

Integrated Switch for Mode-Division Multiplexing (MDM) and Wavelength-Division Multiplexing (WDM)

Brian Stern[1], Xiaoliang Zhu[2], Christine P. Chen[2], Lawrence D. Tzuang[1], Jaime Cardenas[1], Keren Bergman[2], Michal Lipson[1,3,*]

[1]*School of Electrical and Computer Engineering, Cornell University, Ithaca, NY 14853, USA*
[2]*Department of Electrical Engineering, Columbia University, New York, New York 10027, USA*
[3]*Kavli Institute at Cornell for Nanoscale Science, Cornell University, Ithaca, NY 14853, USA*
**ml292@cornell.edu*

Abstract: We demonstrate the first integrated switch for mode-division multiplexing (MDM) and wavelength-division multiplexing (WDM). We show on-chip routing of four 10 Gb/s channels with <-20 dB crosstalk and 0.5-1.4 dB power penalty.
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Mode-division multiplexing (MDM) on-chip can dramatically increase bandwidth density of optical interconnects for datacenters and multi-processors by harnessing the spatial modes of integrated waveguides. Switching wavelength-division multiplexed (WDM) signals has been an important selling point for silicon photonics due to the enhanced bandwidth [1,2], and while multiplexers for WDM and MDM have been developed [3-5], switching remains undemonstrated.

Routing MDM signals is challenging because the mismatched optical properties of spatial modes prevent access to all modes. Because of varying confinement of modes, coupling conditions are mode-dependent and not all modes are accessible. Further, WDM compatibility is challenging if multimode rings are used [6], because each mode has a different free spectral range (FSR).

Here we demonstrate the first integrated multimode switch and achieve access to all modes, by processing the multimode signals in the single-mode regime, in which the modal properties are identical, through efficient conversion to the fundamental mode by phase-matching. We achieve efficient conversion between the multimode and single-mode domains using phase-matching between a multimode waveguide and sets of identical single-mode ring resonators [4,7]. This approach allows individual control of modes, because all channels have identical optical properties [8].

The demonstrated switch directs four data channels, consisting of two transverse electric modes, TE_0 and TE_1, at two wavelengths near 1550 nm, from its input to either of two output ports (Fig. 1a). Each of the four channels can be routed independently of each other for full switching selectivity. The switch first converts all channels into the fundamental mode through phase-matching by optimizing the width, and hence effective index, of the input multimode waveguide to match that of single-mode rings (Fig. 1b). Next, smaller rings with doubled FSRs allow for wavelength-selective switching by tuning their resonances with integrated heaters [9,10]. Finally, both the switched and through-transmitted signals are reconverted to their original modes at either multimode output.

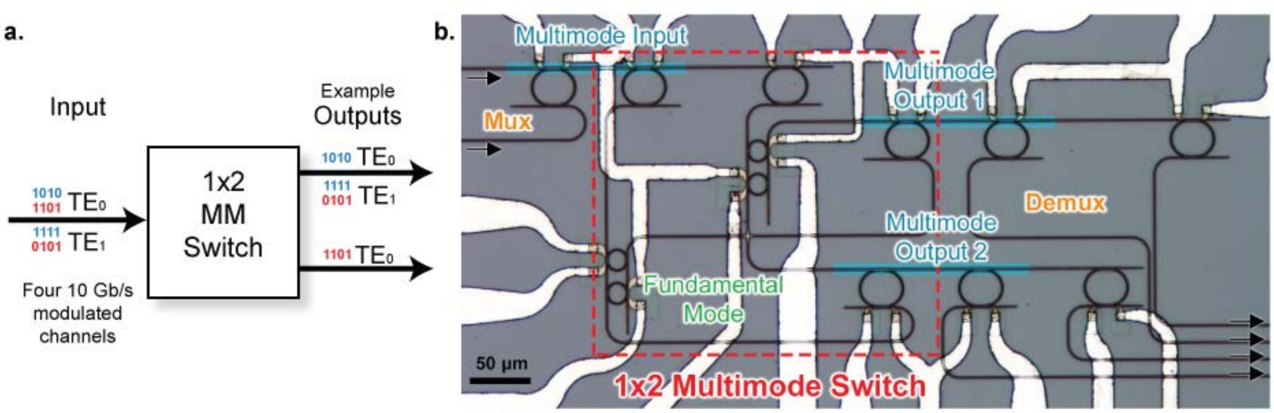

Fig. 1. (a) Block diagram of 1x2 multimode switch operation. The example shows three channels routed to Output 1 and one channel to Output 2. (b) Optical microscope image of fabricated device. The areas highlighted in blue show the multimode waveguides, which transition to single-mode by adiabatic tapering. In order to couple on and off the chip using single-mode edge coupling, its multimode input is preceded by a multiplexer and each output uses a demultiplexer.

We fabricated the switch on silicon-on-insulator (SOI) for high-confinement and compact structures. First, the 250-nm thick waveguides were patterned using electron beam lithography and etched through. The devices were then clad with SiO_2, and Ni was evaporated with a lift-off process to define the heaters. We finally sputtered Al for the metal contacts.

We observe the four individual channels switching to each output with low crosstalk and error-free data transmission. By launching one input mode at a time, we measured crosstalk between all channels lower than -20 dB, ranging from -20.1 to -28.5 dB for the worst-case state for each channel. The measured insertion loss, including on- and off-chip coupling losses, ranges from 6.0 to 9.6 dB for the four channels. Based on measured losses from test structures, the coupling loss is approximately 4.5 dB. The remaining loss of 1.5 to 5.1 dB includes (de)multiplexers in addition to the switch itself. Next, we measured transmission and switching of 10 Gb/s modulated data (Fig. 2a). For all four channels switching to each output, we observe open eye diagrams (Fig. 2b). Comparison with the back-to-back eyes confirms that the switch's output signals are bandwidth-limited, so stronger coupling with the rings should improve the rise and fall times. We finally measured the bit error rate for all channels (Fig. 2c) and show error-free switching (BER < 10^{-9}) with power penalties ranging between 0.5 and 1.4 dB.

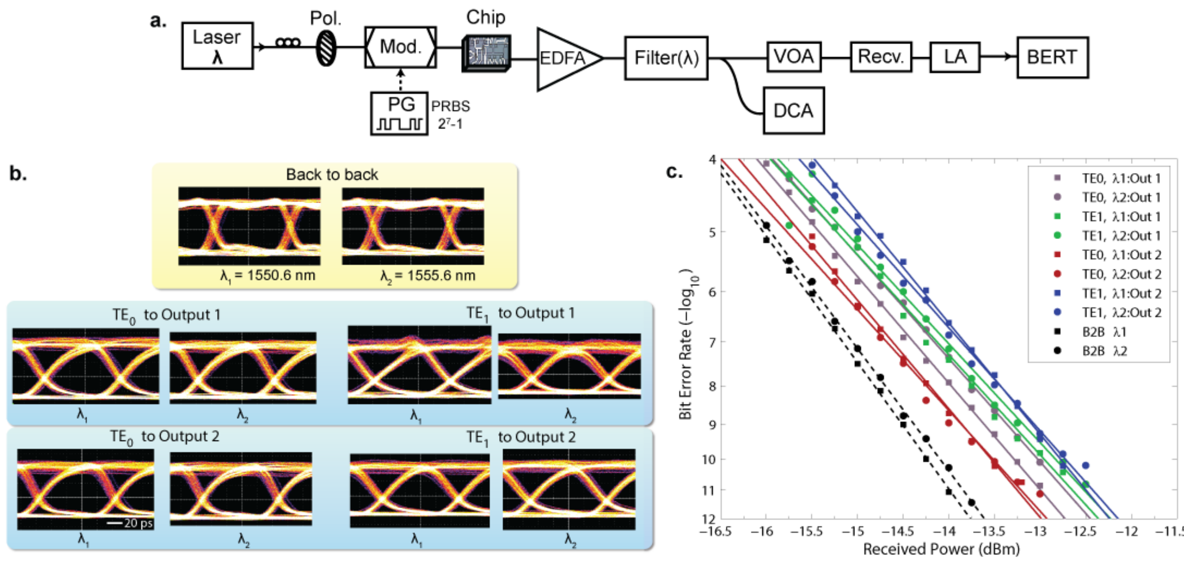

Fig. 2. (a) Test configuration, including tunable laser, electro-optic modulator (Mod.), pattern generator (PG) for a pseudo-random bit sequence (PRBS), Er-doped fiber amplifier (EDFA), tunable band-pass filter (1.4 nm), digital communications analyzer (DCA), variable optical attenuator (VOA), optical receiver (Recv.), limiting amplifier (LA), and bit-error rate tester (BERT). (b) Eye diagrams of the switched signals for all four channels at both outputs are open. (c) Bit error rate measurements show error-free transmission is achieved with power penalties ranging from 0.5-1.4 dB.

This demonstration of an integrated multimode switch establishes MDM as a viable standard for optical interconnects. As the first active device compatible with MDM and WDM, it allows unprecedented scaling of bandwidth density on silicon chips. While each multimode input or output in this demonstration carries 40 Gb/s of bandwidth (4 x 10 Gb/s), the design should be scalable to more modes (e.g. 5-10) and many more wavelengths (e.g. 80 channels). With the ability to route MDM signals with full flexibility, on-chip networks can develop for many nodes connected by high-bandwidth multimode links. The platform we present for processing multimode signals in the single-mode domain also creates the possibility for numerous future applications beyond switching.

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