# Polymer 1×2 Thermo-Optic Digital Optical Switch Based on the Total-Internal-Reflection Effect

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*This letter presents a polymer 1×2 thermo-optic total-internal-reflection digital optical switch (TIR-DOS) with an index contrast of 1.5%-Δ operating at low power consumption. The structure of our 1×2 TIR-DOS was created by adding a reflection port to that of a conventional multimode filtering variable optical attenuator. To improve the total-internal-reflection efficiency, a heater offset was applied to the crossing region of multimode waveguides of the TIR-DOS. The fabricated 1×2 TIR-DOS shows a low electrical power consumption of 18 mW for an on-off ratio of 35 dB.*

*Keywords: Polymer, thermo-optic, digital optical switch (DOS), total internal reflection, variable optical attenuator.*

## I. Introduction

A digital optical switch (DOS) has been considered an essential device that can be used for realizing integrated planar lightwave circuit-type reconfigurable optical add-drop multiplexers (ROADM) [1] and multichannel matrix switches [2]. Among the various types of thermo-optic DOSs, polymer thermo-optic 1×2 DOSs have been preferable due to their low power consumption resulting from the large thermo-optic coefficient of the polymer material [1]-[6]. In general, polymer 1×2 DOSs consist of either a symmetrical [1], [3]-[6] or asymmetrical Y-branch [2]. In a DOS with a symmetrical Y-branch, the heater for controlling the path of light should always be turned on to accomplish the switching functionality. On the contrary, in a DOS with an asymmetrical Y-branch, the light signal can exit to a designed path without turning on the heater at the cost of much higher power consumption.

For application of the polymer 1×2 DOS in multichannel ROADM systems or matrix switches, the device should be compact in size with low power consumption. In particular, having the switching function even in the turned-off state to reduce the number of control heaters is a desirable aspect.

In this letter, we report a polymer 1×2 thermo-optic total-internal-reflection DOS (TIR-DOS) with an index contrast of 1.5%-Δ. Our 1×2 TIR-DOS is composed of a 1.5%-Δ multimode filtering variable optical attenuator (VOA) and a reflection port connected to the VOA. To enhance the TIR efficiency, the heater location of our TIR-DOS is offset to a particular direction from the crossing point of adiabatically transitioned multimode waveguides. We demonstrate experimentally that, in addition to the switching function in the turned-off state, our compact 1×2 TIR-DOS can operate at very low power consumption.

## II. Design of TIR-DOS

Figures 1(a) and 1(b) are schematic diagrams of a conventional multimode filtering VOA and our polymer 1×2 thermo-optic TIR-DOS, respectively. The structure of our 1×2 TIR-DOS was created by adding a reflection port to that of the

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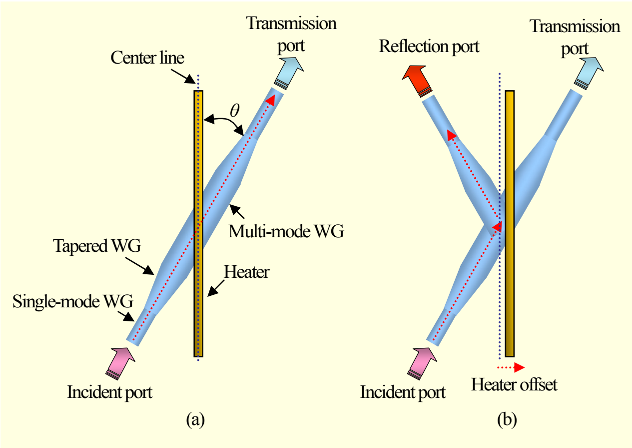


Fig. 1. Schematic diagram of (a) multimode filtering variable optical attenuator and (b) our 1×2 TIR-DOS.

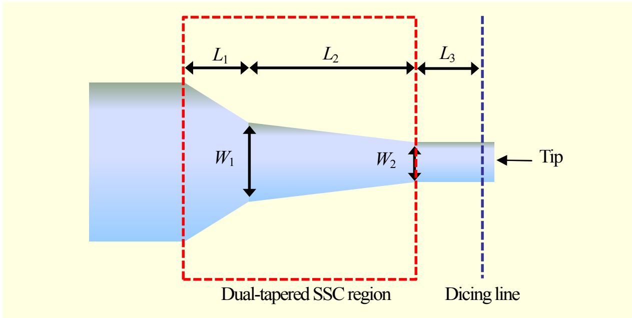


Fig. 2. Structure of dual-tapered SSC in input-output fiber coupling region.

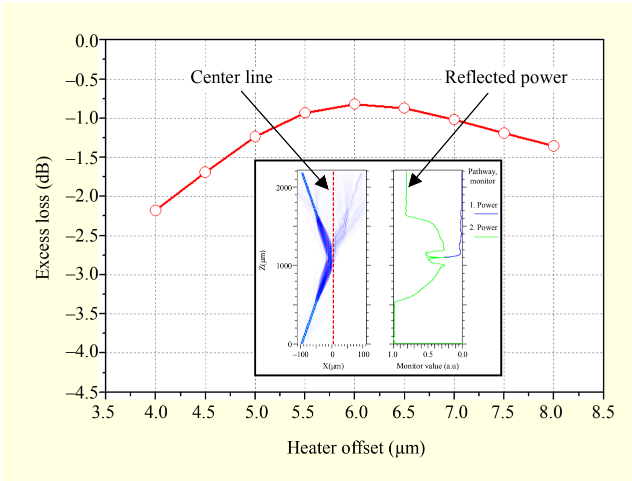


Fig. 3. BPM simulation results for excess losses of reflection port in our 1×2 TIR-DOS due to variations of heater offset.

conventional multimode filtering VOA [7] depicted in Fig. 1(a). The 1×2 TIR-DOS consists simply of a 1.5%-Δ multimode filtering VOA and a reflection port connected to the VOA, as shown in Fig. 1(b). The TIR-DOS can operate according to the following principle. When a heater is turned off, an incident light is adiabatically evolved to be guided along the multimode waveguide and transferred back to the transmission port in a fundamental mode shape. When the heater is turned on, the refractive index under the heater is decreased due to the thermo-optic characteristics of the polymer material. Thus, the incident light is in principle reflected by the TIR phenomenon and exited to the reflection port as shown in Fig. 1(b). However, because of the non-uniform thermal distribution under the heater, the index profile has a gradient function whose shape is determined by the multiplication of the thermal distribution due to the heater and a negative thermo-optic coefficient of the polymer and looks like parabolic [8]. Therefore, the incident light cannot be efficiently reflected when the heater is located at the center line depicted in Fig. 1. To improve the TIR efficiency, the location of the heater is offset to the right from the center line as shown in the Fig. 1(b).

The single-mode waveguide has a core size of 4.5 μm × 4.5 μm with an index contrast of 1.5%-Δ, a lower-clad thickness of 10 μm, and an upper-clad thickness of 5 μm from the core top. The refractive index of the core and that of the clad are 1.394 and 1.373 at 1,550 nm, respectively. The thermo-optic coefficient of the polymers used in this study was $-2.5\times10^{-4}$/°C. The multimode waveguide has a width of 35 μm, a length of 800 μm, and a taper waveguide length of 350 μm. The heater has a width of 5 μm and a length of 800 μm. The heater is optimized to have an angle ($\theta$) of 4° in consideration of both the power consumption and switching isolation in its turned-off state. If the heater angle is decreased, the power consumption for the TIR switching is decreased, as is the switching isolation. We chose the 4° heater angle as it secures a switching isolation of more than 35 dB in the turned-off state. To reduce coupling loss between a polymer waveguide with an index contrast of 1.5%-Δ and a single-mode fiber, a spot-size converter structure is employed in both the input and output waveguide regions. Figure 2 shows the structure of a dual-tapered spot-size converter (SSC). We used design parameters similar to those of the SSC structure proposed in [9], which are as follows: $W_1$=1.5 μm, $W_2$=1.1 μm, $L_1$=500 μm, $L_2$=750 μm, and $L_3$=250 μm. The coupling loss between the SSC structure and the single-mode fiber was calculated to be 0.3 dB/facet. The design parameters of the structure depicted in Figs. 1 and 2 were extracted using a 3D beam propagation method simulator BeamPROP, which is commercially available by Rsoft.

Figure 3 shows simulation results for excess losses caused by the TIR in the reflection port of our 1×2 TIR-DOS with respect to the location of the heater. As shown in Fig. 3, the excess loss was minimized to be about 0.8 dB at a heater offset of 6 μm. The thermal distribution caused by the heater was offset from the center toward the right as shown in Fig. 1(b), and it was converted to an index profile in consideration of the thermo-optic coefficient of the polymer by the help of the BeamPROP simulator. The left side of the inset in Fig. 3 shows the propagation of the incident light reflected by the heater with an offset of 6 μm, and the right of the inset shows the reflected power calculated by an overlap integral method. As expected, we were able to improve the TIR efficiency by offsetting the heater from the center line toward the right, as depicted in Fig. 1(b). The final designed 1×2 TIR-DOS has a length of 5.5 mm including two SSC waveguides.

## III. Experimental Results

The polymer waveguide was fabricated on a silicon substrate using conventional spin coating, standard photolithography, and dry etching processes. LFR series UV-curable polymers [10] were used for the core and clad. The fabricated waveguide had a lower-clad thickness of 9.4 μm, a core thickness of 4.2 μm, and an upper-clad thickness of around 4.7 μm from the core top. A Cr-Au heater was deposited via e-beam evaporation and patterned using a liftoff process. Next, both of the end-facets of a diced TIR-DOS chip were polished, and pig-tailing was accomplished by attaching single-mode fiber blocks. Since two glass lids with a length of 2.5 mm were fixed on both sides of the chip, the fabricated chip length was increased to 10 mm from the designed length of 5.5 mm.

Figure 4 shows the measured switching characteristics of a fabricated 1×2 TIR-DOS chip as a function of applied electrical power. The insertion loss and polarization dependent loss (PDL) of the transmission port were measured at about 1.9 dB and less than 0.15 dB, respectively, in the turned-off state. The insertion loss was analyzed and shown to include a waveguide propagation loss of about 0.65 dB/cm, an input-output fiber coupling loss of about 0.45 dB/facet, and a Y-branch loss of about 0.35 dB. At a low electrical power consumption of about 18 mW, the incident light was almost perfectly switched to the reflection port. The insertion loss of the reflection port was about 2.66 dB, and therefore its excess loss was estimated to be 0.76 dB. The PDL in the turned-on state was similar to that in the turned-off state.

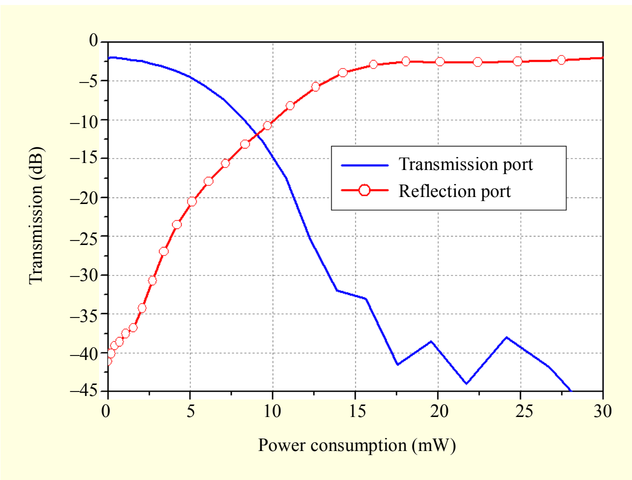


Fig. 4. Measured switching characteristics of fabricated polymer 1×2 TIR-DOS as function of applied electrical power.

The power consumption for an on-off ratio of above 35 dB was as low as 18 mW. Switching isolation values in the turned-off and turned-on states were around 39 dB and 37 dB, respectively, as shown in Fig. 4. The switching curves were obtained shortly after current sweeping operations of about 10 times for stable characteristics. When the TIR-DOS was switched from the turned-on to turned-off state, the switching isolation value in the turned-off state was increased from 39 dB and almost saturated to about 41.4 dB after 100 s. This phenomenon is caused by the volume relaxation (or visco-elastic effect) of the polymer, which is known to be inevitable in the polymer devices [11]. On the other hand, the insertion loss variations were about 0.08 dB to 0.13 dB in the same condition. We believe that the volume relaxation phenomenon can be alleviated by using a thermo-electric cooler. The switching time was measured to be less than 4 ms, proving that our compact polymer 1×2 TIR-DOS clearly operates quite efficiently. Furthermore, we demonstrated that the 1×2 TIR-DOS has a switching function in its turned-off state and shows very low power consumption. In addition, our TIR-DOS can be used as both a bright and dark VOA.

The TIR-DOS evidently has good advantages from the viewpoint of simplicity, compactness capable of reducing chip cost, and low electrical power consumption. However, for commercial use of the TIR-DOS, the insertion loss should be further improved by optimizing the dual-tapered SSC structure and by reducing the waveguide propagation loss due to sidewall roughness. This improvement will lead to raising the reproducibility and manufacturability of our TIR-DOS.

## IV. Conclusion

We realized a polymer 1×2 thermo-optic TIR-DOS with an index contrast of 1.5%-Δ whose structure was created by connecting a reflection port to a conventional multimode filtering VOA. The fabricated 1×2 TIR-DOS has a compact size of 10 mm and shows a low power consumption of about 18 mW for an on-off ratio of more than 35 dB. The switching isolation in the turned-off state is around 39 dB. It also has low insertion losses of about 1.9 dB for the transmission port and 2.66 dB for the reflection port. Excess loss caused by the TIR in the reflection port was only around 0.76 dB. Therefore, our polymer 1×2 TIR-DOS is believed to be well applicable to ROADM systems and matrix switch structures.

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