Demonstration of 160 Gb/s On-chip Mode-division Multiplexing Transmission

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Abstract: We experimentally demonstrate 160 Gbit/s on-chip mode-multiplexed transmission over a multimode silicon-on-insulator (SOI) waveguide using four spatial and polarization modes. 4×4 MIMO-based DSP is used to compensate mode coupling.

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1. Introduction

Mode-division multiplexing (MDM) enhances the capacity of optical communication by transmitting independent optical signals in parallel over multiple spatial modes. MDM transmission over a multimode fiber (MMF) using 36 spatial modes has been demonstrated for long-distance transmission, where multiple-in-multiple-output (MIMO)-based digital signal processing (DSP) is applied to undo modal coupling [1]. On-chip MDM has the potential to achieve high-capacity optical interconnects for data center and high-performance computing applications [2]. However, the performance of the integrated mode (de)multiplexer (MMUX) for high-order modes is sensitive to fabrication variations, which currently limits the total mode count of on-chip MDM transmission [3].

In this paper, we demonstrate an on-chip MDM transmission using MIMO-based DSP to undo mode coupling for the first time. We realize 160 Gbit/s QPSK transmission over a silicon-on-insulator (SOI) multimode waveguide supporting four spatial and polarization modes: TE_0, TE_1, TM_0, and TM_1. This work presents the potential for on-chip MDM with a large mode count.

2. Fabricated On-Chip MDM Device

Figure 1(a) shows the 3D configuration of vertical chip coupling and the on-chip MDM device. Photonic integrated MDM device was fabricated on a SOI wafer by electron-beam lithography and inductively coupled plasma (ICP) etching. Figure 1(b) shows the microscope photo of the fabricated device. Two TE_0 modes and two TM_0 modes are injected into the four input ports, and mode-multiplexed by the polarization beam combiner (PBC) and MMUX. The mode-multiplexed signals are then transmitted over a multimode bus waveguide with a 665-μm length and a 1.5-μm width, along with two multimode bends with a 45-μm bending radius. Different modes are then separated by a polarization beam splitter (PBS) and MMUX at the output. We measured the transmission spectra for all four

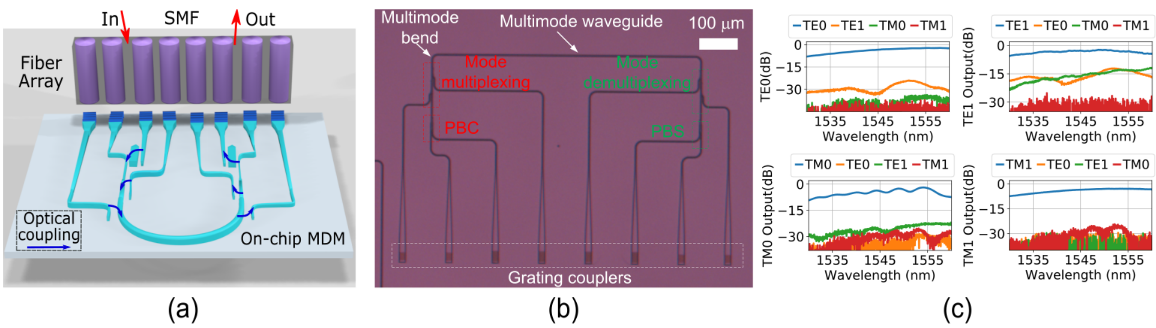

Fig. 1: (a) Schematic drawing of vertical coupling and integrated MDM device, (b) microscope photo of the fabricated mode (de)multiplexing chip, and (c) measured transmission spectra at the four output ports when light is injected into each input port for the TE_0, TE_1, TM_0, and TM_1 mode.

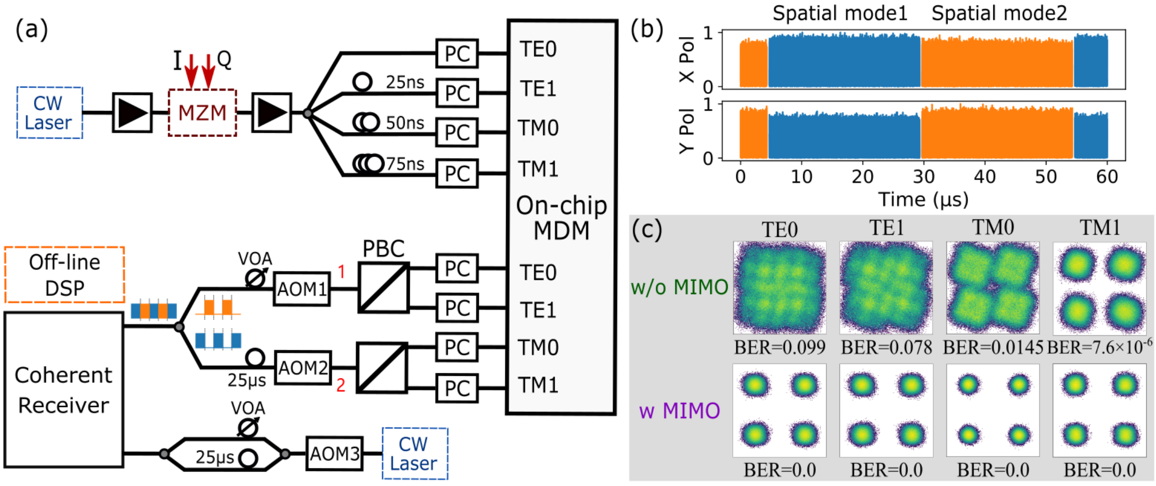

Fig. 2: (a) Setup for on-chip MDM transmission using a TDM receiver and MIMO-based DSP, (b) amplitudes of the two temporally stitched waveforms for the two spatial modes (each spatial mode has two polarization states, and (c) BERs and constellations of the QPSK signals without MIMO (upper) and with MIMO (lower) for the four modes.

outputs by launching light into one input port. The insertion loss and inter-modal crosstalk between the channels are shown in Fig. 1(c). Compared to the other modes, TE_1 mode experiences largest crosstalks at 1553 nm around -6.5 dB.

3. On-chip Mode Multiplexing Transmission

The experimental setup is shown in Fig. 2(a). The light from a tunable CW laser with a 100-kHz linewidth at the wavelength of 1553 nm is modulated by an Inphase and Quadrature (IQ) Mach-Zehnder modulator (MZM) to produce a 20-Gbaud QPSK signal. The amplified signal is split into four and decorrelated with a delay increment of 25 ns, producing 4 copies of the signal which are coupled into the four input ports of the integrated MMUX. Polarization controllers (PCs) are applied to align the input polarization to minimize the coupling loss from the grating couplers. Two transverse modes from the MDM chip are multiplexed after being coupled into the two polarization states of a single mode fiber (SMF) using a PBC. In order to extend the number of simultaneous reception using only one polarization-diversity coherent receiver, the transmitted signals are detected using a time division multiplexing (TDM) scheme [4], which is described as follows. Three acousto-optic modulators (AOM) operated at 50% duty cycle are used as the time gates after the demultiplexer, where the signals are allowed to pass at selected time slots. The AOMs are driven by a 20-kHz square-wave radio frequency (RF) signal. AOM1 and AOM2 act as the gates for the input 1 and 2. A 5-km SMF is used to delay the input 2, which results in a 25 μs time delay. In order to balance the optical power of the two inputs, the input 1 path is attenuated by a variable optical attenuator (VOA). The two spatial modes are captured by a polarization-diversity coherent receiver in sequence at two neighbouring time slots, as shown in Fig. 2(b). The local oscillator (LO) path is gated and delayed in a similar manner to eliminate the impact from the LO phase variations on system performance. In the off-line DSP, the four spatial and polariztaion modes (TE_0, TE_1, TM_0, and TM_1) are reconstructed from the two temporally delayed spatial modes. The mode-multiplexed signals are recovered using a frequency-domain 4×4 MIMO equalizer with 1024 symbol-spaced taps using the data-aided least-mean-square (LMS) algorithm. BERs and constellations of the QPSK signals without MIMO (upper) and with MIMO (lower) for the four modes are shown in Fig. 2(c), which shows the effectiveness of the MIMO-based DSP in compensating the modal coupling.

4. Conclusions

We experimentally demonstrated on-chip MDM transmission with mode coupling compensation using 4×4 MIMO-based DSP, which paves the way for high-capacity optical interconnects using many spatial modes with non-negligible modal crosstalk.

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