402 Gb/s PAM-8 IM/DD O-Band EML Transmission

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Abstract *We demonstrate record 402 Gb/s PAM-8 gross bit rate IM/DD transmission employing a single DAC directly driving an O-band EML. Considering 15.31%-overhead SD-FEC, a net bit rate of 348.62 Gbit/s is achieved over 5km SSMF.*

Introduction

The growth of data center network (DCN) traffic kept a strong momentum in the pandemic, driven by various cloud applications such as video-on-demand, gaming and remote office work, which further drives the research and development of Ethernet transceivers with respect to speed, cost, size and power. Intensity modulation and direct detection (IM/DD) has been enabling a cost-effective interconnect solution to address these challenges. 200 Gb/s/lane IM/DD transmission is under specification in the 800G Pluggable MSA[1] and is under consideration for IEEE beyond 400 Gigabit Ethernet (GbE) standardization. Energy-efficient and high bandwidth (BW) optical components are critical technologies to increase the achievable bit rate of IM/DD transmissions. So far standardized short-reach optical modules for links below 10 km have used O-band opto-electronic components [2]-[10].

Fig. 1(a) summarizes selected recent demonstrations of short-reach IM/DD transmission links at >200 Gb/s bit rates based on O-band optical modulators including directly modulated lasers (DMLs)[2]-[3], electro-absorption modulated lasers (EMLs) [4-7] and Mach-Zehnder modulators (MZM) [8]-[11]. A >100GHz DML has enabled the highest gross bit rate of 393 Gb/s based on discrete multi-tone (DMT) signaling[2]. Due to the bandwidth limitation of the digital-to-analogue converter (DAC), a high BW RF analogue band multiplexer (MUX) was used in [2] to combine data streams from two DACs. With a similar RF MUX configuration, an EML could achieve a gross bit rate of up to 320 Gb/s[4]. O-band MZMs[8-11] have not shown better performance compared to DMLs and EMLs.

In this paper, we report record single-lane 402 Gb/s PAM-8 IM/DD transmission based on a commercially available EML at 1310.9 nm, which represents to the best of our knowledge the highest IM/DD lane rate ever achieved by using O-band optical modulators. The packaged EML, which is shown in an evaluation kit in Fig. 1(b), has a 3-dB bandwidth of 55 GHz as shown in Fig.1 (c). Considering a forward error correction (FEC) with 15.31% overhead and a threshold bit error rate (BER) of 2×10^{-2} [12]-[13], PAM-8 transmission at a net bit rate of 348.62 Gb/s is successfully demonstrated for a transmission distance of 5 km. Compared with the previous O-band DML transmission record [2] we use a single DAC, driver-free modulation and a commercial EML, enabling improved spectral and power efficiency solutions for datacom optics.

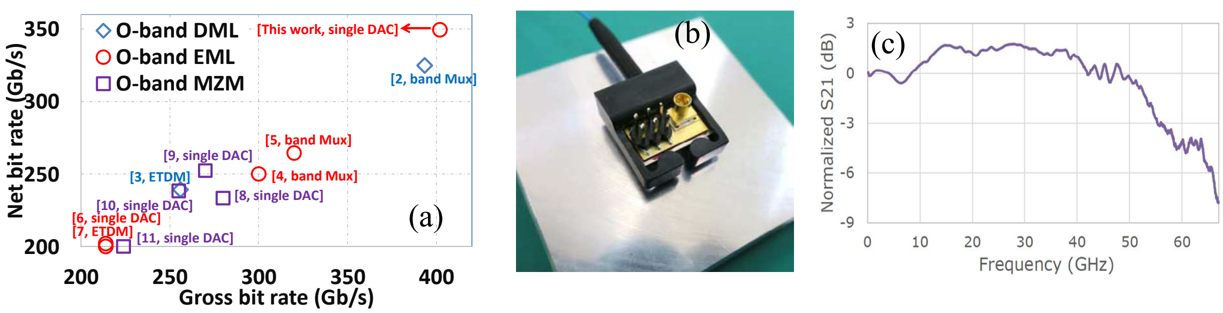

Fig. 1. (a) A summary of short reach IMDD transmissions at lane rates beyond 200 Gb/s based on O-band optical modulators, (b) the packaged O-band EML on an evaluation kit, and (c) its normalized S21 frequency transfer function.

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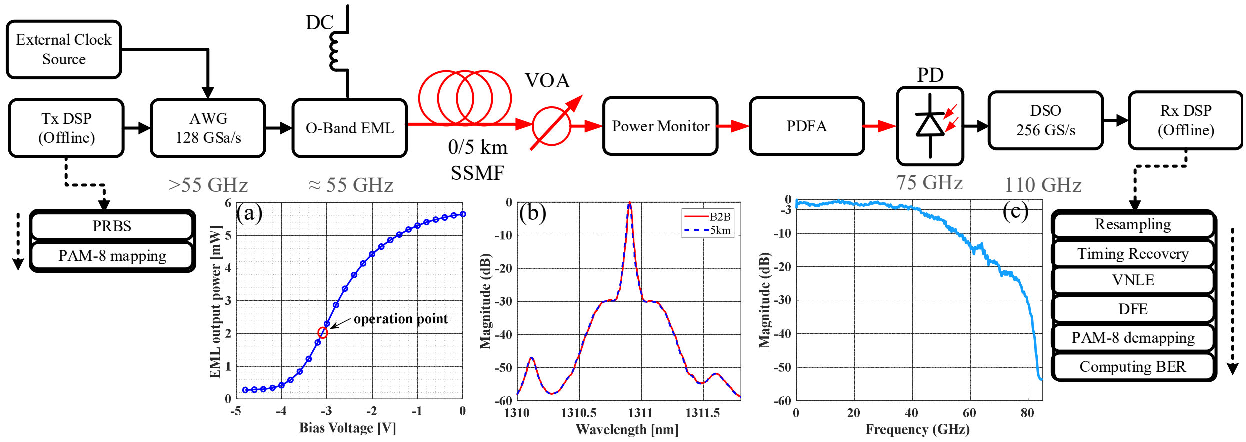

Fig. 2: Schematic of the IM/DD transmission system with transmitter and receiver-side offline DSP. Inset (a) shows the transfer curve of the EML and the operation point. The optical spectrum of the signal for B2B and 5 km is presented in inset (b). Inset (c) shows the power spectrum density of the received signal.

Experimental setup and DSP

The experimental setup is presented in Fig. 2. The 3-dB BW of each electro-optical component is stated below. Offline transceiver digital signal processing (DSP) is also depicted. A pseudorandom binary sequence (PRBS) is mapped to 8-level pulse amplitude modulation (PAM-8) symbols using a Gray mapping. PAM-8 with a symbol rate of 134 Gbaud is generated at 1 sample per symbol (sps). The quantized data is then fed to an arbitrary waveform generator (AWG) with 3-dB BW of >55 GHz and nominal sampling rate of 128 GSa/s. An external clock source set to 67 GHz is used to operate the AWG at 134 GSa/s, i.e. beyond its specification. To achieve stable operation during overclocking, a lower temperature was also maintained.

Afterwards, the driver-free analog driving signal directly modulated an O-band EML (3-dB BW ≈55 GHz), which is biased at -3.1V for linear operation (Fig.2 (a)) whereas a 60 mA current is supplied to the integrated laser diode of the EML. Both optical back-to-back (B2B) and 5 km standard single-mode fiber (SSMF) transmissions are measured. A variable optical attenuator (VOA) is used after the fiber link, followed by a Praseodymium-doped fiber amplifier (PDFA) as pre-amplifier before a 75 GHz PIN photodetector (PD). Using the PDFA, the optical power of the PD input signal is fixed at 7 dBm. An inline optical power monitor is inserted between the VOA and the PDFA.

The received electrical signal is then quantized and captured with a digital storage oscilloscope (DSO), which operates at 256 GSa/s with 3-dB BW set to 80 GHz. Data is captured for different values of received optical power (ROP) obtained adjusting the VOA before the inline optical power monitor. Offline processing at the receiver is based on 2 million samples. For estimating and compensating frequency sampling offset and jitter, timing recovery is performed [14]. After time synchronization, the signal is resampled to 1 sps and processed with a Volterra nonlinear equalizer (VNLE). A memory length of 1111 taps is used for linear equalization to minimize the effect of reflections from the discrete component setup, relatively long copper cables and connectors. In addition to linear taps, 2nd and 3rd order kernels of VNLE with memory length of 11 are used to compensate nonlinearities introduced by AWG, EML and square-law detection. Decision feedback equalization (DFE) with memory length of 2 taps is used after VNLE to reduce post-cursor inter symbol interference (ISI). This processing step is iterated twice, namely the DFE coefficients are calculated in training mode in the first iteration and then used as decision threshold during the second iteration. Afterwards symbols decision is performed on the PAM-8 symbols followed by symbol to bits de-mapping and BER calculation.

Transmission Results and Discussions

The experimental results are presented in Fig. 3 in terms of BER variation over ROP. The results obtained with VNLE complemented with DFE are shown in Fig. 3(a). For the 5 km scenario, the SD-FEC BER threshold is reached at 0.3 dBm, and for the 5 km SSMF scenario a power penalty of -0.9 dB is observed. The negative penalty may be attributed to the compensation of the EML chirp by the residual fiber chromatic dispersion at the wavelength of 1310.9 nm. In addition, Fig.3 (b) shows results under different equalization configurations, where results are obtained with various numbers of taps of a linear feed-forward equalizer (FFE), 2nd and 3rd order VNLE kernels as well as the DFE. A moderate improvement in BER performance with 2nd and 3rd order VNLE

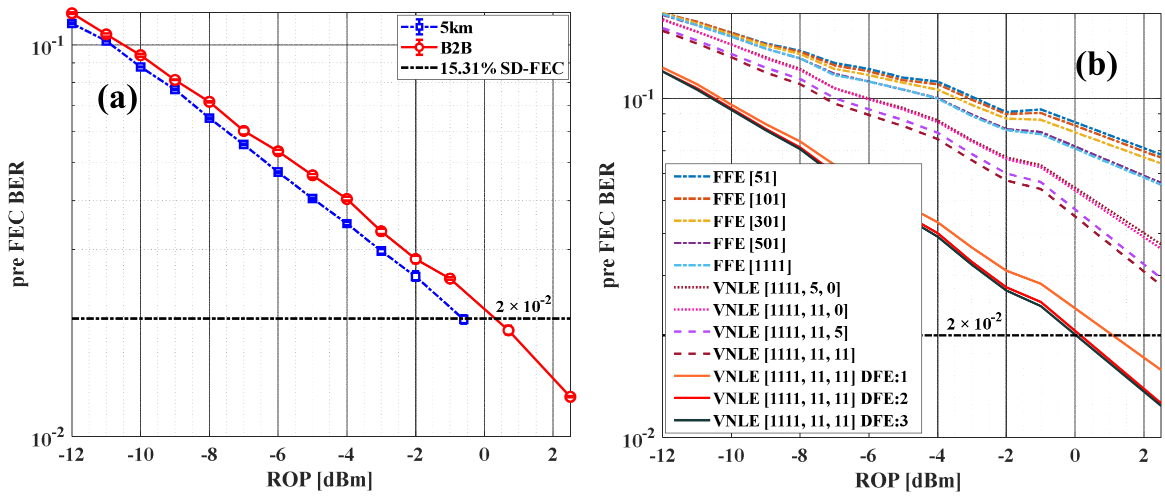

Fig. 3: Experimental results of 134 Gbaud PAM-8 for B2B and 5km transmission (a), and (b) comparison between results with and without VNLE and DFE.

over only linear FFE taps can be observed. Although the VNLE improves the performance and lowers the error floor, there is still a gap to the target SD-FEC threshold requirement. However, a 1-tap DFE together with VNLE significantly improves the BER performance and reaches the SD-FEC threshold at 1.08 dBm. ROP sensitivity is further improved by around 0.8 dB with a 2-tap DFE. Further increase in the number of DFE taps does not bring better performance.

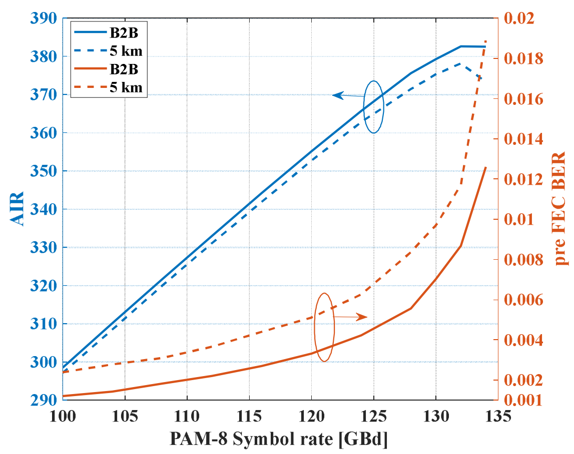

Fig. 4: AIR and pre FEC BER at different symbol rates

Fig. 4 shows the variation of achievable information rate (AIR) and pre FEC BER as a function of symbol rate between 100 Gbaud and 134 Gbaud both for the B2B and 5 km scenarios. Considering SD-FEC with ≈15% overhead and BER threshold of 2×10 2 [12, 13], we can achieve error free transmission at 134 GBd with net bit rate of 348.62 Gb/s, whereas capacity-achieving FEC would result in a net bit rate of 382.54 Gbit/s in the B2B scenario.

Conclusion

We have experimentally demonstrated PAM-8 IM/DD signal transmission over 5 km SSMF with a 402 Gb/s gross bit rate and 348.62 Gb/s net bit rate considering a 15.31% SD-FEC. To the best of our knowledge, this is the highest transmitted gross and net bit rate on a single-lane IM/DD system using an O-band EML and single DAC.

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