Crosstalk-Minimized Polymeric 2 × 2 Thermooptic Switch

Xiaolong Wang, Brie Howley, Maggie Y. Chen, and Ray Chen

***Abstract*—A thermooptic 2 × 2 switch based on the total internal reflection effect is demonstrated. The device, made of ultraviolet curable fluorinated polymer, has an increased half-branch angle of 5°. The purpose of a large half-branch angle is to overcome the volume relaxation phenomenon, which is an intrinsic characteristic of polymers. The device successfully decreases the crosstalk below −40 dB in both the cross and bar states. The fabricated device has a power consumption of only 66 mW in the bar state.**

***Index Terms*—Optical switches, thermooptic effect, total internal reflection effect, volume relaxation phenomenon.**

I. Introduction

The 2×2 optical switches are important elements in applications such as optical add–drop multiplexing (OADM) [1] and optical true time delay [2]. Due to the mature fabrication procedures, planar lightwave circuit (PLC) technology has become competitive for making reliable, low cost, and fast response optical waveguide switches, compared with optomechanical or microelectro-mechanical systems (MEMS) devices [3]. Among various PLC switch configurations, total internal reflection (TIR) switches have the merits of compact size, wavelength insensitivity, and multimode tolerance [4], [5]. Polymers are good materials for optical switches because they can be easily manipulated by methods such as molding, sawing, and dry etching. Additionally, polymers have a large polarization-independent thermooptic (TO) effect (dn/dT), which will make it feasible to fabricate TO devices with low-power consumption.

However, polymer materials have a drawback because of the stability problem. When the operating temperature (T) is below the glass transition temperature (T_g), a limited amount of molecular motion prevents polymers from reaching equilibrium if there is a temperature shift. However, the entropy still drives polymers toward equilibrium, resulting in a gradual change of bulk volume after the temperature stabilization [6]. This so-called volume relaxation phenomenon is an intrinsic characteristic of polymers. Since the bulk densities determine the refractive indexes of polymers, the volume relaxation phenomenon causes the refractive indexes to gradually change in the time domain [7]. As an approximation, the volume relaxation rate is inversely proportional to $T_g - T$ [8], thus the refractive index will be more unstable at higher temperatures. TIR switches require a larger refractive index decrease ($\Delta n \sim 0.01$) in the central waveguide than other PLC structures. For instance, the top cladding beneath the electrode needs to be heated to 97 °C in the bar state with a 3° half-branch angle [9]. At this temperature, the glassy polymers will face a serious volume relaxation problem even when high T_g polymers are used. The result is that the refractive indexes will not return to the initial values as the temperature does. The slightly smaller refractive index in the central waveguide partially reflects the incident light and deteriorates the crosstalk of the device. Experimentally, we observed that the device may require up to 100 h for the performance to stabilize.

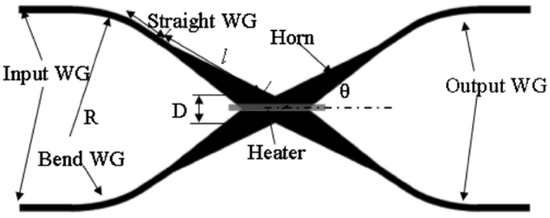

Fig. 1. Schematic diagram of TO TIR switch.

II. Design

In order to overcome this material problem, the half-branch angle of the TIR switch is increased. This design is based on the fact that the interface of two dielectric media causes less reflection to light with a larger glancing angle, which equals the half-branch angle in our design. Due to the amorphous nature of the polymer thin film, the waveguide switch is experimentally confirmed to be polarization independent within $\pm 1\%$. In this letter, 2×2 switches with increased half-branch angles are proposed and fabricated. Fig. 1 shows the schematic diagram of the TO TIR switch. The refractive indexes of the cladding and core are 1.45 and 1.46, respectively, and the waveguide dimension is 6.5×6.5 μm^2. The separation between the input and output waveguide is 250 μm, which is compatible with a standard fiber array. The radii of the bent waveguides are set to be 10 mm, which will cause negligible bending loss and guided mode perturbation. The bent waveguides are then connected by two tapered width waveguides to form an X junction. The electrode heater, which is formed by a thin gold film, is set at the crossing point of the symmetric X junction.

A three-dimensional (3-D) semi-vectorial beam propagation method (SV BPM) is employed to investigate the characteristics of the TIR switch. The half-branch angle θ is a paramount parameter determining the performance of the device. An increased θ will decrease the crosstalk; however, the device will consume more power as well. Fig. 2 shows the simu-

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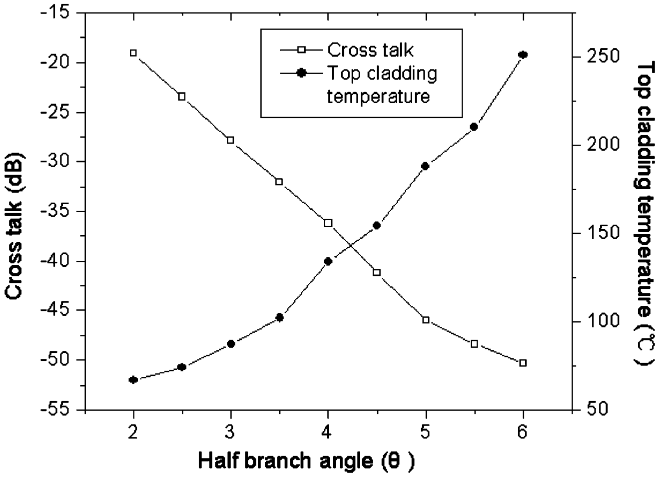

Fig. 2. Crosstalk and top cladding temperatures as functions of half-branch angles.

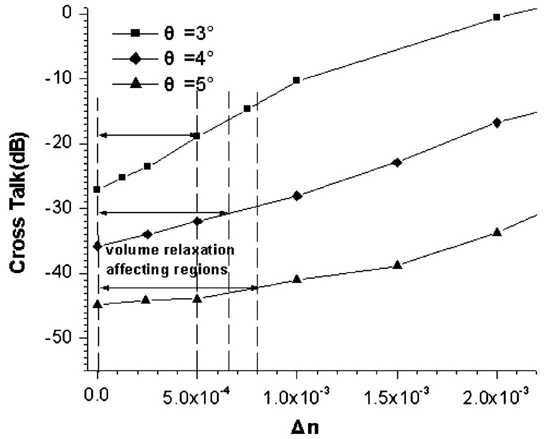

Fig. 3. Crosstalk as a function of index modulation in central waveguide for various half-branch angles.

lated variation of the crosstalk and the top cladding temperature with relation to θ. The top cladding temperature is defined as the highest temperature in the cladding layer when the optical switch works in the bar state by assuming the ambient temperature to be 25 °C. The crosstalk requirement (<-25 dB for most applications) and temperature tolerance ($<200^\circ$ for most polymers) restrict θ to within 3° and 5°.

When the switch is heated, the refractive index of the polymer under the electrode heater is slightly smaller than the other area of the X junction, thus forming an abrupt index interface with an index modulation of Δn. The index modulations by the volume relaxation phenomenon for the 3°, 4°, and 5° half-branch angle switches are approximately 5×10^{-4}, 6.5×10^{-4}, and 8×10^{-4} measured by a Metricon prism coupler, which are marked by "volume relaxation affecting regions" in Fig. 3. Fig. 3 shows the crosstalk as a function of Δn when the half-branch angle (θ) is 3°, 4°, and 5°. When Δn is within the "volume relaxation affecting regions, " the slope decreases as θ increases. This indicates that with a larger half-branch angle, the crosstalk not only decreases but also becomes less sensitive to the refractive index variation. Although a larger half-branch angle requires a higher operating temperature, the device still successfully decreases the crosstalk below -40 dB in both the cross and bar states due to the insensitivity of the crosstalk to the refractive index modulation.

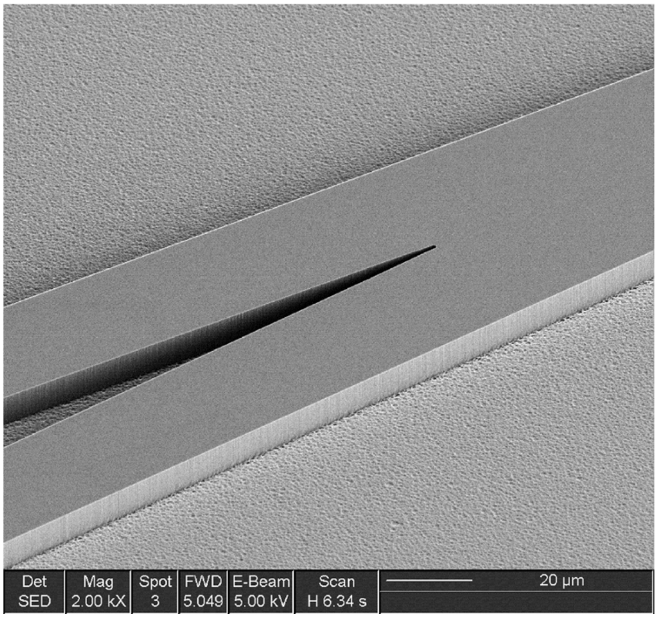

Fig. 4. SEM of fabricated junction showing vertical and smooth side walls.

III. Experimental Result

ZPU12-RI series polymer materials from ChemOptics are employed because of their excellent performance in TO switches [10]. 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. Fig. 4 shows the waveguide core at the junction produced by the RIE processes with vertical and smooth sidewalls. The remaining hard mask is then removed by wet etching and a polymer top cladding layer is spin coated and cured. After that, 5-nm chromium and 300-nm gold films are deposited and patterned to form the electrode heater.

A Thorlabs ASE-FL 7001 P broad-band light source (1.53–1.61 μm) is launched through an optical fiber of 8-μm diameter core into one of the input waveguides of the fabricated device. Fig. 5 shows the time-dependent crosstalk of the switches with 3°, 4°, and 5° half-branch angles in the cross state right after suspending the power supply. By increasing the half-branch angle, the crosstalk is significantly decreased and becomes more stable; the 20-h variation is 10.1 dB of 3°, 5.3 dB of 4°, while only 2.7 dB of 5°.

Fig. 6 shows the optical power in the cross port and the bar port as a response to the electrical driving power. In the working state, the TIR switch with a 5° half-branch angle shows a crosstalk of -40.4 dB in the cross state and -41.5 dB in the bar state. The measured switching curve shows that if the applied driving power is less than 20 mW, the power increase

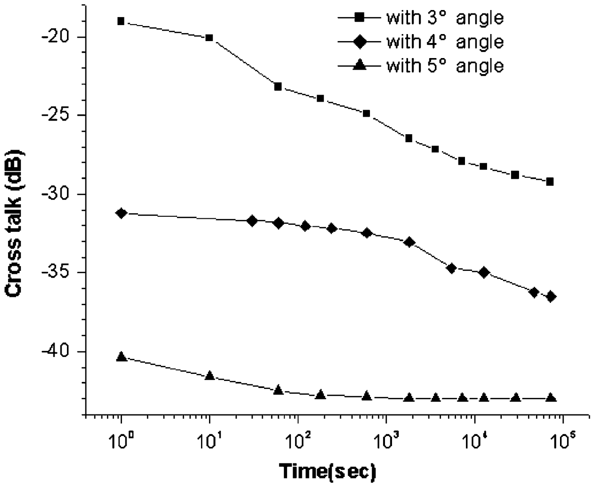

Fig. 5. Time-dependent crosstalk of devices with 3°, 4°, and 5° half-branch angle.

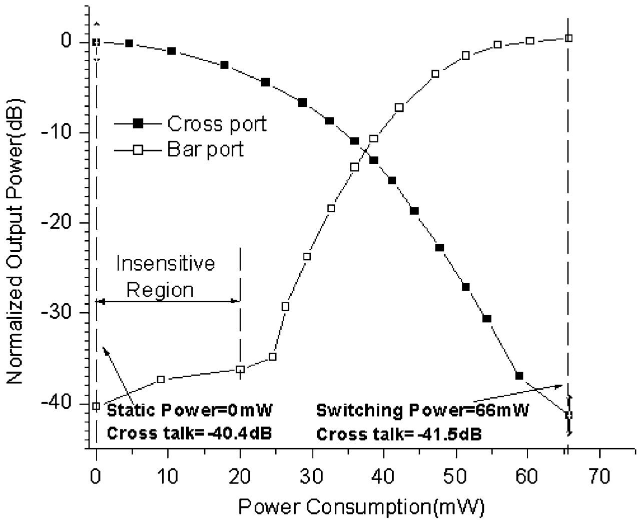

Fig. 6. Optical power in output ports as a response to electrical driving power.

rate in the bar port is much lower than that with higher driving power, which is marked as an "insensitive region" in Fig. 6. The experimental results also verify that the crosstalk is not sensitive to small index variations. The switching power, which is defined as the point at which maximum optical power in the bar port is obtained, is 66 mW in Fig. 6.

The input–output waveguides with 250-μm separations are shortened to reduce the propagation loss. With a total device length of 19 mm, the lowest fiber-to-fiber insertion loss obtained is 2.8 dB and the polarization dependent loss (PDL) is 0.1 dB.

IV. CONCLUSION

We have demonstrated 2×2 thermooptic TIR switches with increased half-branch angles to overcome the volume relaxation problem. As the simulation predicts, the fabricated device successfully suppresses the crosstalk to -40.4 dB in the cross state and -41.5 dB in the bar state. The power consumption in the bar state is 66 mW. The device also achieves a 2.8-dB insertion loss and 0.1-dB PDL.

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