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Nanophotonic On-Chip Interconnection Networks for Energy-Performance Optimized Computing

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1. Introduction

Much recent progress in silicon nanophotonic technology has enabled the prospect of high-performance nanophotonic networks-on-chip (NoCs), which have become very attractive solutions to the growing bandwidth and power consumption challenges of future high-performance chip multiprocessors [1–4]. The design of our high-performance nanophotonic NoC commences at the individual silicon nanophotonic device and produces a full-scale on-chip optical interconnection network.

Nanophotonic NoCs introduce a logical solution to the challenges of interconnecting chip multiprocessors since (1) photonic links provide very large bandwidths, methodically scalable with the wavelength parallelism of the optical domain, and (2) photonic messages can be routed in a highly energy-efficient manner. Moreover, the equivalent power consumption of on- and off-chip photonic signaling makes the on-chip photonic communications infrastructure also beneficial for off-chip memory accesses. Significant advancements in CMOS-compatible silicon nanophotonic technologies have provided a viable path toward the realization of nanophotonic NoCs, due to mature processing capabilities and high index contrast, which affords dense photonic integration. Today, all of the necessary components for constructing simple nanophotonic NoCs (e.g. modulators [5], switches [6–8], photodetectors [9]) have been demonstrated, and designers currently strive toward obtaining performance improvements and increasing the level of device integration [7].

2. Silicon Nanophotonic Network-on-Chip

We have studied electrically-controlled circuit-switched nanophotonic NoCs, arranged in a variety of two-dimensional (2D) topologies, including both blocking and non-blocking arrangements of a torus. An example non-blocking torus topology is depicted in Fig. 1, highlighting all utilized optical pathways and nanophotonic network elements. The most prevalent photonic network element in this topology is the non-blocking four-port bidirectional router, which dynamically routes broadband messages to their appropriate destinations. These networks utilize wavelength-parallel message encoding for optical-domain bandwidth enhancement, and leverage strictly non-blocking functionalities, where multiple messages can simultaneously pass through the photonic routers without contention [7].

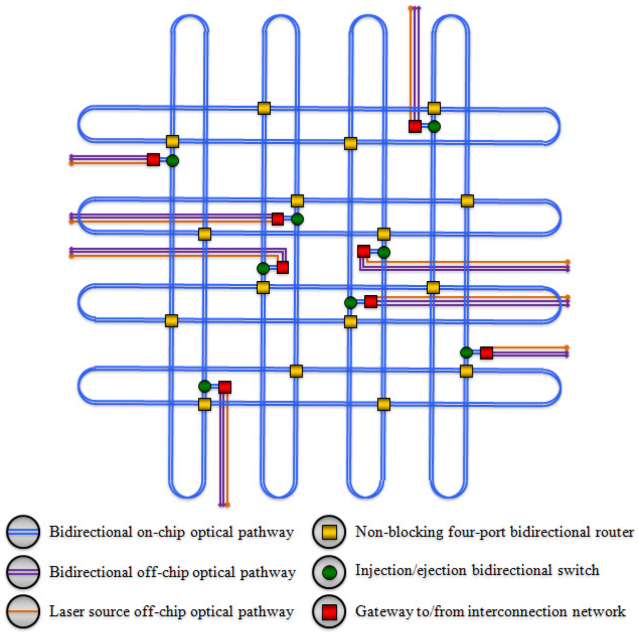

Fig. 1 Topology of the eight-port non-blocking torus nanophotonic NoC, with corresponding optical pathways and nanophotonic network elements.

3. Electro-Optic Silicon Nanophotonic Devices

Electro-Optic Modulator

The silicon nanophotonic electro-optic microring resonator modulator characterized in our work is comprised of a microring resonator coupled to a waveguide (Fig. 2). The waveguides are 450-nm wide and 260-nm tall; the waveguide of the microring has a 50-nm slab that is doped to form the PIN diode structure, with nickel silicide for the electrical contacts. A non-return-to-zero (NRZ) on-off-keyed (OOK) high-speed electrical data signal driving the modulator encodes the data onto a single optical wavelength channel. This electro-optic modulating phenomenon is described by the plasma-dispersion effect, arising from the presence of electrical carriers in the microring resonator, blue-shifting its resonance response. A light source is injected into the device on resonance, and the resonance is electrically toggled, producing the modulated optical data signal [5].

Electro-Optic Switch

The silicon nanophotonic electro-optic microring resonator switch that we have characterized is a 1×2 switch consisting of two coupled microring resonators each

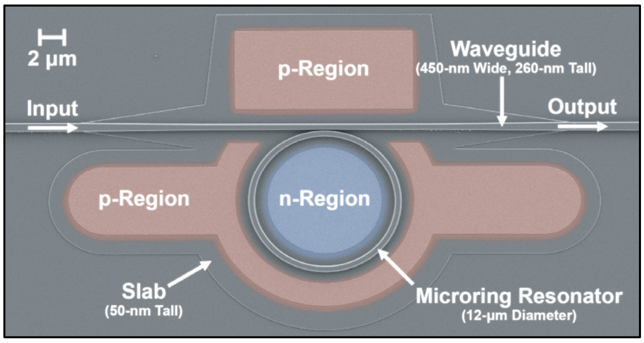

Fig. 2 Top-view scanning-electron-microscope (SEM) image of the silicon microring resonator electro-optic modulator.

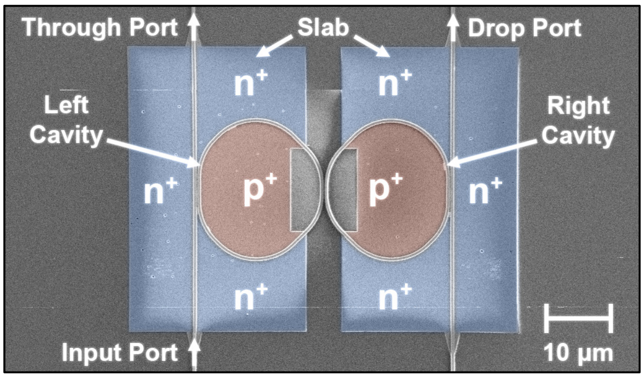

Fig. 3 Top-view scanning-electron-microscope (SEM) image of the silicon microring resonator electro-optic switch.

coupled to a waveguide (Fig. 3). The microring resonators are designed with both racetrack and ring features, with 2π×10-µm cavity lengths. The waveguides are 450-nm wide and 250-nm tall; there is a 40-nm slab near the microrings that is doped to form the PIN diode structures. Switching an optical signal between the through port and the drop port is accomplished with the detuning of the right cavity resonance using the free carrier dispersion effect arising from injecting and extracting electrical carriers through the PIN diode. This switch exhibits a hitless behavior, able to switch optical data at one wavelength channel without interfering with neighboring wavelength channels.

For active switching, we first align the optical signal to be on resonance. When the voltage signal is set high (low), the signal is switched to the through port (drop port). We actively switch the device with a square voltage signal, routing optical data packets to egress from each output port. We have switched an optical signal encoded with 40-Gb/s data, and characterized these optical data packets using system-level measurements on the packetized data at each output port of the switch [6].

4. Silicon Nanophotonic Router

We have fully characterized a non-blocking four-port bidirectional multi-wavelength message router for use in nanophotonic NoC architectures using wavelength-parallel 10-Gb/s signals [7]. These experiments demonstrate the feasibility of using this advanced switching subsystem

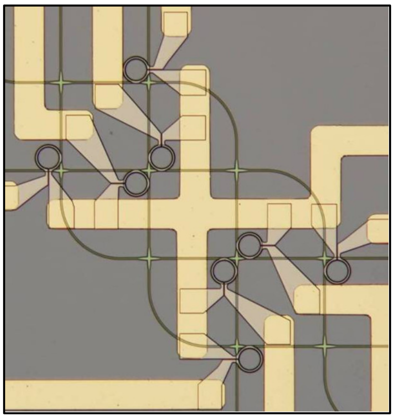

Fig. 4 Microscope image of the fabricated non-blocking four-port bidirectional multi-wavelength message router.

within the dynamically-routed multi-wavelength nanophotonic NoCs.

The nanophotonic router (Fig. 4) consists of both photonic and thermo-electric circuits. Optically, it is composed of waveguides with 450-nm×250-nm cross sections, waveguide crossings that are adiabatically tapered to 2-µm widths at the intersection to minimize reflections, and microring resonators with 20-µm diameters. The structure provides a dedicated path for every I/O combination except U-turns, which are unnecessary in circuit-switched networks. The router employs the minimum eight microring resonators, each coupled to a waveguide crossing, comprising four 1×2 switches (with a single ring at a crossing) and two 2×2 switches (with two rings at a crossing), similar to those individually demonstrated in [6] and [8], respectively. The electronic heaters provide static switch-state configuration using direct-current (DC) resonance tuning.

5. Conclusions

We have developed high-performance nanophotonic NoC topologies leveraging silicon nanophotonic electro-optic microring resonator modulators and switches to achieve dynamically-routed multi-wavelength operation. We have experimentally demonstrated and characterized high-performance silicon nanophotonic devices for use in these nanophotonic NoCs, demonstrating an energy-efficient solution for interconnecting next-generation chip multiprocessors.

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