# 40-Gb/s DPSK Data Transmission Through a Silicon Microring Switch

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***Abstract*— We experimentally demonstrate switching of a 40-Gb/s differential-phase-shift-keyed (DPSK) signal through a coupled silicon photonic microring switch. By simultaneously electro-optically biasing both microring cavities, we achieve 14-dB extinction ratio for signals egressing from both output ports of the switch. Packetized transmission of the 40-Gb/s DPSK signal is achieved with power penalties of 0.6 and 2.4 dB for through port and drop port signals, respectively. The effects of a coupled silicon microring are investigated, showing a broad bandwidth and a linear phase response for the drop port are necessary characteristics for routing 40-Gb/s data through the switch for photonic interconnection networks.**

***Index Terms*— Differential-phase-shift keying, electro-optical devices, microring resonators, packet switching.**

## I. Introduction

SILICON photonic technology offers an attractive solution to the ever increasing bandwidth and energy challenges associated with future chip-scale interconnects by providing higher bandwidth density, lower power consumption, and shorter latencies than traditional electrical solutions. Furthermore, the complementary metal-oxide-semiconductor (CMOS) compatible platform enables low-cost mass production. These advantages have fostered many high-performance silicon photonic devices [1]. Among the many researched silicon photonic devices is the microring resonator, a compact structure that is capable of performing a variety of network functions (i.e. filters, modulators, switches [2], detectors and delay lines) for on-chip interconnection systems. Microring switches can also be electro-optically controlled which enables highly scalable and energy efficient photonic interconnection network.

Wavelength management can be simplified by reducing the number of required wavelength-division-multiplexing (WDM) channels through the use of higher speed data transmission. However, microring-based switches are inherently narrowband due to their sharp Lorentz-shape resonances which leads to spectral distortion and sideband attenuation for high datarate optical signal transmissions [3]. A solution to this problem is the use of coupled microrings, which can be designed with a box-like passband to minimize the above mentioned effects.

Such spectral response also has the merits of low cross-talk and better temperature-drifting tolerance [4].

Broadband electro-optic microring switches are capable of routing wavelength-parallel optical messages through a photonic interconnection network [5-6]. Switching of on–off-keyed (OOK) high-speed optical data at rates of up to 40 Gb/s have been demonstrated [7]. Compared to OOK format, differential-phase-shift-keyed (DPSK) format has the advantage of 3-dB improved receiver sensitivity with balanced detection and has higher tolerance to nonlinear degradation. The benefits of DPSK signaling enable an increased optical power budget that allows for better scalability of photonic interconnection networks. Despite this advantage, the switching of high-speed DPSK signals using microring resonators is challenging due to the frequency discriminator behavior of microrings [6, 8]. In addition, the non-linear phase response of the coupled microrings leads to chromatic dispersion for signals egressing from the drop port which consequentially results in the degradation of a switched optical signal, and will especially impact signals with broader spectrum. Although the transmission of 10-Gb/s DPSK signaling in an electro-optic silicon microring switch has been previously accomplished, the switching of a 40-Gb/s DPSK signal in the microring-based switch represents a greater and different challenge than the 10-Gb/s case due to the significantly broader occupied spectrum and stronger dependence on the phase response.

In this work, we experimentally demonstrate the transmission of a 40-Gb/s DPSK optical signal through a coupled electro-optic microring switch with nanosecond-scale switching transitions, 14-dB extinction ratios, and 0.6-$V_{pp}$ voltage by simultaneously driving both microring cavities. We also validate and investigate the power penalty of using 40-Gb/s DPSK signaling for photonic interconnect networks.

## II. Device Characterization

Figure 1a shows a coupled $1 \times 2$ switch used in the experiment which consists of two microring resonators both integrated with p-i-n diodes. The resonance of each microring can be shifted through carrier-injection of the corresponding diode. Therefore, input optical signals can be switched between through port (off resonance) and drop port (on resonance) by electrical control. Fig. 1b presents a normalized output spectrum of the device for output ports in the passive state

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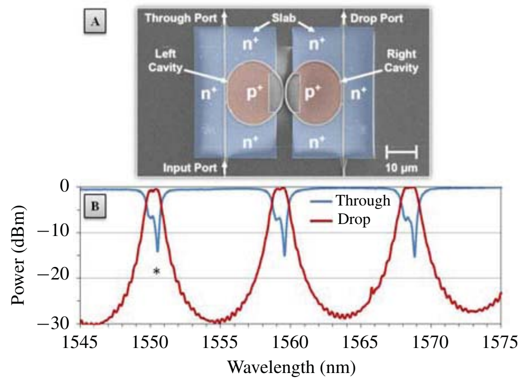


Fig. 1. (a) Scanning-electron-microscope (SEM) image of the device. (b) Spectrum of resonant responses of the device in the passive state.

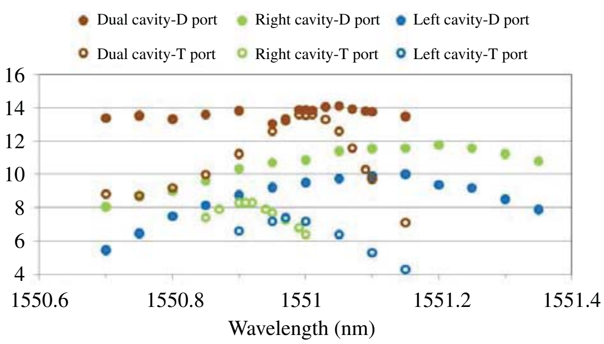


Fig. 2. Measured extinction ratios for drop port (D) and through port (T) across the resonance used in the experiment in the active state by driving left cavity, right cavity, and dual cavity with optimized voltage, respectively.

(before being electrically driven), showing a 9-nm free spectral range (FSR), drop-port 3-dB bandwidth of 1.1 nm, and through port maximum extinction ratio of ∼13 dB.

The input continuous wave (CW) light, initially positioned on resonance, is either switched to through port or drop port with a two-level electric driving signal. To optimize the performance of the switching, we inject electrical carriers into 1) left cavity, 2) right cavity and 3) both of the cavities of the coupled microrings through a PIN diode, respectively. For each case, we optimize the driving voltage at one measured point and then scan the CW light across the resonance near 1550 nm (marked in Fig. 1b with "∗") while maintaining the voltage the same to measure the extinction ratios of a gating signal at both output ports. The results shown in Fig. 2 indicate the highest extinction ratio of 14 dB can be achieved on both output ports by driving both of the cavities simultaneously.

Here, we actively switch both of the cavities with a square wave signal with a 0.6-Vpp with 0.5-V voltage bias and a 100-ns period with a 50% duty cycle, producing 50-ns optical gating packets at both output ports. The rising and falling time (10% to 90% of the signal, shown in Fig. 3) is 1.46 ns and 1.3 ns for through port; 1.71 and 0.87 ns for drop port, respectively. The rise and fall time results are comparable to those reported previously from driving single cavity [6] while the driving voltage is lower and the observed extinction ratio is higher. Moreover, the passband profile is maintained avoiding significant sideband asymmetry of the switched signal. The transmission wavelength used in the experiment is chosen to

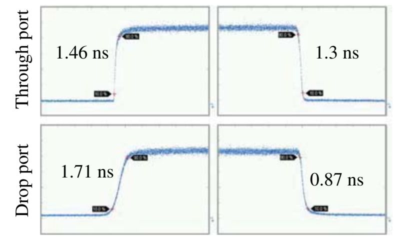


Fig. 3. Transients of gating signals at 1551 nm egressing from both output ports by driving dual cavity.

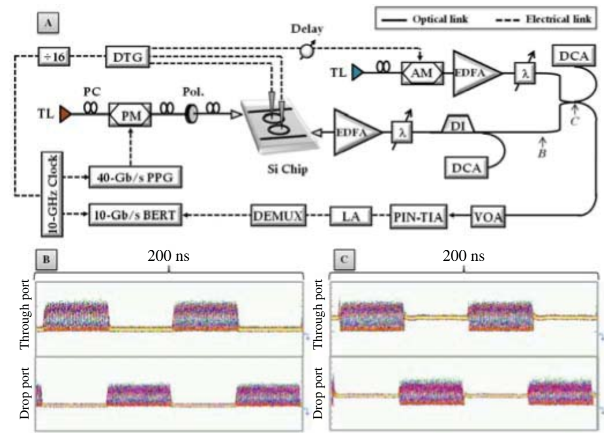


Fig. 4. (a) Experimental setup using the silicon electro-optic microring switch. Waveform monitored in (b) point B and (c) point C shown in the setup.

be 1551 nm because it shows the best extinction ratio and aligns to one channel of the delay interferometer (DI) we used for DPSK demodulation.

## III. Experiment

Figure 4 shows the experimental setup. A CW light at 1551 nm is generated by a tunable laser (TL) source and subsequently modulated by a phase modulator (PM) to generate a DPSK signal. The modulator is driven with a 40-Gb/s, $2^{31}$–1 pseudo-random bit sequence (PRBS) pattern from a pulse pattern generator (PPG). The optical signal then passes through a polarizer and is coupled into an on-chip nano-tapered silicon waveguide using a tapered fiber with –4-dBm average input power. A data timing generator (DTG) switches the switch by contacting the silicon chip with a pair of high-speed RF probes. The optical signal egressing from the chip passes through an erbium-doped fiber amplifier (EDFA), filter ($\lambda$), and a DI with 25-ps delay between the arms.

If we were to directly receive this data, the packetized light combined with the AC-coupled photodetector would result in a strong voltage bias on the RF output data bits, which would be detrimental to proper amplification by the limiting amplifier (LA). In order to overcome this obstacle, we insert an auxiliary light signal in between the data packets to create a near-constant power profile and thus reduce the voltage bias. To this end, a CW light at 1548 nm from a second TL is gated by an amplitude modulator (AM) using a 100-ns period, 50% duty cycle square wave generated by the same DTG. The auxiliary signal is then amplified, filtered, and combined with

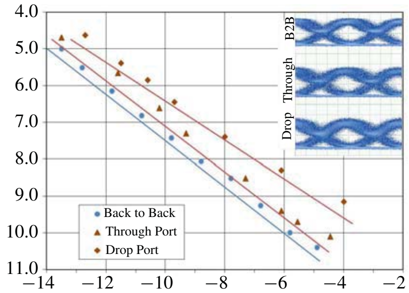


Fig. 5. BER curves for switching of a 40-Gb/s DPSK signal. Inset: respective eye diagrams

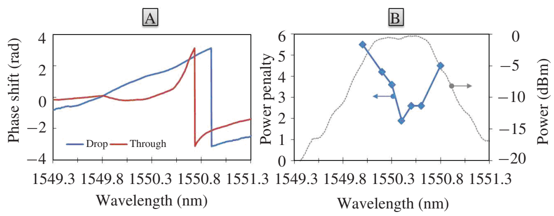


Fig. 6. (a) Measured resonance phase response. (b) Experimental power penalty versus wavelength across the resonance for 40-Gb/s OOK signal and the drop port spectrum.

the switched signal using a 3-dB fiber coupler. The auxiliary square wave signal is delayed such that it is inserted between the data packets. We inspect the switched signal waveform at the output of the DI (Fig. 4b) and the combined signal waveform at the output of the coupler (Fig. 4c) using a digital communications analyzer (DCA).

The combined signal passes a variable optical attenuator (VOA), and is detected using a photodetector (PIN-TIA) followed by a LA, and demultiplexed (DEMUX) to 10-Gb/s data rate before being examined on a BER tester (BERT). The DTG gates the bit-error-rate tester (BERT) over the duration of each optical packet. The DTG, PPG, DCA and BERT are synchronized to a common clock source. The back-to-back is measured using a continuous DPSK signal bypassing the chip, attenuated to the same power as that egressing from the through port of the microring to mimic the fiber-to-fiber loss of the chip, and measured with the same receiver. BER curves on the packetized data are measured (Fig. 5) at each output port of the switch showing 0.6-dB (through port) and 2.4-dB (drop port) power penalty compared to the back-to-back case. Some of the drop port power penalty is attributed to 2-dB extra insertion loss in the drop port compared to the through port.

In order to study the relatively large power penalty for the signal egressing from the drop port, we experimentally investigate the phase response of the coupled microrings and measure the power penalty of a 40-Gb/s optical signal which is transmitted to the drop port of the device in the passive state. The phase response (Fig. 6a) is measured using a modulation phase-shift method [9]. Non-optimized resonance positioning occurs owing to fabrication inaccuracy, thus the drop port has a non-perfect linear phase response which leads to chromatic dispersion and consequentially results in the degradation of high data-rate signals. Due to the lack of wavelength tunable DI for 40-Gb/s DPSK signal demodulation, we measure the power penalty for 40-Gb/s OOK signal across the resonance compared to the back-to-back case (bypassing the chip and attenuated to mimic the through port fiber-to-fiber loss). The normalized drop port transmission spectrum and the 40-Gb/s signal power penalty across the resonance are both plotted in Fig. 6b. The power penalty at BER of $10^{-9}$ shows a minimum 1.9-dB power penalty within the resonance due to the non-perfect linear phase response while it increases sharply as the wavelength is offset to the resonance center due to severe sideband asymmetry incurred. This result affirms the power penalty for the 40-Gb/s packetized DPSK signal egressing from the drop port is partly attributed to the non-perfect linear phase response and sideband asymmetry.

## IV. Conclusion

We have characterized the coupled silicon microring electro-optic switch by driving both cavities to achieve balanced 14-dB extinction ratios for both output ports. We further demonstrated the packetized transmission of a 40-Gb/s DPSK signal through the switch and observed error-free transmission for the through port signal. The power penalty for the drop port is analyzed by studying the phase response and signal degradation across the resonance, showing a broad bandwidth and perfect linear phase response is necessary for high-data-rate signal transmissions. This empirical validation confirms the suitability of the microring switch for varying modulation formats, enabling the option of 40-Gb/s DPSK signaling for next-generation photonic interconnections.

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