Low-Crosstalk 8×8 Silicon Photonic Switch Fabric with Dual-Stage MZI Cells

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Abstract: We demonstrate a strictly non-blocking 8×8 silicon photonic switch fabric with centrally placed dual-stage MZI cells that effectively suppress first-order crosstalk. This thermally actuated device exhibits on-chip loss of <5dB and low-crosstalk of <-40dB. © 2024 The Author(s)

1. Introduction

Optical switching networks are widely recognized as a promising solution to accommodate the rapidly growing data traffic in data centers and high-performance computing systems, since that they offer many advantages including adaptive resource allocation, low latency, high bandwidth per port, and high power efficiency. Silicon CMOS photonics, which provides the route to scalable manufacturing capacity, is as a highly promising platform for photonic integrated switch fabrics with tight light confinement [1]. The Mach-Zehnder interferometer (MZI) is one of the most widely applied switching building blocks. MZIs can operate in over a wide wavelength range with low loss; however, the optical couplers often pose a limitation on the switching passband and extinction because of fabrication imperfections. The imperfect extinction leads to leakage that can largely compromise signal integrity, accompanied by an incomplete conversion efficiency, i.e. insertion loss. For example, a deviation of 2% from an ideal 50% coupling ratio can result in crosstalk degradation to below -30 dB [2]. To mitigate this issue, research efforts have been made in the use of nested switch elements [3,4] and dilated switch topologies [5], both of which trade off device complexity for improved crosstalk performance.

In this work, we present a strictly non-blocking 8×8 silicon photonic switch that is thermally actuated. It is implemented in a double-layer network (DLN) topology with a dual-stage MZI configuration in its central layer. This design effectively mitigates the first-order crosstalk owing to the actively adjustable power levels in the arms. This design also features a smaller number of switching components that greatly helps preserve low switching loss. Experimentally, we demonstrate such a switch fabric with an on-chip loss of less than 5 dB and low crosstalk levels below -40 dB.

2. Switch design and assembly

Figure 1(a) illustrates the schematic of the 8×8 switch design, which utilizes a DLN topology with 64 switch cells in total. Single-stage MZIs are employed as 1×2 and 2×1 path selectors in outer banks, while 2×2 dual-stage MZI cells are placed in the central section, as outlined in the insets. Broadband multimode interferometers (MMIs) are utilized as 3dB couplers to form balanced MZIs for large operational bandwidth. For the dual-stage cells, the first MZI simply serves as an active power adjuster to correct any splitting-ratio errors, thereby mitigating the first-order crosstalk with high extinction ratio. All MZI cells are equipped with a pair of 300 µm-long metal heaters at the back-end for thermal phase tuning. Phase shifters are air-trenched to improve thermal isolation. The device is optimized for TE mode and designed to operate in the C band.

Figure 1(b) shows a photograph of the switch chip fabricated via AMF's silicon photonic multi-project wafer (MPW) run [6], in a footprint of 7.3×5.9 mm^2. Two sets of fiber arrays are used to couple light into and out of the chip via two facets, with a coupling loss of ~ 3 dB per facet. This could be improved by using optical fibers with mode diameters better matched to the Si waveguides. Electrical pads are wire-bonded to customized PCB boards for electrical signal fan-out. Figure 1(c) shows the packaged 8×8 switch device affixed to a copper substrate.

3. Experimental testing and results

An automatic electrical control plane is developed to drive the optical switch fabric that a series of digital-to-analog converter (DAC) codes are first imposed from computer to a microcontroller (STM32), which are subsequently passed to two 40-channel 16-bit DAC boards using serial peripheral interface (SPI). The generated voltages from the DACs are amplified by a driving circuit and drive the TO phase shifters.

Figure 2(a) depicts the experimental setup for the switch calibration and characterization. A C-band tunable laser

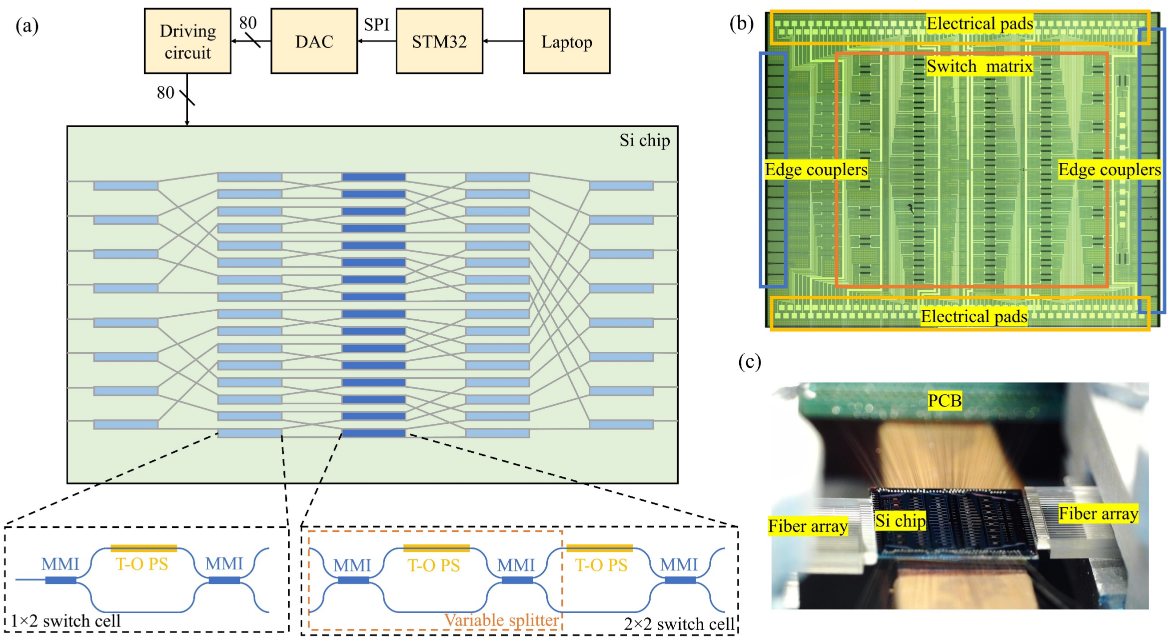
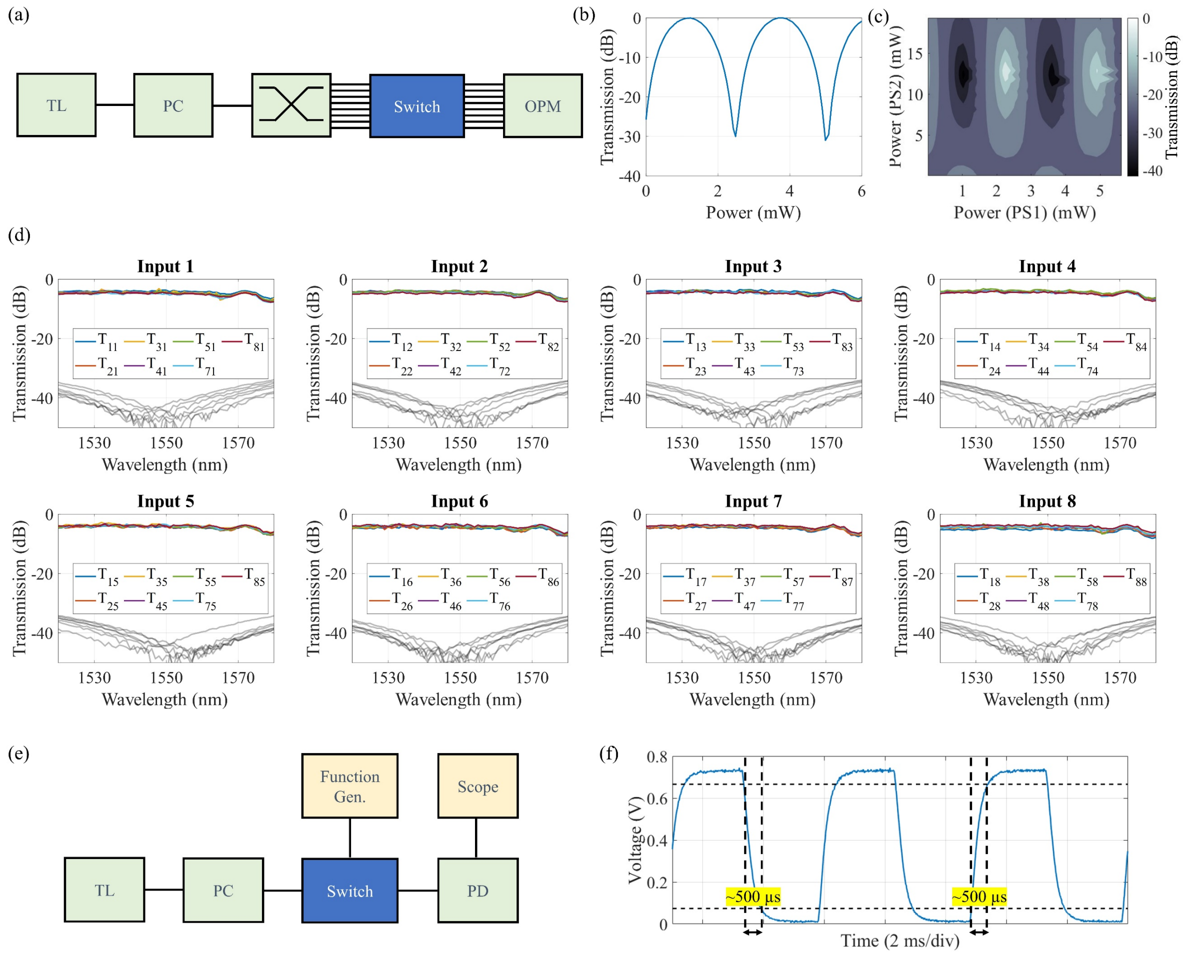


Fig. 1. (a) Schematic of our 8×8 silicon photonic switch fabric. The insets show the electrical control scheme, and the 1×2 single- and 2×2 dual-stage MZI cells. (b) Microscope image of the fabricated switch. (c) Image of the packaged switch chip, which is wire-bonded to customized PCB boards and edge coupled using fiber arrays.

(TL), with its output power set to 0 dBm, is used as the input, while the output signals are collected by an 8-channel optical power meter (OPM). Each MZI cell is calibrated by tuning its phase shifters with the output power collected from corresponded ports monitored to determine its cross and bar states. Note that the calibration of the central dual-stage MZI cells demands a fine-tuning of two sets of bias voltages. Instead of performing a time-consuming two-dimensional sweeping, we employ the Nelder-Mead algorithm to identify the optimal bias voltages [7]. Figure 2(b-c) shows the measured optical power as a function of driving voltages for a representative 1×2 MZI cell and a 2×2 dual-stage MZI cell, respectively. It can be seen that the single MZI element exhibits an extinction ratio of around 30 dB. Owing to the partial dilated arrangement, the first-order leakage is effectively mitigated, thereby only resulting in a second-order crosstalk below -50 dB. Being positioned in the central section, the dual-stage MZI shows a superior extinction ratio exceeding 40 dB. This however bounds the circuit-level performance, the MZI is traversed by two signals at once, i.e., experiencing first-order crosstalk. Subsequently, calibrated bias voltages are cataloged into a look-up table for different path configurations. Figure 2(d) shows detailed spectral characteristics for all measured optical paths within a wavelength window from 1520 nm to 1580 nm. The colored lines highlight the transmission from each input port to all intended output ports, while the grey lines represent the crosstalk leaked to other outputs. Note that the transmission to O6 is absent due to a malfunctioning heater on its paths. Low on-chip propagation losses in between 4 to 5 dB are observed for all optical paths. The slight variations arise from the differences in path length and the number of waveguide crossings. Crosstalk leakage to other ports is below -40 dB at the central wavelength, remains under -35 dB across a >15 nm bandwidth and is consistently less than -30 dB throughout the entire C-band.

Figure 2(e) shows the experimental configuration for transient characterization. Here, a function generator is adopted to produce a 0.2 kHz square wave signal, which modulates the phase shifters to enable dynamic path switching. The time-traced output signal is detected by a photodiode and captured by an oscilloscope. Figure 2(f) shows the transient measurement, with both the rise and fall time being approximate 500 µs. This prolonged switching time, relative to other thermo-optic switches [8], is attributed to the air trenches surrounding the TO phase shifters. While these trenches enhance the power efficiency — requiring only 2 mW to achieve a π phase shift, as illustrated in Fig. 2(b) — but they compromise the waveguide's thermal conduction. Hence, the switching speed can be readily improved, though at the expense of reduced power efficiency.



TL = tunable laser; PC = polarization controller; OPM = optical power meter; PD = photodiode

Fig. 2. (a) Experimental setup for the switch calibration and spectral characterization. (b-c) Normalized transmission vs. driving power measured at 1550 nm for a 1×2 MZI cell, and a 2×2 dual-stage MZI cell, respectively. (d) Normalized switch spectra for all 8×8 IO paths. (e) Setup for the switch transient characterization. (f) Measured transient of path I1→O1 when modulated by a 0.2 kHz square wave.

4. Conclusion

In this article, we present a strictly non-blocking 8×8 silicon switch fabric in the double-layer network topology. Dual-stage MZI cells are employed as a central stage that effectively mitigate the first-order crosstalk. Experimentally, our switch demonstrates a <5 dB on-chip loss with a low crosstalk ratio below -40 dB.

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