Low Loss 8 × 8 Silicon Photonic Banyan Switch

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Abstract—We design and experimentally demonstrate scalable 2×2, 4×4 and 8×8 silicon photonic thermal switches exhibiting low loss, low crosstalk, energy-efficient and error-free data transmission. Insertion loss below 3.1 dB with crosstalk of at most 20.5 dB is measured for the 8×8 SiPh thermo-optic switch.

Keywords—Optical switches, silicon photonics, Mach-Zehnder interferometer, multi-mode interferometer

I. Introduction

The exponential growth of network traffic has motivated dynamic optical switching in datacenters. Current electronic switching technology faces important challenges in datacenters in terms of scalability, bandwidth, switching speed, and power consumption. Optical switching can potentially meet those requirements in datacenter networks. Silicon photonic (SiPh) switch compatible with complementary metal-oxide-semiconductor (CMOS) allow high integration density and low manufacturing cost in an established fabrication process. The most important factors of a large port count switch beyond cost are low insertion loss, low crosstalk, high bandwidth, and low power consumption. These performance metrics become challenging to meet with the large number of building blocks in integrated switching matrices. In this work, multi-mode interferometer (MMI) based thermo-optic switches are described. The MMI used here is optimized to have low insertion loss and high bandwidth with a robust design to fabrication process variation. Our MMI based 2×2 switch exhibits lower insertion loss compare to directional coupler based 2×2 switch [1]. In 8×8 Banyan switch, the cascaded optical bandwidth is over 25 nm of range with an insertion loss below 3.1 dB facilitating WDM data communication. The switch has lower loss than similar works [2] enabling further scalability of the switch to greater port count. Based on the results, a 32×32 Banyan switch's estimated loss is 6.8 dB (14.6 dB) for the shortest (longest) optical data path.

II. Design and Fabrication

In WDM systems, Mach-Zehnder Interferometer (MZI) based switching is suitable for scalability and space switching. A conventional 2×2 MZI building block consists of two MMIs as 3 dB splitter/coupler connected by a balanced dual-waveguide. One of the two waveguides has a phase shifter able to change the phase difference between two paths from 0 to π by thermally tuning the refractive index of Si. Using self-imaging property, a 6 µm wide and 131 µm long 2×2 ports MMI core is optimized (fig. 1(a)). Tapers that are 20 µm long with width of 1.4 µm connect 500 nm wide slab waveguides. A 200 µm long and 5 µm wide Titanium Tungsten (TiW) heater is designed as a phase shifter placed 2 µm above one of the MZI balanced paths between two MMIs.
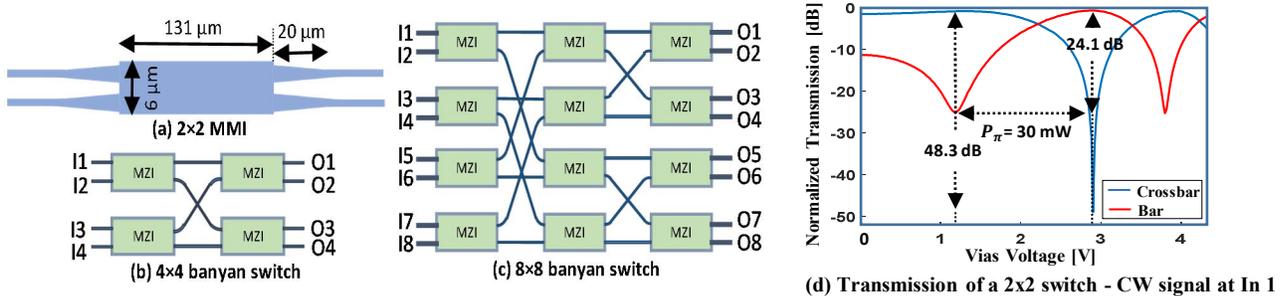

Fig. 1. (a) 2×2 MMI building block; (b) 4×4 thermal switch; (c) 8×8 thermal switch; (d) Measured optical transmission of the 2×2 building block at 1550 nm.

A Silicon-on-Insulator (SOI) wafer is used to fabricate the SiPh switches through Applied Nanotools Inc (ANT). The Electron Beam Lithography (EBL) and Reactive Ion Etching (RIE) processes have been used to fabricate the device using 220 nm thick silicon layer on top of a 2 µm buried oxide layer. A TiW alloy and aluminum thin film are used for the metal heaters and the routing layer, respectively.

III. CHARACTERIZATION OF LOW LOSS SWITCHES

A C-band tunable laser is used to perform the CW measurement. A polarization controller (PC) is connected at the output of the laser source, so that only on-chip quasi-TE optical mode will be excited. Two grating couplers are used to couple light in and out from the device. The output light is measured by an optical power meter. The CW measurements are normalized to the coupling loss. The switches are characterized at 1550 nm considering the design optimization done at 1550 nm. The 2×2 MZI thermo-optic building block exhibits 0.6 dB insertion loss with crosstalk less than -24 dB. The 4×4 switch comprised of four 2×2 MZI building blocks (fig. 1(b)) exhibits less than 1.4 dB of insertion loss (IL) for the shortest switching path (I1-O1). The IL is approximately 2.12 dB for the longest path (I1-O4) with a maximum crosstalk recorded of -21.5 dB. For the 8×8 switch, each switching channel consists of three cascaded MZIs shown in fig. 1(c). Less than 3.13 dB IL is measured for the shortest path (I1-O1) of the 8×8 switch where no waveguide crossing is employed. The longest channel (I1-O8) contains four waveguide crossings. The resulting IL measured is approximately 5.03 dB with a maximum crosstalk of -20.5 dB. The 3 dB bandwidth is greater than 25 nm. The approximate value of the optical loss estimated from the building blocks is shown in table I. The measurement are inline with the estimate, validating the scalability of these switches.
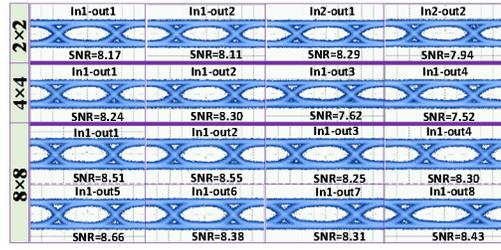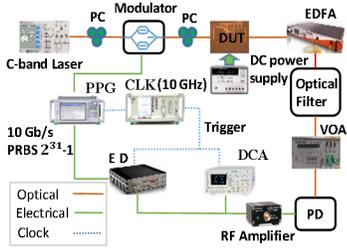

Fig. 2. Experimental setup of RF measurement.   Fig. 3. 10 Gb/s eye diagrams of the 2×2, 4×4 and 8×8 switches for all the corresponding outputs. (100 mV/div).

TABLE I
Optical loss estimation for the longest path of the 8×8 switch

Building block	Unit loss (dB)	Quantity	Total (dB)
2×2 MZI cell	0.6	3	1.8
Waveguide length (mm)	0.38	5	1.9
Waveguide Crossing	0.3	4	1.2
Total on-chip loss	---	---	4.9

Payload transmission is performed to demonstrate the switching performance in a real data transmission system and the experimental setup is shown in fig. 2. In fig. 3, clear open eye diagrams are observed for input-1 to all output ports with a signal to noise ratio (SNR) of at least 7.52 for a BER of 10^{-10}. It is observed that SNRs are slightly better in 8×8 switch due to a more optimized grating coupler which improves the output optical power compared to 2×2 and 4×4 switches.
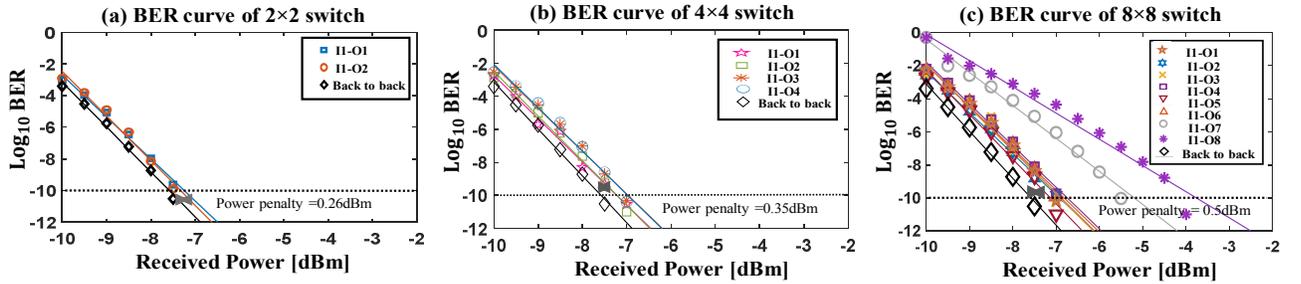

Fig. 4. Logarithm BER as a function of received optical power for input1 to all outputs and back-to-back connection; (a) 2×2 building block; (b) 4×4 banyan switch; (c) 8×8 banyan switch.

The bit error rate (BER) and corresponding power penalties are shown in Fig. 4 for input-1 to all of the outputs at the BER of 10^{-10}. The power penalty varies depending on the routing paths. The minimum (maximum) power penalties are 0.26 dBm (0.5 dBm), 0.35 dBm (0.7 dBm), and 0.50 dBm (4.4 dBm) for 2×2, 4×4 and 8×8, respectively.

The electrical power dissipated by each 2×2 MZI building block for the 'ON' state and 'OFF' state is 34.8 mW and 4.8 mW respectively. Thus, the require 30 mW/π-phase shift represents a $V\pi$ of 1.6 V (fig. 1(d)). If all the MZIs are on 'ON' state, the total power (energy) consumption of the 4×4 and 8×8 switches are approximately 139 mW (3.5 pJ/bit) and 417 mW (5.25 pJ/bit), respectively.

IV. CONCLUSION

We experimentally demonstrated 4×4 and 8×8 banyan thermal switches in SiPh platform exhibiting potential scalability. The switches exhibit low on-chip loss, low crosstalk, and distortion-free data transmission with low power penalty.

REFERENCES

[1] S. Chen and D. Dai, "Ultra-broadband low-loss 2×2 MZI (Mach-Zehnder interferometer)-based thermo-optic switch with bent directional couplers on silicon," *2016 Optical Fiber Communications Conference and Exhibition (OFC)*, Anaheim, CA, 2016, pp. 1-3.

[2] T. Tanemura, L. Langouche and Y. Nakano, "Strictly non-blocking 8×8 silicon photonic switch based on optical phased array," *2015 European Conference on Optical Communication (ECOC)*, Valencia, 2015, pp. 1-3.