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A 2×2 silicon thermo-optic switch based on nanobeam cavities with ultra-small mode volumes

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Abstract **— We propose and experimentally demonstrate a 2×2 thermo-optic (TO) switch implemented by dual photonic crystal nanobeam (PCN) cavities. This structure can achieve low switching power owing to the small mode volumes of the PCN cavities. Extinction ratio of ~15 dB is achieved at through port.**

Keywords **— integrated optics devices, photonic crystals, optical switching devices.**

I. INTRODUCTION

Recent developments in photonic network systems have led to the demand for optical matrix switches with low power consumption and high capacity transmission. A low-power 2×2 optical switch is a critical element for large-scale optical matrix switches [1-2]. Silicon-on-insulator (SOI) offers a very attractive platform to implement optical switches, due to its high index contrast and compatibility with complementary metal oxide semiconductor (CMOS) technology [3]. Thus optical switches based on the relatively large thermo-optic (TO) effect in silicon ($dn/dT = 1.86\times10^{-4}\ K^{-1}$) are promising for optical switching systems including a large number of routing channels [4].

To date, several types of silicon based TO switches have been realized by Mach-Zehnder interferometer (MZI), microring resonator (MRR), and so on [5-6]. The main challenges for these TO switches are small device footprint and low switching power, which are affected by the mode volume and the light-matter interaction in the optical device [7]. TO switches based on photonic crystal nanobeam (PCN) cavities could be an effective solution, due to their high quality factor (Q) and small mode volume (V) [8-9].

In this paper, we propose and experimentally demonstrate a novel 2×2 TO switch based on dual silicon PCN cavities. By thermally tuning the refractive index of the silicon, the resonance wavelength of the PCN cavities can be red-shifted, thus the optical switching can be achieved. The PCN cavity has an ultra-small mode volume, leading to only 2-µm-length for thermal tuning in our device. This is 1/60 of that length for a 20-µm-radius microring based TO switch with a switching power of about 20 mW [10]. Since the switching power is proportional to the length for thermal tuning, the switching power of the proposed TO switch is expected to reduce to ~1 mW. An extinction ratio of ~15 dB is achieved at the through port, and the insertion loss of the drop port is only ~0.66 dB in the experiment.

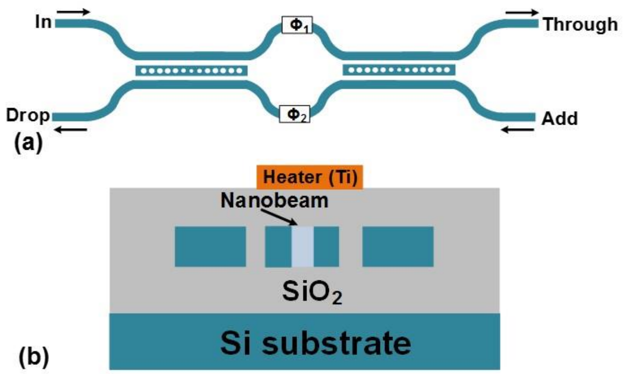

Fig. 1. (a) Schematic diagram of the proposed 2×2 TO switch based on dual PCN cavities. The phase difference between the two arms (Φ_1–Φ_2) is equal to π. (b) Cross-section view of the proposed 2×2 TO switch.

II. OPERATION PRINCIPLE AND DEVICE OPTIMIZATION

Figure. 1(a) shows the basic device schematic structure. The proposed TO switch consists of dual silicon PCN cavities side-coupled to two bus waveguides. For an optimized design of the PCN cavities, two bus waveguides are symmetrically placed at the two sides of a central nanobeam waveguide with equal coupling strengths. The central nanobeam waveguide etched with an array of air-holes forms a Fabry-Perot (F-P) cavity, which consists of a central-taper section and two side-reflector sections [8]. The central-taper section with 13 holes is optimized to reduce the scattering losses and provide high phase matching between the photonic crystal Bloch mode and the waveguide mode. The side-reflector sections are designed as two symmetrical mirrors to reflect light to the central-taper section. To achieve a relatively high Q-factor and a large extinction ratio, the widths of the nanobeam waveguide and the identical bus waveguides are optimized to be 0.565 µm and 0.6 µm, respectively. The gap between the nanobeam waveguide and the bus waveguide is 0.21µm. The cross-section view of the designed device is shown in Fig. 1(b). A micro-heater is put on the top of the PCN cavity for thermal tuning.

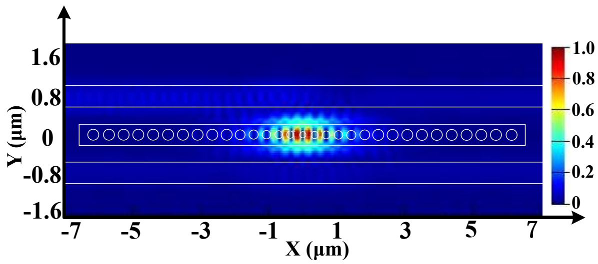

Fig. 2. Calculated electric field distribution of a single PCN cavity.

Based on finite-difference-time-domain (FDTD) method, the mode volume of the single PCN cavity is simulated and shown to approach the fundamental limit of $V = (\lambda/2n)^3$ [9]. The electric field distribution of a single PCN cavity is shown in Fig. 2. It can be seen that the length for thermal tuning is only 2 µm, which is 1/60 of that length for the microring based TO switch with a radius of 20 µm. Thus the switching power of the proposed TO switch is expected to reduce to ~1 mW. And the optical field distribution indicates that the output power transfers equally to each port of the single PCN cavity. In order to realize a high drop transmission at the cross state of the TO switch, the optical switching device is implemented by the cascaded PCN cavities with π phase difference between the two connecting bus waveguides [11].

III. DEVICE FABRICATION AND EXPERIMENT RESULTS

The designed device is fabricated on an SOI wafer with a 220-nm-thick top silicon layer and a 3-μm-thick buried dioxide layer. The micrograph of the fabricated 2×2 TO switch based on dual PCN cavities is shown in Fig. 3. The device is fabricated by E-beam lithography and reactive ion etching (RIE). A thick layer of 1.5 μm of silicon dioxide is deposited by plasma-enhanced chemical vapor deposition (PECVD). A 100-nm-thick patterned titanium layer is sputtered on the oxide to form the micro-heaters, then a 2-μm-thick aluminum layer is sputtered to form the contact pads.

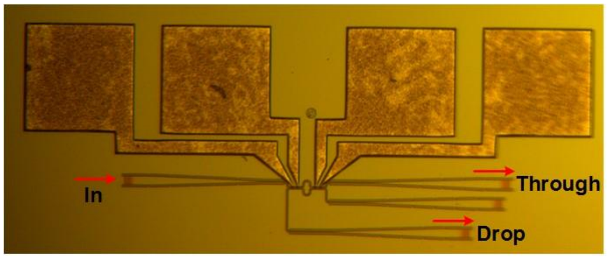

Fig. 3. Micrograph of the fabricated 2×2 TO switch based on dual PCN cavities.

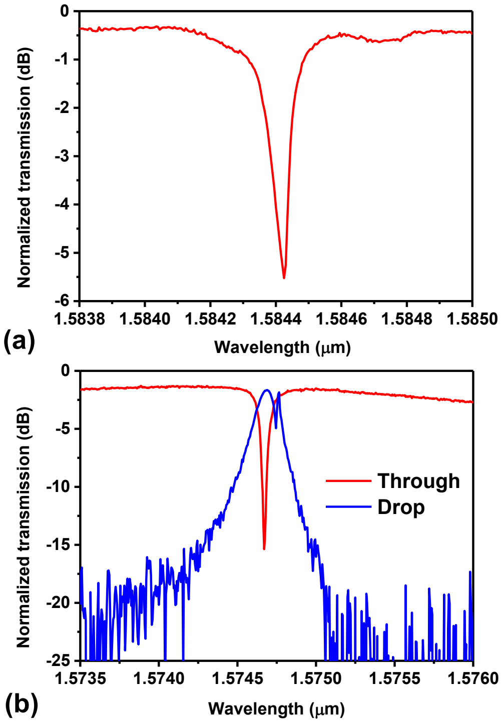

Fig. 4. (a) Normalized transmission spectrum of a fabricated single PCN cavity. (b) Normalized transmission spectra of the fabricated 2×2 nanobeam optical device in through (red line)/drop (blue line) ports.

The optical performance of a single PCN cavity in our fabricated device is firstly evaluated. As shown in Fig. 4(a), the extinction ratio of the transmission spectrum at the through port is ~6 dB, which agrees with the simulation results in Fig.2. Fig. 4(b) shows the normalized transmission spectra of the 2×2 nanobeam optical device. At 1574.54 nm, about 15 dB extinction ratio is obtained at the through port (red line). The insertion loss of the drop port is ~0.66 dB at the resonance wavelength (blue line). The full-width-half-maximum (FWHM) of the through port spectrum is ~0.08 nm with a quality factor of 20000. The switching power is estimated to be ~1 mW. More detailed characterizations and improvement are progressing alone the line towards an ultra-compact, low power, and high extinction ratio 2×2 TO switch based on dual PCN cavities.

IV. CONCLUSION

In conclusion, a compact 2×2 TO switch implemented by dual silicon PCN cavities has been experimentally demonstrated. About 15-dB extinction ratio at the through port and 0.66-dB insertion loss of the drop port are achieved in the experiment. Feasibility study indicates that the switching power of the proposed TO switch can be reduced to ~1 mW.

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