Data Transmission Using Wavelength-Selective Spatial Routing for Photonic Interconnection Networks

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Abstract: Wavelength-selective spatial routing is proposed for photonic networks and demonstrated on an electro-optic microring switch. This technique yields greater path diversity in photonic networks, enabling improved overall network performance.

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1. Introduction

Photonic technology is being proposed as a solution for high-performance computing systems that are increasingly being hindered by performance bottlenecks in their interconnection networks. Photonic interconnects offer two key advantages over their traditional electronic counterparts: 1) they provide orders of magnitude higher bandwidth density by leveraging wavelength-division multiplexed (WDM) transmissions to simultaneously send multiple spectrally-parallel data streams in a single waveguide; and 2) they can be designed to be extremely energy efficient by eliminating the intermediate buffering and routing stages found in electronic networks. For these reasons, a growing number of photonic architectures have been proposed to enrich the overall performance of future computing systems [1–4].

While a variety of photonic interconnection networks have been proposed, several commonalities exist among them. Almost all of these networks leverage microring resonators for their versatility, compact size, energy efficiency, and CMOS compatibility. From an architectural perspective, the networks can generally be classified as either using *wavelength routing* [1,2] or *spatial routing* [3,4] for guiding optical messages through the network. Wavelength routing establishes node-to-node optical lightpaths by using passive optical filters throughout the network, which are tuned in such a way that a source node can transmit to any destination through the selection of an appropriate wavelength channel. In contrast, spatial routing relies on the cohesively guiding of an entire spectrum of channels in a WDM link through the use of an electro-optic microring switch [5]. In comparison, spatial routing induces longer message latencies due to the circuit-switching protocols required to provision the appropriate photonic resources; however, spatial routing achieves higher transmission rates than wavelength routing by capitalizing on WDM for data parallelism rather than routing.

In this work, we propose and demonstrate *wavelength-selective spatial routing* which enhances the aforementioned spatial routing technique by dividing the total set of wavelength channels of the WDM link into several interleaved WDM partitions that can be independently routed within a common physical topology. This novel functionality is enabled by using microring resonators in a way that concurrently leverages their wavelength selectivity and electro-optic controllability. We experimentally demonstrate this concept and report performance measurements of the active transmission of six 10-Gb/s WDM channels through a silicon electro-optic microring switch; the demonstration shows the active routing of a partition of three channels, while leaving the remaining three channels unperturbed.

2. Wavelength-Selective Spatial Routing

Traditional spatially-routed photonic networks are created using optical routers that are composed of electro-optically driven microring resonators. The microring resonators can be controlled to be in an *off-resonance state*,

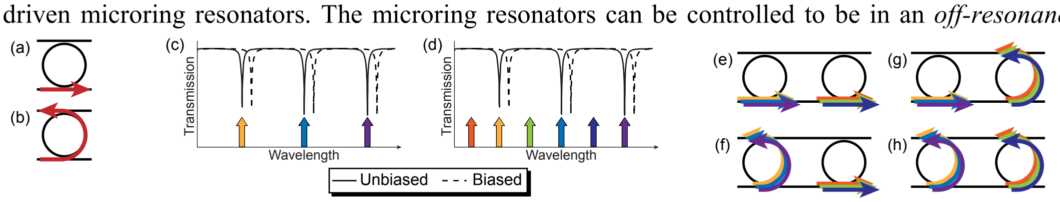

Fig. 1. (a) Off-resonance through-port state and (b) on-resonance drop-port state of a microring resonator. (c) WDM channel positioning (arrows) in traditional spatial routing, relative to the optical spectrum of a microring switch with and without a voltage bias. (d) WDM channel positioning in wavelength-selective spatial routing. (e–h) Four possible configurations of the two-partition 1×2 wavelength-selective spatially routed switch.

which allows an optical signal to pass undisturbed by the microring resonator and to the through port of the switch (Fig. 1a), or in an *on-resonance state* which enables the optical signal to shift into a different waveguide and to emerge out of the drop port of the switch (Fig. 1b). Furthermore, the ring exhibits periodic resonant modes that are simultaneously shifted when a voltage bias is applied, and each resonance can be used to route a separate WDM channel [5]. Fig. 1c illustrates how incoming wavelength channels can be spectrally positioned with respect to the resonant modes of the microring. The transmission properties of the microring switch are altered when the device is electrically biased, thereby enabling switching functionality. In order to establish an end-to-end communication link in a full-scale network, each ring switch along the transmission path must be configured prior to the injection of the optical message. Photonic network configuration is accomplished using a complementary electronic control plane that provisions the optical link in a circuit-switched manner [3]. However, this is problematic as established circuits will cause the resources along the optical path to be blocked for the duration of the optical transmission.

The proposed wavelength-selective spatial routing scheme takes advantage of the unused spectrum that exists between the resonances of the microring by interleaving additional WDM channels between existing wavelength channels (Fig. 1d). These auxiliary wavelength channels will propagate past the microring undisturbed, regardless of whether a bias is being applied. We refer to the original set and the auxiliary set of channels as the *primary WDM partition* and *auxiliary WDM partition*, respectively. Two ring resonators can be cascaded and each aligned to a different WDM partition, forming a 2-partition 1×2 wavelength-selective spatial router. Figs. 1e-1h show the four possible routing configurations for the 2-partition router, illustrating the independent routing of each WDM partition. This switching method can be scaled by interleaving more wavelength channels to create additional partitions. The notion of WDM partitioning is analogous to electronic network multiplexing techniques such as virtual channels and the use of multiple physical networks.

Photonic network designs that leverage wavelength-selective spatial routing will have greater path diversity, enabling improved network-level performance, with a minimal insertion loss penalty. Previous work has shown that waveguide crossings are the largest contributor to insertion loss while the through port ring switch losses contribute a negligible amount [4]. This trend is agreeable for the proposed routing design since we can observe that the number of through port traversals will increase, but no additional crossing traversals will be induced. From a performance perspective, the added path diversity allows multiple communication links to occupy the same waveguides and photonic routers, resulting in reduced network-level contention. Decreased contentions will reduce latencies caused by network resource unavailability, and increase network-level bandwidth due to the higher availability. Moreover, this new switch design can be readily substituted into previous spatial-routed topology designs to produce enhanced versions.

3. Experimental Setup and Results

To validate the WDM-partitioning concept, we demonstrate a slice of the proposed switch design. We use a second-order electro-optic microring switch (Fig. 2a) fabricated at the Cornell Nanofabrication Facility [6]. Previous work has shown active switching of 40-Gb/s data through the device [7]. Our demonstration consists of transmitting two 3-channel WDM partitions, and observing the active switching of the primary WDM partition while the auxiliary partition is unaffected. To the best of our knowledge, this experiment also represents the first demonstration of a WDM data signal being switched through an electro-optic microring resonator. Note that the prior discussion on the proposed routing scheme assumes first-order microring devices; however, this concept can be readily applied to higher order devices. An advantage of the second-order device is that it exhibits hitless characteristics when the modes are shifted off resonance, producing suppressed resonances due to the Vernier effect, and thereby reducing the impact on adjacent wavelength channels.

The experimental setup (Fig. 2b) consists of six continuous-wave (CW) laser sources combined using a dense wavelength-division multiplexer (DWDM). The six channels are simultaneously amplitude modulated using a $LiNbO_3$ modulator (MOD) with a 2^7-1 pseudo-random bit sequence generated by a pulse pattern generator (PPG) at 10 Gb/s. The six wavelength channels are decorrelated at the output of the modulator, amplified (EDFA), aligned for quasi-TM propagation, and injected into the chip using a tapered fiber. The microring switch is electrically contacted using high-speed electrical probes and driven using a data timing generator (DTG). At the output of the chip, a filter (λ) is used to select a single WDM channel. The single channel is then amplified, filtered, and sent

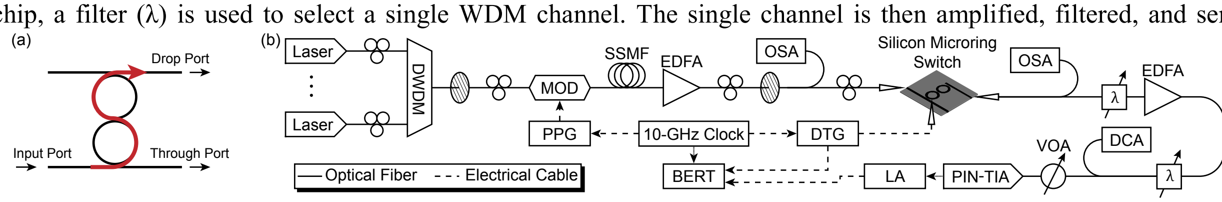

Fig. 2. (a) Second-order micro-ring resonator. Arrow indicates the optical path for the drop port. (b) Diagram of the experimental setup.

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through a variable optical attenuator (VOA). Lastly, the optical channel is fed into a PIN photodiode with a transimpedence amplifier (PIN-TIA), followed by a limiting amplifier (LA). The received data is assessed using a bit-error-rate tester (BERT). A common 10-GHz clock is used to synchronize the PPG, DTG, and BERT. A digital communication analyzer (DCA) and optical spectrum analyzer (OSA) are positioned throughout the setup for capturing eye diagrams and optical spectra.

We first measure the passive optical spectrum of the device, showing three resonant modes which will be used for switching the primary WDM partition (Fig. 3a). To determine the optimal wavelength positioning of the primary WDM partition, we first scanned across the resonant mode centered at 1551 nm using a tunable CW laser on the drop port while optimizing the DTG voltage bias for maximum extinction ratio. With the DTG bias fixed, we then scanned across every mode of interest to measure the extinction ratio on both the through and drop ports. Channels positioned at 1541.25 nm, 1550.05 nm, and 1559.01 nm were selected for having the most balanced extinction between the two output ports (approximately 9-10 dB). The auxiliary partition wavelengths are positioned at 1536.88 nm, 1545.65 nm, and 1554.53 nm, and were arbitrarily selected to lie approximately between adjacent modes. In a fully-implemented version of the router, the auxiliary channels should correspond to the resonances of the secondary microring. The power of each channel at the chip input is set to approximately 0 dBm and the switch is operated with a 100-ns period and 50% duty cycle, resulting in 50-ns long optical packets.

The BER curves are reported in Fig. 3b showing minimal data degradation. The BER curves of the primary WDM partition were shifted by 2.5 dB in order to account for differences in average measured power at the receiver due to the 50% duty cycle at the device output. The shift was analytically calculated based on a 9-dB extinction ratio. In Fig. 3c, we record select 10-Gb/s eye diagrams, 50-ns long optical packets which are representative of all other wavelength channels.

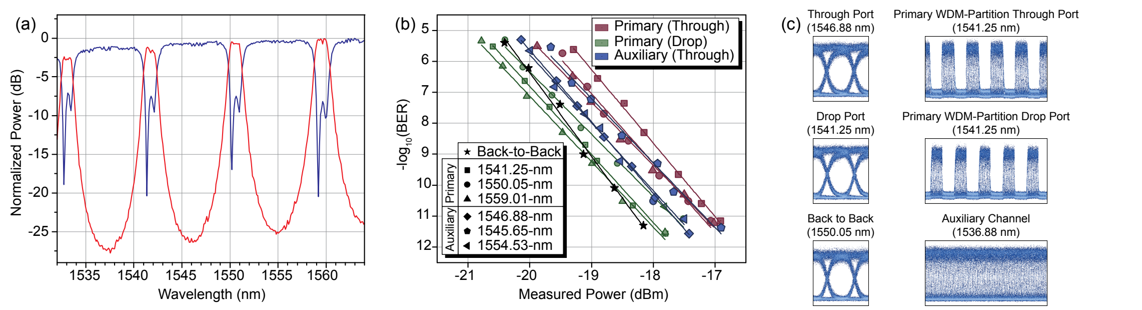

Fig. 3. (a) The through port and drop port spectra of the electro-optic microring switch in the passive state. (b) BER curves for each of the six wavelength channels and the back-to-back case which bypasses the chip. (c) 10-Gb/s output eye diagrams and optical packets at both output ports from the device in the active state.

4. Conclusions

We propose the novel concept of wavelength-selective spatial routing for use in photonic interconnection networks. Compared to previously proposed photonic architectures, this routing technique produces network designs with better path diversity, resulting in lower latency and greater network-level bandwidth. Furthermore, we have experimentally validated the proposed routing scheme using a silicon electro-optic microring switch and shown its feasibility to be leveraged in next-generation computing interconnect architectures.

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