280 Gb/s IM/DD PS-PAM-8 Transmission Over 10 km SSMF at O-band For Optical Interconnects

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Abstract: We experimentally demonstrated single-lane 200G+ IM/DD PAM-*N* system at O-band using SOA and probabilistic shaping (PS) for high-speed short reach optical interconnects. 280 Gb/s PS-PAM-8 signals can transmit over 10 km SSMF.

OCIS codes: (060.2360) Fiber optics links and subsystems; (200.4650) Optical interconnects.

1. Introduction

Propelled by cloud services, the next-generation Ethernet is envisioned to be 800 GbE and/or 1.6 TbE [1]. Conventional intensity-modulation direct-detection (IM/DD) systems still dominate the market for high speed short reach optical interconnects due to its simplicity and low cost compared with coherent solutions [2]. 400GBASE-LR8 with reach up to 10 km, using 4-level pulse amplitude modulation (PAM4) and eight-lane on single-mode fiber (SMF), has been standardized for 400 GbE and is expected to be commercialized [3]. Thanks to the development of broadband electronic and optoelectronic components, it gives a possibility to achieve single-lane 200G and beyond, which can reduce the required wavelength resource and the number of required optical components substantially. Several 200G+ per lane short reach transmission experiments have been demonstrated recently, based on PAM or discrete multi-tone (DMT) with either integrated or separated lasers and modulators [4-6]. At C-band, the link distance is less than 2 km without optical chromatic dispersion (CD) compensation. At O-band, 214 Gb/s PAM4 signal transmission over 10 km SMF was demonstrated using praseodymium-doped fiber amplifier (PDFA) with larger footprints and high costs [4]. To reduce the size and cost, the integrated semiconductor optical amplifier (SOA)-PIN chip based receiver has been designed and demonstrated [5]. Meanwhile, probabilistic shaping (PS) with adaptive shaping gain has been successfully used for coherent fiber optical systems with large capacity and long distance. However, there are few reports on PS for high speed short reach systems with limited peak power [6]. SOA and PS can be potentially used for 200G+ per lane IM/DD systems at O-band over 10 km SSMF.

In this work, we experimentally demonstrated IM/DD 100 Gbaud PAM4 and PS-PAM8 signals transmission using SOA and PS. Digital time-domain pre-equalization (Pre-EQ) method is applied to mitigate the bandwidth limitation, and clipping method as an effective method is used to reduce the peak-to-average power ratio (PAPR) of PS signals. 230 Gb/s PS-PAM8 at 7% HD-FEC threshold and 280 Gb/s PS-PAM8 at 20% SD-FEC threshold can be realized after 10 km SMF transmission with the BER of 3.8×10^{-3} and 2×10^{-2}, respectively, which, to the best of our knowledge, is a new record for SMF transmission at O-band.

2. Experimental setup

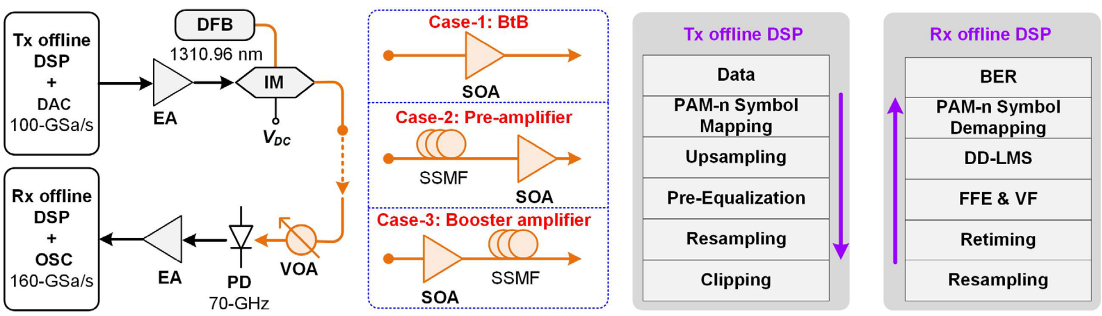

Fig.1. Experimental setup and three different transmission cases with detailed Tx and Rx offline DSP blocks.

The experimental setup and offline DSP flow are shown in Fig. 1. The transmitter consists of a DFB laser with 30 dB internal isolator and operating at 1310.96 nm, a 60 GHz IM modulator, a 65 GHz electrical amplifier (EA), and a high-speed DAC. The 100 Gbaud PAM-n drive signals are generated with the 100 GSa/s DAC (35 GHz analog bandwidth), and then amplified by the EA before driving the IM. The IM is biased at quadrature point with a laser input optical power of 7.6 dBm. Three different transmission cases are considered (case-1: BtB case with SOA and without fiber, case-2: with SOA using as a pre-amplifier, case-3: with SOA using as a booster amplifier), as shown in Fig. 1. After 10 km or 15 km SMF transmission with an average loss of 0.33 dB/km at 1310 nm, a variable optical attenuator (VOA) is used to adjust the received optical power (ROP) for sensitivity measurement to test the SOA performance. At the receiver side, the signal is detected by a 70 GHz photodiode and amplified by another 65 GHz EA, and then captured by a 160 GSa/s oscilloscope with 63 GHz bandwidth and processed by offline DSP.

In the Tx offline DSP, uniform PAM4 and PS-PAM8 are both generated. Gray-mapped regular PAM4 symbols with a length of 2^{15} are mapped; PS-PAM8 symbols with different entropies are generated by using Maxwell-Boltzmann (MB) distribution, and Gray-mapping is also used [7]. After two times oversampling and digital Pre-EQ using 19-tap feed-forward equalization (FFE) FIR, the symbol sequence is resampled to one sample per symbol and loaded to the DAC at Baud-rate sampling. Pre-EQ processing can result in higher PAPR, especially for PS-PAM8 signal, and the system performance will degrade [8]. Hence, hard clipping method is used to reduce the PAPR. In the Rx offline DSP, the captured offline data is first resampled to two samples per symbol, then a squaring time recovery is applied to remove the timing offset and jitter from the data. Afterwards, 19-tap T/2-spaced FFE, 189-tap T-spaced Volterra Filter (VF), and 189-tap T-spaced decision directed least-mean-square (DD-LMS) equalizer are used to recover signals. In order to reduce the impact of the tap number on the system performance, a larger tap number is chosen to ensure that the system has the best performance. Finally, the BER can be calculated after PAM-n demodulation based on the recovered signal. Before the fiber transmission measurement, the Pre-EQ FIR is estimated based on the transfer function of FFE equalizers under BtB case. After convergence, the FIR for Pre-EQ can be calculated from the FFE filters after normalization.

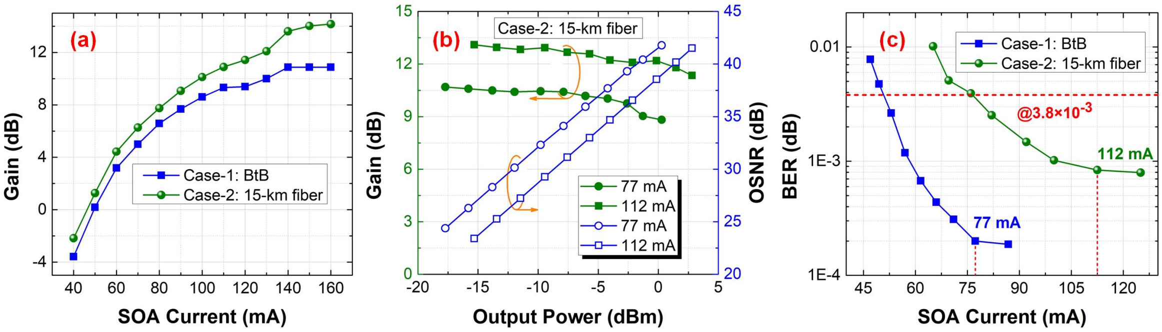

Fig.2. The performance of SOA for 100 Gbaud PAM4 signal. (a) SOA gain versus SOA bias current; (b) SOA gain and OSNR versus output power; (c) BER versus SOA bias current.

We tested the performance of SOA with 100 Gbaud PAM4 signal under case-1 and case-2. Fig. 2(a) shows that the gain of the SOA functioning as a pre-amplifier after 15 km fiber transmission is higher than BtB case, i.e., the small-signal has higher SOA gain. The SOA gain and OSNR of 100 Gbaud PAM4 signal versus optical output power of the SOA with 77 mA and 112 mA SOA bias current, are shown in Fig. 2(b). When optical output power is about 2 dBm, the peak power of input PAM4 signal does not exceed the saturation output power, and additional pattern effects cannot occur. About 2-dB SOA gain with 112 mA bias current is achieved compared with 77 mA when optical output power is about 0 dBm. However, about 2-dB OSNR improvement with 77 mA can be achieved compared with 112 mA, which is because the higher drive current induces higher ASE noise. Fig. 2(c) shows the BER performance with 100 Gbaud PAM4 versus SOA bias current. There is a trade-off between noise and nonlinear impairments. The optimum SOA operating current of 77 mA and 112 mA are then used for BtB and 15 km fiber transmission, respectively.

3. Results and discussion

Figs. 3(a) and 3(b) show the BER performance against the ROP with the 100 Gbaud PAM4 signal under case-2 and case-3, respectively. Note that, PAM4 signal does not use clipping in our fiber transmission measurement. The SOA bias current is 99 mA for 10 km fiber transmission. We keep the same SOA current for case-2 and case-3 tests. It can be observed that 200 Gb/s PAM4 was transmitted over 10 km and 15 km without any CD compensation methods under both case-2 and case-3 at 7% HD-FEC threshold. However, there exit 1.3 dB and 2.2 dB power penalty for 10 km and 15 km fiber when SOA is used as a booster amplifier, respectively. The BER performance after case-3 is slightly better than case-2 because lower SOA output power results in smaller ASE noise. Fig. 3(c) shows the optical spectra with Pre-EQ and SOA.

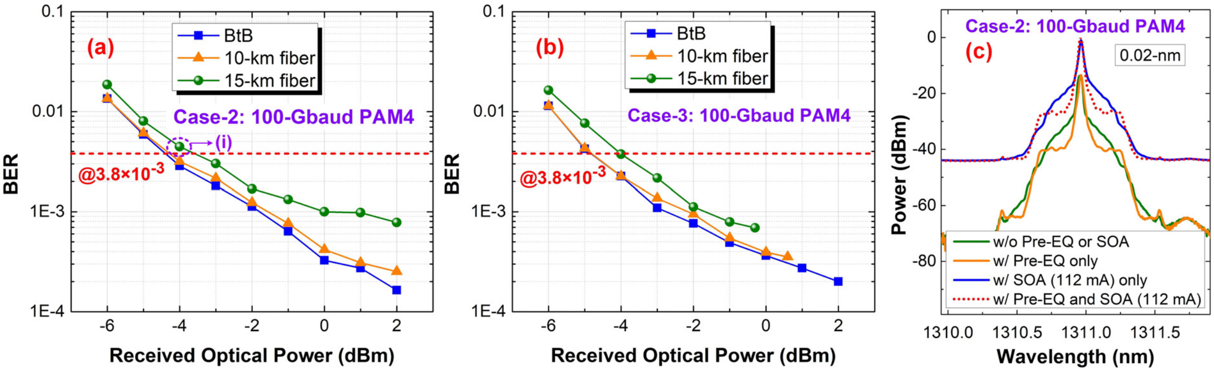

Fig. 3. Experimental results for 100Gbaud PAM4. (a) and (b) BER versus ROP under case-2 and case-3, respectively; (c) the optical spectra of 100 Gbaud PAM4 signal with different cases.

For the IM/DD systems, SOA can be used as a pre-amplifier due to high output power. Hence, for 100 Gbaud PS-PAM8 tests, only case-2 is considered. By varying shaping factor, different PS-PAM8 bit rates with different entropies are generated. Fig. 4(a) shows the BER of 100 Gbaud PS-PAM8 versus different bit rates for BtB, 10 km, and 15 km. 230 Gb/s at 7% HD-FEC threshold after 15 km fiber as well as 260 Gb/s and 280 Gb/s at 20% SD-FEC threshold after 10 km fiber can be achieved, respectively. The BER performance versus ROP with different bit rates is measured and shown in Fig. 4(b). 10 km fiber transmission causes no power penalty compared to BtB case. From Fig. 3(a) and Fig. 4(b), we also find that about 1 dB receiver sensitivity improvement of 200 Gb/s PAM4 is achieved compared with 200 Gb/s PS-PAM8 (2-bit/symbol) after 10 km fiber at HD-FEC limit. Insets (i)-(iii) show the recovered symbols, eye diagram and histograms for 100 Gbaud PAM4 and 100 Gbaud PS-PAM8 with different entropies (2.3 bit/symbol and 2.8 bit/symbol) under different cases, respectively.

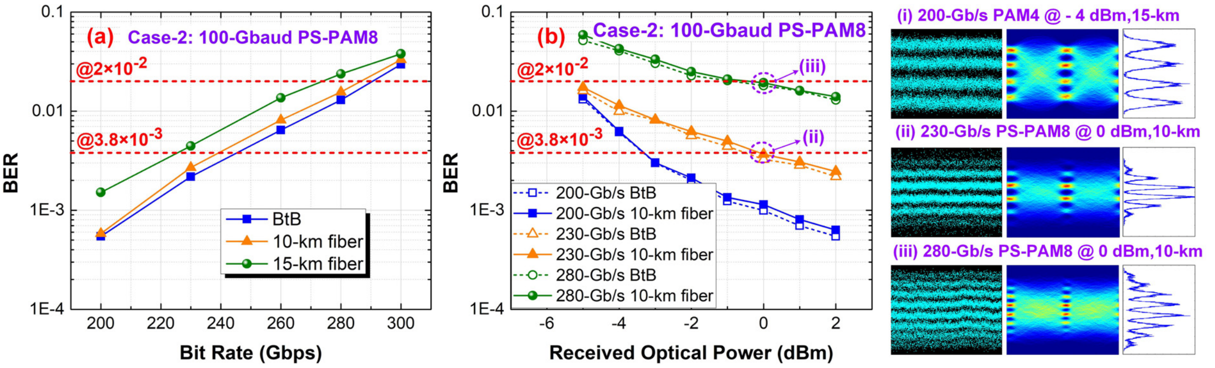

Fig. 4. Experimental results for 100 Gbaud PS-PAM8. (a) and (b) BER versus different bit rates and ROP under case-2, respectively. Insets (i)-(iii) are recovered symbols, eye diagrams and histograms, respectively.

4. Conclusions

Single-lane 200G and beyond IM/DD PAM transmission over 15 km SMF is experimentally demonstrated at O-band using SOA, PS and DSP. For 200G+ IM/DD systems, SOA may be used as a pre-amplifier to achieve high receiver sensitivity and extend transmission reach. 230 Gb/s and 280 Gb/s PS-PAM8 can be realized after 10 km SMF transmission at 7% HD-FEC limit and 20% SD-FEC limit, respectively. This is the first time to demonstrate PS technique for 200G+ per lane IM/DD over 10 km SMF fiber, making it a promising scheme for 800 GbE and/or 1.6 TbE short-reach applications. *This work was partially supported by National Key R&D Program of China (2018YFB8000905) and Natural National Science Foundation of China (61935005，61922025, 61527801, 61675048, 61720106015, 61835002, and 61805043).*

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