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Polyimide-waveguide-based thermal optical switch using total-internal-reflection effect

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A total-internal-reflection waveguide switch with an X junction was designed and fabricated by using the thermo-optic effect of polyimide materials. Experimental results show that the crosstalk is below −28 dB at the wavelength of 1.55 μm. The switching power with the current electrode is 132 mW, which can be reduced to 20–30 mW with an optimized design together with electroplating to form a thick conducting path. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1511814]

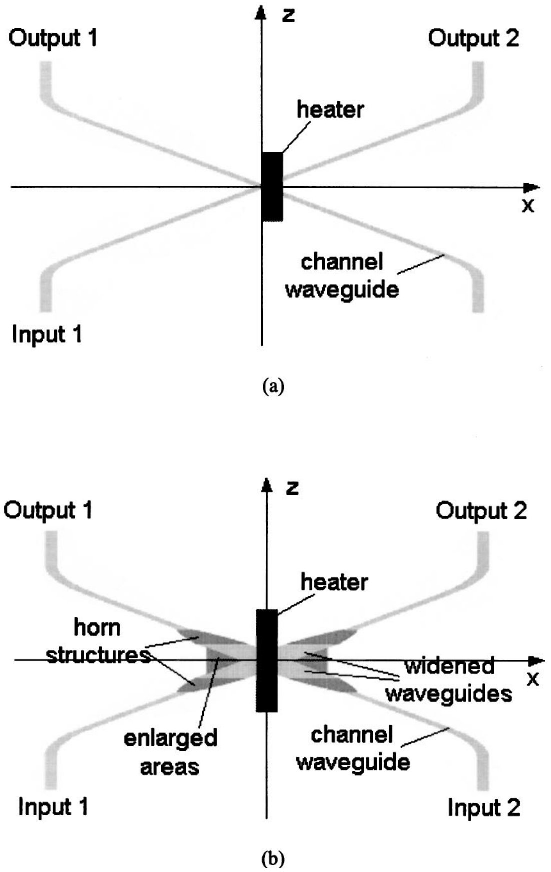
The optical true-time-delay (TTD) network is the key module for wideband photonic phased-array antennas (PAA).[1,2] To realize a polymer-based monolithic optical TTD module by using switched optical waveguide circuits, polymeric optical switches need to be integrated with polymeric waveguide delay lines. Because the thermo-optic (TO) effect of polymeric materials is polarization independent and sufficiently strong, polymer-based TO switches are potential candidates for the integrated optical TTD module. Many polymer-based TO switches of various designs have been reported, such as digital optical switches (DOS),[3] Mach–Zehnder interferometer (MZI) switches,[4] and directional coupler switches.[5] In this article, we demonstrate a TO total-internal-reflection (TIR) polymeric switch with an X junction. This TIR waveguide switch can be designed as a 2×2 switch which is preferred in the monolithic optical TTD module. The TIR switch also exhibits wavelength independence and its operation is not sensitive to drive power changes. We designed and fabricated the TIR TO switch using polyimide materials.

The TO effect of polymeric materials is negative, i.e., the refractive index of polymeric materials decreases as the temperature increases. 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. 1(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. Since the crossing angle of the X junction is large enough, generally above 4°, the light launched into input 1 is transported to output 2 (defined as the ‘‘cross’’ state), when the heater is not powered. 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), in an ideal model, thus demonstrating a 1×2 switch.

In reality, the heater-generated temperature distribution is a gradient field along the X coordinate (Fig. 1) 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 monomode waveguides, as shown in Fig. 1(a), cannot guide the reflected light efficiently.

In Fig. 1(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[6] are employed to connect the widened waveguides with the input and output access waveguides.

Because the propagation path of the reflected light is arc-like and the widened waveguides and enlarged areas are used in our design, it becomes feasible to use this new structure as a 2×2 nonblocking optical switch by symmetrically



(a)

(b)

FIG. 1. Schematic diagram of the TIR optical switch: (a) the basic structure and (b) the proposed structure.

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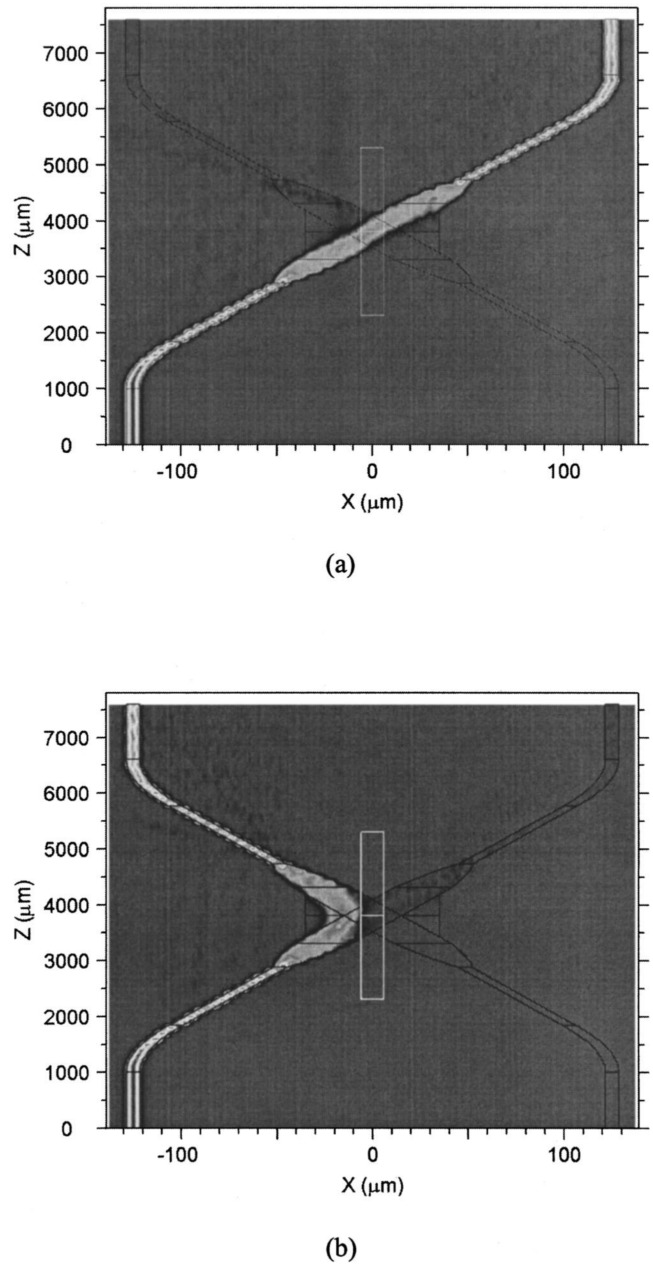

(a)

(b)

FIG. 2. 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 the total reflection takes place.

setting the heater electrode at the crossing point of the X junction, as shown in Fig. 1(b).

Based on the above design concepts, the TO TIR polymeric optical switch was simulated and its parameters were optimized by using the beam propagation method (BPM). Figure 2 shows the simulated operation of the TO TIR polymeric switch, in which we assumed that the Ultradel 9120 and Ultradel 9020 (both from Amoco Chemicals with a refractive index of 1.535 and 1.527, respectively, at the wavelength of 1.55 μm) were used as the core and cladding materials, respectively, and the size of the channel waveguide was 7 μm×7 μm. The width of the widened waveguides is 30 μm and the angle between the two crossing waveguides is 6°. Simulation results show that the crosstalk of both the cross state and the bar state is less than −30 dB, the insertion loss caused by the structure is below 0.5 dB, and the switching property is polarization independent.

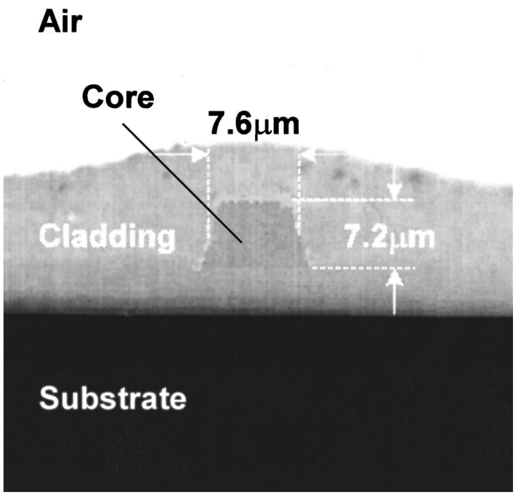

FIG. 3. Cross section of the polyimide waveguide.

In our experiments, the polyimide optical waveguide switches were fabricated on silicon wafers. A thin chromium layer was first deposited on the substrate to enhance the adhesion of the polyimide material. Then an 8-μm-thick Ultradel 9020 layer was spin coated as the bottom cladding. Since Ultradel 9000 series polyimides function as negative photoresists, the Ultradel 9120 core of the channel waveguide was formed by a conventional photolithography process. After the core was full baked, the Ultradel 9020 top-cladding layer was spin coated. The thin film heater was made by sputtering deposition of titanium/gold followed by wet etching. To facilitate end-fire coupling, both ends of the samples were polished. Figure 3 shows a cross section of the polyimide waveguide.

The samples of the TO TIR polyimide switches were characterized on an optical bench using a computer-controlled setup. Since WDM techniques will be employed in our PAA experiments and the designed switch is expected to be able to work under a wideband light signal at the window of 1550 nm, an amplified spontaneous emission (ASE) light source with a spectral range from 1530 to 1610 nm was applied to do the measurement. An SMF28 single-mode fiber was used to butt couple the light into input 1 and input 2 of the switches, respectively, and the output power at both output 1 and output 2 was measured.

Figure 4 shows a typical switching characteristic measured in our experiments while the simulated results are also shown for comparison. In the cross state, in which no electric power is supplied to the heater, the measured crosstalk is less than −29 dB. At a driving power of about 132 mW (3 V ×44 mA), the total reflection takes place and the switch has a crosstalk below −28 dB. Because the accessing portions of the heating electrode, which refer to all the electrode excluding the portion right above the X-junction waveguide, were not optimized in our experiment, driving is not efficient. To enable the driving power to be applied efficiently, electroplating can be used to increase the thickness of the accessing electrodes. In this way, the switching power will be reduced to 20–30 mW. Meanwhile, the power dissipation can be easily regulated in the heater and the switching speed can reach milliseconds.

The average insertion loss is 10 dB. However, compared

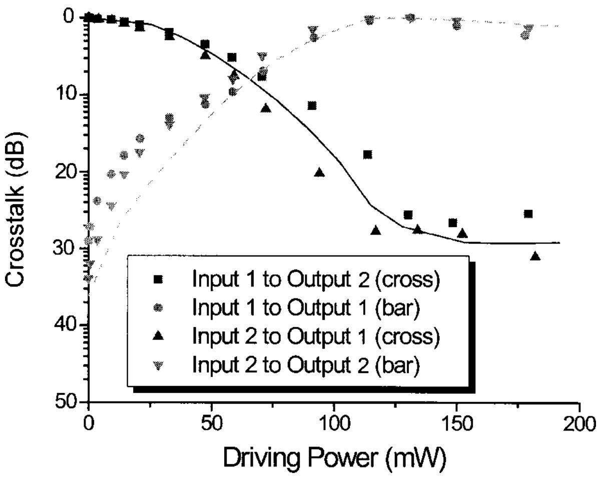

FIG. 4. Typical switching characteristics of the TIR polyimide switch. Scattered dots: measured results; solid and dashed lines: BPM simulated results for the cross state and the bar state, respectively.

with straight waveguides on the same chip, the device only has an excess loss of 0.6 dB in the bar state and 1.2 dB in the cross state. The relatively high insertion loss is mainly caused by the material absorption of Ultradel 9000 series polyimides at 1.55 μm (about 6.9 dB for the 2.7-cm-length waveguide) and the coupling loss at both end faces of the samples (about 1.1 dB for each end). The light from the ASE light source is nonpolarized. We measured the insertion loss for TE and TM modes, respectively, by using a polarizer to control the polarization direction. Although the TM mode of the polyimide waveguide has 11.2 dB insertion loss that is about 2 dB larger than that of the TE mode, no obvious polarization-dependent loss (PDL) introduced by the device structure was observed.

We proposed a TIR optical switch using the thermo-optic effect of polymers and discussed its fabrication with polyimide materials in this article. The measured crosstalk is less than −28 dB. The switching power is about 132 mW, which can be lowered to 20–30 mW by improving the driving efficiency. This TO TIR optical switch meets the requirements for monolithic integrated optical TTD module. Being a nonblocking 2×2 switch, it also can be applied in optical fiber communication systems.

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