Silicon 1 × 2 Mode- and Polarization-selective Switch

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Abstract: We experimentally demonstrate an on-chip silicon 1×2 switch that routes 8 data channels on 4 modes and 2 polarizations. The insertion losses are < 8dB, and the crosstalk values are below -15dB. The 8 channels are tested with a 72-Gb/s signal.

OCIS codes: (230.3120) Integrated Optics; (130.4815) Optical switching devices.

1. Introduction

The transmission capacity in an optical fiber has grown ~ tenfold every four years [1]. Multiple dimensions of an optical carrier, including time, wavelength, polarization, amplitude and phase, have been employed to increase the data rate. Mode-division multiplexing (MDM) offers a new dimension to increase capacity by utilizing the spatial modes of fibers or waveguides. MDM communications were demonstrated in few-mode fibers [2] and silicon photonic integrated circuits [3].

At network nodes, switching of data signals from an input to output ports is an essential requirement. Wavelength selective switches (WSS's) have been studied and deployed in systems. A recent study used MDM signals on different wavelengths to enable 4-channel switching [4]. However, to date there has been no report on any selective switch to route mode- and polarization-multiplexed signals at the same wavelength.

In this paper, for the first time to the best of our knowledge, we experimentally demonstrate an on-chip silicon 1 × 2 mode- and polarization- selective switch (MPSS) operating on one wavelength. In analogy to a 1 x k WSS that routes any wavelength channel from an input port to any one of the k output ports, our 1 x 2 MPSS can dynamically route a selected subset of 8 data channels on 4 modes and 2 polarizations to one of the two output ports. In this MPSS chip, the insertion losses are lower than 8 dB, and the crosstalk values remain below -15 dB for all channels at 1550 nm. The 8 channels are tested with an optical signal in the format of intensity-modulated direct-detection orthogonal frequency division multiplexing (IM-DD-OFDM) with quadrature amplitude modulation (QAM) having a net data rate of 72 Gb/s. This signal is injected into the chip, routed through each channel of the 1 × 2 MPSS, and tested in bit error ratio (BER) performance. Furthermore, the capacity of the switch can be scaled by 8 times when combining with conventional WDM technology, creating a new mode-polarization-wavelength selective switch (MPWSS) architecture.

2. Device structure and operation principle

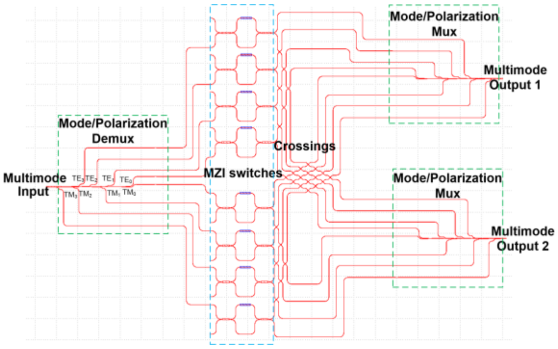

Fig. 1 Schematic configuration of the 1 × 2 MPSS for 4 modes and 2 polarizations.

The schematic configuration of the 1 × 2 MPSS for 4 modes and 2 polarizations is sketched in Fig. 1, which can route 8 channels of TE_0 ~ TE_3 and TM_0 ~ TM_3. The MPSS consists of a polarization beam splitter (PBS), a mode de-multiplexer, 8 1 × 2 thermo-optic Mach-Zehnder interferometer (MZI) switches, 28 waveguide crossings, 2 polarization beam combiners (PBCs), and 2 mode multiplexers. Signals carried by the mode- and polarization-channels are inputted from the multimode bus waveguide and de-multiplexed into 8 channels by the PBS and the mode de-multiplexer. Each channel is then routed by the corresponding TE_0 or TM_0 MZI switch. The designs of the PBS/PBC, the mode multiplexer, and the thermo-optic MZI switch are optimized based on Refs. [5, 6]. The PBS is

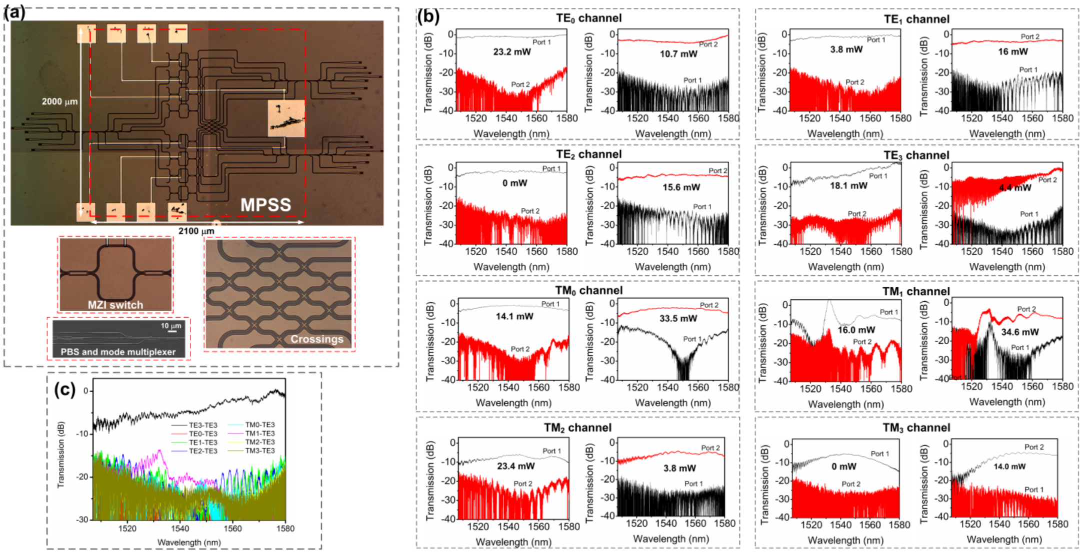

Fig. 2 (a) Photos of the fabricated silicon 1 × 2 MPSS for 4 modes and 2 polarizations. (b) Measured transmission spectra at the two output ports of the 8 channels of the MPSS, respectively. (c) Measured inter-modal crosstalk of the TE$_3$ channel.

implemented by a three-waveguide coupler consisting of two narrow waveguides (w_1 = 0.4 μm) and a wide waveguide (w_2 = 1.035 μm). The mode multiplexers are realized by cascaded directional couplers consisting of a narrow access waveguide and a multimode bus waveguide. The widths of the multimode waveguides for the TE$_1$ ~ TE$_3$ and the TM$_1$ ~ TM$_3$ channels are 0.845, 1.299, 1.693, and 1.045, 1.720, 2.423 μm, respectively. The waveguide crossings based on multi-mode interferometer (MMI) are designed to achieve low loss and crosstalk by 3D-FDTD simulations, with the width and length of the MMI optimized to be 1.73 μm (1.73 μm) and 7.84 μm (6.14 μm) for the TE$_0$-TE$_0$ (TM$_0$-TM$_0$) case, respectively.

3. Device fabrication and characterization

The devices were fabricated on a SOI wafer (220-nm-thick silicon on 3-μm-thick SiO$_2$) by E-beam lithography (Vistec EBPG 5200) and inductively coupled plasma (ICP) etching. A 1-μm-thick SiO$_2$ cladding was deposited using plasma enhanced chemical vapor deposition (PECVD). 100-nm-thick Ti heaters and 1-μm-thick Al contact pads were formed by the lift-off process. The microscope photo of a fabricated MPSS chip is shown in Fig. 2(a). The insets depict the microscope and scanning electron microscope images of the mode multiplexer, the thermo-optic MZI switch, the PBS and the crossings. The footprint of the MPSS is less than 2100 μm × 2000 μm.

In order to couple signals in and out of the chip using grating couplers, a mode (de)multiplexer is added to the input(output) port of the MPSS. The transmission spectra of the MPSS were measured and normalized to that of identical grating couplers and mode (de)multiplexers fabricated on the same chip. A tunable continuous wave (CW) laser (Keysight 81960A) and an optical power meter were used to characterize the device. The measured transmission spectra of the 8 channels are provided in Fig. 2(b), respectively. Taking the TE$_0$ channel as an example, the optical signal is switched to output port 1 when the MZI heating power is 23.2 mW. The signal goes to output port 2 when the applied heating power is 10.7 mW. The insertion loss is < 3.5 dB, and the intra-modal crosstalk value is below -21 dB at 1550 nm. For all the other channels, the optical signals can be routed to one of the output ports independently by driving the MZI switches with different powers, respectively. The insertion losses are < 8 dB, and the intra-modal crosstalk values are below -16 dB for all the channels at 1550 nm. For the inter-modal crosstalk, the TE$_3$ channel exhibits the worst performance in the mode multiplexer [5]. The measured inter-modal crosstalk value at 1550 nm is < -15 dB, as shown in Fig. 2(c). The PBSs can be used to reduce the inter-modal crosstalk [7].

4. Switching experiment and discussions

The experimental setup for the on-chip MPSS demonstration is shown in Fig. 3(a). A CW light at 1550 nm from the tunable laser is launched into a 25-GHz Mach-Zehnder modulator (MZM) (FTM7939EK). The MZM is biased at the quadrature point and modulated by an electrical 40-GSa/s IM-DD-OFDM-32-QAM signal. The OFDM signal is generated by an arbitrary waveform generator (AWG) (Keysight M8195A) with a resampling process. At the transmitter-digital signal processor (Tx-DSP), the overheads for synchronization, equalization, cycle prefix, guard band at low frequency and optimization [8] are 0.1%, 3.9%, 1.9%, 1.5%, 1.5%, respectively. The raw data rate of the output signal is 91.2Gb/s. Then an erbium doped fiber amplifier (EDFA) amplifies the output signal of the MZM.

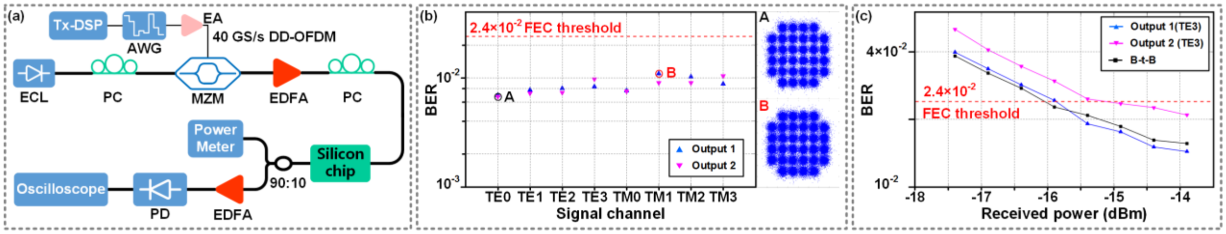

Fig. 3 (a) Experimental setup. ECL: external cavity laser. PC: polarization controller. EA: electrical amplifier. (b) Measured BERs of the OFDM-32-QAM signals. (c) BER curves versus received power.

The amplified signal is injected into the MPSS by a grating coupler. We tested one input port at a time due to the lack of a fiber array. On-chip optical signal switching was achieved. The output signal was coupled out, amplified, detected by a 40-GHz photodetector (PD, XPDV2120R) and followed by an 80-GSa/s real-time oscilloscope (Lecroy LabMaster 10-36Zi-A) for data collection.

All the channels were measured with the same optical powers at the input ports of the chip, and they exhibit similar performances, as shown in Fig. 3(b). The BERs are below the threshold of 2.4×10^{-2} for third-generation soft-decision forward error correction (FEC) with a 20% overhead [9]. Hence, a net data rate of 91.2 × (1-20%) = 72.9 Gb/s is achieved and the routing capacity of the MPSS is 8 × 72.9 = 583.2 Gbit/s at a single wavelength. The relatively high raw BER is mainly attributed to the limited resolution of the electronic AWG (6 bits). We measured the power penalty of the TE_3 channel having the worst inter-modal crosstalk performance. As seen in Fig. 3(c), the power penalties of the signal through two output ports are approximately 0.2 dB and 0.9 dB, respectively.

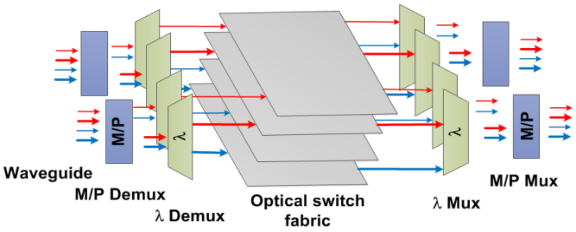

Fig. 4 Schematic configuration of the proposed MPWSS.

The capacity of the switch can be further increased when combining with conventional WDM technology. Such a new MPWSS architecture is shown in Fig. 4. Mode and polarization de-multiplexers are placed before the wavelength de-multiplexers as the latter ones are single mode devices. Thus, compared to a conventional WSS, the MPWSS capacity could be effectively increased by a factor of the mode- and polarization-channel count, i.e., an 8-times increase based on this particular work while maintaining the same switching granularity. Mode adapters are needed to interface with few mode fibers off the chip for external communications.

5. Conclusions

To the best of our knowledge, we experimentally demonstrate the first on-chip silicon 1 × 2 MPSS operating on one wavelength, which can dynamically route 8 channels on 4 modes and 2 polarizations. The insertion losses are < 8 dB, and the crosstalk values are below -15 dB. The 8 channels are tested with a 72-Gb/s signal. We further propose a new MPWSS architecture.

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