Silicon 4×4×8λ space-and-wavelength selective optical switch with resonant phase shifters

Rui Ma[1], Lingzhi Luo[1], Tongyun Li[1], Chunhui Yao[1], Jing Zhang[2], Minjia Chen[1], Peng Bao[1], Günther Roelkens[2], Richard Penty[1], Qixiang Cheng[1,*]

[1]*Electrical Engineering Division, Department of Engineering, University of Cambridge, Cambridge CB3 0FA, U.K*
[2]*Department of Information Technology (INTEC), Photonics Research Group, Ghent University-imec, 9052 Ghent, Belgium*
**Author e-mail address: qc223@cam.ac.uk*

Abstract: A silicon 4×4×8λ space-and-wavelength selective optical switch in a modified dilated Banyan topology is demonstrated with Mach–Zehnder interferometers and resonant phase shifters. All 128 routing channels exhibit >30dB extinction ratio and > 60GHz passband.

1. Introduction

The exponential growth of cloud computing, machine learning (ML), and artificial intelligence (AI) has significantly increased demand for data, computational power, and storage resources, necessitating datacenter networks to efficiently manage massive data volumes [1, 2]. Meeting such demand hinges on the development of advanced switching networks, with bandwidth requirements projected to exceed 100 Tbps by 2024 [3]. Optical switches, leveraging the inherent advantages of optical communication, such as ultra-high bandwidth, low latency, and energy efficiency—offer a promising path forward [4]. They can effectively alleviate the performance bottlenecks associated with conventional electronic interconnects, while enabling efficient data transmission across multiple wavelengths and spatial paths simultaneously. Specifically, space-and-wavelength reconfigurable optical switches are critical for communication networks utilizing wavelength division multiplexing (WDM) schemes, as they allow for selective routing of arbitrary optical signals based both spatially and spectrally [5]. However, scaling these switches presents considerable challenges, particularly in replicating switching planes while managing complexity and minimizing the footprint of integrated subsystems [2].

In this paper, we present a silicon 4×4×8λ space-and-wavelength selective optical switch in a modified dilated Banyan topology, where 8 wavelength channels are independently controlled through thermal tuning of microring-based resonant phase shifters. This design combines the high tuning efficiency and wavelength selectivity of microring resonators (MRRs) with the broad bandwidth and stability of Mach-Zender interferometers (MZIs), positioning it as a promising solution for high-performance, multi-dimensional switching networks [6]. Figure 1(a) illustrates the switch schematic, featuring 4 input and 4 output ports as well as 8 routing wavelengths, allowing a total of 128 optical routing paths. The modified dilated Banyan architecture is employed to reduce the in-band crosstalk, while the signal fan-out and fan-in are achieved by 2×2×8λ switch elements (SEs) and passive combiners, respectively. This configuration greatly simplifies control circuitry and packaging, making it suitable for large-scale, high-density datacenter interconnects.

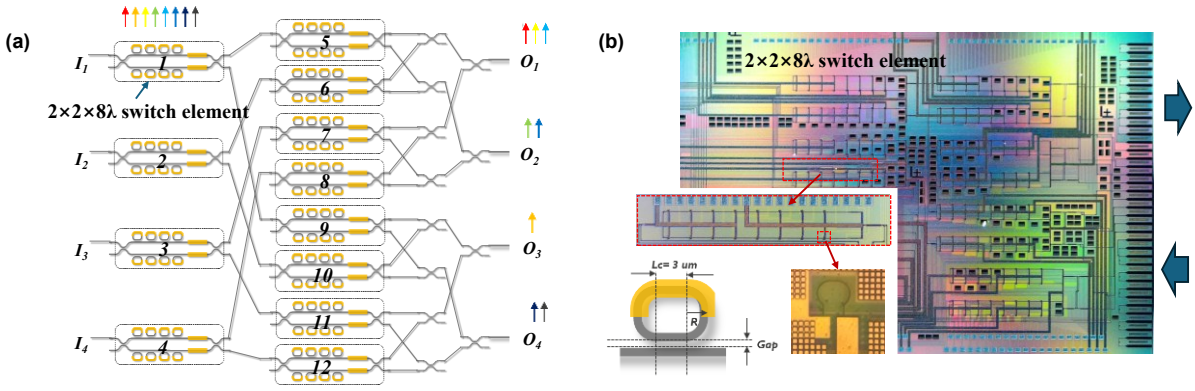

Fig. 1. (a) Schematic of a photonic switch connecting various electronic resources. (b) Microscope image of the 4×4×8λ switch fabric, a 2×2×8λ switch SE and a MRR.

2. Design and fabrication

Figure 1(b) presents the microscope image of the fabricated 4×4×8λ switch, consisting of twelve 2×2×2λ SEs. It was fabricated through a Multi-Project-Wafer (MPW) run using a commercial silicon-on-insulator (SOI) platform provided by IMEC. The switch has a compact footprint of <32 mm², including electrical pads. The 200 μm spacing between adjacent MRRs minimizes thermal crosstalk. The inset in Figure 1(b) displays a microscope image of a 2×2×2λ SE, which consists of a symmetric MZI and 8 pairs of over-coupled MRRs, enabling the simultaneous switching of 8 wavelength channels. These over-coupled MRRs act as highly efficient, compact, narrowband phase shifters, with each pair capable of differential operation to create symmetric passbands that define specific wavelength channels. The on-off state of each wavelength channel is controlled by thermally tuning the MRR pairs. When driven in a push-pull configuration, optical switching is achieved with excellent extinction ratio, bandwidth, and enhanced manufacturing tolerance.

We have proposed an analytical method to evaluate the SE performance using a transmission circle chart, as detailed in [7]. Based on this model, the MRRs have a racetrack shape with a 6 μm radius and a 3 μm coupling section, optimized to filter eight wavelength channels with 200 GHz spacing in the O-band. The MRRs achieve over 25 dB ER, over 50 GHz bandwidth, and a 1.5 dB insertion loss (IL). The gap between the MRR and bus waveguide is 150 nm to maintain over-coupling conditions. To route a wavelength channel from an input port to a target output port, the two 2×2×8λ switch elements at the first and second stage of the switch fabric should be well-controlled. For example, to allocate wavelength channel 1 from port I_1 to port O_1, one MRR in the MRR pair at SE 1 and SE 5 should be red-shifted, while the other is blue-shifted, creating a -π phase difference between the MZI arms at that wavelength. A phase bias of π/2 should also be added in one arm of the MZI at both SE 1 and SE 5. Similarly, if we want to allocate wavelength channel 1 from port I_1 to port O_3, a π phase shift should be applied at SE 1, and a -π phase difference between the two MRRs at SE 9 should also be introduced.

3. Results and analysis

The switch chip is electrically wire-bonded to a customized PCB board, and optically aligned to an O-band tunable laser source at the input ports and a photodiode at the output ports via edge-coupled fiber arrays. The switch features a total of 192 MRRs and 12 phase shifters, all controlled by a 16-bit high-resolution digital-to-analog converter to apply the necessary bias voltages.

The measured optical power maps are shown in Figure 2, indicating the insertion loss (IR) and crosstalk leakage of sixteen routing paths (port I_1 – I_4 to port O_1 - O_4) for eight wavelength channels. The IR values are represented by colored triangles and the crosstalk leakage values are represented by colored squares. The IL is around 10 dB from all the MRR pairs, 2×2 MMIs and waveguide crossings. The nearly 2 dB IL variation among different port pairs are attributed to fabrication deviation of MRRs and different numbers of waveguide crossings on different route paths.

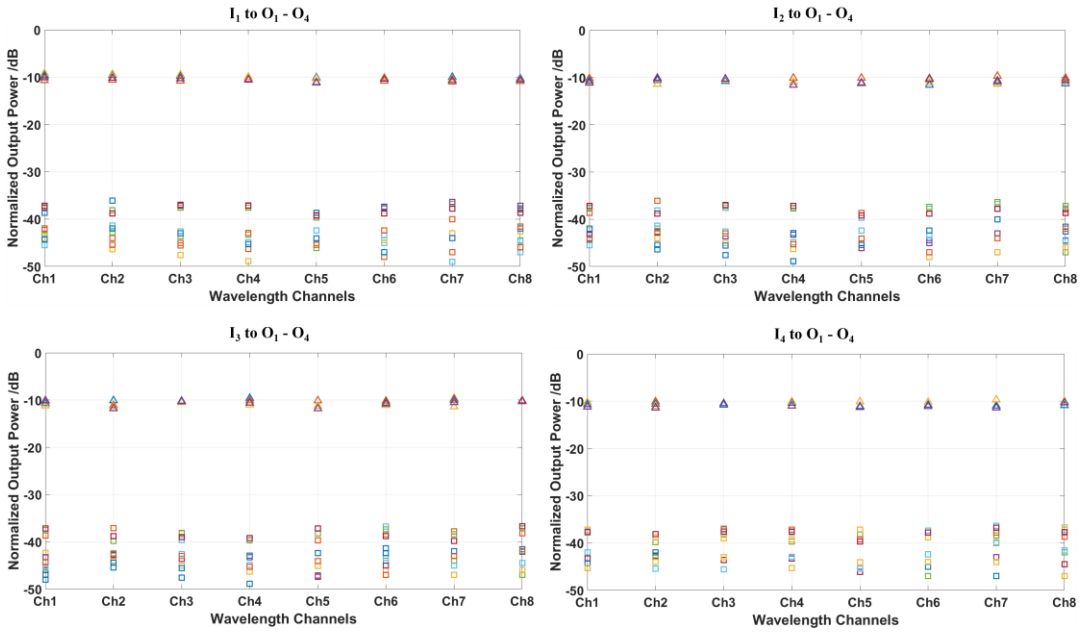

Fig. 2. Measured optical power map of the optical switch for the 8 wavelength channels.

The measured crosstalk ranges between −36 dB and −49.0 dB. This crosstalk variation is caused by the imperfect tuning of the MRR pairs for different route paths, due to the limited resolution of DACs in the customized control board. The crosstalk can thus be further reduced by optimizing the applied voltage to the MRRs and phase shifters using an optimization algorithm

To showcase the independent controlling of each wavelength channel, a routing path from port I_1 to port O_1 is evaluated with signals in eight wavelength channels. Figure 3(a) shows the transmission spectra of this path when eight wavelength channels are tuned to the on-state. Each adjacent channel has a spacing of 200 GHz at O band. All these channels show an extinction ratio (ER) of over 30 dB. Figure 3(b) shows the ability to allocate any wavelength channel independently. Channels 2, 5 and 6 are routed to port O_2 while the other channels remain at port O_1. The measured crosstalk at channels 2, 5 and 6 are 31 dB, 28 dB and 25 dB, respectively. The spectrum for all paths across the eight channels are superimposed, as shown in Figure 3(c). The measured 3dB bandwidth of all the channels is over 60 GHz at a central frequency of 230.6 THz (1300 nm).

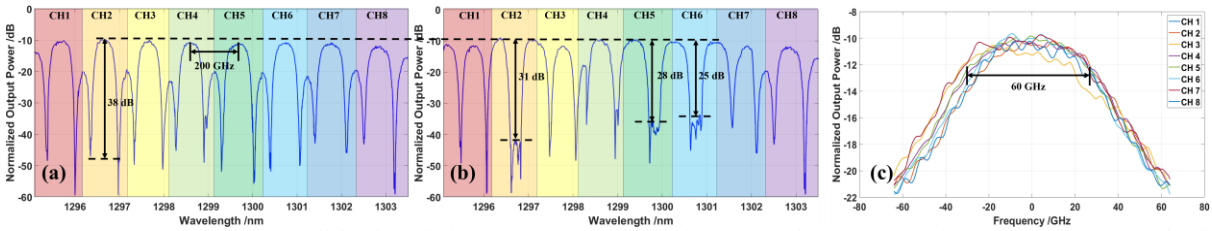

Fig. 3. (a) Transmission spectra of all the channels from I_1 to O_1. (b) Transmission spectra of CH1, 3, 4, 7 ,8 from port I_1 to O_1. (c) Passband of all the 8 channels.

4. Conclusion

In this work, we demonstrate a silicon 4×4×8λ photonic switch fabric in a modified dilated Banyan topology, incorporating Mach-Zehnder interferometers and resonant phase shifters. The core building block of this switch fabric is the 2×2×8λ switch element, where 8 over-coupled MRR phase shifters are integrated into each arm of the MZI to enable independent control of multiple wavelength channels.

The switch has been experimentally demonstrated to independently route 8 distinct wavelengths, achieving an extinction ratio exceeding 30 dB and a passband over 60 GHz in all routing channels. With its compact footprint, high performance, and efficient control of wavelength channels, this design is poised to be a key component in advancing multistage space-and-wavelength selective optical switching for future data center networks.

Acknowledgements

This work was funded by the UKRI-EPSRC, project QUDOS (EP/T028475/1); and the European Union's Horizon Europe Research and Innovation Program, project PUNCH (101070560); and the European Union's Horizon Europe Research and Innovation Program, project INSPIRE (101017088).

References

[1] S. J. Ben Yoo, "Prospects and challenges of photonic switching in data centers and computing systems," Journal of Lightwave Technology, 40.8, 2214–2243 (2021).

[2] Qixiang Cheng, "Recent ad-vances in optical technologies for data centers: a review," Optica, 5.11, 1354-1370 (2018).

[3] Qixiang Cheng, "Photonic switch fabrics in data center/high-performance computing networks," Integrated Photonics for Data Communication Applications. Elsevier, 265-301 (2023)

[4] Xiaojun Chen, "A Review of SiliconBased Integrated Optical Switches," Laser & Photonics Rev., 17.4, 2200571 (2023).

[5] Kazuhiro Iked, "Large-Scale and Multiband Silicon Photonics Wave-length Cross-Connect Switch With FSR-Free Grating-Assisted Contra-Directional Couplers." Journal of Light-wave Technology, 42.12, 4310-4316 (2024).

[6] Yishen Huang, "Push—pull microring-assisted space-and-wavelength selective switch," Optics Letters, 45.10, 2696-2699, (2020).

[7] Lingzhi Luo, "Unlocking Electro-optic Resonant Phase Shifting for Multi-dimensional, Ultra-dynamic Photonic Switches," arXiv preprint arXiv:2403.02866 (2024).