Cascaded active silicon microresonator array cross-connect circuits for WDM networks-on-chip
(invited)

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ABSTRACT

We propose a design of an optical switch on a silicon chip comprising a $5 \times 5$ array of cascaded waveguide-crossing-coupled microring resonator-based switches for photonic networks-on-chip applications. We adopt our recently demonstrated design of multimode-interference (MMI)-based wire waveguide crossings, instead of conventional plain waveguide crossings, for the merits of low loss and low crosstalk. The microring resonator is integrated with a lateral p-i-n diode for carrier-injection-based GHz-speed on-off switching. All 25 microring resonators are assumed to be identical within a relatively wide resonance line width. The optical circuit switch can employ a single wavelength channel or multiple wavelength channels that are spaced by the microring resonator free spectral range. We analyze the potential performance of the proposed photonic network in terms of (i) light path cross-connections loss budget, and (ii) DC on-off power consumption for establishing a light path. As a proof-of-concept, our initial experiments on cascaded passive silicon MMI-crossing-coupled microring resonators demonstrate 3.6-Gbit/s non-return-to-zero data transmissions at on- and off-resonance wavelengths.

Keywords: silicon photonics, microresonators, microring, networks-on-chip, optical switch, optical interconnect, waveguide crossings

1. INTRODUCTION

With the technology trend in parallel computing using an increasing number of computational cores on a single computer chip, on-chip interconnections with low-power consumption, high-data-rate, and low-latency are imperative for next-generation high-performance multi-core computer chips$^{1,2}$. Although packet-switched electrical interconnections based on conventional topologies have been proposed and implemented for multi-core data communications$^3$, it is well known that the traditional electrical interconnections impose severe limitations such as high-power consumption with the accompanied thermal issues, and electrical-limited data bandwidth$^4$. As an alternative approach to on-chip interconnections, researchers have long proposed optical interconnections$^5$$^7$. The key merits of the optical approach using integrated waveguides and photonic devices include low-power consumption for the signal transmission, and a large data bandwidth carried by an optical channel. Furthermore, ultra-high-bandwidth data transmission can be attained using wavelength-division-multiplexing (WDM) technology$^8$, with each photonic message split and carried by multiple wavelength channels of only moderate data rate. However, unlike electrical interconnections, there is yet no practical on-chip photonic buffer that enables photonic packet-switching as in the fiber-optic networks. Thus, this is likely to limit the on-chip photonic data transmission to an end-to-end transmission once the light path is established without buffering. Though such approach may not be desirable as a packet-switch, optical interconnections with the key merits of low-power consumption and low latency independent on the data rate$^9$$^{10}$ is still technology appealing as an optical circuit-switch.

In this respect, photonic networks-on-chip (NoC) using silicon photonics offers a potential alternative interconnection
technology that is compatible with complementary metal-oxide-semiconductor (CMOS) process. Over the past few years, a myriad of passive and active silicon photonic devices have been demonstrated as potential building blocks for photonic NoC applications. Notably, for low-loss transmission, IBM group reported silicon wire optical waveguides with propagation loss down to ~1.7 dB/cm. For high-speed data modulation, Cornell group pioneered GHz-speed carrier-injection-based silicon microring modulators (with the latest demonstration up to 12.5 Gbit/s data rate). Moreover, Luxtera group reported high-speed silicon modulators with data rate up to 10 Gbit/s using a depletion type silicon microring modulator. For on-chip optical detection, L. Scharas et al. (IBM) demonstrated highly efficient SiGe-based photodetectors. Besides, for potentially on-chip light sources, Intel group demonstrated low-threshold continuous-wave silicon Raman lasers, and in collaboration with UCSB group demonstrated III-V-on-silicon evanescent lasers. Previously, our research group also demonstrated various microresonator-based and waveguide-based devices on a silicon chip including microring resonator coupled waveguide crossing-based cross-connect filters using conventional wire waveguide crossings and multimode-interference (MMI)-based wire waveguide crossings, carrier-injection-based silicon microdisk modulators, and microring modulators, and reconfigurable microring resonator-based filters using coherent interference of optical resonances.

Here, we propose an optical circuit-switch on a silicon chip comprising a 5 × 5 waveguide cross-grid array side-coupled with an array of carrier-injection-based microring resonator switches, targeting a single wavelength channel data rate of 10 Gbit/s. We mitigate the waveguide crossing insertion loss and crosstalk using MMI-based wire waveguide crossings. As a proof-of-concept, we experimentally study the high-speed data transmission in a cascaded passive microring-crossings structure. We estimate the loss budget of the proposed switch, and outline design issues and potential mitigations. We envision that our proposed architecture can be a meaningful step toward optical interconnections between multiple cores on a computer chip.

2. PHOTONIC NETWORK ARCHITECTURE

A passive photonic NoC can be realized by using fixed wavelength assignment and dynamic time-slot pre-allocation. However, such passive photonic networks impose complicated designs and offer poor scalability. For large-scale-integrated photonic circuits, a photonic switching NoC should be more desirable. One way to design such photonic NoC in a compact footprint, as suggested by K. Bergman’s group, is to employ high-speed silicon microring-based switching elements as building blocks. Indeed, microring arrays have long attracted research interests to realizing multiple-port filters and switches on a chip due to their compact size and the microring resonator high-Q resonances. Here, we propose 5 × 5 silicon microring resonator-based switching elements as building blocks for a photonic mesh NoC. The 5 × 5 array configuration comprising 5 optical input-ports and 5 optical output-ports is particularly relevant for optical interconnections on a multi-core computer chip, as the array enables each processing node to communicate with other processing nodes in North, South, West, and East directions in an optical cross-grid network via submicrometer-sized silicon wire waveguides.

Figure 1(a) schematically illustrates a two-dimensional (2-D) mesh NoC connecting 16 cores on a single chip. The switching elements in this photonic network are controlled by an electronic network. This design is favorable for transmitting high-bandwidth data in an end-to-end fashion as in a circuit-switch once the light path is established upon an electronic control signal.

Figure 1(b) shows our initial design of a 5 × 5 nonblocking switch node comprising a 5 × 5 array of cross-connected identical microring resonators working at the same wavelength channel. This nonblocking switch node can be controlled by a simple routing algorithm, which enables arbitrary one-to-one interconnection of any of the five input-ports to any of the five output-ports without contention. The connecting input-ports in the four directions are labeled as Iwest, Inorth, Ieast, and Isouth. Whereas the corresponding output-ports are labeled as Owest, Oeast, Onorth, and Osouth. Icenter and Ocenter denote local connecting ports for the core which connects to a modulator and a receiver as the electrical-optical (EO) interface (see Fig. 1(a)).
By operating with only a single wavelength channel that is at an off-resonance wavelength of the identical microring resonators, a signal transmission path between any input-port and any output-port can be established by switching on only one microring resonator at the intersection between the corresponding horizontal and vertical waveguides. Each data path only takes a single 90° turn. We note that full-duplex communications between I/O ports in different directions (e.g. I_{west}-to-O_{south} and I_{north}-to-O_{west}) are possible via different waveguide pathways that do not crossover, albeit the path loss can differ due to the different numbers of crossings in the data paths (e.g. see blue dashed arrows in Fig.1(b)). Besides, different data paths that crossover at a single grid point can be simultaneously established (e.g. I_{center}-to-O_{east} and I_{north}-to-O_{center}), yet with the tradeoff of possible signal crosstalk induced interference between the two data paths. Keen observer may also find our proposed 5 × 5 switch node configuration (Fig. 1(b)) only represents a general layout and does not explicitly suggest the physical layout for actual interconnection in a 2-D mesh network. It is however entirely possible to reconfigure the 20 available waveguide ports for realistic physical connection. Figure 1(c) illustrates one possible configuration.

Fig.1 (a) Conceptual illustration of a 2-D photonic mesh network-on-chip architecture for a multi-core computing system based on a cross-connect switch array. (b) Schematic of the proposed cross-connect switch node. This 5 × 5 nonblocking switch node comprises 25 identical microring resonator-based switches operating at the same wavelength channel. Only one microring resonator-based switch is switched on for establishing a single light path. The dashed arrows illustrate possible light paths connecting different input-ports to different output-ports. The thin arrows denote possible crosstalk paths due to light scattering at the crossing junction. I: input, O: output. (c) Schematic of a cross-connect switch node with the I/O ports configured for practical port connections in a 2-D photonic mesh network.

Photonic NoC that comprises physically crossed waveguides favor scalability and network design simplicity. Besides, a monolithic waveguide crossing structure can be preferred to a three-dimensional vertically-coupled waveguide crossing structure in multiple layers for the ease of simple fabrication without multi-layer alignment. However, the conventional high-index-contrast silicon submicrometer wire waveguide crossing is known to introduce extra insertion loss and crosstalk due to light scattering at the waveguide intersection. The typical silicon submicrometer wire waveguide crossing imposes ~1 dB insertion loss and exceeding 20-dB crosstalk in the intersecting waveguide, thus limiting the utilization of conventional waveguide crossings in photonic circuits. In light of this, we adopt our recently demonstrated MMI-based wire waveguide crossings in this 5 × 5 switch node in order to mitigate the crossing insertion loss and crosstalk.

3. SILICON MICRORING ELECTRO-OPTIC CROSS-CONNECT SWITCH

Here, we analyze the single cross-connect switch comprising a silicon microring resonator-based switch coupled with a MMI-based wire waveguide crossing. We assume carrier-injection-based switching mechanism based on our recent work and others in the literature. We analyze the cross-connect performance in terms of its switching speed,
DC power consumption, and the waveform distortion. We also reveal our initial measurements of cascaded passive silicon microring resonator-based cross-connect filters.

3.1 Principle and design

The waveguide crossing performance is significantly improved using our designed MMI-based crossing. The self-image property of multimode interference in the crossing center reduces the crossing insertion loss and crosstalk\textsuperscript{25}. Our previous experiment\textsuperscript{25} demonstrated that the MMI-based crossing with 0.35 $\mu$m bus waveguide on a SOI substrate exhibited $\sim$0.4 dB insertion loss per crossing and low crosstalk, while the controlled wire waveguide crossing exhibited exceeding 1 dB insertion loss per crossing. Figure 2(b) shows the 2-D finite-difference time-domain (FDTD) simulated throughput-port transmission spectrum and crosstalk of a MMI-based crossing, suggesting broadband insertion loss of $\sim$0.12 dB per crossing and crosstalk below -40 dB. We assume a MMI waveguide width of 1.1 $\mu$m and length of 4.3 $\mu$m. With a tapered waveguide of $\sim$3-$\mu$m length in between the bus waveguide of 0.4-$\mu$m width and the MMI waveguide, the crossing enables side-coupling with a 12-$\mu$m-diameter microring resonator, giving an overall footprint on the order of 100 $\mu$m$^2$ for a single MMI crossing-based switch.

![Fig. 2](image)

Fig. 2 (a) Schematic of a silicon MMI-based waveguide crossing-coupled microring resonator switch. The microring is integrated with a lateral p-i-n diode. $V_d$: driving voltage across the p-i-n diode. Inset: switching scheme at a signal wavelength $\lambda_0$. Solid line: “off” state transmission spectrum at port T. Dotted line: “on” state transmission spectrum at port T. (b) 2-D FDTD simulated transmission spectrum (red line) and crosstalk (blue line) of the MMI-based crossing with bus waveguide width of 0.4 $\mu$m, MMI waveguide width $W_m = 1.1$ $\mu$m, MMI length $L_m = 4.3$ $\mu$m, tapered waveguide length $L_t = 3$ $\mu$m, for light wavelengths around 1550 nm.

T: Throughput, C: Crosstalk

Figure 2(a) illustrates the schematic of the single microring resonator-based cross-connect switch with an integrated lateral p-i-n diode surrounding almost the entire microring resonator. The inset depicts the device principle. We set the signal wavelength $\lambda_0$ corresponding to an off-resonance wavelength of the microring resonator at off-state ($V_d = 0$ V), and to the carrier-dispersion-induced blueshifted resonance wavelength of the microring resonator at on-state (upon a fixed forward $V_d$). Thus, the optical signal at $\lambda_0$ launched from port I of the horizontal waveguide is transmitted to the throughput-port T at the off-state, and is routed to the vertical drop-port D at the on-state.

Compared with other known approaches to inducing carrier dispersion effect (i.e. carrier accumulation by a MOS capacitor\textsuperscript{32} and carrier depletion by a reverse-biased pn diode\textsuperscript{18}), forward-biased p-i-n diodes have the advantage of providing relatively large effective refractive index change in the silicon waveguide by spatially overlapping the injected carriers with the mode field. Given the submicrometer-sized microring waveguide cross-section, the carrier injection time can be on the order of sub-ns, enabling a data path to be quickly established with minimum latency. By the same token, the injected carriers need to be swept out by reverse biasing the diode in order to quickly take off a data path without imposing latency. Based on the recent advances in GHz-speed carrier-injection-based silicon microring modulators\textsuperscript{20, 26, 33}, it should be totally feasible to attain GHz-speed circuit-switching upon a peak-to-peak voltage of a few volts. The driving voltage also depends on the microring resonance Q-factor. Higher-Q resonance requires lower
injected carrier concentration change, thus lower applied voltage and potentially faster optical tuning speed (assuming the cavity lifetime is shorter than free carrier transit time). For resonance Q of $\sim 10^4$, we see that a minimum resonance wavelength shift for switching is $\sim 0.15$ nm in the 1550 nm wavelengths, requiring carrier injection of $\sim 1 \times 10^{17}$ cm$^{-3}$ (assuming only ¼ of the microring is integrated with the p-i-n diode). Such free carrier concentration change only requires a forward bias voltage near the diode threshold (below 1 V). The diode current for a 12-μm-diameter microring is only on the order of 10 μA, indicating a low DC power consumption in order to establish a data path. Our previous experimental work$^{17}$ indicated a DC switching power of $\sim 20$ μW. We note that a switching time on the order of sub-ns for a microring resonance Q of $\sim 10^4$ should be entirely feasible with the micrometer-sized p-i-n diode design assumed above.

3.2 Single microring cross-connect filter line shape and bandwidth

![Fig. 3](image)

Fig. 3 (a) (b) FDTD-simulated TE-polarized throughput- and drop-port transmission spectra for (a) MMI-based crossing-, and (b) plain crossing-coupled microring resonator with radius of 6.5 μm and bus waveguide of 0.3 μm. (c) and (d) FDTD-simulated mode-field patterns of our MMI-based crossing-coupled microring resonator for input light at (c) off-resonance wavelength, and (d) on-resonance wavelength. Inset of (d): zoom-in view of the mode-field pattern in the MMI crossing region. The self-image property in the crossing center reduces the light scattering in the junction.

Figures 3(a) and (b) show the FDTD-simulated throughput- and drop-port transmission spectra of the MMI-based crossing filter and the plain crossing filter. The MMI-based crossing filter exhibits symmetric resonance line shapes, whereas the plain crossing filter displays asymmetric Fano resonance line shapes. We reason that the symmetric resonance line shape is more desirable than the asymmetric line shape for interconnections. Figures 3(c) and (d) show the FDTD-simulated mode-field patterns of the MMI-based crossing filter at off- and on-resonance wavelengths. The self-image in the crossing center suppresses the light power leakage to the horizontal waveguide through the junction. Thus, the self-image reduces the Fano-type interference between the resonant drop-port transmission and the coherent background crosstalk from the self-channel leakage, resulting in the desirable symmetric resonance line shape$^{34}$ (Fig. 3(a)).

The ideal switch should have a broadband switching feature in order to route the optical signal without severe waveform distortion. The high-Q resonance of a microresonator tends to distort the non-return-to-zero (NRZ) optical signal data.
waveform in high-bandwidth systems due to the nonuniform attenuation of the narrow-band microresonator-based filter\textsuperscript{32}. In light of this, we may need to tailor the passband of microresonators\textsuperscript{36} that are sufficiently wide-band in order to minimize the waveform distortion. Nonetheless, the tradeoff is that a higher injection current is imposed in order to blueshift the wide-band resonance for establishing a data path, and thereby increasing the DC power consumption and consequently the heat load.

Previously, our research group also studied the filtered waveform but only in the throughput-port transmission of a narrow-band notch filter, in the context of all-optical NRZ-to-pseudo RZ (PRZ) data format conversion\textsuperscript{31}. Here, we use the same modeling method (based on linear filtering) in Ref.[31] to model the transmitted waveform in the throughput-port for a 10-Gbit/s NRZ optical pulse at a resonance wavelength, also assuming a notch filter response with a single bus waveguide coupling and a resonance extinction ratio of 30 dB. Figure 4 illustrates the input 10-Gbit/s NRZ signal (assuming a rise- and fall-time of 5 ps) and the modeled transmitted waveform in the throughput-port assuming a resonance Q-factor of 10\textsuperscript{3}, 5 \times 10\textsuperscript{3}, and 10\textsuperscript{4}. We see that for 10-Gbit/s data rate optical signal transmission, a relatively broadband filter with a resonance Q-factor on the order of 10\textsuperscript{3} should be desirable in order to minimize the modulation sideband transmission in the throughput (and also minimize the waveform distortion in the drop-port). Nonetheless, it should be emphasized that as our cross-connect array only uses the drop-port transmissions, the PRZ waveforms in the throughput transmission may only be viewed as part of the cross-connect filter characteristics but does not incur channel crosstalks.

### 3.3 Cascaded passive microring resonator array cross-connect filters

As a proof-of-concept, we experimentally study the transmission spectra and the NRZ waveform distortion of the passive MMI-based coupled microring cross-connect filter in a 2 × 2 filter array\textsuperscript{37}. Figure 5(a) shows the scanning electron micrograph of our fabricated device on a SOI substrate. We adopt square-shaped microring resonators with straight waveguide sections for enhanced side-coupling with the wire waveguides, and four 90\textdegree-bends. Microrings R\textsubscript{1} and R\textsubscript{2} are designed to be identical with a 90\textdegree-bend radii r\textsubscript{1} and r\textsubscript{2} of 20 µm, whereas microring R\textsubscript{3} is designed to be slightly larger with a 90\textdegree-bend radius r\textsubscript{3} of 20.3 µm. Figure 5(b) shows our measured TE-polarized (electric field parallel to the chip) throughput-port transmission spectrum when the light is launched from input-port I\textsubscript{1} and through two MMI-based crossings. We discern two sets of resonances, labeled as A and B. We observe a high extinction ratio of ~20 dB for resonance A and a low extinction ratio of ~8 dB for resonance B, while both display a relatively high Q-factor of ~12,000. Figure 5(c) shows the correspondingly measured drop-port transmission spectra at port-D\textsubscript{11} after two crossings and port-D\textsubscript{12} after three crossings. We identify resonance A to microring R\textsubscript{1} and resonance B to microring R\textsubscript{3}. Due to fabrication imperfections, microrings R\textsubscript{1} and R\textsubscript{2} turn out to be slightly mismatched in size, and thus transmission at port-D\textsubscript{11} only suggests a first-order filter response. It is worth mentioning that in our previous work\textsuperscript{37}, we observed cascaded coupled-microring filter transmissions from a different device but of the same design as the light was routed through the identical microresonators R\textsubscript{1} and R\textsubscript{2}.
Fig. 5 (a) Scanning electron micrograph of our fabricated MMI-based microring cross-connect filter array [37]. (b) Measured throughput-port transmission spectrum at port-T₁ when the light is launched from port-I₁. (c) Measured drop-port transmission spectra from port-D₁₁ (blue line) and port-D₁₂ (pink line) when the light is launched from port-I₁.

Figures 6 show the measured 3.6-Gbit/s NRZ signal transmission waveforms and their corresponding eye diagrams at an off-resonance wavelength and at resonances A and B. Figure 6(a) shows that the throughput-port transmission waveform at an off-resonance wavelength follows the input NRZ signal. Figure 6(b) shows the throughput-port transmission waveform at resonance A. As mentioned above (Fig. 4), the narrowband resonance throughput transmission yields an undesirable waveform of PRZ pulses corresponding to the NRZ signal transition edges. Figures 6(c) and (d) show the measured drop-port transmission waveforms at resonances A and B. In both cases, we see only marginally distorted NRZ waveforms compared with the off-resonance throughput. Figures 6(e) and (f) show the measured open eye diagrams. We remark that the noise fluctuations observed are due to the amplified spontaneous emission noise from our erbium-doped fiber-amplifiers in the experimental setup.

Fig. 6 Measured transmissions of a 3.6-Gbit/s NRZ waveform and the corresponding eye diagrams (PRBS 2^{15}-1). (a) Throughput-port transmission of an off-resonance carrier wavelength \( \lambda_{\text{off}} \) (~1542.0 nm); (b) Throughput-port transmission at resonance A (~1552.2 nm); (c) Drop-port transmission at resonance A; (d) Drop-port transmission at resonance B (~1552.6 nm); (e) Eye diagram of drop-port transmission at resonance A; (f) Eye diagram of drop-port transmission at resonance B.

4. CONCLUSIONS AND OUTLOOK

In summary, we have presented our initial study on our proposed silicon photonic switch node using cascaded waveguide crossing-coupled microring resonator-based switches in a 5 × 5 waveguide cross-grid array. The simple design of utilizing only one-way cross-connections between an input-port and an output-port, and independent waveguide
pathways for building a data path, should favor interconnections in a 2-D mesh network among multiple cores. For establishing a light path in a single switch node, the on-off switching power consumption is only on the order of 10 μW as only one microring is switched-on. However, our switch node may have drawbacks in terms of a relatively large footprint and the crossing array still imposes considerable optical power loss. Although the MMI design is targeted at mitigating the crossing insertion loss, the 0.1 dB insertion loss at each crossing according to our numerical simulations is still a major concern in the optical power budget of a large mesh intra-chip network. Even for a single switch node, the longest light path encounters 9 MMI-crossing junctions, resulting in ~1 dB junction induced loss. Besides, the optical power loss depends on the submicrometer-sized waveguide transmission loss. State-of-the-art fabrication technology has already demonstrated silicon wire waveguide (510 nm × 226 nm dimensions) with ~1.7-dB/cm propagation loss for TE-polarized light19. Thus, we see that for the proposed 5 × 5 switch of a small 100 μm × 100 μm footprint, the optical loss is dominant by the crossings insertion loss, while for the on-chip mesh network with cm-length optical interconnections, the waveguide propagation loss still needs to be accounted for. Furthermore, the optical waveform distortion due to the non-uniform attenuation of a narrow-band resonance should be properly accounted for, and a sufficiently wide-band resonance should be adopted for a high-data-rate signal transmission. It is conceivable that high-order coupled microring resonators at each crossing grid can help tailor the filter passband. The power budget in such photonic network must also include the dynamic power consumption in the high-speed data modulation process38.

In passing, we note that the switch node proposed here is compatible with wavelength-division multiplexing (WDM) technology8. We can split each photonic message into different wavelength channels separated by a free spectral range of the microring resonator, which can simultaneously filter the different wavelength channels. As in the fiber-optic network, the multiple wavelength channels each carrying high-speed data offer an accumulated ultra-high-bandwidth interconnect NoC. However, the WDM technology imposes multiple laser sources or a spectrally sliced broadband light source with wavelength channels that are properly aligned with the microring resonances. Together with the augmented number of high-speed modulators, it is however not clear to us at this point that the WDM technology offers a competitive advantage compared with using single wavelength channels for interconnect NoC applications.

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REFERENCES


Appendix

Switch physical layout