4×4 Nonblocking Polymeric Thermo-Optic Switch Matrix Using the Total Internal Reflection Effect

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***Abstract*—A polymeric 4×4 nonblocking thermo-optic switch matrix that uses the total internal reflection effect, is designed and fabricated. The switch matrix has a total device length of 39.3 mm, a fiber-to-fiber insertion loss ranging from 8.7 to 4.5 dB, and a worst case cross talk of -23.3 dB. The device also achieves a low power consumption of 96 mW and a switch response time of 2.1 ms.**

***Index Terms*—Optical switches, polymer, reflection, switch matrix, thermo-optic effect.**

I. Introduction

OPTICAL switches using total internal reflection (TIR) have been investigated intensively [1]–[3] owing to their wavelength insensitivity and compact size. Furthermore, TIR switches can be easily expanded to form a crossbar switch matrix that has great potential in optical cross connects (OXC) for the evolving optical communication networks. There have been several reports of very compact 4×4 crossbar optical switch matrices using the electro-optic TIR effect on $LiNbO_3$ [4] and InGaAsP/InP [5] substrates. But these types of switch matrices suffer from polarization dependence and high insertion loss. Polymer or silica-based switch matrices, using the high and inherently isotropic thermo-optic effect, can achieve low insertion loss, polarization insensitivity, and low-cross talk. However, the reported $N \times N$ ($N = 16$ is the input/output waveguide number) switch matrices are composed of either digital optical switches (DOS), or directional coupler Mach–Zehnder interferometer (DC MZI) switch units [6], [7]. The cascaded 16×16 switches have lengths of 10.4 and 66 cm, respectively. Therefore, the yield will be low, making it more difficult to integrate the switch matrices with other photonic devices. Additionally, each switch unit needs a constant heating power applied in both the cross and bar states, so the total power consumption will increase proportionally to N^2, reaching 6.4 and 17 W, respectively according to [6] and [7]. High power consumption will cause many problems, such as temperature drift, device lifetime deduction, and heavy system load. These drawbacks limit the scale of the switch matrix.

II. Design

A polymeric switch matrix that uses the thermo-optic TIR effect outperforms all other thermo-optic devices in size and power consumption requirement mentioned above. In this paper, we propose a compact 4×4 nonblocking thermo-optic switch matrix using the TIR effect. The crossbar schematic diagram is shown in Fig. 1, where the switch unit uses the proposed structure reported in [2].

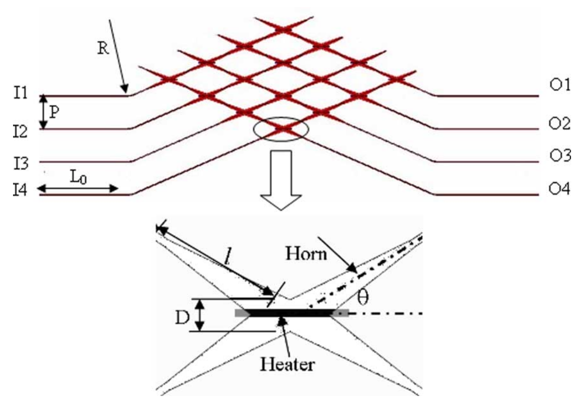

Fig. 1. Schematic diagram of the 4×4 crossbar switch matrix.

For an arbitrary $N \times N$ switch matrix, the channel distance between each input waveguide is P, the half-branch angle of each switch unit is θ, the curve waveguide radius is R, and the input/output waveguide length is i_0. The total device length is derived as

$$L = \frac{W}{2\tan\theta} + 2L_0 + 2R\left[\sin\theta - (1-\cos\theta)\frac{1}{\tan\theta}\right] \quad (1)$$

where $W = 2NP$ is the device width. The actual device width must be larger, owing to the presence of electrical pads and lead lines. The equation given in (1) predicts that crossbar optical switch matrices using the TIR effect can be much more compact than the MZI or DOS structures. Using the geometric parameters from [2], [6] and [7], the total lengths of $N \times N$ optical switch matrices are plotted in Fig. 2. For $N \geq 4$, the total length of a TIR switch matrix is much shorter than those of the MZI or DOS structures.

TIR switches consume no driving power in the cross state, which is a desirable feature for crossbar switch matrices, because most of the switch units will work in the cross state. The total power consumption will be proportional to N, while the other configurations need N^2 activated switch units. Based on the recent experimental result, each switch unit consumes 24 mW of driving power. Therefore, the total power consumption for the 4×4 switch matrix is up to 96 mW.

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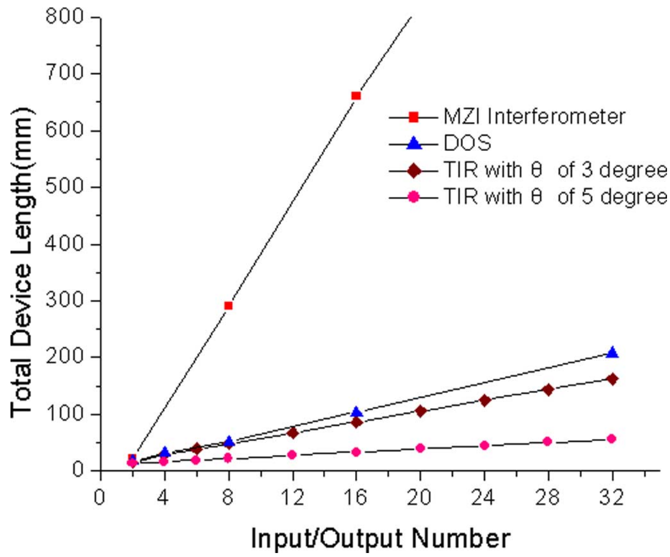

Fig. 2. Total device lengths as a function of the input/output number.

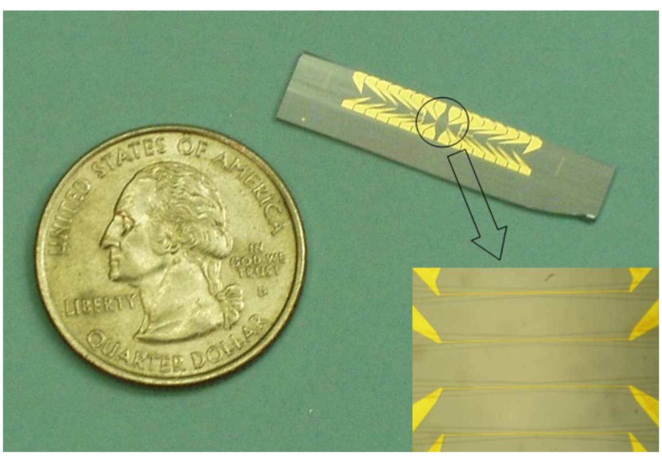

Fig. 3 Fabricated 4 × 4 switch matrix with electrical heaters and pads.

III. Fabrication and Experimental Results

ZPU12-RI series polymer materials from ChemOptics are employed because of their excellent performance in TO switches [8]. First, a layer of ZPU12-450 ($n = 1.45$ at 1.55 μm) is spin coated onto a silicon wafer as the bottom cladding. After UV and thermal curing, a second layer of ZPU12-460 (n = 1.46 at 1.55 μm), which serves as the core layer, is spin coated. Then, a 100 nm SiO_2 film is grown by plasma-enhanced chemical vapor deposition (PECVD) at 200 °C as the hard mask, and is properly defined by reactive ion etching (RIE) to form the channel waveguides in the core material. The remaining hard mask is then removed by wet etching and a polymer top cladding layer is spin coated and cured. After that, a 5-nm chrome and 300-nm gold film is deposited and patterned to form the electrical heater. In the last step, the device is cleaved and the facets are polished to form good coupling interfaces with single mode fiber arrays. Fig. 3 shows the fabricated 4 × 4 optical switch matrix with electrical heaters and pads. The pitch between the input/output

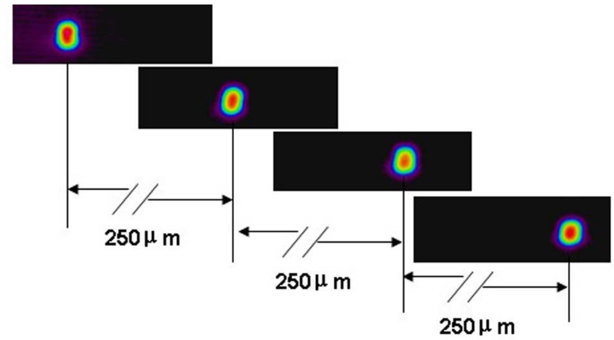

Fig. 4 Near-field patterns from the output waveguides.

TABLE I
Output Powers of the 4 × 4 Switch Matrix (dBm)

Input \ Output	1	2	3	4
1	(3.31), -24.29 -21.99, -20.01	-24.55, (3.98) -21.62, -20.12	-23.86, -23.23 (4.65), -20.34	-25.92, -24.18 -22.33, (5.32)
2	(4.01), -22.78 -21.34, -19.37	-44.49, (4.59) -21.02, -19.32	-44.11, -42.55 (5.38), -19.03	-44.22, -42.45 -41.5, (6.01)
3	(4.51), -23.34 -22.12, -18.33	-43.1, (5.40) -22.34, -18.44	-45.61, -42.18 (6.12), -18.23	-49.06, -48.14 -45.91, (6.85)
4	(5.45), -20.22 -20.12, -20.88	-46.97, (6.18) -20.3, -20.81	-48.76, -47.8 (6.98), -20.55	-46.33, -43.46 -41.4, (7.50)

waveguides is 250 μm and the half-branch angle of each switch unit is 3°.

A Thorlabs ASE-FL 7001 P broadband light source (1.53–1.61 μm) is launched through a single-mode optical fiber with an 8-μm-diameter core into one of the input waveguides of the fabricated device. All 4 × 4 switching configuration is experimentally confirmed. When the input light is coupled into I2, the switch units (I2, O1), (I2, O2), (I2, O3), and (I2, O4) shown in Fig. 1 are activated sequentially to route the optical signal to different output waveguides. (I2, O1) refers to the switch unit at the cross point of waveguide I2 and O1, and so on for the other switch units. Fig. 4 shows the near-field patterns of the output from O1 to O4 measured by a charge-coupled device (CCD) camera.

A typical switching characteristic of a single switch unit has a cross-state power consumption of 0 mW and a bar-state power consumption of 24 mW [9]. Table I shows the output powers at all working configuration. The values are recorded sequentially from O1 to O4 and the values with parenthesis are for the desired output waveguides. The input light intensity is measured to be 12 dBm. From this table, we can conclude that the fiber-to-fiber insertion loss of the switch matrix is from -8.7 to -4.5 dB, and the cross talk is below -23.3 dB.

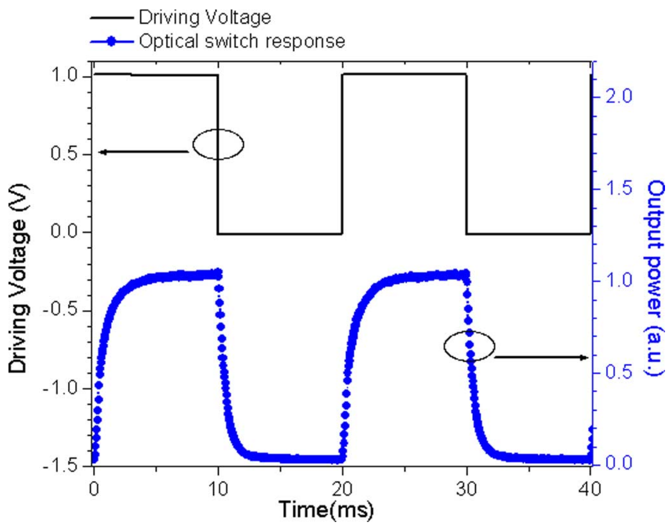

Fig. 5 Driving electrical signal and responding optical signal with a 2.1-ms delay.

The switching speed of the polymeric thermo-optic switch is determined by the thermal conductivity and layer thickness of the polymer material. A higher thermal conductivity and smaller polymer thickness will lead to a greater speed. The optical response with respect to the electrical driving power is shown in Fig. 5, when the light is launched into I1 and monitored from O1 with the activated switch unit of (I1, O1). C1 represents the electrical driving signal and C2 represents the responding optical signal. The 10%–90% rising time and 90%–10% falling time are measured to be 1.3 and 2.1 ms, respectively.

IV. Conclusion

We fabricated a polymeric 4×4 nonblocking thermo-optic TIR switch matrix. The device has a total length of 39.3 mm and achieves a power consumption of 96 mW by using the crossbar scheme and the zero power consumption feature of the TIR switch unit in the cross state. The -8.7- to -4.5-dB insertion losses, -23.3-dB cross talk and 2-ms switching time are acceptable for most applications. Moreover, this expandable configuration has great potential for larger scale switch matrices.

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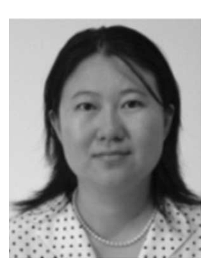

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