MZI-based non-blocking SOI switches using integrated thermo-optic phase-shifter

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Abstract: A 4×4 MZI based non-blocking Beneš switching matrix is designed in O-band using compact 2×2 building blocks with integrated resistive heaters. Switching power is measured to be 21 mW/π-phase shift in an individual switch element.
OCIS codes: (130.3120) Integrated optics devices; (130.4815) Optical switching devices; (200.4650) Optical interconnects

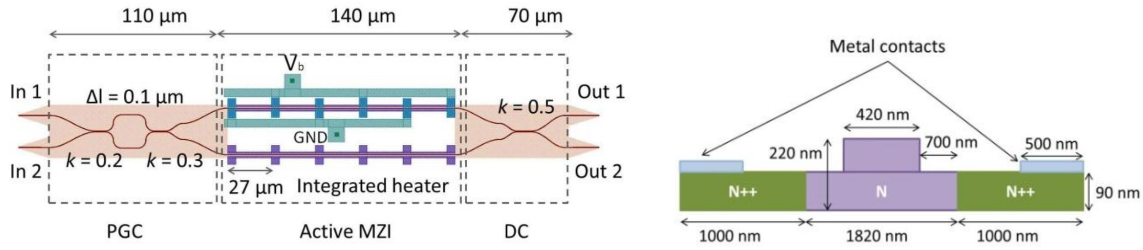
1. Introduction

Silicon-on-insulator (SOI) based optical interconnection networks are promising solutions in overcoming the challenges of higher bandwidth-density requirement and power consumption in data centers. Dense integration of CMOS compatible, low cost, low power and compact footprint optical components such as modulators and switches are essential in short reach optical interconnects. SOI is an attractive platform to build thermo-optic switches due to the large thermo-optic coefficient of silicon ($\partial n/\partial T = 1.94 \times 10^{-4} K^{-1}$ at λ = 1310 nm) with high thermal conductivity and high refractive index contrast. Thermally tuned MZI switches have been reported with relatively fast switching of a few microseconds with reasonable power and high extinction ratio. However, these switches have large footprint [1, 2] limiting their application for large port-count switch matrix. Thermo-optic phase shift is typically provided by an over-clad heater which requires additional fabrication steps for metallization and complex device design [3]. Moreover, optimization of optical loss and operating power related to the dimension and spacing of the metallic heater is challenging. Fabrication variation and strong wavelength-dependence of the 3-dB couplers as well as the phase shifters of the MZI limit the ideal extinction ratio and insertion loss to a narrow wavelength range [4] imposing challenges in realizing wideband switches suitable for high throughput WDM systems. MZI with 30 dB extinction ratio over a large operating band (1260 nm – 1610 nm) has been demonstrated in [5]. However, these switches used silica based technology with larger footprint and limited tunability. In this work, we demonstrate a thermo-optically tuned broadband MZI switch in the O-band (1260 nm – 1380 nm) with a compact device footprint of only 0.01 mm^2. The thermal tuning is done by resistive elements using highly doped silicon slab parallel to the silicon rib waveguide [6]. A wavelength insensitive phase generating coupler (PGC) is used instead of directional couplers to ensure broadband operation.

2. Design of the switching matrix

A compact model of MZI based thermo-optic switch is demonstrated for transverse electric (TE) mode transmission in O-band. The 2×2 MZI switch has a small footprint of 320 μm length by 35 μm width, using a 420 nm × 220 nm silicon waveguide structure with a 90-nm-height silicon slab. Fig. 1(a) shows the dimensions of MZI based 2×2 switch with a 140 μm long active MZI section. The input and output couplers of the MZI consist of a Phase Generating Coupler (PGC) and a 3-dB directional coupler, respectively. The PGC design parameters are optimized through numerical analysis and are found to be $\kappa_1 = 0.2$, $\kappa_2 = 0.3$ and $\Delta l = 0.131\lambda_c$=0.1μm. Fig. 1(b) shows the cross-section of the MZI arm. The thermo-optic phase shift in the active MZI arm is achieved by highly n-doped 1000 nm wide silicon slabs placed 700 nm away from the waveguide rib. Both arms of the MZI are identically doped to balance the loss. High concentration of doping decreases the ohmic resistance causing low-resistance path allowing efficient power absorption by resistive heating. The waveguide rib is surrounded by oxide for better heat confinement. The center of the waveguide is lightly n-doped to reduce the optical loss in the core region. The metal contacts for bias voltage (V_b) and ground (*GND*) connections are placed alternatively along the active arm to form five segments such that electric current encounters ten resistive loads connected in parallel to each other where each resistor is 27 μm long and 1 μm wide. In this way, the current can flow parallel to the rib waveguide which reduces optical loss. The 2×2 MZI switch is used as the building block for the 4×4 Beneš switching matrix, shown in Fig. 2(a).

The proposed MZI structure involves less fabrication steps as no metallic heater and associated mask lithography are required to incorporate over-clad metal layers since the heaters are based on resistive element implemented with N/N+ doped silicon. The devices were fabricated at the Institute of Microelectronics (IME A*STAR) through a multi-project wafer (MPW) service organized by the Canadian Microelectronics Corporation (CMC).

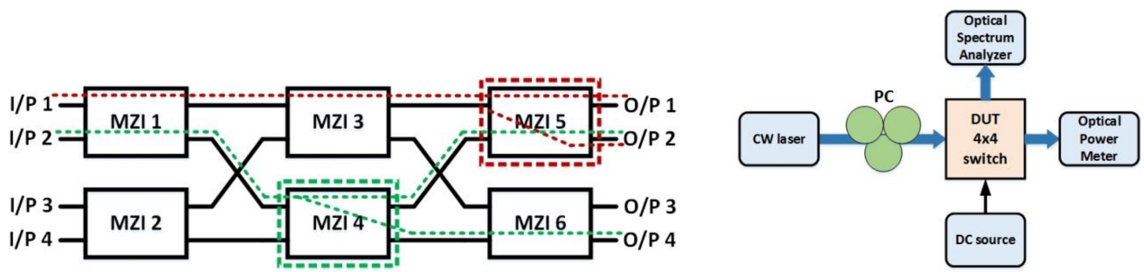


(a) (b)

Fig.1. (a) Schematic of 2×2 MZI-based switch with an integrated thermo-optic phase shifter, (b) cross-section schematic of the MZI arm.

3. Experimental Setup

Six 2x2 MZI building blocks are interconnected in a rearrangeable non-blocking Beneš 4×4 switching matrix (Fig. 2(a)). Optical input and output are coupled to four input and four output grating couplers, respectively, making up for the 4×4 matrix, through an eight fiber array controlled by a three-axis stage. Fig. 2(b) shows the optical experiment setup where a continuous wave (CW) laser source (wavelength tuning range 1260 nm – 1380 nm) and a polarization controller is used prior to the input of the chip. A varying DC bias voltage applied to one of the identical arms of the MZI switches enables to characterize the extinction ratio and crosstalk at the optical output ports. The outputs are measured using an optical power meter and an optical spectrum analyzer (OSA).



(a) (b)

Fig.2. (a) Schematic of a 4×4 Beneš MZI switch matrix where the red and green dotted lines correspond to the optical paths for transmissions shown in Fig. 3(c) and (d), respectively; (b) schematic of the experimental setup.

4. Results

The total Ohmic resistance of the ten segments is measured up to 3.5V bias and found to be approximately 180 Ω. The resistance of each segment is estimated to be 1.8 kΩ. The bar and crossbar transmission responses of the 2×2 MZI switch is first measured for different bias voltages (V_b), reported in Fig. 3(a) when the CW optical input is at input 1, shown as ‘In1’ in Fig 1(a). A CW light from a tunable laser source is swept from 1325 nm to 1375 nm, while its output power is fixed at 0 dBm (1 mW). A fiber-to-fiber total insertion loss of 12 dB is obtained for a waveguide test structure with two grating couplers. The transmission response of the switch is normalized to the waveguide response to estimate the insertion loss and crosstalk of the 2×2 switch in both bar state (Output 1) and cross state (Output 2). Although the device was designed for 1310 nm, optimal performance is observed around 1360 nm due to a shift in 3dB bandwidth of the grating coupler. For the crossbar configuration or ‘OFF’ state, the 2×2 MZI switch has an insertion loss of approximately 1 dB (V_b = 1V), and for the bar configuration or ‘ON’ state, the insertion loss is approximately 3.7 dB (V_b = 2.2V). The crosstalk of the switch is around -11.5 dB in ‘OFF’ state and -13 dB in ‘ON’ state. The imbalance in insertion loss and crosstalk between the two outputs is attributed to the fabrication sensitivity of the directional couplers and probable misalignment of the fiber array. In Fig. 3(b), the bias voltage is swept over 0V to 3.5V and the optical transmission is captured. The bar and crossbar state extinction ratios are 7.6 dB and 13.5 dB, respectively. The extinction ratio remains almost the same over 50 nm wavelength range allowing a broadband response. A voltage of V_π = 1.2V with a bias of 2.2V was required to switch between the two states. The power consumptions in the ‘OFF’ state and ‘ON’ state are estimated from current measurements, and were found to be 6 mW and 27 mW, respectively, requiring 21 mW switching power for π-phase shift.

As the switches are not packaged at this moment, all switches of the 4×4 matrix cannot be simultaneously controlled. At most two switches of the 4×4 switch fabricated are accessible using electrical probes. A subset of the full 4×4 switch is characterized at this point. The optical power at the output ports are measured with an optical power meter for 16 possible I/P – O/P configurations at the ‘OFF’ states of all MZI’s. The measured output power ranged from 6 dB to 17 dB. Fig. 3(c)-(d) show the optical transmission spectra of the matrix switch at various output ports for some specific sets of bias conditions. Optical paths for each of the two configurations are shown in Fig. 2(a). In this characterization, only one voltage bias level is tuned at a time while keeping the other MZI building blocks fix to bar or crossbar states. For example, when the CW signal is applied at I/P 1 and V_b is applied at MZI 5 (Fig. 3(c)), the bias voltage for bar port (O/P 1) and crossport (O/P 2) is 1.7V and 2.7V, respectively. Output powers at 2.7V bias in O/P 1, O/P 2, O/P 3 and O/P 4 are measured to be -5.0 dB, -25.3 dB, -7.1 dB and -8.4 dB respectively.

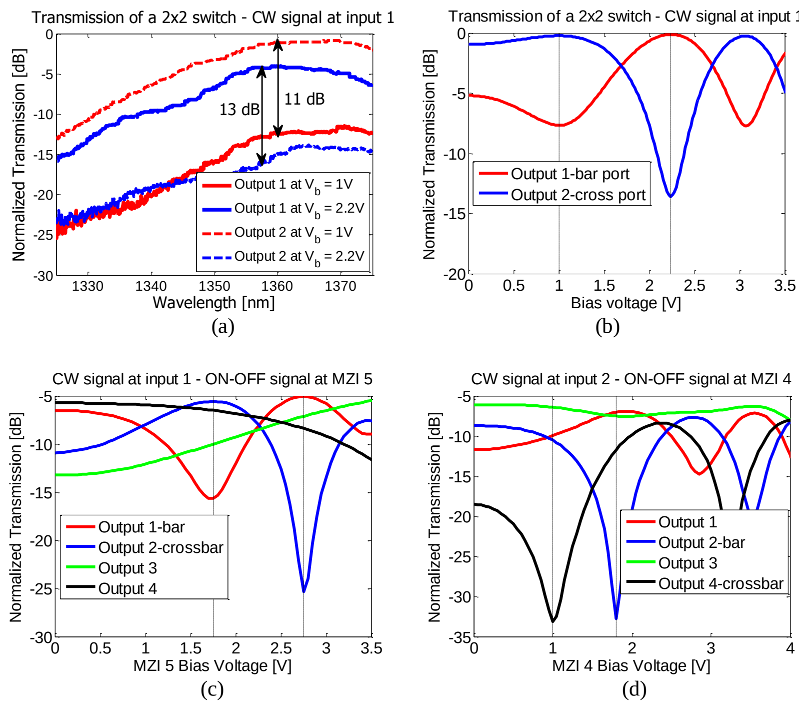


Fig.3. (a) Optical transmission of 2×2 switch in two different bias voltages; (b) optical transmission of 2×2 switch for varying bias voltage from 0V to 3.5V; (c-d) examples of optical transmission of 4×4 switch at specific switching condition where bias voltage is applied to only one MZI at a time. The optical paths are shown in Fig. 2(a) with red and green dotted lines corresponding (c) and (d), respectively.

5. Conclusion

The paper presented the characterization results of thermo-optically tuned rearrangeable non-blocking 4×4 optical switches in SOI consisting of compact 2×2 MZI building blocks of 0.01 mm^2 with integrated thermal phase shifter. The overall resistance of the switch is measured to be 180 Ω. The 'OFF' state and 'ON' state electrical power dissipated by each 2×2 MZI switch is 6 mW and 27 mW respectively requiring 21 mW/π-phase shift representing a V_π of 1.2V. The 2×2 switch exhibits 3.7 dB insertion loss and -13 dB crosstalk in 'ON' state and approximately 13.5 dB extinction ratio at the crossbar port. The switch enables broadband operation over 50 nm wavelength range facilitating WDM data communication.

Acknowledgments

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6. References

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