On-Chip Mode-division Multiplexing with Modal Crosstalk Mitigation

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Abstract: We experimentally demonstrate modal crosstalk mitigation over an on-chip mode-division multiplexing link employing low-coherence matched detection. 20-Gbaud QPSK and 8-PSK mode-multiplexed signals are successfully transmitted with a maximum modal crosstalk of -6.5 dB. © 2020 The Author(s)

OCIS codes: (060.1660) Coherent communications; (130.3120) Integrated optics devices.

1. Introduction

On-chip mode-division multiplexing (MDM) has shown great potential for high-capacity optical interconnects in data center and high-performance computing applications [1]. Integrated mode (de)multiplexer (MMUX) supporting a few modes can usually achieve low modal crosstalk < -15 dB [2]. Recently, efforts have been placed on multiplexing more high-order modes to increase the total mode count to 10 [3]. However, these devices perform significantly worse with the increase of the mode count, exhibiting increased modal crosstalk of more than -10 dB. The performance of the MMUX for high-order modes is more sensitive to fabrication errors [3], which makes it difficult to further scale up the system capacity without using multiple-in-multiple-output (MIMO) digital signal processing (DSP) at the the receiver to undo modal coupling [4]. It is also challenging to tightly bend the multimode waveguides for compact routing due to the mode mismatch between the straight and the bent multimode waveguides. To tackle the bending issues, dedicated designs requiring high-precision fabrication have been investigated [5, 6].

In this paper, we propose to mitigate on-chip modal crosstalk using low-coherence matched detection, which relies on the short coherence length property of amplified spontaneous emission (ASE) noise [7]. We achieved a line rate of 180 Gbit/s mode-multiplexed 8 phase-shift keying (8-PSK) transmission over a silicon-on-insulator (SOI) multimode waveguide supporting 4 spatial and polarization modes: $\mathbf{TE_0}$, $\mathbf{TE_1}$, $\mathbf{TM_0}$, and $\mathbf{TM_1}$ modes. No MIMO-based DSP is applied in signal recovery even though the worst-case modal crosstalk is larger than -7 dB. This proof-of-concept demonstration shows the potential to achieve on-chip MDM transmission with a large mode count immune to modal crosstalk introduced either from the MMUX or waveguide bending.

2. On-Chip MDM Circuit and Modal Crosstalk Mitigation

Figure 1(a) shows the 3D configuration of the on-chip MDM and its vertical chip coupling. Photonic integrated MDM device was fabricated on a silicon-on-insulator (SOI) wafer (220-nm-thick silicon on 3000-nm-thick silica) by electron-beam lithography (Vistec EBPG 5200$^+$) and inductively coupled plasma (ICP) etching. A 1-μm-thick SiO2 cladding was deposited using plasma enhanced chemical vapor deposition (PECVD). A microscope photo of the fabricated device is shown in Fig. 1(b). Figure 1(c) depicts the magnified scanning electron microscope (SEM) image of an integrated polarization beam combiner (PBC) and MMUX. The PBC is based on directional couplers that are used to separate or combine the $\mathbf{TE_0}$ and $\mathbf{TM_0}$ polarizations. The MMUX is implemented by two asymmetric directional couplers to (de)multiplex the high-order modes ($\mathbf{TE_1}$ and $\mathbf{TM_1}$) [8]. Four fundamental modes (two $\mathbf{TE_0}$ modes and two $\mathbf{TM_0}$ modes) are injected into the four input ports, and mode-multiplexed by the 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 another set of PBC and MMUX at the output.

A 24-channel 127-μm-pitch fiber array is mounted on the silicon chip using ultra-violet (UV) light curable adhesive. The fiber-to-chip coupling loss is around 5.7 dB per facet. The measured insertion losses of the PBC are

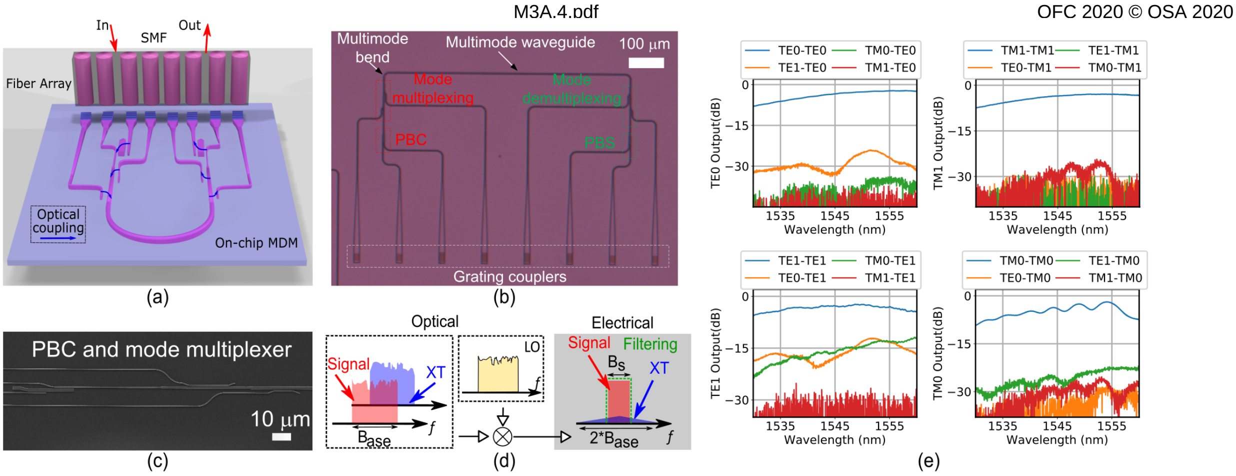

Fig. 1: (a) Schematic drawing of vertical coupling and integrated MDM device, (b) microscope photo of the fabricated mode (de)multiplexing chip, (c) magnified SEM image of a PBC and a mode multiplexer, (d) schematic of crosstalk mitigation using low-coherence matched detection ($\mathbf{B_s}$: electrical signal bandwidth and $\mathbf{B_{ase}}$: optical bandwidth of the ASE source), and (e) measured transmission spectra at the four output ports when light is injected into each input port for the $\mathbf{TE_0}$, $\mathbf{TE_1}$, $\mathbf{TM_0}$, and $\mathbf{TM_1}$ mode.

0.21 and 0.54 dB for the $\mathbf{TE_0}$ and $\mathbf{TM_0}$ polarization, respectively. The insertion losses of the MMUX at 1550 nm are 2.62 and 1.56 dB for the $\mathbf{TE_1}$ and $\mathbf{TM_1}$ mode, respectively. We measured the inter-modal crosstalk between the channels by launching light into one input port and measuring optical spectra at all outputs. The transmission spectra for all four outputs are shown in Fig. 1(e). Compared to the other modes, $\mathbf{TE_1}$ mode experiences largest crosstalks at 1553 nm around -6.5 dB, which will introduce a substantial penalty in conventional optical coherent detection as the in-band crosstalk [9].

In order to mitigate modal crosstalk, we choose to use low-coherence matched detection [7], where continuous wave (CW) light sources can be avoided and only a cost-efficient broadband ASE noise source is needed, used as both the signal carrier and local oscillator (LO). Due to the randomness of the ASE noise, small temporal delays between the modes can be sufficient to unmatch the waveforms. Signals coupled from co-propagation modes will spread over a broad frequency range ($2\times\mathbf{B_{ase}}$, where $\mathbf{B_{ase}}$ is the bandwidth of the ASE source) due to waveform mismatch after matched detection, as illustrated in Fig. 1(d). As the ratio between the electrical signal bandwidth $\mathbf{B_s}$ and $\mathbf{B_{ase}}$ is small, a large amount of crosstalk power will be removed with electrical spectral filtering which significantly reduces the in-band crosstalk.

3. Experimental Setup and Results

The setup to demonstrate on-chip MDM transmission with modal crosstalk mitigation using low-coherence matched detection is shown in Fig. 2(a), and the photo of the packaged device is given in Fig. 2(b). An optical switch is used at the transmitter to switch between a tunable CW laser with a 100-kHz linewidth for conventional coherent detection and a low-coherence broadband source, produced by a filtered ASE noise for low-coherence matched detection. One copy of the source was modulated by an Inphase and Quadrature (IQ) Mach-Zehnder modulator (MZM) to generate a 20-Gbaud QPSK or an 8-PSK signal, while the other copy was used as the LO for matched detection at the receiver. We transmitted the LO on the $\mathbf{TM_1}$ mode and 3 decorrelated signals over the $\mathbf{TE_0}$, $\mathbf{TE_1}$ and $\mathbf{TM_1}$ modes. 1-m and 2-m SMF was used for decorrelating the signals and unmatching the waveforms, respectively. Four polarization controllers (PCs) were used to align the input polarization to minimize the coupling loss from the grating couplers. An optical switch at the receiver was used to select one of the three

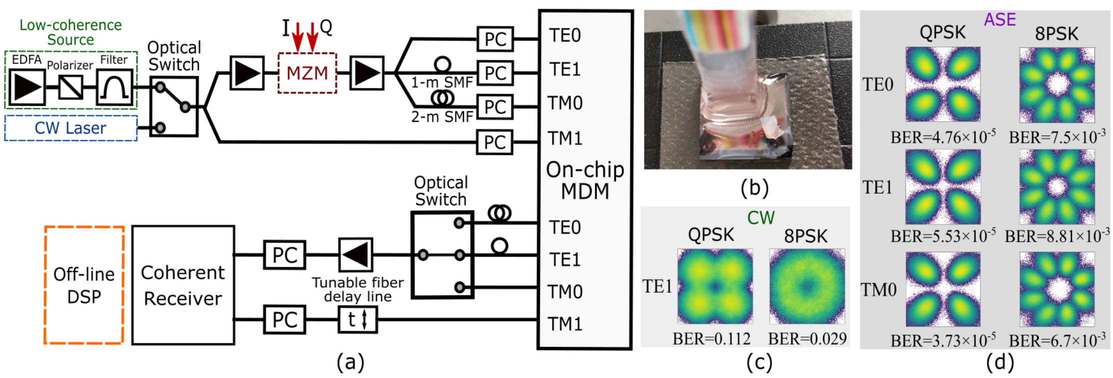

Fig. 2: (a) Setup for on-chip MDM transmission with modal crosstalk mitigation employing low-coherence matched detection, (b) photo of the fully packaged MDM circuit, BER and constellation of QPSK and 8-PSK signals using (c) conventional coherence detection using CW light for the $\mathbf{TE_1}$ mode and (d) low-coherence matched detection with $\mathbf{B_{ase}}$=3 nm for the three modes.

modes for detection. A tunable fiber delay line was used at the LO path to better match the delay. Off-line DSP including downsampling, timing synchronization, frequency offset compensation, optical carrier recovery and BER calculation is applied for signal recovery. MIMO-based DSP, which is usually applied to equalize mode coupling in conventional coherent detection is avoided.

To compare the performance of the two detection schemes, the central wavelengths of the CW laser and the ASE source were both set to 1553 nm, where the maximum modal crosstalk occurs. BER and recovered signal constellations for both detection schemes are given in Fig. 2(c) and (d). Strong modal crosstalk dramatically degraded system performance in the conventional coherent detection. However, both QPSK and 8-PSK signals can be properly recovered in low-coherence matched detection for all the three modes using an ASE source with a bandwidth $\mathbf{B_{ase}}$ of 3 nm, which confirms its capability in optical crosstalk mitigation. Figure 3(a) and (b) show the measured BERs of both QPSK and 8-PSK signals for the $\mathbf{TE_1}$ mode as the central wavelength is scanned from 1530 nm to 1560 nm. It can be observed that matched detection always provides a better performance and the achieved BERs are consistent over the whole C band and below 2×10^{-4} and 2×10^{-2} for the QPSK and the 8-PSK signal, respectively. The BER curve of the conventional coherent detection follows the summed crosstalk from the other three modes. It indicates that the system performance is mainly limited by the crosstalk. Figure 3(c) and (d) show the measured BER as a function of $\mathbf{B_{ase}}$ in matched detection at different central wavelengths. It can be observed that the optimum $\mathbf{B_{ase}}$ for both modulation formats is around 3 nm. Ideally, larger $\mathbf{B_{ase}}$ should be beneficial in improving system performance since a wider spectrum spread after matched detection can further lower the crosstalk power within the electrical signal bandwidth, which is experimentally confirmed as $\mathbf{B_{ase}}$ is gradually increased to 3 nm. As $\mathbf{B_{ase}}$ further increases, the performance starts to degrade, which can be attributed to the mode-dependent dispersion that distorts the waveform more extensively as the bandwidth gets larger.

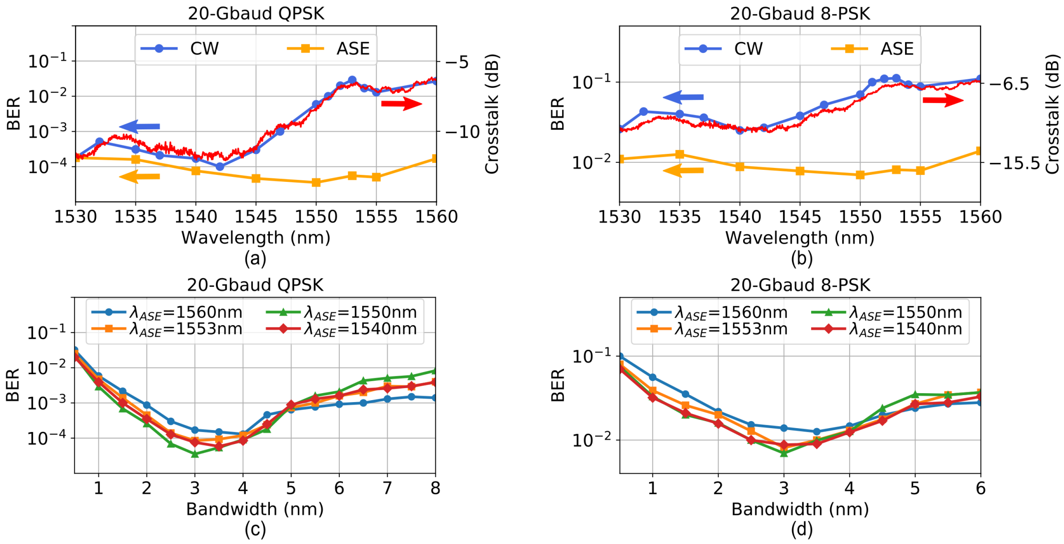

Fig. 3: Measured BER as a function of source central wavelength of (a) QPSK and (b) 8-PSK signal for both conventional coherent detection and low-coherence matched detection with $\mathbf{B_{ase}}$=3 nm, BER versus $\mathbf{B_{ase}}$ of (c) QPSK and (d) 8-PSK signal at different central wavelengths.

4. Conclusion

We successfully demonstrated on-chip modal crosstalk mitigation employing low-coherence matched detection, which can potentially enable on-chip MDM with a large mode count while avoiding joint MIMO processing.

This work was supported in part by the National Natural Science Foundation of China (Project No. 61420106011, 61635006, 61601277, 61601279, 61835008) and the Science and Technology Commission of Shanghai Municipality (Project No. 17010500400, 18511103400).

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