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Broadband 4×4 Switch Matrix using Fifth-order Resonators

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Abstract: A 4×4 crossbar switch is implemented and fully demonstrated using a matrix of fifth order resonators. Broadband 40Gb/s routing is demonstrated with a power penalty of only 0.3dB and a switch extinction ratio of 27dB.

OCIS codes: (250.5300) Photonic integrated circuits; (230.4555) Coupled resonators; (250.6715) Switching

1. Introduction
The combination of very high fabrication tolerances afforded by CMOS technology and the possibility to create high confinement Silicon on Insulator (SOI) waveguides with modest loss has lead to considerable renewed research into micro-ring resonator technology. One promising line of research exploits the electrical tuning of highly wavelength selective transfer functions to create optical switching circuits. Work has primarily focused on the implementation of multiple, single-order micro-rings placed at the intersect of multiple meandering waveguides to create 'optical router' elements for torus interconnection [1,2]. While conceptually attractive, the micro-ring inherently trades on-state optical bandwidth against off-state signal extinction [3] compromising the ultimate levels of connectivity. Additionally, nanoscale fluctuations in manufactured layer thicknesses and feature size dimensions can lead to resonant wavelength fluctuations in nominally-identical ring resonators of up to 1nm across a circuit [4,5]. High-order ring resonant elements have been demonstrated to separately optimize on-state bandwidth and off-state signal extinction [6], and this broadened bandwidth has been highlighted as a potential route to relaxed wavelength tolerance. Recently we have demonstrated high-order resonators in 1-D arrays to create 1×4 switches [7]. In this work, we implement the first two-dimensional array of high order resonant switch elements. Namely a 4×4 crossbar matrix. Using a photonic design approach which is resilient to many of the major anticipated fabrication variations [3], we design, implement and demonstrate operation for circuit elements which are fully actuated with one single micro-heater at each cross-point element and allow signal routing for sixteen path combinations.

2. Switch matrix
The optical switch matrix is implemented with SOI technology. The Silicon waveguides are nominally 500nm-wide and 220nm-thick and are buried within SiO₂ upper and lower cladding layers of thicknesses 1.2μm and 2μm. Waveguides are tapered out to surface gratings for chip-to-fiber optical coupling. They are also tapered out to the waveguide crossings which have been implemented with 32μm long and 3μm wide multi-mode interference couplers. The photonic wiring for the high-order switch elements and the micro-heaters are shown in Figure 1 for the mask layout, and a photograph of the circuit. The detail for one fabricated switch element is inset.

![Fig. 1.](image)

Fig. 1. (a). Schematic of the waveguides in the 4×4 switching circuit. (b). Schematic of the micro-heaters in the 4×4 switching circuit. (c). Microscope image of fabricated 4×4 higher order switch matrix with micro-heaters on top. (Inset). Inset is a detailed microscope image showing a switch elements. The switch elements are arranged on a horizontal grid of 300μm.

Each element is interconnected on a grid of orthogonal waveguides. In figure 1a, the input waveguides enter from the right side of the image and are numbered 1 through 4. The output waveguides exit from the lower edge of the image. Figure 1c shows the circuit as fabricated. The photonic circuits are produced by the ePIXfab foundry and diced to a 12mm×12mm sample size. The micro-heaters are fabricated afterwards. A metal sequence of 100nm Ti,
20nm Pt and 300nm Au is initially evaporated and patterned to define micro-heater elements and the on-chip wiring which leads out the electrical connections to wire-bond pads at the chip boundary. The Au is selectively etched from the pairs of 3μm wide heater elements to increase their combined parallel resistance. The resistance of the measured heater element is in the range 394-400Ω. The on-chip wiring to the micro-heaters is 18.5μm wide and retains the top layer Au to reduce the resistance and ensure maximum localized heating. A patterned polyimide passivation layer is applied to reduce heater degradation during operation. The insulator is opened at the bond pads for connection to a printed circuit board by means of wire bonds. One connection from each micro-heater is connected to a common ground line. Four such lines are visible in figure 1b as tracks extending from the top to bottom of the image. The remaining sixteen connections are individually addressable and are visible as the vertical tracks with originate only from the bottom of the image in figure 1b.

3. Experiment
The performance of the switch matrix is assessed by measuring the optical transfer function and the integrity of data routed for all 16 paths. Polarization controllers are used as the circuit is optimized for TE polarization. The surface grating couplers incur an estimated loss of 6.0dB for each fiber to chip coupling. The loss across the circuit is path dependent, with the path from input 1 to output 1 exhibiting the smallest additional on-chip loss of 3.0dB and the path from input 4 to output 4 exhibiting the maximum on chip path loss of 9.7dB. These losses are consistent with predicted switch element performance and waveguide loss for the foundry quoted 2.4 dB/cm waveguide losses [5].

10Gb/s routing experiments have been performed for all paths. A tunable laser is operated at a wavelength 1544nm and is externally modulated at 10Gb/s with a 2^{31}-1 pseudorandom binary sequence (PRBS) via a Mach-Zehnder modulator. For a small number of selected measurements where the optical path loss is too high, a fiber amplifier is used in combination with 0.9 nm full-width at half-maximum band-pass filter prior to the switch matrix input. The output from the chip is then connected to an avalanche photodiode based XFP receiver and consequently a bit error rate tester. Bit error rate is measured for all the input and output combinations for the 4x4 switch matrix. Performance data are summarized in terms of the power penalty at 10^{-9} bit error rate in Table 1.

| Table 1. POWER PENALTY FOR 10Gb/s SIGNAL ROUTING ACROSS 4x4 MATRIX |
|-----------------|-----------------|-----------------|-----------------|-----------------|
| **Inputs**      | **Outputs**     |                 |                 |                 |
|                 | 1               | 2               | 3               | 4               |
| 1               | 0.0 dB          | 0.9 dB          | 0.4 dB          | 0.6 dB          |
| 2               | 0.2 dB          | 0.5 dB          | -0.5 dB         | 0.3 dB          |
| 3               | -0.2 dB         | 0.4 dB          | 0.0 dB          | 1.2 dB          |
| 4               | 1.0 dB          | 0.9 dB          | 0.8 dB          | 1.1 dB          |

Power penalty is observed to vary between -0.5dB and 1.2dB. Small negative penalties may be attributed to measurement level precision and changes in losses when connections are interchanged. The largest penalties are observed for some of the longer paths through the circuit. The longest path from input 4 to output 4 passes six off-state ring-resonators which will incur additional loss. For each measurement the on state ring bias is optimized to minimize transmission loss. On state bias voltages are within the range 5.1 – 6.73V. The majority of measurements are performed with zero bias to the off-state rings. However the measurements using output column 2 and output column 3, require that the micro-heaters intersecting with input row 1 must also be actuated such that the switch elements are tuned to off-state. The need to tuning to off-state for these two rings is a direct result of waveguide size variations across the wafer, but these are readily mitigated with an applied bias of 3.83V and 3.55V respectively. In addition to resonant wavelength variations, there is also a sensitivity of power penalty to the absolute wavelength detuning between resonance and signal which has been predicted through theoretical study [3] and experimental measurements [7]. Here fluctuations in power penalty of fractions of a dB have been observed which correlate with amplitude ripple observable in the on-state pass-band.

40Gb/s signal routing has additionally been performed for a representative path from input 2 to output 2. The tunable laser is operated at 1543nm and a 2^{31}-1 PRBS is applied to an on-off-keyed Mach-Zehnder modulator. A fiber amplifier and optical filter are placed after the circuit to compensate loss. Back to back measurements are performed for comparative purposes by replacing the switch matrix with a fixed equivalent path loss of -21.1dB using a variable optical attenuator before the fiber amplifier. A power penalty of only 0.3dB is measured, marginally smaller than that observed for the previous measurements at 10Gb/s and as given in Table 1. Figure 2c
and figure 2d show the eye diagrams recorded using a SHF 41210B optical receiver after the transmitter and after routing via input 2 to output 2. Measurements are presented for a mean power into the receiver of -9.9dBm.

![Eye Diagrams](image)

**Figure 2.** Performance data for the path from input 2 to output 2.
(a) Bit error rate measurements for 40Gbps PRBS with length $2^{31}-1$
(b) Optical path transfer function
(c) Eye diagram for the transmitter into input 2. Input power at the receiver is -9.9dB.
(d) Eye diagram from output 2. Input power at the receiver is -9.9dB.

Figure 2b shows the measured transfer function of the path between input two and output two. Consistently with the data summarised in Table 1, the micro-heater at the intersect of input row 1 and output column 2 is also actuated to turn the resonance off the signal wavelength and set the switch element in off state. The on-state element at the intersect between input row 2 and output column 2 is actuated to on-state with a 4.53V bias voltage. While these voltages applied across 400Ω are not state of the art in terms of power efficiency, it is worth emphasizing that five resonators are being tuned simultaneously. No thermal isolation techniques have so far been applied, and this is expected to have a significant impact in the required tuning power. For these measurement conditions, an off-state extinction ratio of 27dB may be anticipated from the transfer function in figure 2b. The on-state bandwidth is observed at the 3dB width is observed to be 127GHz.

4. Conclusions
We have successfully demonstrated signal routing at 10Gbps in all paths of a 4×4 switch matrix with power penalties below 1.2dB. 40Gb/s signal routing for the representative path from input 2 to output 2 reveals a power penalty of 0.3dB.

5. References