\beta_b - \beta_a}{2}; \text{ and}$$

$$\kappa = c\int \psi_a{}^* \psi_b \Delta\varepsilon dxdy$$

The schematic of the designed couplers are shown in Fig.1 Each of them consists of two identical waveguides with width 5 μm. The design difference is on its separation parameter; one with 3 μm and the other is 5 μm.

III. ION-EXCHANGE

Under certain conditions, it is possible to replace some of the network modifier ions of glass by others with the same valence and chemical properties. In the so called exchanged region, thus it modifies the glass property. The new ions have different polarizabilities, sizes, and mobilities and thus increasing the refractive index in selected areas of glass substrate.

By exposing the glass surface to the melt nitrates solution, the Ag^{3+} ion is diffused into the glass and exchanges with Na^+ ions. This is called thermal ion exchange process, where the introduction of the ions is diffusion driven. In our work a mixture of $NaNO_3$, KNO_3, and $AgNO_3$ at a ratio of 50:50:1 mole % are used. The melting point is at 220^{0}C and the exchange process is at 250^{0}C, the maximum obtainable refractive index contrast is 0.078 (at the surface) [3,4,5].

V. EXPERIMENTAL AND SIMULATION RESULTS

The ion exchange process was done on Corning glass with refractive index of 1.515, and the surface index difference of 0.078 was obtained. Figure 2 shows the waveguide depth increases with time. It should be noted that while the ion diffuses perpendicular to the mask opening, it also diffuses laterally.

Five samples are fabricated based on the two different designs. Sample 1 and 2 have the waveguide separation of 3 μm. Exchange times for these samples are 1 minute and 5 minutes respectively. Whereas samples 3, 4, and 5 have the separation of 5 μm, with the exchange time of 1 minute, 5 minutes, and 8 minutes respectively. The width all waveguides is fixed at 5 μm, and the interaction or coupling length is 2000 μm.

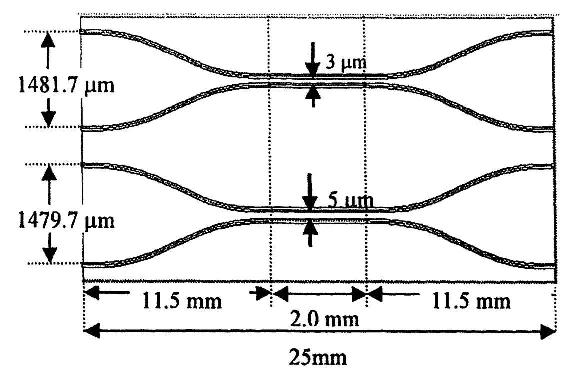

Fig. 1 Schematic diagram of two directional couplers design.

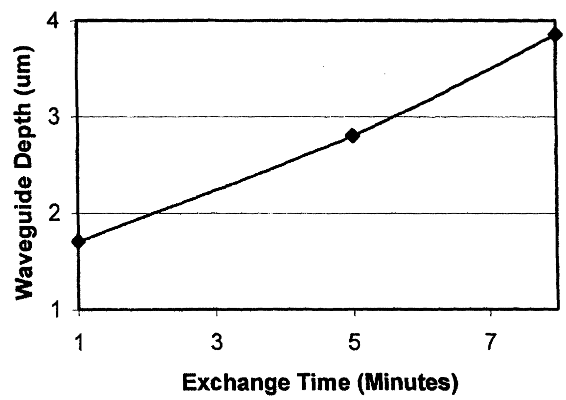

Fig.2 Waveguide depth increases as ion exchange time increases.

Table 1 summaries the specification of the two directional couplers. The output ratio of both channels for sample 1, 2, 3, 4, and 5 are shown in Fig. 3a, 3b, 3c, 3d, and 3e respectively.

Table 1. Specification of DC in Figure 1

Figure 3	(a)	(b)	(c)	(d)	(e)
Sample	1	2	3	4	5
Time (min)	1	5	1	5	8
Guide spacing (μm)	3	3	5	5	5
Guide width (μm)	5	5	5	5	5

Sample	1	2	3	4	5
m (nm^{-1})	6E-4	1E-4	5E-4	10E-4	6E-4

The power transfer between the two arms changes with the wavelength and is measured

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by the slope *m* of the graph for each sample. It is difficult to discuss and draw the relationship of the slope obtained related with the device design data. As the ion exchange time is made longer, the spacing in the coupling region becomes smaller and at the same time the depth of the embedded guide is deeper. The variation of the width and the depth of the waveguides will changes the coupling behavior between the two guides. Figures 3(a) to 3(e) show how the power ratios between the two output ports change with the wavelength for all five samples respectively.

VI. Conclusions

Time for ion exchange process plays very important role where we have shown experimentally that the coupling behavior in directional couplers changes dramatically. By fabricating many more samples with various parameters a more clear trend can be observed and may be a some conclusions can be suggested. This may help to determine the exact manufacturing steps process if ion-exchange is adopted as the fabrication method. However from this work we discover that a number of planar waveguide directional couplers with different coupling ratios can be made from a single design only, ie. by allowing different time duration during the fabrication.

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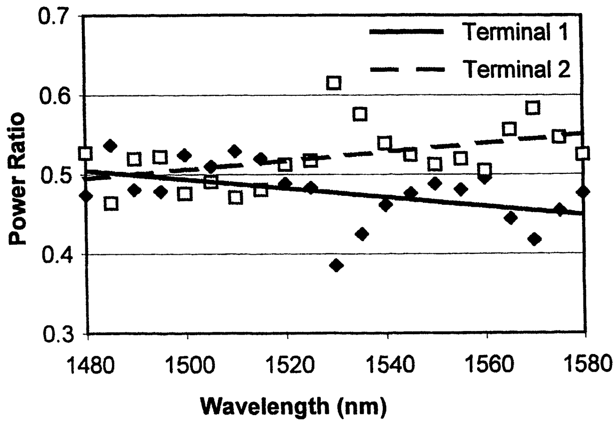
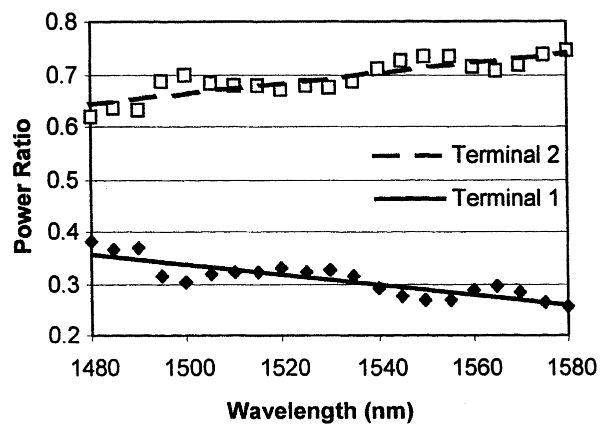
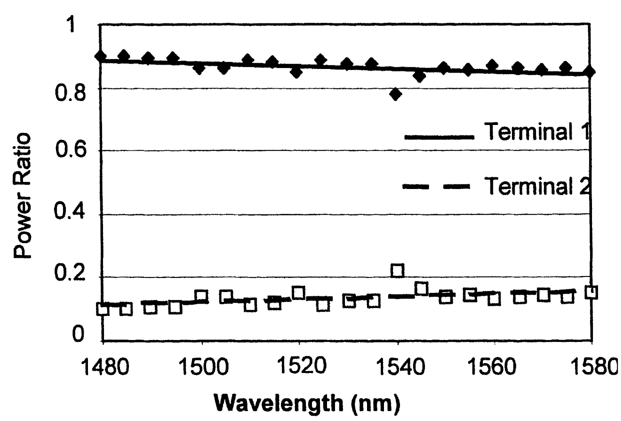


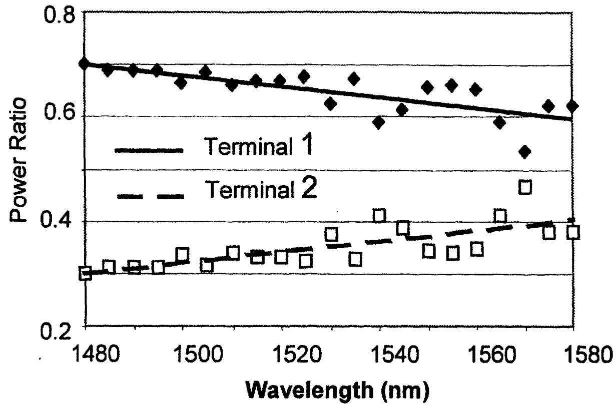
(a)



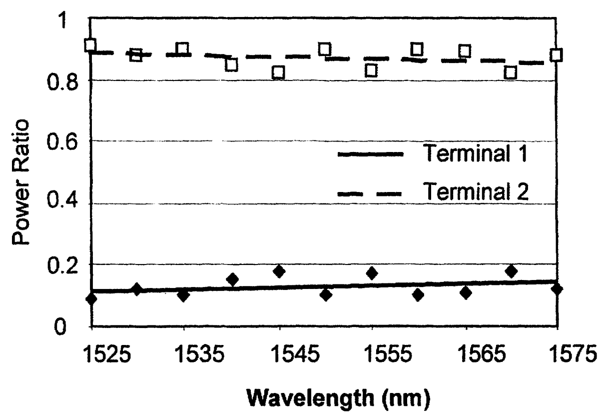
(b)



(c)



(d)



(e)

Fig. 3 Output power ratio dependence on wavelength at both channel of the five fabricated samples corresponding to wavelength of 1480 nm to 1580 nm. The gradient for the graph in (a) Sample 1, 6.0 x 10^{-4} nm^{-1}, (b) Sample 2, 1 x 10^{-4} nm^{-1}, (c) Sample 3, 5 x 10^{-4} nm^{-1}, (d) Sample 4, 1 x 10^{-3} nm^{-1}, (e) Sample 5, 6 x 10^{-4} nm^{-1}.