Single-span IM/DD Transmission over 120-km SMF with a Silicon Photonic Mach-Zehnder Modulator and THP

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Abstract: We experimentally demonstrate up to 120-km dispersion-uncompensated transmission in a SiP MZM-based IM/DD system. 28/42-Gbaud DSB PAM4 signal is transmitted over 80/120-km SMF enabled by Tomlinson-Harashima precoding and receiver-side linear equalization.

1. Introduction

The growing data traffic in mobile fronthaul and data center interconnections have driven the increasing demands of high-speed and short-reach optical transmission systems. Intensity modulation / direct detection (IM/DD) systems are attractive approaches due to their cost effectiveness and power efficiency. On the other hand, small-footprint silicon photonics (SiP) platform provides a promising solution for high-capacity integration. Recently, SiP Mach-Zehnder modulators (MZMs) have been widely applied in IM/DD systems. In [1], 176-Gb/s 4-level pulse amplitude modulation (PAM4) signal transmission over 1-km standard single mode fiber (SSMF) was achieved, with the bit error ratio (BER) below the 20% hard-decision forward error correction (HD-FEC) threshold. In [2], net 180-Gb/s PAM8 signal was transmitted over 2-km SMF with the soft-decision FEC (SD-FEC) threshold. The transmission distances of SiP MZM-based IM/DD system were mostly limited to 20 km, since the detected signals suffer power fading effect resulting from the interplay between chromatic dispersion (CD) and square-law detection of photodiode (PD). The power fading effect can be mitigated by transmitting a single sideband (SSB) signal, at the expense of IQ modulator and an increased number of digital-to-analog converter (DAC). Another solution is applying an optical bandpass filter (OBPF) to generate a vestigial sideband (VSB) signal, while the costly sharp-roll-off OBPF is required. For practical high-speed and short reach applications, extending the reach of SiP MZM-based IM/DD system without increasing the cost is highly desired. The authors in [3] demonstrated that the power fading can be effectively mitigated in digital signal processing (DSP) using feedback equalization such as decision-feedback equalization (DFE), which, however, suffers the error propagation (EP) effect. Fortunately, by placing the feedback equalization at the transmitter, the EP effect can be avoided and a more reliable transmission can be achieved; this technique is known as Tomlinson-Harashima precoding (THP) [4, 5]. To date, the THP has shown excellent performance in combating the power fading and bandwidth limitation in PAM signal transmission systems [6].

In this paper, we employ THP for improving the CD tolerance of the SiP MZM-based IM/DD system. Low-cost SiP MZM is implemented to generate the DSB PAM4 signal. The THP is applied to deal with the power fading while the inter-symbol interference (ISI) is mitigated using receiver-side linear equalization. We experimentally demonstrate a 28-Gbaud DSB PAM4 signal transmission over 120-km SMF, and a 42-Gbaud DSB PAM4 signal transmission over 80-km SMF in a SiP MZM-based IM/DD system without dispersion compensation. To the best of our knowledge, we achieve the longest single-span transmission distance of 120 km for DSB IM/DD without optical filtering and dispersion compensation based on a SiP MZM at C-band.

2. Operation principle

Fig. 1(a) depicts the schematic diagram of the THP technique. The pre coder consists of a feedback circuits and a 2M modulo operation. The feedback coefficients B(z) is obtained using EP-free-DFE in the experiment, and the 2M modulo operation constrains the output amplitudes to (-M, M], where M = 4 for PAM4 signal. The histograms of the input signal and the transmitted signal are shown in inset (i) and (ii), respectively. At the receiver, feedforward equalizer (FFE) is employed to mitigate the impairments and the equalized signal is extended, as indicated in inset (iii). Thus, the 2M modulo is required to recover the PAM4 signal, whose histogram is shown in inset (iv). Fig. 1(b) presents the micrograph of the SiP-MZM fabricated in Advanced Micro Foundry (AMF). The electrical ports are arranged in a series-push-pull fashion, and the optical waveguide arms are optically imbalanced, which enables bias adjustment through tuning the wavelength of the DFB. A 13-dB fiber to fiber insertion loss was measured. The reported bandwidth of the SiP-MZM is 35 GHz with a 0-V reverse bias voltage and 39 GHz with a 2-V reverse bias voltage, respectively. The reverse bias voltage was set to 0 V in our experiment.

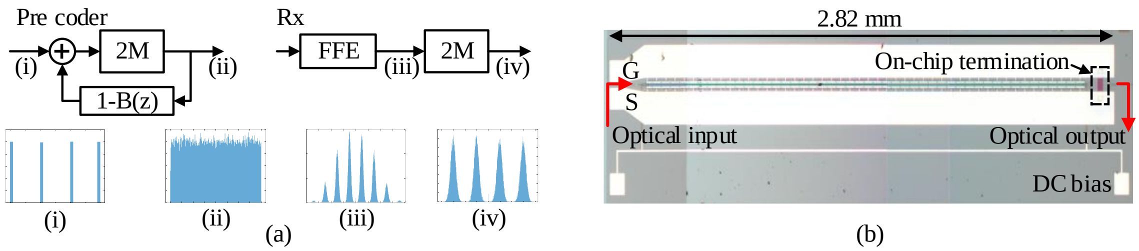

Fig. 1 (a) The schematic diagram of the THP technique. Inset (i-iv) The histograms of input signal, transmitted signal, equalized signal, and recovered signal, respectively. (b) The micrograph of the SiP-MZM.

3. Experimental setup and results

The experimental setup of the SiP-MZM-based IM/DD system is depicted in Fig. 2(a). At the transmitter side, a 10-dBm continuous light from a distributed feedback (DFB) laser is fed into the SiP-MZM, with a polarization controller (PC) aligning the polarization state of the light and the SiP-MZM. In the experiment, the wavelength of the DFB was tuned to 1549.06 nm to realize a quadrature bias condition of the SiP-MZM. A DAC (Micram DAC4) operating at 100 GSa/s is used to generate the PAM4 signal, which is amplified by a 23-dB electrical amplifier (EA) and then applied to drive the SiP-MZM. The optical modulation index is optimized through changing the DAC output amplitude. The optical signal after the SiP-MZM is boosted to different launch powers utilizing an erbium doped fiber amplifier (EDFA), and launched into 80/120-km SMF for transmission. At the receiver, the received optical power (ROP) is varied through a variable optical attenuator (VOA). Then, the signal is amplified utilizing another EDFA, followed by an OBPF to filter out the out-of-band noise. After a PD, the detected signal is captured using a digital storage oscilloscope (DSO) (LeCroy 59Zi-A) operating at 160 GSa/s. Tx and Rx digital signal processing (DSP) flow charts are presented in Fig. 2(b) and 2(c), respectively. In the Tx DSP, the PAM4 symbol stream is generated using binary data, and the synchronization and training sequences are added. Then, the THP is implemented. After being up-sampled, the signal is pulse-shaped by a root raise cosine (RRC) filter with a roll-off factor of 0.01. Finally, the signal is resampled to 100 GSa/s and sent to the DAC. At the receiver, the signal is firstly resampled to 2 samples per symbol (sps) and synchronized. Then, a $T_s/2$, T_s is the symbol duration, FFE is applied to mitigate the ISI. The 2M modulo is implemented to recover the PAM4 signal, and the BER is then calculated. In the experiment, to obtain the THP coefficients, the PAM4 signal without THP is firstly transmitted and FFE and DFE are both employed at the receiver. The feedback coefficients in the DFE is stored and applied in the transmitter-side THP. Then, the TH pre-coded signal is transmitted and recovered using only FFE at the receiver.

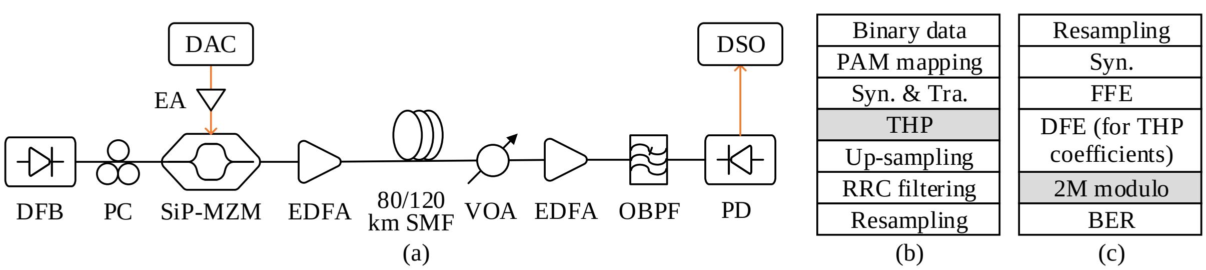

Fig. 2 (a) Experimental setup of the SiP-MZM-based IM/DD system. (b) Tx DSP flow charts. (c) Rx DSP flow charts. The THP and 2M modulo in the grey blocks are performed only if the THP is employed.

In the experiment, we optimized the parameters in the EP-free DFE condition; this is reasonable since the THP can be regarded as the transmitter-side version of EP-free DFE, thus the BER of the EP-free DFE is a reliable reference for the THP. Fig. 3(a) shows the BER versus the signal amplitude output by the DAC in two transmission scenarios: 42-Gbaud PAM4 transmission over 80-km SMF, and 28-Gbaud PAM4 signals transmission over 120-km SMF. The optimal amplitude is 500 mV for 42-Gbaud signal while 400 mV for 28-Gbaud signal. Then, at the optimal amplitude, we sweep the launch power using the EDFA in the transmitter, and the results are presented in Fig. 3(b). As indicated, a higher launch power is needed for 28-Gbaud signal to compensate the higher loss due to the longer transmission distance. The best BER performance is 1.42×10^{-2} and 1.71×10^{-2} for 42-Gbaud and 28-Gbaud signal, respectively. Provided the optimum DAC output amplitude and launch power, the feedback coefficient of THP is obtained using EP-free DFE, then the TH pre-coded signal is transmitted and detected. The electrical spectra of the detected signals are plotted in Fig. 3(c). One can observe that the power fading effect is severe after the fiber transmission for both signals. Fortunately, THP can recover the signal that suffers the power fading. Fig. 3(d) illustrates the BER as a function of ROP in two conditions. A BER of 1.79×10^{-2} is achieved for the 42-Gbaud signal transmission over 80-km SMF, and 1.99×10^{-2} for 28-Gbaud signal transmission over 120-km SMF. Compared to the results of EP-free DFE, slightly BER penalties are observed for two signals, which is due to the penalty of precoding. The inset (i) and (ii) present the histogram of the 42-GBaud PAM4 signal before and after the FFE, while the results of 28-Gbaud signal are plotted in the inset (iii) and (iv), respectively. Although the signals experience severe power fading after the transmission, they are successfully recovered with THP and receiver-side linear equalization

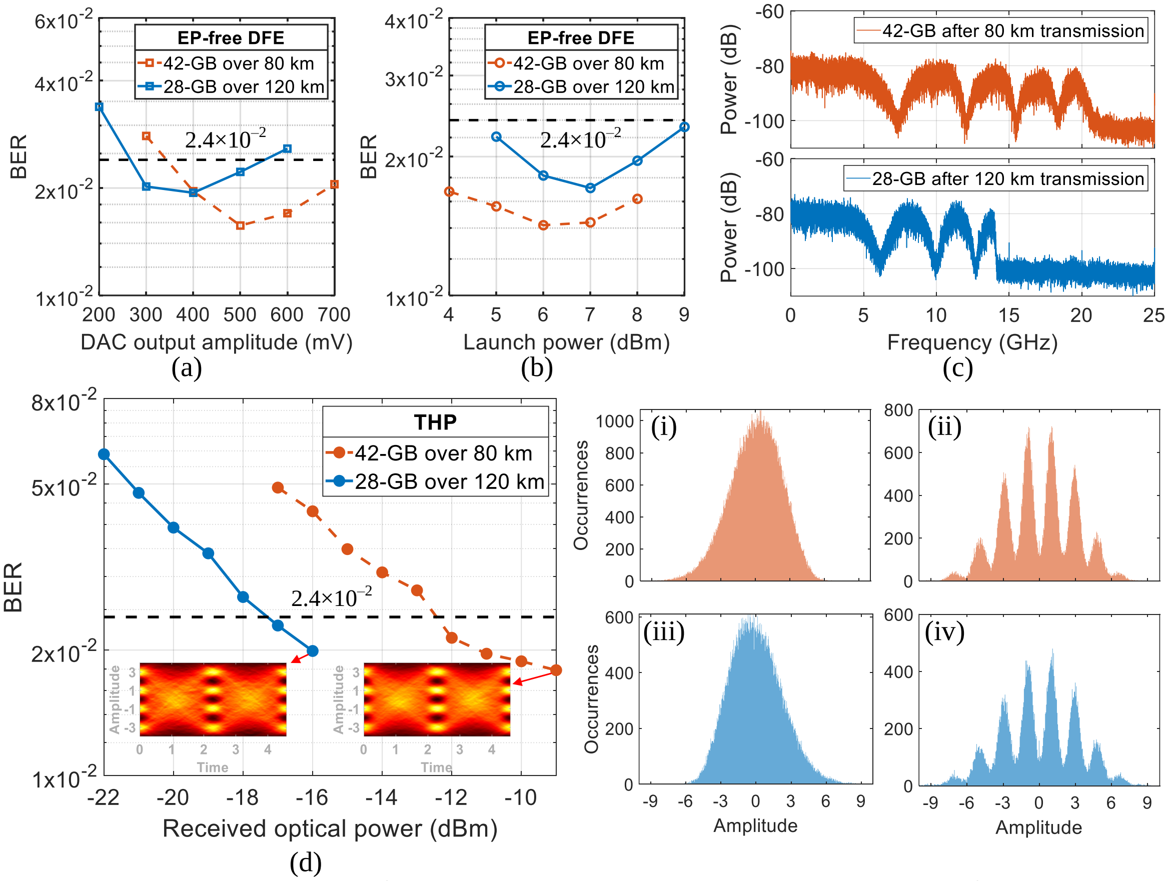

Fig. 3. (a) BER versus DAC output amplitude for 42-Gbaud and 28-Gbaud PAM4 signals. (b) BER versus launch for 42-Gbaud and 28-Gbaud PAM4 signals. (c) The detected spectra of 42-Gbaud and 28-Gbaud PAM4 signals. (d) BER versus ROP for 42-Gbaud and 28-Gbaud PAM4 signals. Inset (i-ii) The histograms of 42-Gbaud PAM4 signals before and after FFE at –9-dB ROP, respectively. Inset (iii-iv) The histograms of 28-Gbaud PAM4 signals before and after FFE at –16-dB ROP, respectively.

4. Conclusion

We utilized THP technique to extend the reach of SiP MZM-based IM/DD system. The DSB signals which suffer severe power fading can be recovered with THP and receiver-side linear equalization. We successfully transmitted 28/42-Gbaud DSB PAM4 signal over 120/80-km SMF without dispersion compensation. To our best knowledge, the longest single-span reach of 120 km is achieved for DSB SiP MZM-based IM/DD systems at C-band without optical filtering and dispersion compensation.

5. References

[1] Y. Zhu, F. Zhang, F. Yang, L. Zhang, X. Ran, Y. Li, and Z. Chen, "Toward Single Lane 200G Optical Interconnects With Silicon Photonic Modulator," J. Lightwave Technol., **38**, 67-74 (2020).
[2] M. S. Alam, X. Li, M. Jacques, Z. Xing, A. Samani, E. EI-Fiky, P-C Koh, and D. V. Plant, "Net 220 Gbps/λ IM/DD Transmssion in O-Band and C-Band With Silicon Photonic Traveling-Wave MZM," J. Lightwave Technol., **39**, 4270-4278 (2021).
[3] R. Rath, D. Clausen, S. Ohlendorf, S. Pachnicke, and W. Rosenkranz, "Tomlinson–Harashima Precoding For Dispersion Uncompensated PAM-4 Transmission With Direct-Detection," J. Lightwave Technol., **35**, 3909-3917 (2017).
[4] M. Tomlinson, "New automatic equalizer employing modulo arithmetic," Electron. Lett., vol. **7**, 138–139 (1971).
[5] H. Harashima and H. Miyakawa, "Matched-transmission technique for channels with intersymbol interference," IEEE Trans. Commun., **20**, 774-780 (1972).
[6] Q. Hu, M. Chagnon, K. Schuh, F. Buchali, and H. Bülow, "IM/DD Beyond Bandwidth Limitation for Data Center Optical Interconnects," J. Lightwave Technol., **37**, 4940-4946 (2019).