Efficiency Improvement of an O-band SOI-MZI Thermo-optic Matrix Switch

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***Abstract* —A low-power, broadband SOI 4×4 thermo-optic Beneš switch is demonstrated in O-band using 2×2 MZI with integrated phase-shifter. The crosstalk improves to less than −22 dB over 50 nm with an efficient switching power of 21 mW by optimized tuning of the bias voltage.**

Keywords—Integrated optics; Optical switching devices; Optical interconnects; Waveguides

I. Introduction

Silicon-on-Insulator (SOI) based thermo-optic switches exploit 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. These attributes enable switching time in the microsecond range with potentially high extinction ratio (ER) and low energy consumption. However, these switches use overclad metal heaters requiring additional fabrication steps for metallization and complex device design [1]. Their footprint also limits their application for large port count switch matrix. And as other SOI-based devices, the optical bandwidth of the switch's directional couplers and phase shifters are subject to fabrication variations limiting their suitability as wideband switches for WDM systems. Broadband thermo-optic switches have been reported in [2-4] for C-band. SOI based efficient and low-power broadband thermo-optic switches are required in the O-band to leverage their applications in data centers to realize short-reach optical interconnects.

In this work, we design and experimentally demonstrate a thermo-optically tuned broadband 4×4 rearrangable non-blocking Beneš switch for the O-band (1320 nm – 1380 nm). Thermal tuning is achieved with resistive elements using highly doped silicon slab parallel to the silicon rib waveguide [3]. A wavelength insensitive phase generating coupler (PGC) instead of directional couplers allows broadband operation. To the best of our knowledge, this is the first report of a broadband thermo-optic SOI switch in O-band.

II. Design and Simulation

The 2×2 switch, shown in Fig.1(a), is designed using a 420 nm wide and 220 nm high silicon core with a 90-nm-height silicon slab for transverse electric (TE) mode transmission at λ_c = 1.31 µm. The 2×2 switch has a compact footprint of 320 µm length and 35 µm width (0.0112 mm^2). Detailed design of the phase shifter and the 2×2 MZI switch can be found in [4].

The thermal phase-shifter and PGC are designed by optimization of physical dimensions for low switching power and broadband operation. The PGC design parameters are optimized through numerical analysis and are k1 = 0.2, k2 = 0.3 and Δl = 0.131λ_c = 0.1 µm; where k1, k2 and Δl are the coupling coefficients of the first and second directional couplers, and the path length difference in the PGC arms, respectively. Fig. 1(b) is the simulation results of the temperature in the waveguide, T (red), and the associated phase shift, Δφ (blue), with respect to the bias voltage in steady-state condition. A 2 V bias is required for a π-phase shift enabling switching between the MZI output ports. The total ohmic resistance of the phase shifter is estimated from simulation to be 170 Ω corresponding to a switching power of 23.5 mW which is less than the power required in metal heater based phase shifter of 30 mW [5]. A 21 °C temperature rise is observed in the waveguide core at 2 V bias from the initial room temperature value (27 °C at 0 V).

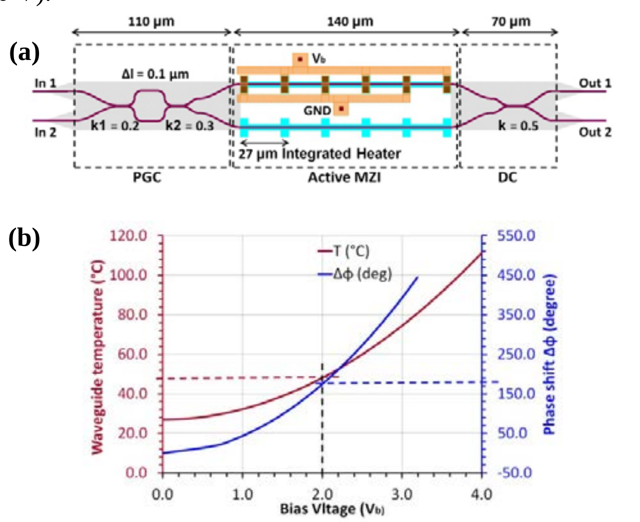

Fig. 1. (a) Schematic of the 2×2 MZI-based switch with an integrated thermo-optic phase shifter; (b) simulated temperature rise and phase shift at different bias voltages.

III. Experimental Results

The initial characterization results showed that the 2×2 switch exhibits an insertion loss (IL) of −3.7 dB, a crosstalk of −13 dB in 'ON' state, and an ER of 13.5 dB at the crossbar port [4]. Further characterization of the switch showed a 2.7 dB IL imbalance and a 1.5 dB crosstalk imbalance between the 'ON' (bar) and 'OFF' (crossbar) states, which is attributed to the fabrication sensitivity of the directional couplers and probable misalignment of the fiber array. The measured power consumption is 21 mW ($V_\pi = 1.2$ V) for a π-phase shift which is in good agreement with the expected power consumption of 23.5 mW. A square wave at 120 kHz with fall and rise times of 16 ns was used to characterize the switching speed. The measured rise and fall times using a fast photodetector (bandwidth of 15 GHz) was observed on a real-time oscilloscope, shown in Fig. 2(a). The 10% to 90% rise and fall times are 1.6 µs and 2.0 µs, respectively.

The optical powers at the output ports of the wire bonded 4×4 switch, shown in Fig. 2(b), are measured for 16 possible input port (I/P) to output port (O/P) configurations with all MZI's optimally biased. The crosstalk among the output ports varies for the cross states and bar states, respectively. A configuration is shown by the red dotted line in Fig. 2(b) where I/P 2 is connected to O/P 2 through the MZI-1/MZI-5/MZI-3 path. The normalized optical transmission is shown in Fig. 2(c) where the crosstalk at 1365 nm at O/P 1, O/P 3 and O/P 4 are −23.8 dB, −40.1 dB and −47.1 dB, respectively with a −4 dB IL at O/P 2. For the same I/P-O/P configuration, the bias voltage is varied over 0 V – 4 V at MZI 5, shown in Fig. 3(d), while other MZI's are biased at their bar states. The optimum bias point occurred at 1.95 V and an 18 dB ER is observed at O/P 2.

If the MZI's are not optimally biased for a specific I/P-O/P routing path, their switching states cannot be properly predicted since the ON/OFF states of the idle MZI's are not precisely controlled. Consequently, a leakage of optical power occurs from the targeted input to the non-targeted outputs resulting in power imbalance and crosstalk degradation [4]. As the switches consist of directional couplers sensitive to process variation and thermal drift, the effective optical path length varies among the switch elements resulting in random phase difference between two MZI arms. As a result, the 'OFF' states (crossbar) of idle switches undergo a variation in power consumption from different bias voltage requirement per MZI building blocks. Consequently, all MZI building blocks in the switch matrix must be biased in a known state to reduce this variation.

For the deployment of large port-count switch matrices, an automated characterization scheme such as in [6] efficiently assesses the optimum bias voltage of each of the MZI. A look-up table based centralized controller as in [7] can then maintain this value for a more efficient operation of the switch matrix.

IV. Conclusion

We report for the first time on a thermo-optically tuned 4×4 Beneš switch matrix consisting of compact and broadband 2×2 MZI building blocks enabling broadband operation over 50 nm. Switch performance as an individual element and as a building block of the 4×4 matrix is characterized at optimal bias condition. The elementary MZI facilitates its application in WDM data communication.

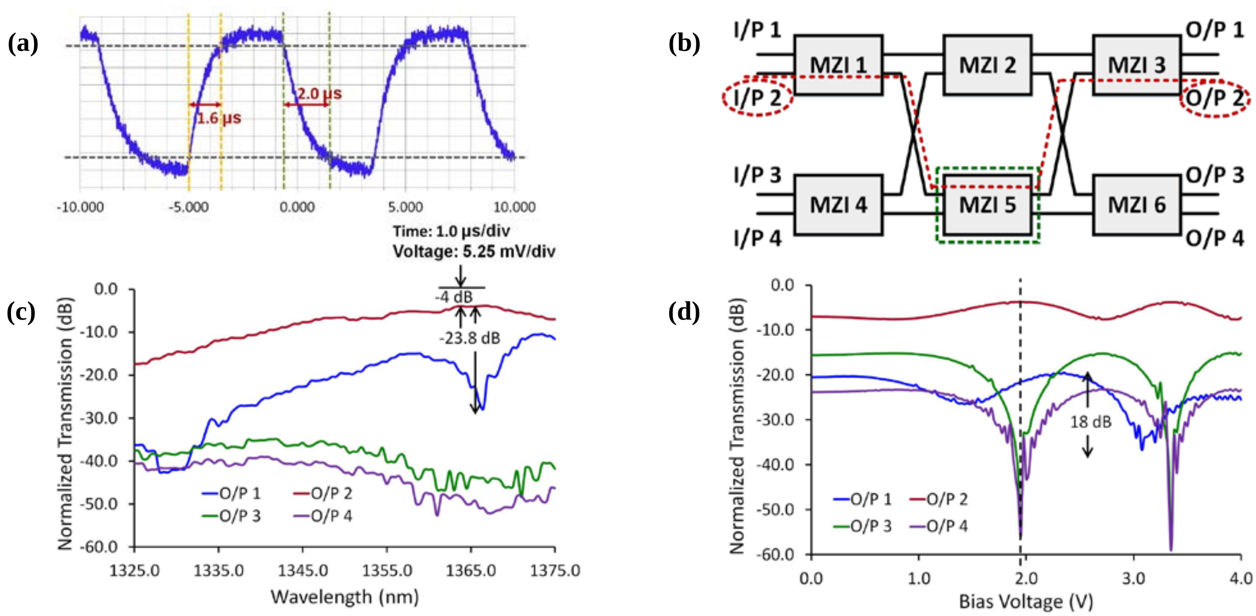

Fig. 2. (a) ON-OFF switching of the 2×2 switch; (b) schematic of the 4×4 switch with the optical path between I/P 2 and O/P 2 shown in red; (c) optical transmission of the 4×4 switch for the I/P 2 – O/P 2 configuration; and (d) optical transmission for the same traversal with bias voltage sweep in MZI 5.

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