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Silica-Based MMI-MZI Thermo-Optic Switch with Large Tolerance and Low PDL

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Silica-based 2×2 thermo-optic (TO) switch using the MMI couplers which have a large fabrication tolerance of 110 (μm were fabricated and operated. Important features of the proposed switch are shown to be a polarization dependency loss of 0.1 dB, an extinction ratio of 32.7 dB, and a power consumption of 202.8 mW.

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I. INTRODUCTION

Due to their high fiber coupling efficiency and long-term stability, silica-based optical devices are used in many kinds of hybrid integrated optical devices such as optical add/drop multiplexers (OADM) [1] and N×N matrix switches [2]. However, for these devices, as the number of incorporated units is increased, fabrication tolerance, polarization dependency, and power consumption become important factors for reliable and practical operations.

For commercially efficient fabrication of an optical device, the fabrication tolerance has to be considered. Because an optical splitter is the basic component, the fabrication tolerance of optical splitters is a very critical factor for the prices of commercial products. There are two kinds used often; directional couplers and MMI couplers. When compared with the MMI coupler, the directional coupler has a short imaging length and extended interference at the two bent waveguides which are both sides of the directional coupler [3]. On the other hand, the MMI coupler has been frequently used and successfully tested experimentally to create an optical device with compactness, low polarization dependency, and large fabrication tolerance [4, 5].

In this paper, we report the fabrication tolerance of the silica-based MMI coupler in the experimental results, and then eight different length MMI couplers are employed in 2×2 MMI-MZI TO switches. The MMI-MZI TO switches have been also measured their optical characteristics to prove the suitability of the silica-based MMI couplers.

II. MULTIMODE WAVEGUIDE

The central structure of an MMI coupler is a waveguide designed to support a large number of modes. A number of access waveguides are placed at its beginning and at its end as input and output waveguides. A silica-based step-index multimode waveguide structure is normally defined by width W_M, core refractive index n_r, and overclad and underclad refractive indices n_c.

In general, the effective widths of each of the guided modes $W_{e\nu}$, which can be explained by the Goos-Hähnchen shift, can be approximated by the effective width W_{e0} corresponding to the fundamental mode [6],

$$W_{e\nu} \cong W_{e0} = W_M + \frac{\lambda_0}{\pi\sqrt{n_r^2 - n_c^2}}\left(\frac{n_c}{n_r}\right)^{2\sigma} \equiv W_e \quad (1)$$

where $\sigma = 0$ for TE and $\sigma = 1$ for TM, and λ_0 is a free-space wavelength.

The beat length of the two lowest-order modes is

$$L_\pi \equiv \frac{\pi}{\beta_0 - \beta_1} \cong \frac{4n_r W_e^2}{3\lambda_0} \quad (2)$$

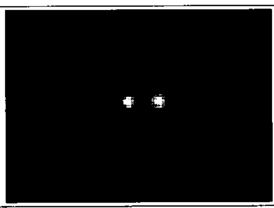
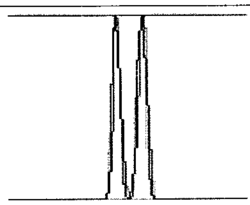
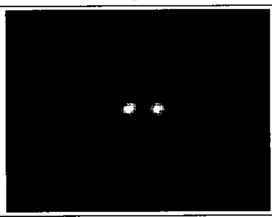
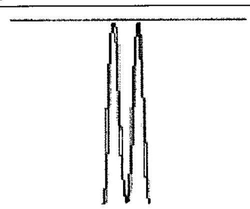
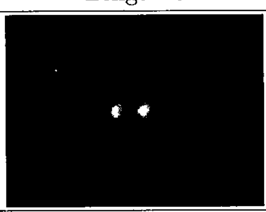
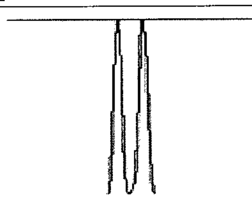
where β_0 and β_1 are the propagation constants of the fundamental mode and the first-order mode, respectively. They can be explained by using the binomial expansion.

The multimode waveguide for this research is formed of silica material and as a buried structure with index difference of 0.75 %. In the previous research [7], PDL has been measured below 0.3 dB in 2×2 strip-loaded waveguide MMI couplers. Because of their waveguide structure and material, the waveguide has an extremely high value on the index difference from the value of the model of this research. So, it can be shown that a multimode waveguide with a lower index difference has a lower value of the TE/TM difference of the term $(n_c/n_r)^{2\sigma}$ in (1). Moreover, the beat length which is a very important factor for MMI couplers is quadratically dependent on the effective width from (2).

III. FABRICATION TOLERANCE

Because silica material is amorphous, the length of the MMI coupler is adjusted by the cut-back method through polishing. Before the fabrication of the MMI coupler, computer simulation using the finite difference method (FDM) has been done for the MMI coupler with width of 25 μm, height of 7 μm, overclad thickness of 9 μm and underclad thickness of 14 μm. The access waveguides, as input and output waveguides, are placed at the four edges of the multimode waveguide for general interference and their dimension is 7×7 μm^2. The length of the 3-dB MMI coupler is 1507 μm from the simulation result. Then, the general MMI coupler is fabricated to be longer than the simulation result by commonly used technologies such as thermal oxidation, FHD, and ICP. The fabricated MMI coupler is polished and the output images and relative output intensities for every cut-backed MMI coupler have been measured. Table 1 shows the measurement results.

TABLE 1. Output profiles and intensities for the MMI coupler with 25 μm-Width and Various Lengths.

	
Length of MMI Coupler = 1430 μm	
	
Length of MMI Coupler = 1490 μm	
	
Length of MMI Coupler = 1540 μm	

As shown in Table 1, two self-images in the general MMI coupler remained and their balance is stable in the length of the MMI coupler from 1430 μm to 1540 μm. From the result, the fabrication tolerance is defined as 110 μm for the general MMI coupler.

IV. TO SWITCH APPLICATION

The schematic configuration of the 2×2 TO switch is shown in Fig. 1. The TO switch is composed of two 2×2 general MMI couplers, and a phase shifter with a thin film heater and heat insulating grooves. The cross sectional structure of the phase shifter is shown in the sub-box of Fig. 1. Because the trench width limits the trench depth according to the ICP etching process, the trench depth is decided to be the same as the value of the overclad height added to the core height. So, 16 μm-deep trenches were formed as heat insulating grooves on either side of the single-mode waveguides of the phase shifter. Because of the trench width limitation, there are four bent waveguides which have the bending radius of 5000 μm to connect the phase shift arms and the MMI couplers. In the phase shifter, 2.5 mm-long Cr thin film heaters were also formed on the two single-mode waveguides of the phase shifter.

Switching operation of the 2×2 TO switch using general MMI coupler is well described by MMI theory [6]. Without phase shift, i.e. for initial condition of the TO switch, the output signal emerged totally at output 2 (output 1) when the input signal is launched at input 1 (input 2). For switching operations, one of two heaters in the phase shifter is heated by electric power until the optical signal in the heated single-mode waveguide has π-phase shift, then the launched input signal at input 1 (input 2) appeared totally at output 1 (output 2). In addition, the phase shift of the switch as a function of temperature difference can be expressed as

$$\Delta\phi = \frac{2\pi}{\lambda_0}\left(\frac{dn}{dT}\right)_{SiO_2} \Delta T \, L_H \tag{3}$$

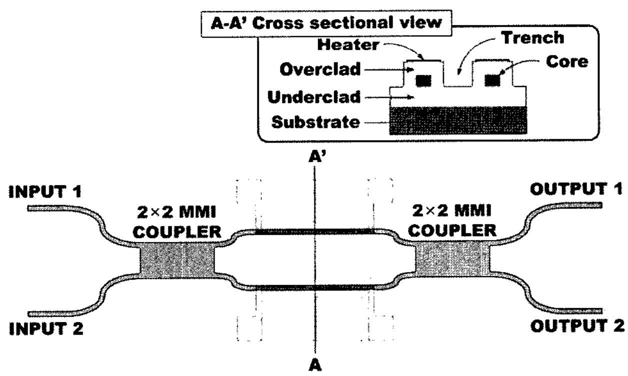


FIG. 1. Schematic top view of the TO switch using 3-dB MMI couplers and cross sectional view of the phase shift arms.

where $(dn/dT)_{SiO2} = 1\times10^{-5}\ K^{-1}$ is the thermo-optic coefficient of silica material, ΔT is the change in the temperature (degrees Kelvin^{-1}), and L_H = 2500 μm is the heater length. Equation (3) shows that a temperature change of 18.24 °K is needed to achieve a π-phase shift.

V. EXPERIMENT RESULTS

The silica-based 2×2 TO switches using cascaded two general MMI couplers which have the fabrication tolerance of 110 μm and heat insulating grooves are fabricated by the standard silica-on-silicon PLC technologies (Fig. 1). Fig. 2 shows the normalized optical output intensities of output 2 for the fabricated MMI-MZI TO switches using general MMI couplers of eight different lengths (1480 μm ~ 1520 μm) which is in the range of the fabrication tolerance. The reference value of the normalization is the output intensity of the single-mode waveguide which is the same length as the TO switches. The optical input signal, which has a wavelength of 1.55 μm, was launched at input 1 and the eight models have been measured five times each.

As shown in Fig. 2, the average excess loss is calculated as 0.7 dB. Fig. 2 shows that all the output characteristics of the eight switches are almost stable, so the range of the fabrication tolerance of 110 μm is acceptable.

Next, a MMI-MZI TO switch using the general MMI coupler with the length of 1505 μm was packaged and its characteristics measured. Fig. 3 shows the measured switching characteristics of the 2×2 switch applying dc voltage to the thin film heaters. As shown in Fig. 3, the initial output ratio is 100:0, and then optical output can be switched at π-phase shift. The heater resistances were measured at 7.16 KΩ for the upper heater and at 7.89 KΩ for the lower heater. The input and the output waveguides are extended by V-groove blocks and flat-facet single-mode fibers. The required electric power for switching operation was 202.8 mW.

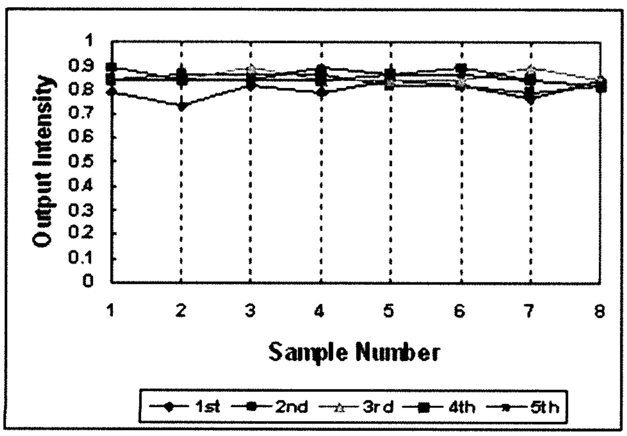


FIG. 2. Normalized output intensities for TO switches with eight different lengths of 3-dB MMI coupler.

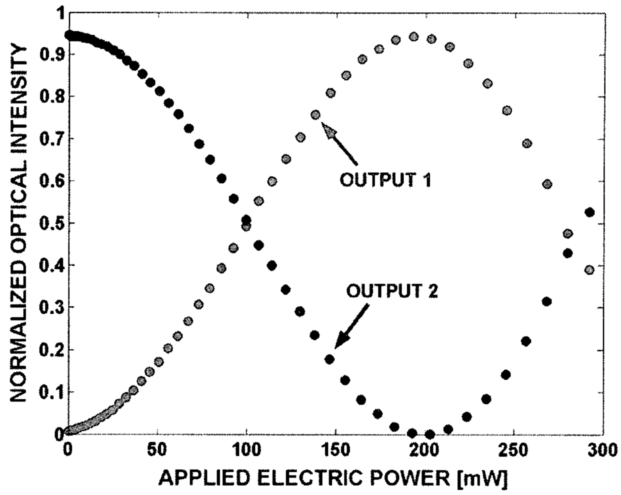


FIG. 3. Measured switching characteristics of the TO switch.

Polarization dependency loss (PDL) was also measured only 0.1 dB for the fiber-attached 2×2 TO switch. This fine result can be explained by the term of effective width in (1) and (2). In addition, extinction ratio has been measured and the value is 32.7 dB.

The response times for rising and falling times are 735 μs and 750 μs, respectively. These fairly fast response times were achieved by forming heat insulating grooves and relatively thin under-cladding. However, because of the index difference, total cross sectional dimension of the single-mode waveguide is large, and this results in not very fast response time.

VI. CONCLUSION

We have designed and measured the silica-based thermo-optic switches using multimode interference couplers which have a large fabrication tolerance of 110 μm. To verify the fabrication tolerance, MMI-MZI switches using eight different lengths of MMI coupler were formed and have been demonstrated. The average value of the excess losses for the eight MMI-MZI switches is 0.7 dB. One of the switches has its switching characteristics tested, and the polarization dependency loss of 0.1 dB, the extinction ratio of 32.7 dB, and switching power consumption of 202.8 mW are found as results. Especially, the fabrication process and packaging method for the TO switches are very standard and widely used methods. Finally, we have successfully studied the MMI coupler with large fabrication tolerance to easily suit commercial applications.

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