A 260 Gb/s/λ PDM Link with Silicon Photonic Dual-Polarization Transmitter and Polarization Demultiplexer

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Abstract *We demonstrate a silicon-photonic dual-polarization transmitter with an integrated on-chip laser, transmitting 260 Gb/s PAM-4 data on a single wavelength carrier, and a single-chip polarization demultiplexer, recovering the polarization multiplexed signals with a TDECQ of 3.0 dB for both polarizations.*

Introduction

Silicon photonics technology has been increasingly employed to meet the demand of explosive bandwidth growth in data center interconnects [1, 2]. As the industry moves towards next-generation optical networks at 400 Gb/s and beyond, new silicon photonics designs are required to support the higher per-channel data capacity. One possible solution is to continue improving the modulator performance and increase the data rate beyond 100 Gbaud. As a result, 128 Gb/s NRZ [3] and 200 Gb/s PAM-4 [4] per channel data rate using silicon micro-ring modulators have been reported recently. Another attractive approach is polarization division multiplexing (PDM), where two data streams are transmitted on two orthogonal polarizations to double the data rate in one wavelength channel. For example, a dual-polarization silicon transmitter supporting 256 Gb/s PAM-4 data transmission has been previously demonstrated using an off-chip light source and polarization demultiplexer with discrete components, as well as off-line signal processing [5].

We report a PDM link including a silicon photonic dual-polarization transmitter with an on-chip laser and an on-chip polarization demultiplexer, achieving 260 Gb/s PAM-4 data transmission on a single wavelength. The demultiplexed eye diagrams showed a TDECQ of 3.0 dB for each of the two polarizations without any off-line signal processing.

Integrated Dual-Polarization Transmitter and Polarization Demultiplexer

The schematic of the on-chip dual-polarization transmitter and the polarization demultiplexer (demux) chips are illustrated in Fig. 1. In the transmitter, an on-chip hybrid laser [1,2] serves as the light source with TE polarization. The light power is split equally into two paths. A micro-ring modulator (MRM) in each path modulates the input light and encodes data. A polarization rotator (PR) is used to rotate the polarization of one of the data paths from TE to TM polarization. Then, the two data paths with orthogonal polarizations are combined by a polarization beam combiner (PBC) into a single waveguide and coupled into a single-mode fiber (SMF) through a polarization-insensitive optical coupler (OC). The polarization demux chip consists of a polarization-splitter-rotator (PSR) and a Mach-Zehnder interferometer (MZI) with thermo-optic phase tuners. The combination of PSR and MZI with phase tuners acts as a tunable polarization controller that can transform the input polarization into any polarization state by adjusting the phase tuners [6]. When the PDM signals, which have undergone polarization rotations in the fiber, are coupled into the demux chip, the two orthogonal polarizations can be separated by adjusting the phase tuners. They are then coupled out of the demux chip and measured by a digital communication analyzer (DCA).

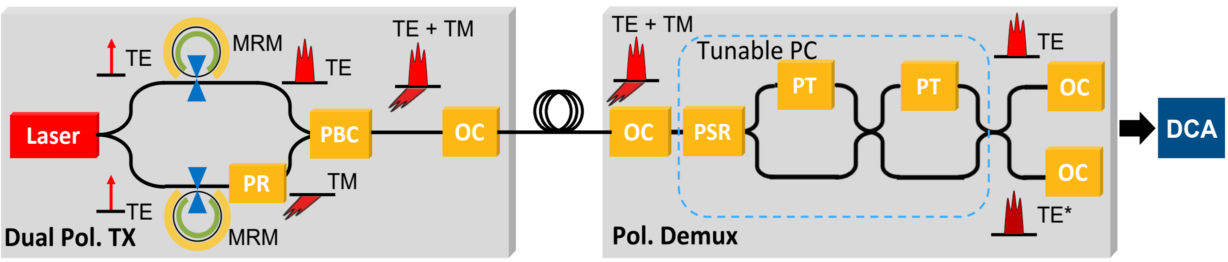

Fig. 1: Schematic of the on-chip dual-polarization transmitter (Tx) and polarization demultiplexer (demux). TE/TM: transverse electric/magnetic; MRM: micro-ring modulator; PR: polarization rotator; PBC: polarization beam combiner; PSR: polarization splitter and rotator; OC: optical coupler; PT; phase tuner. PD: photodetector; DCA: digital communication analyzer. TE*: TE light carrying the data from the TM path.

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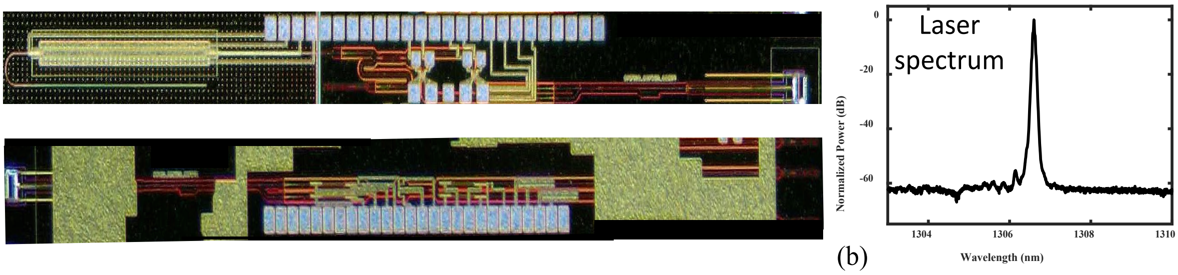

Fig. 2: (a) Microscope images of the dual-polarization transmitter and polarization demultiplexer chips. (b) Normalized optical spectrum of the integrated on-chip laser.

Fabrication and Characterization of the Dual-Polarization Transmitter and Polarization Demultiplexer

The dual-polarization transmitter and the polarization demux are fabricated using Intel's silicon photonics process. Their microscope images are shown in Fig. 2(a). The transmitter has an integrated hybrid laser with 13 dBm output power at 1306.7 nm (Fig. 2(b)). The two high-speed MRMs share similar design and performance with our previously reported devices [7]. The MRMs are PN-junction depletion type modulators with integrated thermo-optic phase tuners, a radius of 10 μm, and a loaded quality factor of 3500. The PR and PBC make use of adiabatic mode coupling/evolution between TM and higher order TE modes for the polarization rotating and combining functions. The PSR combines the functions of the PR and PBC but is used in the reversed direction. The polarization extinction ratio (PER) between the TE and TM modes of the PSR was measured to be 25 dB, and the tunable polarization controller consisting of the PSR and MZI has a measured insertion loss of less than 1.0 dB.

Experimental Setup and Results

The experimental setup is shown in Fig. 3. Two independent data streams with PRBS13 and PRBS15 pattern were generated from an arbitrary waveform generator (AWG) with 45 GHz analog bandwidth. The two signals were independently amplified by two RF amplifiers A high-speed GSGSG RF probe was used to apply the electrical drive signals to the two MRMs in the dual-polarization Tx. The amplified voltage swing and DC bias applied to the MRM are 2.2 V_{pp} and -3 V, respectively. The input optical power to each MRM was 10 dBm. The resonances of the MRMs were aligned to the laser wavelength using thermo-optic phase tuners [7]. The generated PDM signals in the transmitter were then coupled into a SMF of about 3-meter long through a polarization insensitive optical coupler. On the receiver side, a polarization demux chip was used to recover the transmitted data. An optical amplifier was used to compensate for the coupling losses of ~7 dB in and out of the demux chip. The demultiplexed signals were measured using a DCA with a 65-GHz optical sampling head. In addition, an off-chip polarization demultiplexer (shown in the inset of Fig. 3) was also used for comparison. The latter approach makes use of an off-the-shelf polarization controller (PC) and polarization beam splitter [5].

The results of the high-speed data transmission using the dual-polarization transmitter and on-chip polarization demux are presented in Fig. 4. Figure 4 (a) and (b) show 72 Gb/s NRZ eye diagrams of the recovered TE and TM signals after the on-chip polarization demux without any equalization. The measured SNR (Q-factor) was 3.2 for both TE and TM eye diagrams while their corresponding extinction

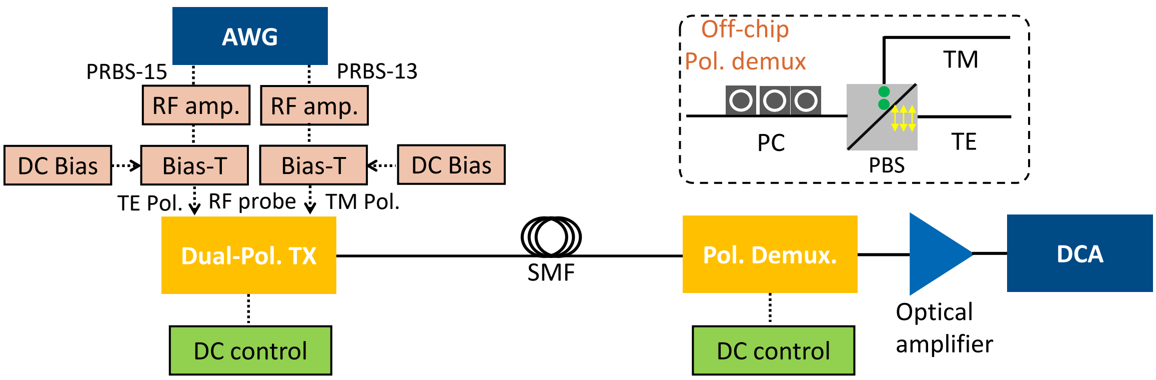

Fig. 3: Experimental setup to demonstrate data transmission using silicon photonic dual-polarization Tx and polarization demux. Inset is off-chip polarization demux. AWG: arbitrary waveform generator; SMF: single-mode fiber; PC: polarization controller; PBS: polarization beam splitter.

ratios are 3.5 and 3.0 dB, respectively. By applying a 7-tap feed-forward equalization (FFE), the SNR measurement results were improved to 6.2 for both polarization channels. We also modulated the two MRMs with 130 Gb/s PAM-4 signals, and the recovered signals using the on-chip polarization demux are shown in Fig. 5 (a). With a 5-tap equalizer, the measured TDECQ of both TE and TM signals is 3.0 dB for a target symbol error rate of 3.8 × 10-3 (hard decision - forward error correction limit). We also measured the transmitted dual-polarization signals using an off-chip demultiplexer with discrete components. Figure 5(b) compares the measured TDECQ of the PDM link for PAM-4 transmission at different data rates using on- and off-chip polarization demux. As expected, the TDECQ decreases with reduced data rate. With the on-chip polarization demux, the TDECQ of the recovered PAM-4 signals at 112 Gb/s is reduced to 2.7 dB for both polarizations. There is about 0.4 dB TDECQ penalty between the off- and on-chip polarization demux. Such penalty can be attributed to the additional noise from the optical amplifier used after the on-chip polarization demux. The data rate of 260 Gb/s is currently limited by the MRMs, which could be improved [3,4], suggesting that a single wavelength channel capacity of 200 Gb/s per polarization or 400 Gb/s per wavelength is possible

Conclusions

We have demonstrated the first integrated single-wavelength dual-polarization optical transmitter with an on-chip hybrid laser. The two high-speed MRMs in the transmitter can generate 72 Gb/s NRZ or 130 Gb/s PAM-4 signals on each of the two polarizations to achieve an aggregate data rate of 144 Gb/s and 260 Gb/s, respectively. By using an integrated single-chip polarization demux, the PDM data streams are separated, and the eye diagrams are measured with an SNR of 6.2 and a TDECQ of 3.0 dB for the NRZ and PAM-4 signals, respectively. These results indicate strong potential for silicon photonic PDM transceivers to support single-wavelength-channel data rates of 400 Gb/s and beyond for future data center interconnect.

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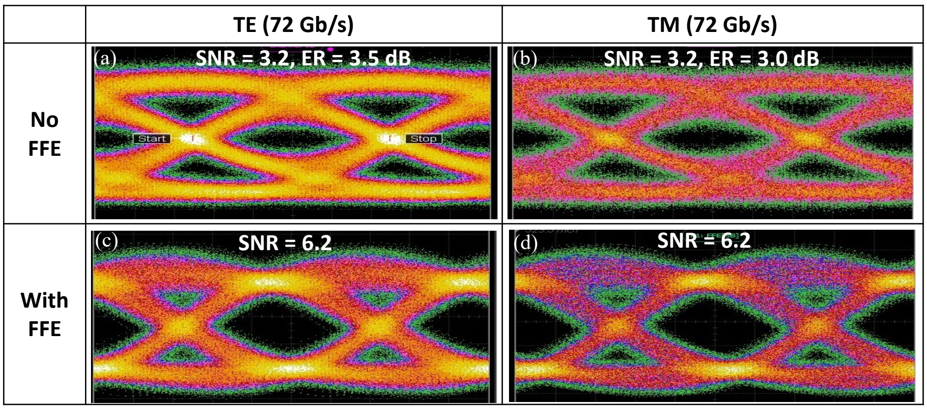

Fig. 4: 2 × 72 Gb/s NRZ eye diagrams of the demultiplexed TE and TM signals using on-chip polarization demux without (a, b) and with (c, d) FFE.

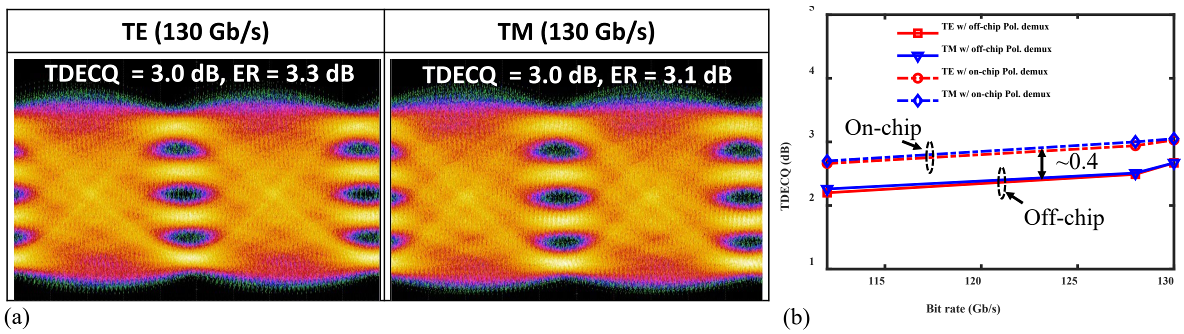

Fig. 5: (a) 2 × 130 Gb/s PAM-4 eye diagrams of the demultiplexed TE and TM signals using the on-chip polarization demux, (b) The measured TDECQ of the PDM link for PAM-4 transmission as a function of the bit rates with off- and on-chip polarization demux.

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