Compact dual-mode thermo-optic switch based on multimode interference coupler

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***Abstract*—We demonstrate a dual-mode thermo-optic switch based on multimode interference coupler. With the driving power of 41 mW, the measured extinction ratios of the switch for E_{11} and E_{12} modes are 19.4 dB and 12.3 dB, respectively. The switching times are ~1.6 ms.**

***Keywords*—Mode-division multiplexing; Thermo-optic switch; polymer waveguide; Multimode interference**

I. Introduction

To meet the ever-increasing demand for data transmission capacity in optical communication systems, many different multiplexing techniques have been developed. At present, the transmission capacity of standard single-mode fibers (SMFs) has reached their fundamental capacity limit of ~100 Tbit/s. However, due to the nonlinearity effect of the fiber and the limitation of fiber fuse phenomenon, it is difficult to further improve the transmission capacity of the SMFs [1]. Mode-division multiplexing (MDM) technology has achieved a multiplication of communication capacity in a new dimension, which employs orthogonal optical mode channels to transmit data. MDM technology can effectively increase the transmission capacity using only one wavelength carrier, which can effectively reduce the complexity and power-consumption of the on-chip management in an optic network and has received extensive attention [2-4].

Multimode optical switch plays an important role in MDM optical communication, which can add flexibility and reconfigurability to the systems [5,6]. The traditional multimode switch is usually based on the demultiplexing-processing-multiplexing technique [7], which uses de-multiplexers, single-mode switch arrays and multiplexers. Such scheme is stable, but this process increases switching complexity, footprint and power consumption. The application of multimode optical switch will avoid the demultiplexing-processing-multiplexing process, which can route the multimode signals simultaneously. Moreover, the optical switches based on planar light-wave circuits have been widely concerned because of its flexible design and small size [8], and a variety of different waveguide structures have been developed to form the optical mode switches.

In this paper, we proposed a dual-mode thermo-optic (TO) switch based on multimode interference (MMI) coupler and verify the performance experimentally by using polymer waveguides. We optimized the structural parameters of the presented switch by using Rsoft software. The device was fabricated by using simple spin-coating, photolithography, and wet-etching process. The footprint of the device is about 1.2 mm. We characterized the performance of the device at 1550 nm wavelength. The switching function was achieved for both E_{11} and E_{12} modes when the modulating electrode is heated, which is consistent with the simulation results.

II. Design and Experiment

A. Device Structure and Simulation

As schematically shown in Fig. 1(a), the dual-mode switch is based on the MMI coupler, which consists of two dual-mode waveguides as the input and output waveguides, a multimode waveguide, and two tapered waveguides. The switch is designed on polymer platform with silicon as substrate, EpoClad (n_{clad}=1.559) as cladding material and EpoCore (n_{core}=1.569) as core material. The width and the height of the dual-mode waveguide is fixed at 4.5 µm and 9.0 µm, respectively, to support only E_{11} and E_{12} modes. The width of the multimode waveguide is set at 25 µm to support higher order modes and the length is optimized to be 797 µm by using Rsoft software. The width and length of the tapered waveguides are set at 8 µm and 150 µm, respectively, which are used to connect the input (output) waveguide and the multimode waveguide to decrease crosstalk at the connection. The cross-section of the proposed switch is shown in Fig. 1(b), a 10-µm-wide electrode heater is placed on one side of the multimode waveguide with a distance of 2 µm from the multimode waveguide.

According to the optimized waveguide dimensions and structure, we further simulated the switching performance of the dual-mode TO switch. The simulated optical transmission as a function of the heating temperature is depicted in Fig. 2(a). The maximum extinction ratios for E_{11} and E_{12} modes are 32.9 dB and 28.7 dB, respectively, when the temperature variation is 32 K and 34 K. The insets of Fig. 2(a) show the simulated optical field distribution of the proposed dual-mode switch at the “on” and “off” state for the two guided modes. Fig. 2(b) shows the thermal distribution of the electrode heater in the cross-section of the multimode waveguide at 33 K heating temperature. The proposed switch has the advantages of compact footprint, large working bandwidth and big fabrication tolerance.

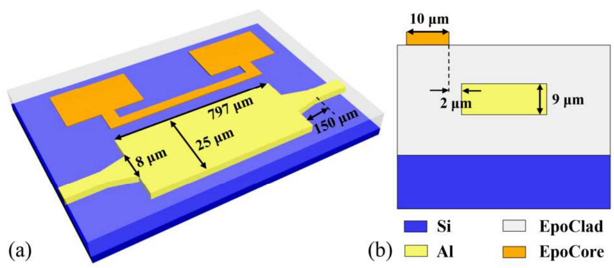

Fig. 1. (a) Schematic diagram and (b) cross-section view of the proposed dual-mode TO switch.

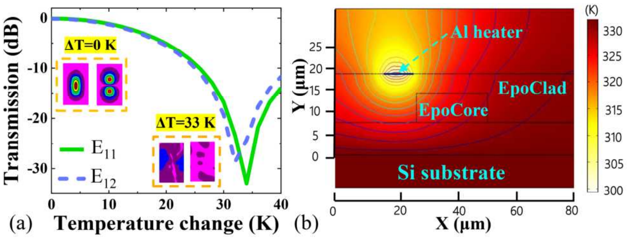

Fig. 2. (a) The simulated optical transmission as a function of the heating temperature of the device for E_{11} and E_{12} modes at 1550 nm wavelength. (b) The thermal distribution in the cross-section of the multimode waveguide at 33 K heating temperature.

B. Device Preparation

We fabricated the MMI-based polymer waveguide dual-mode TO switch with the optimized parameters by using the conventional spin-coating, photolithography and wet-etching processes. A 7-μm-thick EpoClad was first spin-coated onto the silicon substrate to form the lower-cladding. After that, a 9-μm-thick EpoCore film was spin-coated onto the prepared lower-cladding to form the core layer. Then the waveguide pattern was transferred via standard 365-nm ultraviolet (UV) lithography and wet-etching methods. Subsequently, a 7-μm-thick EpoClad upper-cladding was prepared onto the sample by spin-coating process. Finally, a 200-nm-thick aluminum (Al) electrode heater was fabricated by thermal evaporating, UV lithography and wet-etching processes. The microscopic images of the cross-sections of the dual-mode waveguide and multimode waveguide are shown in Figs. 3(a) and 3(b), respectively. The sidewalls of the waveguides are steep and smooth, which is helpful to decrease the loss of the device.

C. Device Performance Measurement

Finally, we characterized the performances of the device.

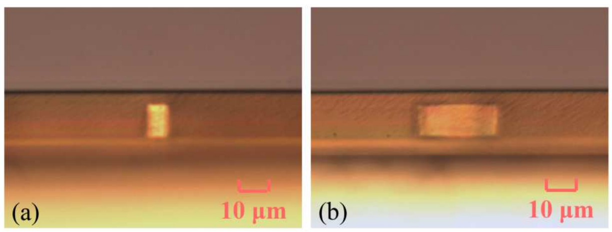

Fig. 3. The microscopic images of the cross-sections of (a) the dual-mode waveguide and (b) the multimode waveguide.

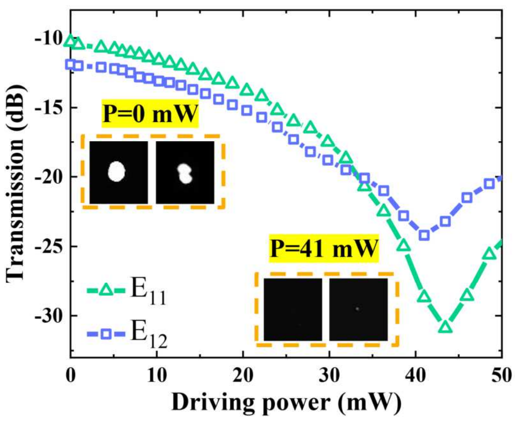

Fig. 4. Measured optical transmission from the output port of the device at different electric driving power for E_{11} and E_{12} modes. The insets show the near-field images taken at output port for the two modes at "on" and "off" state, respectively.

A light beam at 1550 nm generated from a tunable semiconductor laser (TSL-510, Santec) was coupled into the input port of device. The measured optical transmission from the output port of the device at different electric driving power for E_{11} and E_{12} modes are shown in Fig. 4. The measured extinction ratios for E_{11} and E_{12} modes are 19.4 dB and 12.3 dB, respectively, at the power consumption of 41 mW. The insertion loss of the device for E_{11} and E_{12} modes are 10.3 dB and 11.9 dB, respectively. The insets of Fig. 4 show the near-field images taken at output port for the two modes at "on" and "off" state, respectively. Besides, we also measured the response times of the switch, as shown in Fig. 5. The rise and fall times for E_{11} mode are 1.24 ms and 1.56 ms, respectively, and those for E_{12} mode are 1.44 ms and 1.64 ms, respectively.

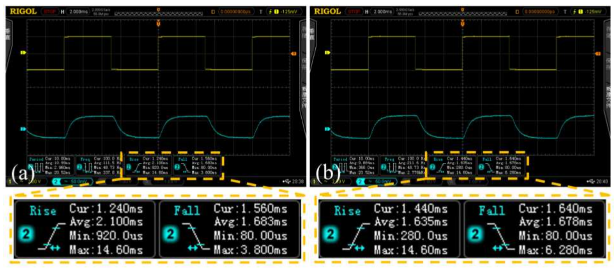

Fig. 5. Oscilloscopic displays of the temporal responses of the device for (a) E_{11} mode and (b) E_{12} mode.

III. Cunclusion

In summary, we have theoretically designed and experimentally demonstrated a MMI-based dual-mode TO switch based on polymer waveguide. The measured insertion losses are less than 11.9 dB and the extinction ratios are higher than 12.3 dB for both the two modes, at 1550 nm wavelength. The proposed switch is suitable for on-chip MDM system and large-scale integrated photonic circuit systems.

References

[1] T. Morioka, Y. Awaji, R. Ryf, P. Winzer, D. Richardon, and F. Poletti, "Enhancing optical communications with brand new fibers," IEEE Commun. Mag. vol. 50, pp. s31–s42, Feb. 2012.

[2] D. Dai, J. Wang, and Y. Shi, "Silicon mode (de)multiplexer enabling high capacity photonic networks-on-chip with a single-wavelength-carrier light," Opt. Lett. vol. 38, pp. 1422–1424, May 2013.

[3] M. Ye, Y. Yu, J. Zou, W. Yang, and X. Zhang, "On-chip multiplexing conversion between wavelength division multiplexing-polarization division multiplexing and wavelength division multiplexing-mode division multiplexing," Opt. Lett. vol. 39, pp. 758–761, Feb. 2014.

[4] J. Wang, P. Chen, S. Chen, Y. Shi, and D. Dai, "Improved 8-channel silicon mode demultiplexer with grating polarizers," Opt. Express vol. 22, pp. 12799–12807, May 2014.

[5] Q. Huang, W. Jin, and K. S. Chiang, "Broadband mode switch based on a three-dimensional waveguide Mach–Zehnder interferometer," Opt. Lett. vol. 42, pp. 4877-4880, Dec. 2017.

[6] N. P. Diamantopoulos, M. Hayashi, Y. Yoshida, A. Maruta, R. Maruyama, N. Kuwaki, K. Takenaga, H. Uemura, S. Matsuo, and K. Kitayama, "Mode-selective optical packet switching in mode-division multiplexing networks," Opt. Express vol. 23, pp. 23660-23666, Aug. 2015.

[7] L. Yang, T. Zhou, H. Jia, S. Yang, J. Ding, X. Fu, and L. Zhang, "General architectures for on-chip optical space and mode switching," Optica vol. 5, pp. 180-187, Feb. 2018.

[8] T. Lian, M. Zhu, S. Sun, X. Sun, Y. Che, B. Lin, X. Wang, and D. Zhang, "Mode-selective modulator and switch based on graphene-polymer hybrid waveguides," Opt. Express vol. 30, pp. 23746-23755, Jun. 2022.