High-Speed 2×2 Switch for Multi-Wavelength Message Routing in On-Chip Silicon Photonic Networks

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Abstract

A 2×2 multi-wavelength silicon switch, enabling low-power on-chip message routing with ultra-compact footprints, is designed, fabricated, and tested with switching ratios, transition times, and power penalties reported.

Introduction

High-performance microprocessors are clearly trending toward multi-core architectures with a growing number of cores, and are therefore requiring an increasingly efficient and low-power communications infrastructure to achieve the desired level of bandwidth and connectivity. Silicon photonic networks-on-chip provide an effective solution to the power and bandwidth limitations of existing electrical interconnection networks used within chip multiprocessors [1].

Silicon photonic device technology provides a path toward realizing these integrated networks [1, 2], and silicon microring resonators have become a vital functional component of these systems, having already been used to achieve tunable filters [3] and multi-bit delays [4], as well as electro-optic [5] and all-optical [6] modulators. Complementary to these devices and crucial for message routing in integrated networks is a high-speed, low-power, and compact switch, designed for multi-wavelength messages. A 1×2 single-resonator comb-switching device [6] was recently used to actively switch 20 continuous-wave (CW) wavelength-division-multiplexed (WDM) channels with nanosecond transitions, and was shown passively to operate with negligible interchannel crosstalk [7]. A similar 1×2 switch, based on a fifth-order coupled-resonator, has also been reported [8]. In the present work, the first ever 2×2 version of the silicon multi-wavelength switch is reported. The results verify switching transitions below 2 ns with up to 11.5 dB of extinction. Power penalties are measured for the six-channel, 10-Gb/s per channel, wavelength-striped, packetized messages. In addition to providing the important added functionality of a second input port, this device represents the fundamental building block required for constructing non-blocking network topologies [2], along with enabling more complex high-functionality routing structures.

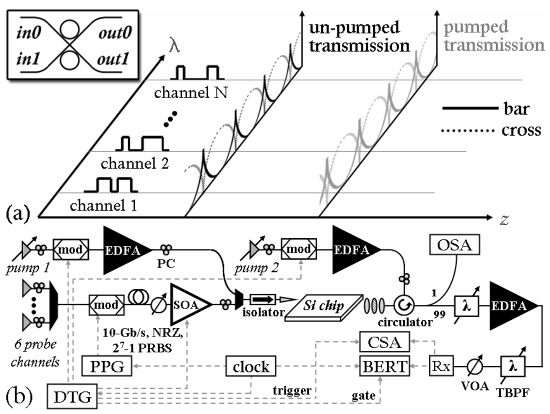

Figure 1: (a) Diagram of multi-wavelength packet structure and switching scheme with inset of device and port labels. (b) Experimental setup schematic.

Multi-Wavelength Switch and Testbed

The device, fabricated at the Cornell Nanofabrication Facility, consists of silicon waveguides (250-nm × 450-nm cross sections) which are under- and over-clad with 3-μm-thick silica layers. Fig. 1a (inset) illustrates the switch layout and port labels. The resonant modes of one ring are wavelength-tuned to overlap the other ring's modes by local thermo-optic tuning. Designed to accommodate 10-Gb/s data, the modes have 3-dB band-widths of 0.1 nm, on average. With no applied pump, each wavelength of the input signal overlaps one mode such that the switch implements the bar state (i.e. *in0-out0*, *in1-out1*). A pump changes the state by shifting the wavelengths at which the modes occur so that the channels no longer couple to either ring. The cross state (i.e. *in0-out1*, *in1-out0*) is then obtained when the pump is applied. The pump, comprising two 1.5-μm wavelength lightwaves (co- and counter-propagating), injects carriers into each ring waveguide via two-photon absorption (TPA). By using 100-μm diameter rings, the free-spectral range is reduced to 1.6 nm, allowing high-bandwidth wavelength-parallel data to be switched by a single device (Fig. 1a). Moreover, the switching power per throughput bandwidth decreases when wavelength channels are added, as the switching power remains constant.

The setup (Fig. 1b) involves probe and pump signal generation, fiber-waveguide coupling, and test and measurement. The multi-wavelength probe is generated by six distributed-feedback lasers and a dense wavelength-division multiplexer (DWDM). *ITU C*-band channels C22, C24, C33, C35, C37, and C43 are employed (1543–1560 nm wavelengths) and are collectively modulated at 10-Gb/s with a signal driven from a pulse pattern generator (PPG). Channel decorrelation is performed by 25 km of single-mode fiber. A semiconductor optical amplifier (SOA) gates the data into 9.6-ns packets recurring every 12.8 ns. The SOA is driven by a data timing generator (DTG), which also gates the BER tester (BERT) over the arrival of the switched packets. The pump signals are independently generated, modulated, and amplified. The co-propagating pump (pump 1, C51) is combined with the probes using a second DWDM. The counter-propagating pump (pump 2, C18) is injected using a circulator. The pump waveforms are actualized by the DTG. Average powers prior to coupling are 18 dBm (pump 1) and 17 dBm (pump 2). The signals are injected into the inverse-tapered waveguides using a tapered fiber and extracted with lenses and a TM-transmitting polarizer. The output is monitored by an optical spectrum analyzer (OSA), while one channel is filtered and pre-amplified. The received signal is evaluated using a communications signal analyzer (CSA) and BERT.

Dynamic Measurements

The pump beams are modulated with 12.8-ns pulses recurring every 102.4 ns, such that one in eight of the incoming packets from port *in0* is switched to port *out1*, while the others propagate to port *out0*. By injecting a single-channel CW probe in place of the multi-channel data, we observe the envelope of the switched signal (Fig. 2a). The short transition times (less than 2 ns each) allow fast state changes enabling closely spaced optical packets. Extinction ratios of 11.5 dB (*in0-out0*) and 7.8 dB (*in0-out1*) are

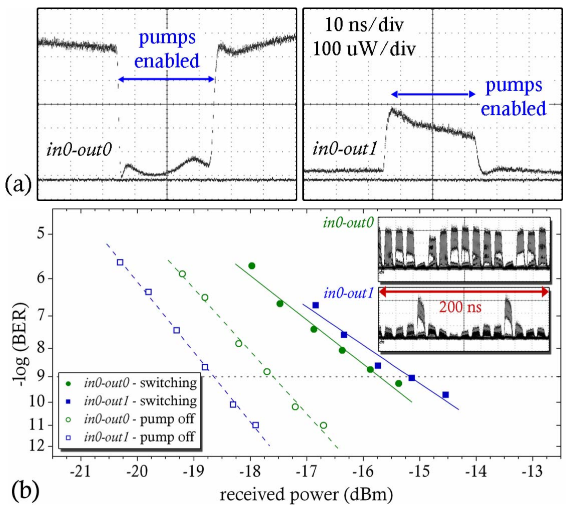

Figure 2: (a) CSA traces (16-point average) showing the switching envelope for two labelled paths. (b) BER curves representing these paths under dynamic and static states of the switch with waveform insets.

observed. The insertion loss of path *in0-out1* is higher than *in0-out0*, due to the TPA-induced free-carrier absorption generated by the pump. This also affects the port-to-port crosstalk, defined for path *in0-out0* (*in0-out1*) as the ratio of the on-state power through *in0-out0* (*in0-out1*) to the off-state power through *in0-out1* (*in0-out0*). This describes the amount of power leaked to the undesired output, degrading a message incident from the other input. The measured crosstalk is 12.3 dB (7.0 dB) for path *in0-out0* (*in0-out1*).

BER measurements are taken during dynamic operation using the same pump signals and the six-channel data packets. C35 is chosen for evaluation. BER curves are recorded for paths *in0-out0* and *in0-out1* during both dynamic (high-speed switching) and static (pump disabled) operation (Fig. 2b). The power penalty at a BER of 10^{-9} is 1.9 dB (3.5 dB) for path *in0-out0* (*in0-out1*). The larger cross-state penalty is expected because of the added loss and amplified spontaneous emission (ASE) noise encountered.

Further performance improvements and power reductions are expected with electronic carrier injection [5]. Coupled-resonator systems may also provide thermal stability and broader passbands in future devices [8].

Conclusions

We have designed, fabricated, and measured an ultrafast multi-wavelength 2×2 switch for use in integrated silicon photonic networks. Initial results with 10-Gb/s data using an all-optical pumping scheme show 11.5 dB of extinction with under 2-ns transition times. The switch completes a toolbox of instrumental photonic components required in the design and implementation of high-functionality chip-scale routing structures for interconnection networks in high-performance computing systems.

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