Silicon Photonic Devices for Optical Switching in Wavelength, Polarization and Mode

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Abstract: We present our recent work on thermal-optical switching on silicon chips, including two nanobeam switches with wavelength tuning, and a mode and polarization selective switch having a 748-Gb/s capacity on a single wavelength.
OCIS codes: (130.3120) Integrated optics devices; (130.4815) Optical switching devices

1. Introduction

Optical communication technologies have been advancing rapidly for several decades. Multiple dimensions of an optical carrier, including time, wavelength, polarization, amplitude, and phase, can be exploited to increase the data-carrying capacity. In multiplexing technologies, wavelength division multiplexing (WDM) has been widely employed in optical transmission and switch systems. Recently, mode-division multiplexing (MDM) offers a new dimension to further increase the information capacity in addition to the WDM technique.

In reconfigurable optical networks and data centers, switching of an incoming data stream to an arbitrary output port in a network node is a basic requirement. Among the materials and devices of choice, silicon photonic integrated switches have attracted much attention in recent years, due to the advantages of compact footprint, low power consumption, and compatibility with CMOS fabrication processes.

In this paper, we present our recent work on optical switching in wavelength, polarization and mode using silicon photonic devices with thermo-optical (TO) tuning. In a large-capacity high-radix N × N switch, 2 × 2 crossbar switches are the building blocks. In our work, we have implemented 3 types of 2 × 2 switches, with the first two switches tuned in wavelength [1,2], and the third one operated in polarization and mode [3,4].

2. Wavelength switch using cascaded nanobeam resonators [1]

The 2 × 2 wavelength switch consists of two cascaded nanobeam cavities as shown in Fig. 1(a). Each cavity has a central nanobeam waveguide sandwiched by two bus waveguides with equal coupling strengths, thus creating a 4-port system. The central nanobeam waveguide is a one-dimensional photonic crystal nanobeam (PCN) waveguide with an array of air holes divided into a central-taper section and two side-reflector sections. The widths of the nanobeam waveguide and the identical bus waveguides are 0.565 μm and 0.6 μm, respectively. The gap between the nanobeam waveguide and the bus waveguide is 0.21 μm. Fig. 1(b) shows the cross section of the nanobeam cavity. Since the nanobeam resonator is a standing-wave device, the optical power distributes equally to the four output ports (25% each), meaning a maximum extinction ratio of 6 dB. In order to realize high extinction ratios at the cross state of the switch, two identical resonator structures are cascaded with a π-radian phase difference between the two connecting bus waveguides. Fig. 1(c) show the simulated optical spectra at the through and the drop ports, respectively. The switching state can be changed by tuning the resonant wavelengths with the micro-heaters.

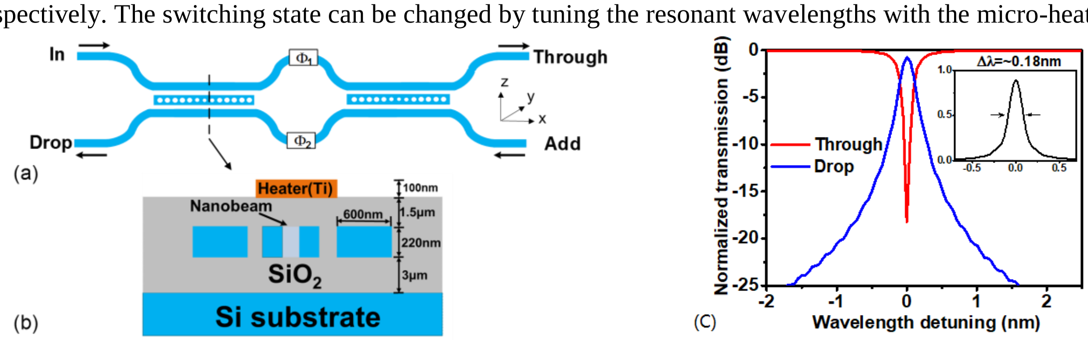

Fig. 1. (a) Schematic diagram of the 2 × 2 switch based on cascaded 3W cavities. (Φ1 – Φ2) is π to ensure a high extinction ratio. (b) Cross-section view of the 3W section. (c) Simulated optical spectra at the drop and the through ports.

The device was fabricated by E-beam lithography and reactive ion etching (RIE) on an SOI wafer having a 220-nm-thick top silicon layer and a 3-μm-thick buried dioxide layer. The micrograph of the fabricated 2 × 2 TO switch is provided in Fig. 2(a). The optical device footprint is 30 μm × 150 μm. The lengths of the heater #1 and heater #2 for tuning the nanobeam resonators are ~13 μm, and the length of the heater #3 for a π phase difference is ~150 μm. Fig. 2(b) shows the SEM image of a resonantor. The device was wire-bonded to a printed circuit board, as shown in Fig. 2(c). Fig. 2 (d) provides the measured spectra corresponding to three different heating powers of 0 mW, 0.16 mW and 0.53 mW. The device works at the cross state if the applied heating power is P_1 = 0 mW. The switch changes to the bar state if the applied power is P_2 = 0.16 mW. Thus, only ~0.16 mW is required to change the state from the cross state to the bar state. Here the heating power is defined as the increased power relative to the cross state. At 1583.75 nm, the insertion losses are 0.2 dB and 1.5 dB in the bar and cross states, respectively, and the crosstalk value is -15 dB in both cases. The measured TO tuning efficiency is as high as 1.23 nm/mW.

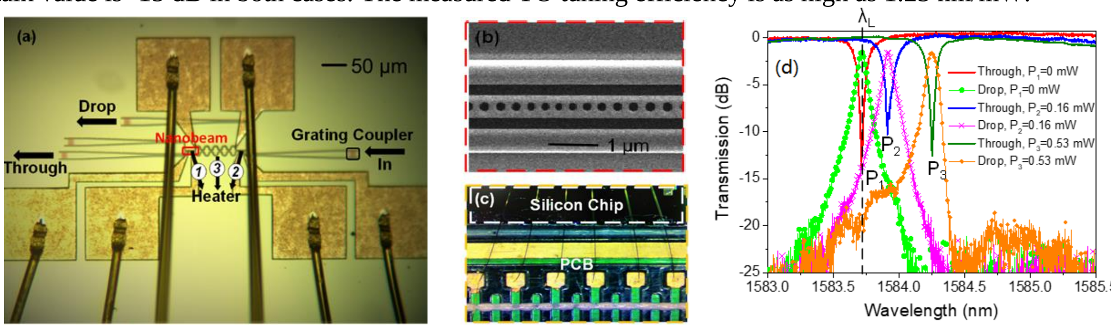

Fig. 2. (a) Microscope photo of the fabricated 2 × 2 wavelength-tunable TO switch based on cascaded 3W structure. (b) SEM photo of the fabricated 3W cavity. (c) Device with wire-bonding to a PCB. (d) Optical spectra at the Through and Drop ports with different tuning powers.

3. Wavelength switch using parallel nanobeam resonators in a Mach-Zehnder interferometer (MZI) [2]

In section 2, the demonstrated 2 × 2 switch has a footprint of 30 μm × 150 μm, which is mainly occupied by the long connecting arms needed for achieving a π-radian phase difference through thermal tuning. Here we attempt to reduce the footprint by using a parallel dual-nanobeam structure in a MZI configuration. The input light is split into two branches; each is sent into a nanobeam waveguide. The two nanobeam waveguides are combined at the output by a directional coupler, forming a simple MZI structure. Since no additional phase tuning between the two arms of the MZI is needed, the switching device can be made more compact. Figure 3(a) shows the structure of the 2 × 2 switch. Two nanobeam cavities are embedded in two arms of an MZI. The waveguide width and length of the 3-dB directional couplers are 0.45 μm and 11.5 μm, respectively. The gap between the waveguides in the directional couplers is 0.2 μm. The 2 × 2 switch was fabricated on a SOI platform using the similar process as aforementioned. The lengths of the microheaters are 10 μm. Figure 3(b) is the micrograph of the fabricated 2 × 2 switch. The inset provides the zoomed-in view of the dual-nanobeam MZI with a footprint of 38 μm × 84 μm. Fig. 4 shows the measured transmission spectra of the 2 × 2 switch in the steady state, the cross state, and the bar state, respectively. In the cross state, the two nanobeam cavities in the two MZI arms are aligned by heating the resonator with the shorter wavelength. To achieve the bar state, the nanobeam cavity with the longer resonance wavelength is heated. The tuning efficiencies of the two heaters are ~0.57 nm/mW and 0.51 nm/mW, respectively.

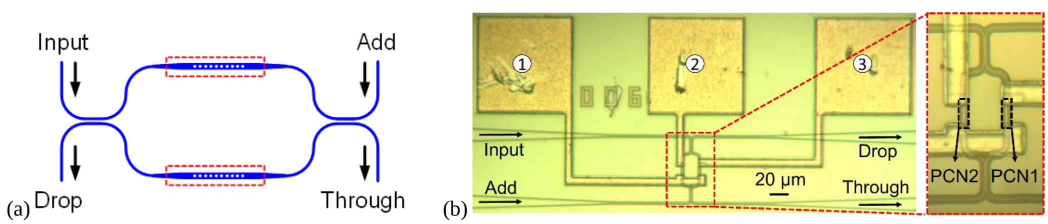

Fig. 3. (a) Structure of the nanobeam MZI switch. (b) Microscope photo of the fabricated switch.

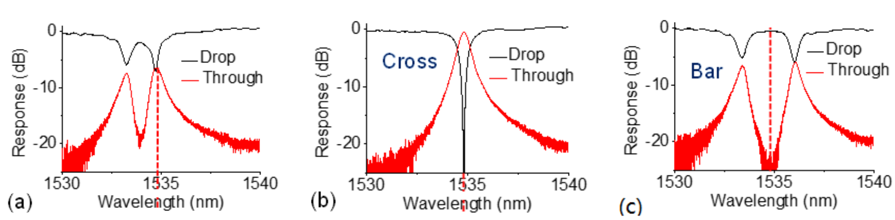

Fig. 4. (a) Optical spectra at the Initial state. (b) The two nanobeam resonators are aligned by heating the nanobeam resonator in one arm with the shorter wavelength. (c) The two nanobeam resonators are tuned off by heating the second nanobeam resonator in another arm.

4. Mode and polarization selective switch (MPSS) [3] and its system performance [4]

In addition to wavelength switching, signals can be multiplexed, de-multiplexed and switched in mode and polarization dimensions to increase the capacity. A conventional wavelength selective switch (WSS) can route any wavelength channel from one input port to any output port, while here we discuss a new switch that can route mode- and polarization- multiplexed signals. The on-chip silicon 2 × 2 MPSS is schematically shown in Fig. 5(a), which can route 4 channels of TE_0, TE_1, TM_0 and TM_1 modes. Input signals are firstly de-multiplexed by the polarization beam splitters (PBSs) and the mode de-multiplexers, and then routed by the corresponding TE_0 or TM_0 MZIs. At the output, they are combined and sent to O_1 or O_2 port. The proposed MPSS device needs to couple to few-mode fibers for application in optical fiber communications. The micrograph of the fabricated chip is shown in Fig. 5(b). The overall insertion losses of all channels are lower than 8.6 dB at 1550 nm, and the measured inter-modal crosstalk values are lower than -23.2 dB for all the channels at 1550 nm.

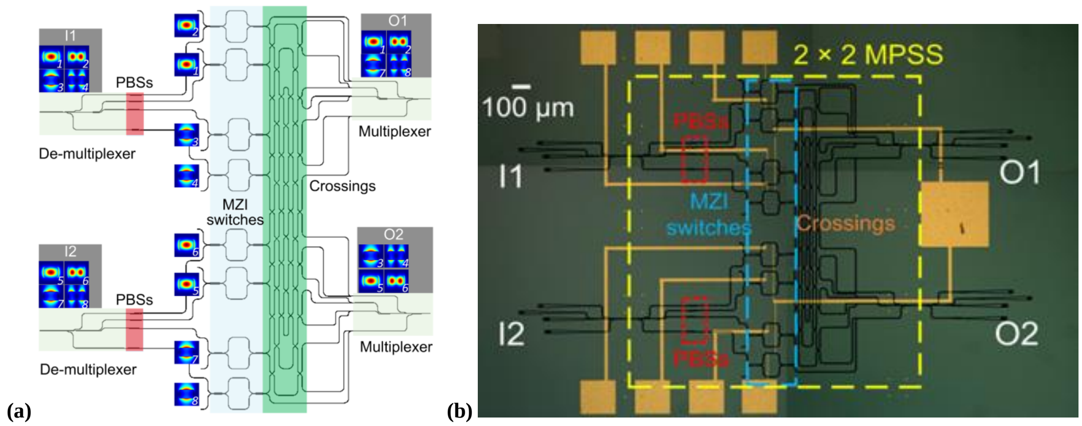

Fig. 5. (a) Schematic configuration of the 2 × 2 MPSS for 2 modes and 2 polarizations. (b) Microscope photo of a fabricated MPSS chip

To characterize the system performance with high speed data, we used the experimental setup in Fig. 6(a). An orthogonal frequency division multiplexed (OFDM) signal with a resampling rate of 60 GSa/s is sent into the MPSS by grating couplers. Bit loading is used with 64-, 32- and 16- quadrature amplitude modulation (QAM) mapping, and 64% subcarriers are allocated for 64-QAM data. A raw data rate of 100.0 Gb/s and a net data rate of 93.5 Gb/s are obtained with BERs shown in Fig. 6(b). The switching capacity is therefore 2 × 4 × 93.5 = 748 Gb/s/λ.

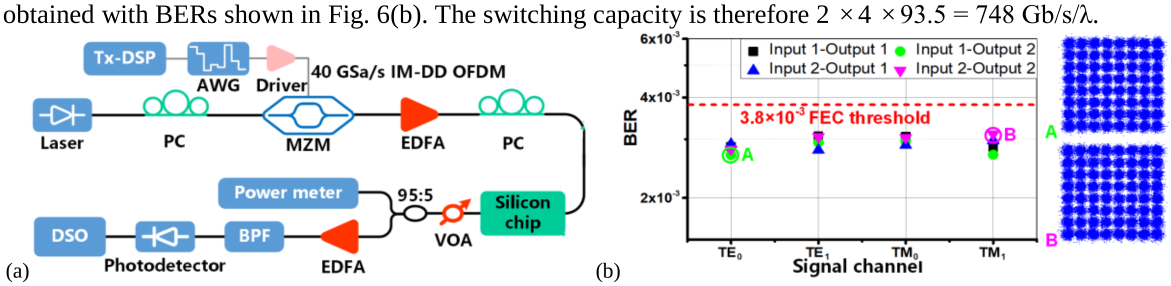

Fig. 6. (a) Experimental setup for testing the MPSS chip. (b) BER performances

5. Conclusion

We have demonstrated a 2 × 2 wavelength switch using two cascaded nanobeam cavities with a low switching power of 0.16 mW. To reduce the footprint of the switch, we also demonstrated a 2 × 2 wavelength switch using two nanobeam resonators in a parallel MZI configuration, showing a footprint of 38 μm × 84 μm. Furthermore, to increase the capacity, we proposed and demonstrated a 2 × 2 mode and polarization selective switch. The switch can route 4 data channels with 2 modes and 2 polarizations on a single wavelength having a capacity of 748 Gb/s/λ.

6. References

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