

# Optical Amplification-Free 310/256 Gbaud OOK, 197/145 Gbaud PAM4, and 160/116 Gbaud PAM6 EML/DML-based Data Center Links

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**Abstract:** We demonstrate a record 310/256 Gbaud OOK, 197/145 Gbaud PAM4, and 160/116 Gbaud PAM6 EML/DML-based IM/DD links without any optical amplification with performance below the 6.25% overhead HD-FEC threshold after 100-m/6-km SMF, respectively.  
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## 1. Introduction

The booming internet traffic sets highly challenging requirements for Data Center links. Scaling the capacity to 1.6 Tbps per link in an economically viable way is the key [1]. Moreover, we need to have low latency for high-speed computing. This leads to a choice of intensity modulation and direct detection (IM/DD) system with the highest baudrate possible. That would allow reducing the number of lanes required to achieve the 800 Gbps and 1.6 Tbps capacities per link. Multilevel pulse amplitude modulation (PAM) can be used to increase the capacity for bandwidth-limited components when the signal-to-noise ratio is enough to achieve performance below 6.25% overhead (OH) hard-decision forward error (HD-FEC) threshold of  $4.5 \times 10^{-3}$ . To relax this requirement, it is worth looking into on-off keying (OOK) to increase the baudrate significantly. For instance, a thin-film lithium niobate Mach Zehnder modulator or ring resonator modulator offers low driving voltage and high bandwidth at the expense of an external laser [2-4]. A plasmonic modulator has been used to achieve 222 Gbaud [5] and 220 Gbaud [6] OOK, yet the setup included optical amplifiers, which increases power consumption. That is also the case for setups with the impressive uncooled transmitters based on directly modulated laser (DML) [7] and externally modulated laser (EML) [8].

In this paper, we show 310/256 Gbaud OOK, 197/145 Gbaud PAM4, and 160/116 Gbaud PAM6 EML/DML-based optical links without any optical amplification with performance below 6.25% OH HD-FEC threshold after single-mode fiber (SMF) links and opened eye diagrams. For the EML-based transmitter at optical-back-to-back (ob2b) we achieve 256 Gbaud OOK signal performance below the KR-FEC threshold of  $2.1 \times 10^{-5}$  and 200 Gbaud PAM4 signal performance below the HD-FEC threshold. This is a significant improvement compared to [9,10].

## 2. Experimental configuration

Figure 1(a) shows the experimental setup with C-band EML-based [11] and O-band DML-based [12] transmitters. OOK, PAM4, and PAM6 modulation formats at different baudrate for each transmitter are generated offline in MATLAB. We use a random binary sequence of >1 million samples generated by the Mersenne Twister with a shuffled seed number. The symbols are digitally upsampled to 4 samples per symbol, pulse-shaped with a root-raised-cosine (RRC) of different roll-off factors depending on baudrate and modulation order (for DML from 0.05 to 0.85 and for EML from 0.01 to 0.5), and then decimated to 256 GSa/s to match the sampling rate of the arbitrary waveform generator (AWG, prototype of Keysight M8199B). The AWG output voltage swing is 2.3 Vpp after embedded electrical amplification. In the case of the C-band EML, the module is directly connected to the AWG output with a 1-mm connector adaptor as can be seen in the inset in Fig.1(a). For the O-band DML, a 110-GHz bias-tee is used to deliver the laser bias current. A 1-mm connector adaptor is used to connect the bias tee to the output of AWG. Also,

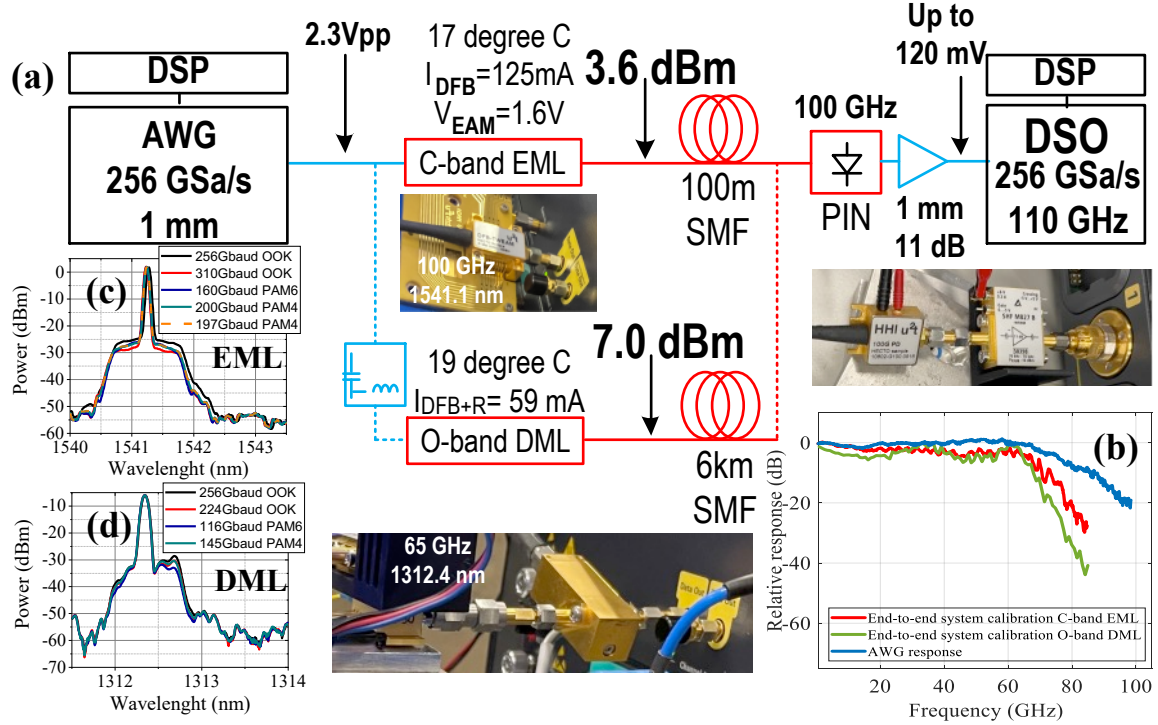


Fig. 1. (a) Experimental setup for EML/DML-based Data Center Links. (b) Calibrated end-to-end system amplitude responses. (c) The optical spectra of modulated EML. (d) The optical spectra of modulated DML.

as the DML is in the package with a 1.85 mm connector and an adaptor to 1-mm is needed, see the inset in Fig.1(a). This affects the performance of the DML-based transmitter at a high baudrate. The EML is regulated to operate at 17°C to emit +3.6 dBm optical power after electro-absorption modulation, and the DML is regulated at 19°C and has an output power of +7 dBm when biased. The bias currents are shown in Fig.1(a). Due to the different operational bands of the two transmitters varied transmission distances can be achieved, i.e., 100-meter SMF for the C-band EML-based transmitter, and 6-kilometer SMF for the O-band DML-based transmitter. A 100-GHz PIN photodiode is connected to a packaged electrical amplifier of 11 dB gain with a 1-mm adaptor at the receiver as one can see in the inset of Fig.1(a). In this configuration, we can deliver up to 120 mV of an electrical signal to a 110-GHz real-time digital storage oscilloscope (DSO, 256 GSa/s, Keysight UXR1104A). Calibrated end-to-end amplitude responses of the EML and DML-based setups without the optical fiber link are shown in Fig. 1 (b). The intrinsic response of the AWG is shown as a reference. The optical spectra (0.1 nm) for the modulated EML-based and DML-based transmitters are shown in Fig. 1 (c) and (d), respectively. The signal is processed offline with a matched filter, a timing recovery and down-sampling process based on maximum variance, a symbol-spaced decision-feedback equalizer (DFE) with different feedforward (FF)-tap and feedback (FB)-tap configurations, and the BER is counted. We can use post-equalization only thanks to the fact that the 20-dB end-to-end system bandwidth for both setups is above 70 GHz.

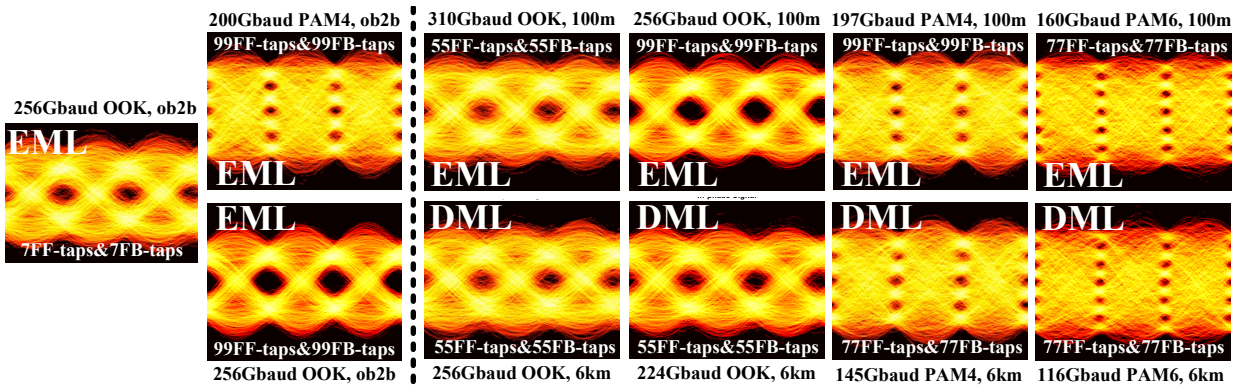


Fig. 2. Eye diagrams for both EML and DML configurations after transmission over SMF.

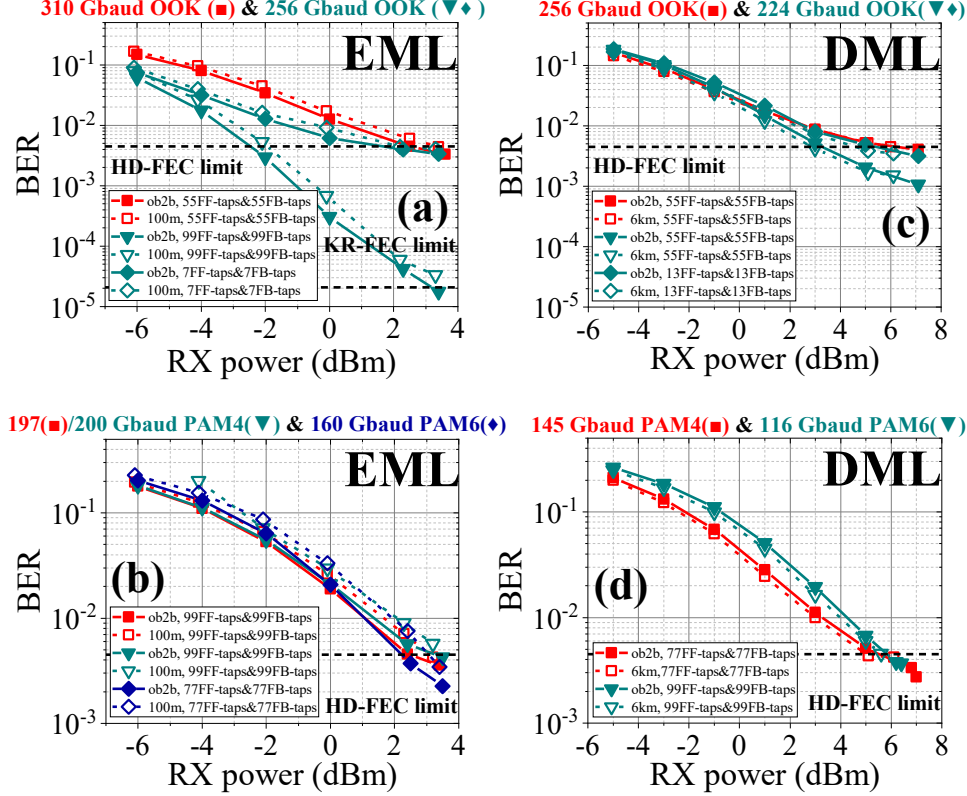


Fig. 3. BER results as a function of RX power for (a) 310 Gbaud and 256 Gbaud OOK with EML, (b) 197Gbaud, 200 Gbaud PAM4 and 160 Gbaud PAM6 with EML, (c) 256 Gbaud and 224 Gbaud OOK with DML, (d) 145 Gbaud PAM4 and 116 Gbaud PAM6 with DML.

### 3. Experimental results

Figure 2 shows selected eye diagrams for both the EML- and the DML-based optical links, captured at the highest received optical power (RX power) with the same DFE configuration as used for the BER curves. We first show eye diagrams for the EML-based transmitter at ob2b for 256 Gbaud OOK and 200 Gbaud PAM4 signals. Then we show eye diagrams for all modulation formats and both transmitters after transmission over a different length of SMF depending on the operational band. Figure 3 shows the BER versus RX power for both links. In Fig. 3(a) 310 Gbaud and 256 Gbaud OOK signals are shown. We manage to achieve performance below the KR-FEC threshold for 256 Gbaud OOK signal at ob2b with 99 FF-taps & 99 FB-taps. The number of taps can be relaxed to 7 FF-taps & 7 FB-taps for performance below the 6.25% OH HD-FEC threshold. We also show 197/145 Gbaud PAM4, and 160/116 Gbaud PAM6 EML/DML-based optical link performance below 6.25% OH HD-FEC threshold in Fig.(b)-(d).

### 4. Conclusions

We demonstrate optical amplification-free EML/DML-based optical links at record baud rates with performance below the 6.25% overhead HD-FEC threshold, paving the way for low lane count solutions towards 1.6 Tbps.

### 5. Acknowledgement

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