Polymer Based Thermo-optic Switch for Optical True Time Delay

Xiaolong Wang[a], Brie Howley[a], Maggie Y. Chen[b], Qingjun Zhou[a], Ray Chen[a] and Panoutsopoulos Basile[c]
[a]Microelectronics Research Center, University of Texas at Austin, Austin, Texas 78758
[b]Omega Optics, Austin, Texas, 78758
[c] Naval Undersea Warfare Center, Newport, RI 02841

Abstract:

A thermo-optic switch using total internal reflection waveguide was fabricated for optical true time delay. Experimental result shows that the crosstalk in the bar state is as low as -42dB and the total insertion loss is only -4dB at the wavelength of 1.55µm. A power consumption of 130mW and switching speeds of 2ms are obtained as well, which makes the device qualified to be used in the application of optical true time delay.

1. Introduction

Recently, there has been increasing interest in optical true-time delay (TTD) [1, 2]. TTD can be used in wideband photonic phased-array antennas (PAA), which have the advantage of controllable beam steering without physically repositioning the antenna aperture. Comparing with electrical TTD, optical TTD techniques offer unique features for high performance antenna systems, such as wide bandwidth, compact size, reduced weights and low electromagnetic interference.

One practical way to implement continuous TTD is to integrate polymer based thermo-optic switches with fixed polymer waveguide delay lines [3], as shown by Fig.1.

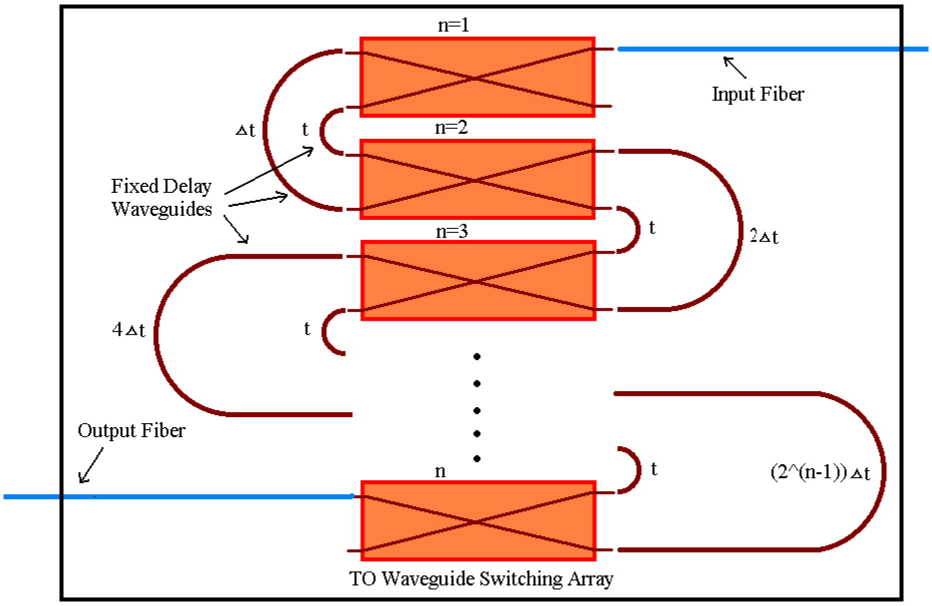


Fig.1 Schematic of the proposed optical TTD module

Integrated Optics: Devices, Materials, and Technologies IX, edited by Yakov Sidorin,
Christoph A. Wächter, Proc. of SPIE Vol. 5728 (SPIE, Bellingham, WA, 2005)
0277-786X/05/$15 · doi: 10.1117/12.588669

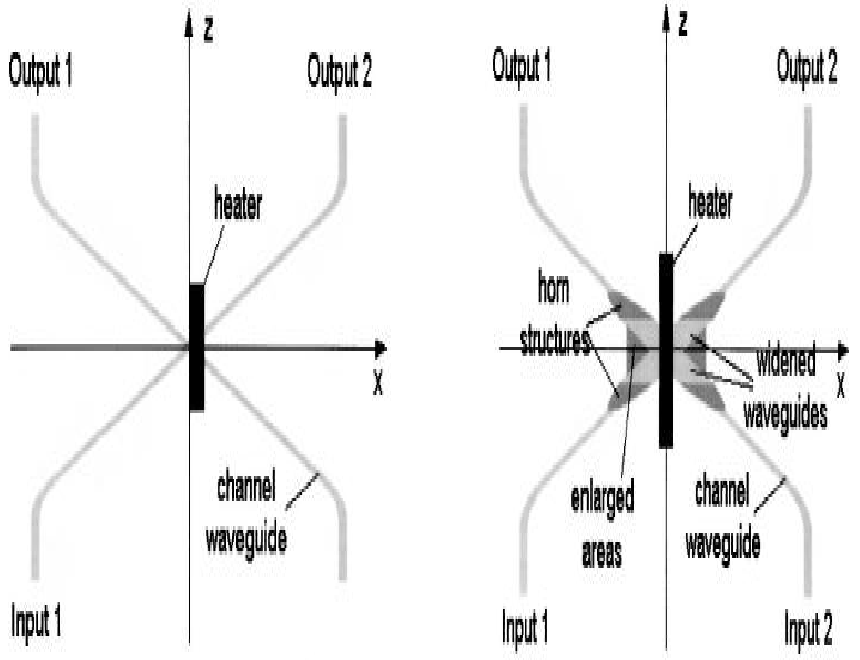
A single mode input fiber is butt coupled to a 2×2 optical switch (n=1). A planar lightwave circuit (PLC) comprised of two different lengths of polymer waveguides is positioned at the output ports of the n=1 switch. Depending on whether the bar state or cross state of the switch is chosen, light is delivered to the waveguide with length of l or 1+Δl. These waveguides are then connected once again to another 2×2 optical switch (n=2) and the output ports are coupled to two more waveguides of lengths l and $1+2\Delta l$. This sequence is continued with lengths of the short waveguides remaining at a length of l and the long waveguide sections increasing in length according to $\Delta l \cdot 2^{(n-1)}$. The time delay, t, provided by these fixed delay waveguides is given by $t = \frac{L \cdot n_{eff}}{c}$

where *L* is the length of the waveguide, c is the speed of light in vacuum, and n_{eff} is the effective index of the waveguide. Obviously, 2×2 optical switches play a critical role in this module. The switches are required to have the characteristics of low insertion loss (especially for multi-bit delay when switches are serialized), low polarization dependent loss (PDL), low cross talk, short device length (to get compact module size, for implement of a system on chip), low power consumption and reasonable switching speed. It is not an easy job to get all the desired features simultaneously, for instance, switching speed and power consumption of thermo-optic (TO) switches are trade off. For a given structure, we can only achieve faster speed with the expense of higher power.

II. Schematic Design

We chose polymer based TO switching using total internal reflection (TIR) because the TO effect is polarization independent and highly efficient. Additionally, TIR structures have the merits of compact size, wavelength insensitivity and multimode tolerance [4, 5].

The TO effect of polymeric materials is negative, i.e., the refractive index of polymeric materials decreases as the temperature increases. For the ZPU12 series polymer we use, the thermo-optic coefficient is -1.7×10^{-4}. Thus, a TIR optical switch may be formed if a heater is set at the crossing point of a symmetric X junction as shown in Fig. 2(a). The X junction is composed of two crossing polymeric channel waveguides. The heater is electrically driven and fabricated on the top cladding layer of the channel waveguides. If the crossing angle of the X junction is large enough, generally greater than 4°, the light launched into input 1 is transported to output 2 (defined as the "cross" state), when the heater is not powered. In an ideal model, when sufficient driving power is applied to the heater, the light is reflected at the crossing point of the X junction and propagates to output 1(defined as the "bar" state), thus demonstrating a 2×2 switch. In reality, the heater-generated temperature distribution is a gradient field along the X coordinate(Fig. 2) and so the light cannot be reflected with a sharp reflection angle at the crossing point of the X junction. Instead, the reflected light path should be arc-like. That means a simple crossing structure of two waveguides, as shown in Fig.2 (a), cannot guide the reflected light efficiently. In Fig. 2 (b), we propose a TIR switch structure. Enlarged areas at the waveguide-crossing section are introduced to efficiently support the light propagation. Meanwhile, to decrease the optical loss caused by diffraction, waveguides are widened at the waveguide-crossing section. Horn structures are employed to connect the widened waveguides with the input and output access waveguides.

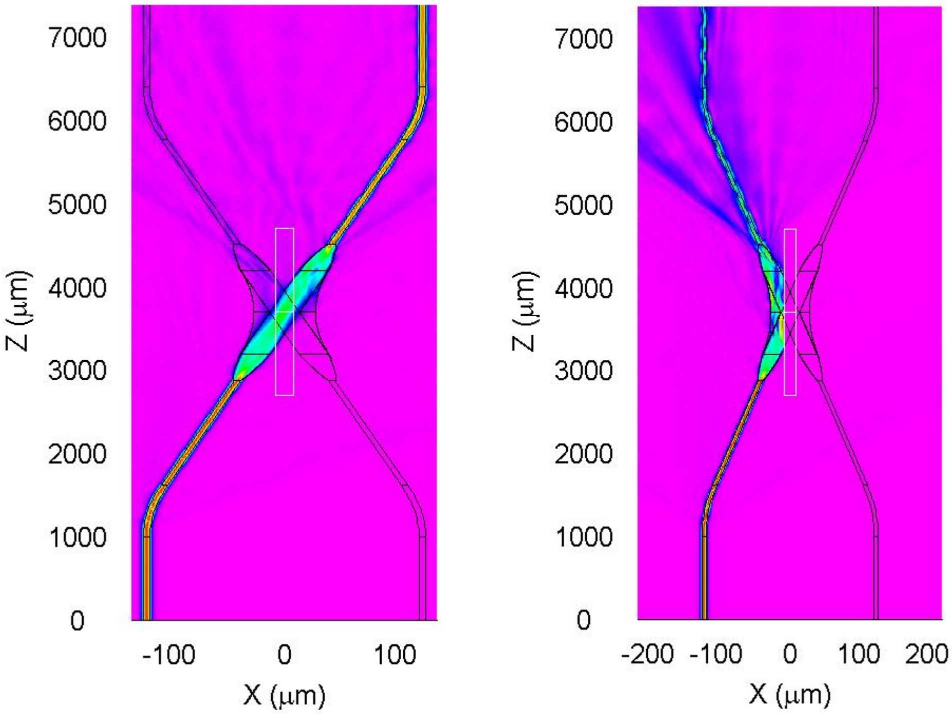


(a) (b)

Fig.2 Schematic diagram of the TIR optical switch: (a) the basic structure and (b) the proposed structure

III. Simulation

The TO TIR polymeric optical switch was simulated and its parameters were optimized by using the beam propagation method (BPM). Fig.3 shows the simulated operation of the TO TIR polymeric switch, in which we assume the core and cladding material to be ZPU12-460 and ZPU12-450 (from ZenPhotonics), with refractive indices of 1.46 and 1.45 respectively at the wavelength of 1.55μm. The size of the channel waveguide is 7μm×7μm. The width of the widened waveguides is 30μm and the angle between the two crossing waveguides is 6°. If the refractive index difference is 0.01 and the dimension is as large as 7μm×7μm, the waveguide will support up to two guiding modes along x and y direction. Such a waveguide is a multimode waveguide. This implementation is adopted because: first, large cross section will increase the coupling efficiency of the waveguide to single mode fiber; second, the large index differences can reduce the optical delay line bending radii, which will be integrated with TO switch in our future work, thus making the optical TTD module more compact; third, weakly multimode waveguide will not introduce any detectable dispersion due to the short device length and the large weight of the fundamental mode compared to higher order modes.

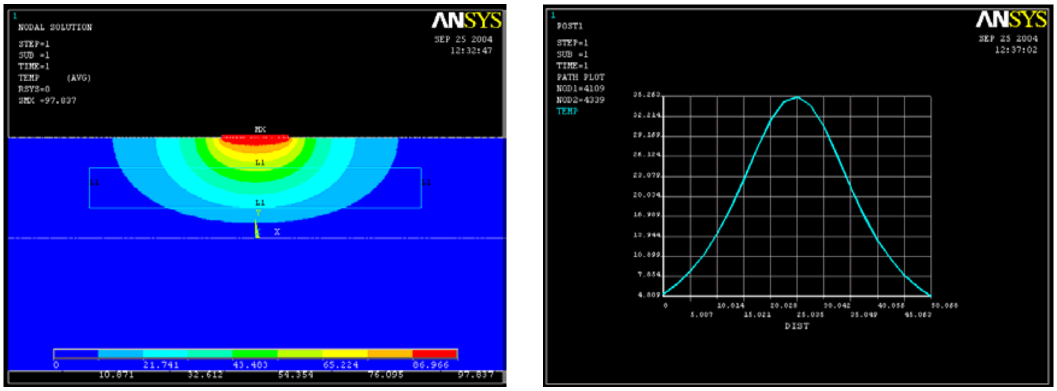


(a) (b)

Fig.3 Simulated Operation of the 2×2 TO TIR polymeric switch: (a) the cross state in which no electric power is applied and (b) the bar state in which the heater is powered and total internal reflection takes place

Optical simulation was carried out on Beamprop from Rsoft Photonics CAD Suite, using a 3-D semi-vector beam propagation method (3-D SVBPM). Result shows that the crosstalk of both the cross state and bar state is less than -25dB. The insertion loss caused by the structure is below 0.5dB in cross state and 3.5dB in bar state. We can see that the loss is much worse in bar state, in which TIR will generate mode perturbation and cause energy radiation since we assume abrupt index change at the heating junction. Actually, thermal expansion will introduce a gradient index distribution and switch the light path smoothly. The power uniformity in the cross state and the bar state will be better than 3dB, that has already been confirmed by our experiment.

The temperature distribution, power consumption and switching speed effects require thermal simulations. In order to simplify the simulation, we adopted 2-D finite element analysis (FEA) method which is a good approximation when the heater length is much longer than the heater width. In simulations, only the heat conduction is taken into consideration while radiation and convection are ignored. This assumption is valid if the temperature is not too high. The electrode length is assumed to be 1000μm and the power consumption is 30mW.



(a) (b)

Fig.4 Thermal steady state of the active region (a) temperature distribution (b) temperature distribution along the x-direction in the center waveguide

Fig.4 shows the thermal steady state in the active region. The temperature of the heater can rise up to 97℃ while the center of the waveguide beneath the heater is kept below 35℃. The temperature difference between the center of the waveguide and the edge of the waveguide is over 30℃, corresponding to index difference of 0.0051. This is large enough to generate total internal reflection. Fig.5 shows the transient state of the active region, i.e., we apply the driving electric signal and heat up the polymer. After the temperature becomes stable, we stop heating and the temperature falls down. By this method, we can predict the switching time of the TO switch. The upper curve is the temperature change in the electrode, while the lower one is in the waveguide center. The rise time and fall times are both approximately 1ms.

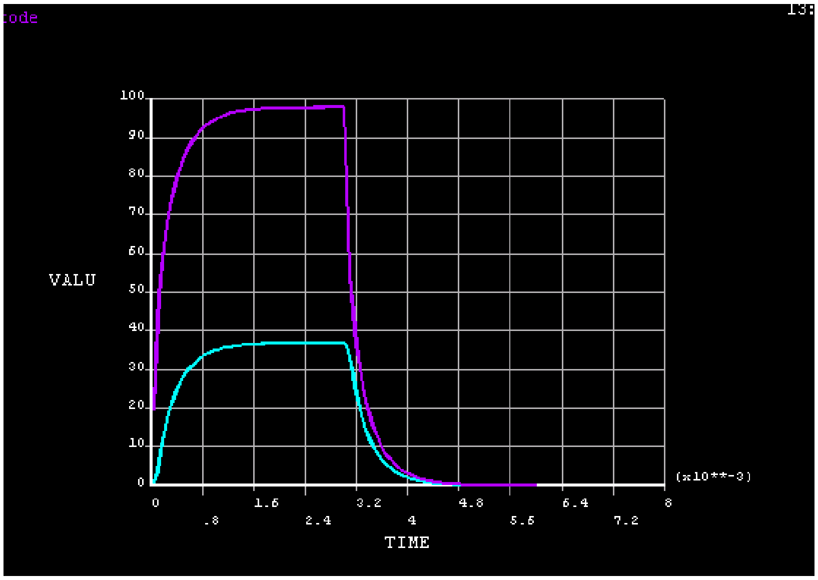


Fig.5 Simulated temperature cycle

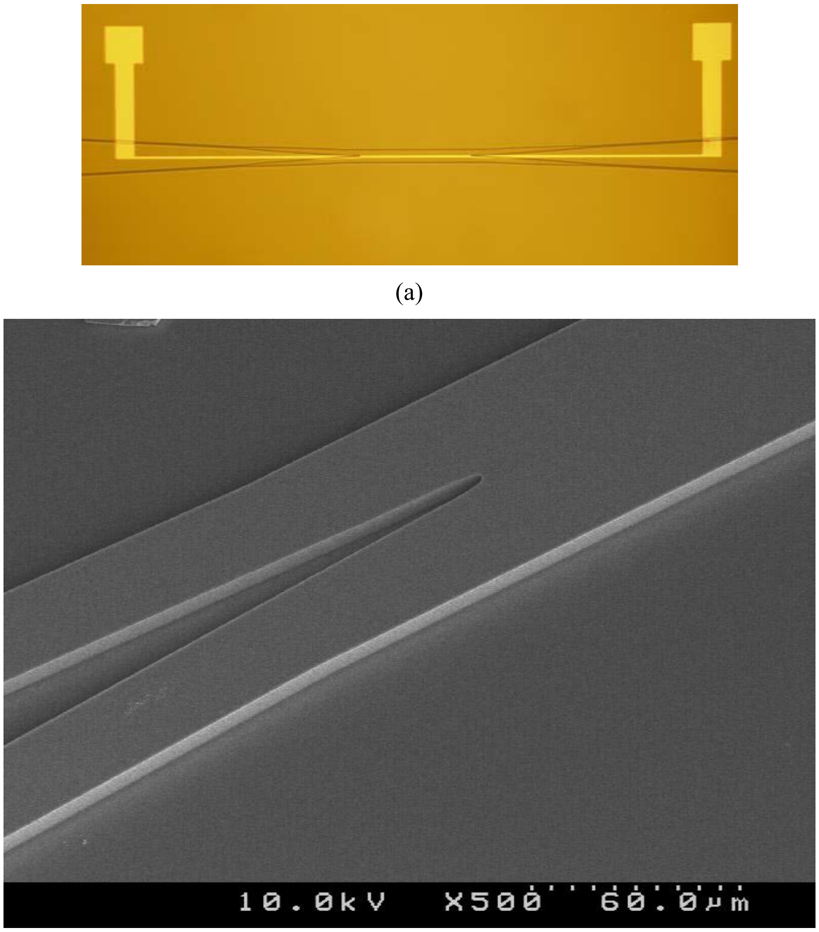
IV. Fabrication

ZPU12-RI series polymer materials from Zenphotonics are employed to make waveguides on silicon wafers. First, a layer of adhesion promoter ZAP1020 was spin coated on a silicon wafer. Then we coated a 6μm thick ZPU12-450 bottom cladding, which was UV cured and thermally baked under the protection of N_2. In the same way, we formed the

7μm thick ZPU12-460 core layer. A 50 nm gold film was deposited by evaporating and patterned by photolithography and wet etching. This thin layer of gold film acts as a hard mask for reactive ion etching (RIE). The polymer is etched to a depth of 7.2μm (a little bit over etched) and coated with another layer of ZPU12-450 as a top cladding. Following that, a 300nm gold film was deposited on top cladding and patterned by photolithography. Wet etching was used to form the heating electrodes. In the last step, the device was cleaved and the facets were polished to get a good coupling interface.

V. Experiment Result

Fig.6 (a) shows the microscopic picture of the described TIR switch. The enlarged square pads were formed to apply the current probes. Fig.6 (b) shows the SEM of the crossing waveguide right after RIE.



(a)

(b)

Fig.6 (a) microscopic picture of the TO switch (b) SEM of the crossing waveguide

Fig.7 shows the testing setup of the TO switch. For a typical Mach-Zehnder switch, the switch will only be able to work at a narrow wavelength band. But for TIR structures, if we apply enough power, the switches can be operated over a wide wavelength band. We use THORLABS ASE-FL 7001P broad band light source (1.53-1.61μm) to confirm this. The TO switch is mounted on a fixed stage and the input fiber can be precisely positioned by Newport PM500-C Precision Motion Controller. We put an objective lens near the waveguide facet and use a CCD camera (Electrophysics Micro

Viewer 7290A) to monitor the near field pattern. An electrical switching signal from a Protek B-801 sweep function generator was applied to switch the optical signal from one outport to the other. Fig.8 shows the near field pattern in the cross state and the bar state. We replaced the lens with a single mode fiber to collect the output light and guide it to a photo detector (Newport 818 IR). The optical response was monitored by a Tektronix 485 oscilloscope to produce the power-switching curve and dynamic response curve of the TO switch. Fig. 9 shows the switching characteristics as a function of the applied power. Fig.10 shows the dynamic optical response in the bar outport.

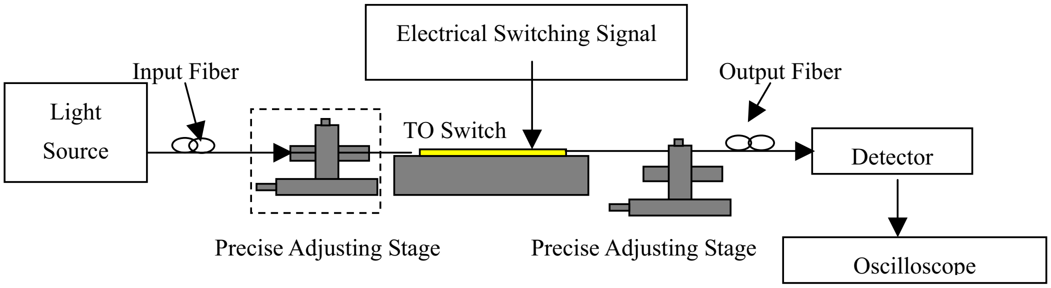


Fig.7 Setup for testing TO switch

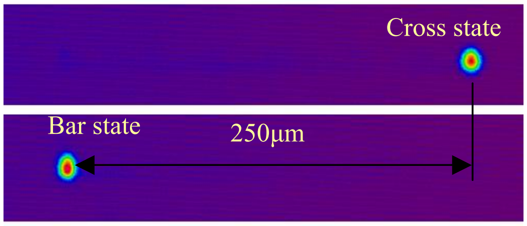


Fig.8 near field pattern in cross state and bar state

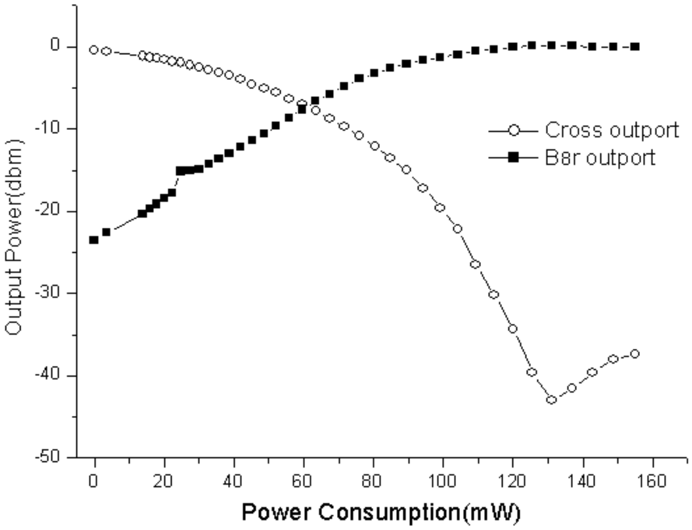


Fig.9 switching characteristics as function of applied power

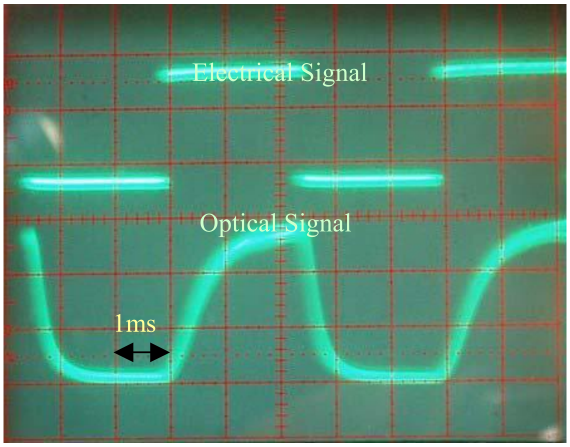


Fig.10 optical response from the port active in bar state

As a summary, the total insertion loss (single mode fiber in, single mode fiber out) of the device is -4dB. The power consumption of the switch in bar state and cross state is 130mW and 0mW respectively, while the crosstalk is -42dB and -25dB. The switching time for the thermo optic switch is around 2ms and 1ms for rising and falling, which is quite close to the thermal simulation in Part III.

VI. Conclusion

We have implemented a thermo-optic switch using total internal reflection for optical TTD. The performance of the switch makes it suitable to be used in real system. Currently, the main problem of the switch is that the cross talk in cross state is only -25dB due to the leakage from the X junction to the opposite access. This problem can be solved by increasing the crossing angle and modify the crossing junction shape.

Acknowledgements

This work was supported by Contract N00039-03-C-0057; Linda L.Whittington, SPAWAR/PEO C4I & Space, SBIR Program Manager.

References

1. Y.Chen, R.T.Chen, “A fully packaged true time delay module for a K-band phased array antenna system demonstration”,IEEE Photonics Tech. Lett., 14 (8): 1175-1177, 2002
2. J.D.Shin, B.K.Lee and B.G.Kim, “Optical true time-delay feeder for X-band phased array antennas composed of 2×2 optical MEMS switches and fiber delay lines”, IEEE Photonics Tech. Lett., 16(5): 1364-1366, 2004
3. B. Howley, "A continuously tuneable optical true time delay based phased array antenna system”, master degree thesis, the university of Texas at Austin, May 2004
4. C.S Tsai, B.Kim and F.R. Akkari, “Optical channel waveguide switch and coupler using total internal reflection”, IEEE Journal of Quantum Electronics, 14(7): 513-517, 1978
5. J.Yang, Q.Zhou and R.T.Chen, “Polyimide-waveguide-based optical switch using total-internal –reflection effect”, Applied Physics Letters, 81(16): 2947-2949, 2002