Compact and Power Efficient 2 × 2 Thermo-Optical Switch Based on Dual-Nanobeam MZI

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Abstract: A compact 2×2 thermo-optical switch based on a dual-nanobeam MZI is experimentally demonstrated. The footprint is 38 μm×84 μm. The heating powers for the cross and bar states are ~2.66 mW and ~2.36 mW, respectively.

OCIS codes: (130.3120) Integrated optics devices; (230.5298) Photonic crystals; (130.4815) Optical switching devices.

1. Introduction

Optical switches have been studied as critical components for reconfigurable networks and datacenters [1]. High-radix $N \times N$ switches are needed to meet the requirement of wavelength division multiplexed (WDM) systems with high port counts. A 2 × 2 crossbar switch is the building block of a high-radix $N \times N$ switch. To realize an $N \times N$ optical switch with small footprint and low power consumption, the 2 × 2 optical switch should be designed to be compact with high power efficiency [1,2].

Silicon photonics offers competitive advantages to implement large-scale optical switches due to its compact footprint, low power consumption, and compatibility with complementary metal oxide semiconductor (CMOS) electronics [3]. Various schemes have been demonstrated to realize compact and low-power thermo-optical (TO) switches based on silicon microring resonators (MRRs) [4] and Mach-Zehnder interferometers (MZIs) [5]. The footprint and power consumption of the optical switches are affected by the optical mode volumes and the light-matter interactions in the optical devices [6,7]. Compared with previous device configurations, the photonic crystal nanobeam (PCN) cavity is advantageous in realizing low-power optical switches due to its ultra-small mode volume [8]. Besides, PCN cavities have resonant modes which enable WDM-based optical interconnects. Two structures based on PCN cavities are suitable for 2 × 2 switches: (1) a MZI composed of a pair of three-waveguide couplers, each containing a central nanobeam [9,10]; (2) a dual-nanobeam MZI, which is a MZI with embedded nanobeam cavity in each arm [2]. In our previous work, we experimentally demonstrated a 2 × 2 TO switch based on the first structure [10] with a footprint of 30 μm × 150 μm mainly occupied by the long MZI arms needed for thermal tuning, which can be reduced by using the dual-nanobeam MZI structure.

In this paper, we experimentally demonstrate a 2 × 2 TO switch based on the dual-nanobeam MZI. The footprint of this switch is 38 μm × 84 μm. By thermally tuning one nanobeam cavity with the shorter resonance wavelength, the two nanobeam cavities in the two MZI arms can be aligned to obtain the cross state of the switch. To achieve the bar state, instead of tuning both of the nanobeam cavities, only the nanobeam cavity with the longer resonance wavelength is heated. This lowers the power consumption compared to the case of tuning two nanobeam cavities. The heating powers for the cross and bar states are ~2.66 mW and ~2.36 mW, respectively.

2. Device structure and simulation

Figure 1(a) shows the 2 × 2 switch based on the dual-nanobeam MZI. Two nanobeam cavities are embedded in two arms of an MZI. If 3-dB directional couplers are used, the outputs at the drop and through ports are equal to the reflection and transmission of a nanobeam cavity, respectively. The waveguide width and length of the 3-dB directional couplers are 0.45 μm and 11.5 μm, respectively. The gap of the waveguides in the directional couplers is 0.2 μm. The structure of the nanobeam cavity is illustrated in Fig. 1(b), which was proposed in [11]. The width of the waveguide w is 0.67 μm, the center-to-center distance of the holes a is 0.3 μm. The radii are chosen as: $r(i) = 0.33a\,(1 - i^2/17^2)$, ($i$ = 0, 1, ..., 8), $r(i) = 0.33a\,(1 - 8^2/17^2)$, ($i$ = 9, ..., 20). The coefficient 0.33 is designed to achieve a resonance wavelength near 1550 nm. 5-μm-long tapers are used to connect the nanobeam cavities and the 0.45-μm-wide waveguides.

The nanobeam is simulated by using the Lumerical 2.5D variational finite-different time-domain (FDTD) software. Figure 1(c) shows the simulated electric-field distribution of the nanobeam at a resonance wavelength of 1547.968 nm. It can be seen that the light power concentrates in a small area and the effective length for thermal tuning is ~6 μm. The light is mainly confined in the silicon rather than the holes, which is preferred in thermal tuning

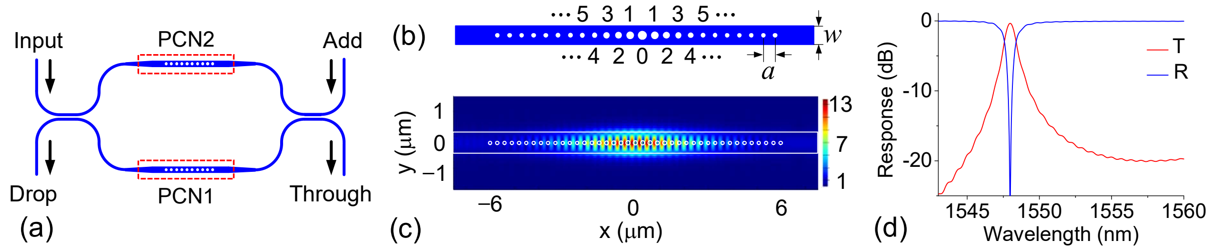

Fig. 1. (a) 2 × 2 switch based on the dual-nanobeam MZI. (b) Structure of the nanobeam cavity. (c) Simulated electric-field distribution at the resonance wavelength. (d) Simulated transmission and reflection spectra of the nanobeam. PCN: photonic crystal nanobeam.

of the silicon. The transmission and reflection spectra of the nanobeam are plotted in Fig. 1(d). The insertion loss (IL) and the 3-dB bandwidth (BW) of the transmission spectrum are 0.35 dB and 0.875 nm, respectively.

3. Device fabrication and measured transmission spectra

The 2 × 2 switch was fabricated on a SOI platform with a 220-nm-thick top silicon layer and a 3-μm-thick buried oxide layer. The silicon waveguides were fabricated by E-beam lithography (EBL) and an inductively coupled plasma (ICP) etching process. A 1-μm-thick silica layer was deposited over the whole device by plasma enhanced chemical vapor deposition (PECVD). Two 100-nm-thick Ti microheaters and three 2-μm-thick Al pads were fabricated using lift-off processes. The lengths of the microheaters are 10 μm. Figure 2 shows the micrograph of the fabricated 2 × 2 switch. The insert shows the zoomed-in view of the dual-nanobeam MZI, which has a footprint of 38 μm × 84 μm.

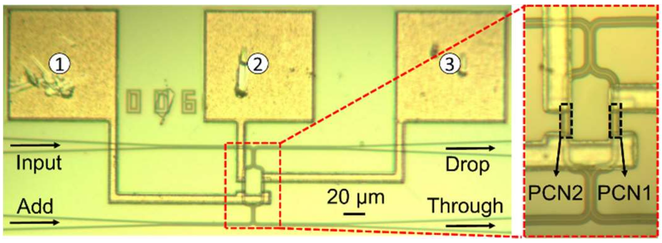

Fig. 2. Micrograph of the fabricated 2 × 2 switch. The inset is the zoomed-in view of the dual-nanobeam MZI.

A tunable laser (Keysight 81960A) is used to scan the fabricated device with a step size of 1 pm. Grating couplers are used to couple light between the device and optical fibers with a coupling loss of ~7 dB/facet. The measured transmission spectra of the 2 × 2 switch without thermal tuning are shown in Fig. 3(a). It can be seen that the resonance wavelengths of the two nanobeam cavities are not aligned due to fabrication errors. The difference between the two resonance wavelengths is 1.555 nm. By thermally tuning the nanobeam cavity with the shorter resonance wavelength (PCN1), the two nanobeam cavities can be aligned. DC probes are used for electrical connections with the metal pads. Two DC probes are contacted with the metal pads 1 and 3 with the metal pad 1 as the 'ground'. A tuning power of ~2.66 mW is used to align the resonance wavelengths. The measured transmission spectra with the aligned resonance wavelengths are plotted in Fig. 3(b), which is the cross state of the switch at an operation wavelength of 1534.799 nm. Note that the aligned resonance wavelength (1534.799 nm) is longer than the resonance wavelength of PCN2 before tuning (1534.710 nm), which can be attributed to the thermal crosstalk between the nanobeam cavities. Figure 3(c) shows the resonance wavelength of PCN1 as a function of the heating power. The tuning efficiency of PCN1 is ~0.57 nm/mW.

To achieve the bar state of the switch, the resonance wavelengths should be shifted away from 1534.799 nm and they do not need to be aligned anymore. Thus, the bar state can be achieved by tuning only PCN2, which is a power-efficient tuning scheme as PCN1 is not heated. This tuning scheme works as long as the two resonance wavelengths are set shorter than the operation wavelength, which can be easily satisfied. As long as the resonance wavelengths of PCN1 and PCN2 are far enough from the operation wavelength, the crosstalk at the operation wavelength is low. To tune PCN2, two DC probes are contacted with the metal pads 1 and 2 with the metal pad 1 as the 'ground'. With a tuning power of ~2.36 mW, the resonance wavelength of PCN2 is tuned from 1534.710 nm to 1536.042 nm, as plotted in Fig. 3(d). The resonance wavelengths of PCN2 under different heating powers are shown in Fig. 3(e). The tuning efficiency of PCN2 is ~0.51 nm/mW.

For the cross state in Fig. 3(b), the IL, the crosstalk (CT), and the BW at the through port are 0.5 dB, –22 dB, and 0.778 nm (99 GHz), respectively. For the bar state in Fig. 3(d), the IL and the CT are measured to be 0.4 dB and –22

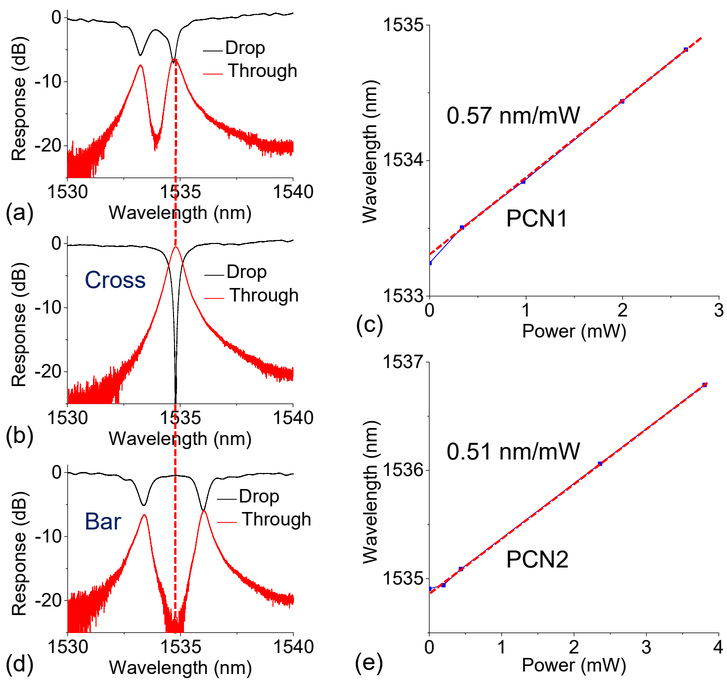

Fig. 3. (a) Measured transmission spectra of the switch without thermal tuning. (b) Measured transmission spectra at the cross state by tuning PCN1. (c) Resonance wavelength of PCN1 versus the heating power. (d) Measured transmission spectra at the bar state by tuning PCN2. (e) Resonance wavelength of PCN2 versus the heating power.

dB, respectively. The relatively higher heating powers compared to [10] are attributed to the larger mode volume and lower Q (~2000) in this work, which can be improved by optimizing the device structural parameters.

4. Conclusion

We experimentally demonstrate a 2 × 2 TO switch based on the dual-nanobeam MZI. The footprint of the switch is 38 µm × 84 µm. The cross state is achieved by heating PCN1 with a power of ~2.66 mW and a thermal tuning efficiency of ~0.57 nm/mW. For the cross state, the IL, the CT, and the BW at the through port are 0.5 dB, –22 dB, and 0.778 nm (99 GHz), respectively. The bar state is achieved by tuning PCN2 with a heating power of ~2.36 mW. The bar state IL and the CT are 0.4 dB and –22 dB, respectively.

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