106.25 Gbaud 4-Level Pulse Amplitude Modulation Links Supporting (2x)100Gigabit Ethernet on Single Lambda

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Abstract: We experimentally demonstrate and compare EML- and DML-based optical interconnects with 106.25 Gbaud NRZ-OOK and PAM4 for computing applications. The results show that both transmitters can be used to enable optical-amplification-free transmissions with low-complexity DSP.

1. Introduction

High bandwidth density, low latency, and high reach computing application impose critical challenges on electrical links to scale the bandwidth in an energy-efficient manner. The computing possibilities per unit area can be scaled by digital processing performance. However, bottleneck for the useful computing power is the ability to transmit digital signals to processing units with enough I/O bandwidth [1]. Therefore, energy-efficient optical links with low-complexity and low-latency that can seamlessly interface with the electrical links are highly desirable. Per the latest standardization draft on 100Gigabit/200Gigabit Ethernet specifications, one would expect these links operate at the same rate as the electrical interfaces (N×106.25 Gb/s) with low-coding-gain forward error correction (FEC) to ensure low latency [2],[3]. Moreover, considering the volume of such optical links in the data centers, the optical transceivers are preferred to be compact with low energy consumption [4]. From the component level, novel optoelectronic technologies are required to enable such stringent requirements. Several optical modulators that can be co-integrated with lasers provide low-cost solutions for highs-peed optical interconnects, including thin-film lithium niobate modulator [5], micro-ring modulator [6], electro-absorption modulated laser (EML) [7] and directly-modulated laser (DML) [8]. From the system level, optical amplifications for these types of links are not desirable unless absolutely necessary [9]. Besides, the complexity of the digital signal processing (DSP) ASIC is also expected to be constrained for such low-latency computation scenarios.

In this paper, we report on an experimental study of short-reach transmission of 106.25 Gbaud non-return-to-zero on-off-keying (NRZ-OOK) and 4-level pulse amplitude modulation (PAM4) with two types of integrated optical transmitters, i.e., a 100-GHz Class C-band EML [7] and a 65-GHz Class O-band DML [8]. We constrain our experimental configuration to be optical-amplification free and apply in the receiver a low-complexity decision-feedback equalizer (DFE) of 9-feedforward taps and 9-feedback taps. The results show that both transmitters have the potential to enable energy-efficient short-reach optical interconnects for (2×)100 Gigabit Ethernet applications.

2. Experimental configuration

Figure 1(a) shows the experimental setup with the two different integrated optical transmitters side by side. Two modulation formats, namely, NRZ-OOK and PAM4, both at 106.25 Gbaud, are generated offline in MATLAB from a random binary sequence of >1 million samples using the Mersenne Twister with a shuffled seed number. The symbols are firstly upsampled digitally to 4 Sample per symbol, pulse-shaped with a root-raised-cosine (RRC) of 0.15, and then decimated to 256 GSa/s to match the sampling rate of the arbitrary waveform generator (AWG, M8199B, Keysight). The output voltage swing of the AWG is configured to be 2.3 Vpp after embedded electrical amplification. For the C-band EML, the laser module (see Fig. 1 (a) inset) is directly connected to the AWG output with a 1-mm connector without any adaptor to preserve the broad bandwidth. For the O-band DML, a 110-GHz

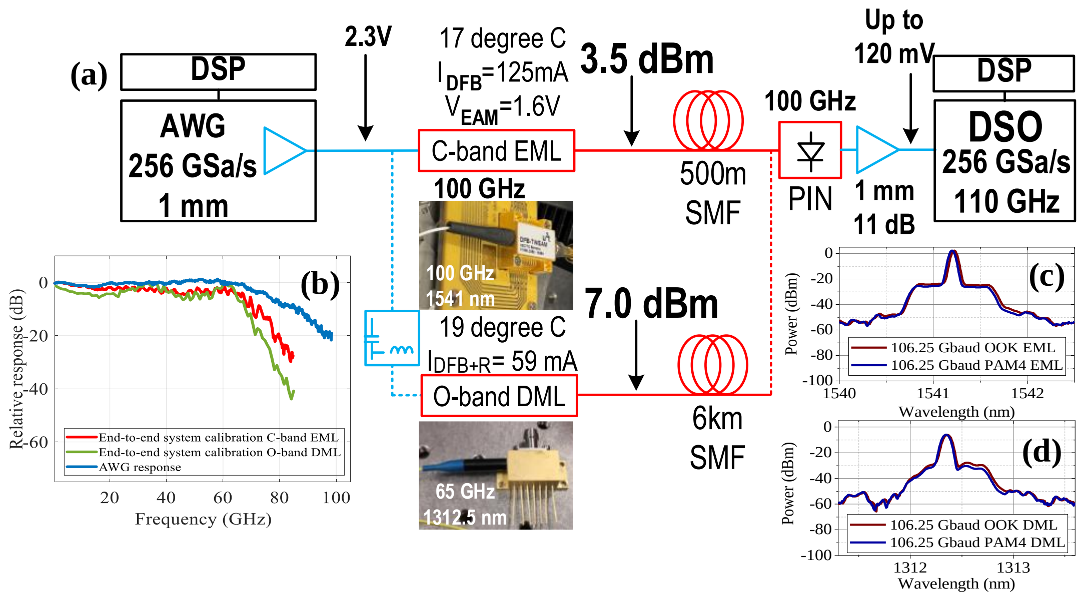

Fig. 1. (a) Experimental setup. (b) Calibrated end-to-end system amplitude responses for both EML and DML configurations. (c). The optical spectra of modulated EML. (d) The optical spectra of modulated DML.

bias-tee is used to deliver the laser bias current and the modulation signal to the laser, and a 1-mm to 1.85-mm adaptor is used to connect to the module (Fig. 1 (a) inset). Both laser modules require temperature control for stable operation. The EML is regulated to operate at 17°C to emit sufficient power (+3.5 dBm in this case) after electro-absorption modulation, and the DML is regulated at 19°C and has an output power of +7 dBm when biased at linear region with modulation. Due to the different operational bands of the two transmitters yielding different chromatic dispersion (CD) coefficients, we target different transmission distances, i.e., 500-m single-mode-fiber (SMF) for the C-band EML, and 6-km SMF for the O-band DML. At the receiver, the same 100-GHz PIN photodiode (PD) is used to receive the signals from both transmitters. A packaged electrical amplifier (EA) of 11 dB gain, which has 1-mm connectors for both the input and the output, is used to amplify the PD output signal and deliver it to the 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 setup without the optical fiber link are shown in Fig. 1 (b). The intrinsic response of the AWG is shown as a reference. One can observe that the 20-dB bandwidth is above 70 GHz for both configurations. The optical spectra for the modulated EML and DML are shown in Fig. 1 (c) and (d), respectively. Finally, the signal is processed with a matched filter, a timing recovery and down-sampling process based on maximum variance, a symbol-spaced decision-feedback equalizer (DFE) with 9-feedforward (FF) taps and 9-feedback (FB) taps, and the BER performance is counted after the offline demodulation. The low-complexity post-equalization configuration is possible thanks to the broad end-to-end system bandwidth.

3. Experimental results

We evaluate the transmission performance of the two individual transmitters with both modulation formats under study, respectively. Figure 2 shows the BER results as a function of the received optical power at the PD. For the C-band EML, we tested with 500-m SMF transmission, whereas for the O-band DML the transmission distance is configured to be 6 km thanks to its high output power and the low chromatic dispersion. To accurately extrapolate the BER performance when the number of counted errors are very small or zero, particularly for the NRZ-OOK cases, we use the importance sampling technique to estimate the BER [9]. In Fig. 2 we show both counted BER and estimated BER for all the test cases. One can observe that the estimated BER curves overlap with the counted BER almost perfectly in all the cases, indicating an accurate BER extrapolation at high received optical power where the counted BER values become zero. For the 106.25 Gbaud NRZ-OOK cases, with the C-band EML as the transmitter, KR-FEC (2.18×10^{-5}) limit [11] can be achieved at about -4 dBm, and BER of 1×10^{-15} (virtually "error-free") can be reached at around 0 dBm after 500-m SMF transmission per the estimated BER curves. With the O-band DML transmitter, the KR-FEC limit can be reached at around -2 dBm, whereas an error floor is observed at a BER of around 1×10^{-13}, which may be limited by the transmitter SNR and other imperfections in this case. No penalty is observed between the ob2b and 6-km SMF transmission owing to the low CD at O-band. For the 106.25 Gbaud PAM4 cases, with the C-band EML we could reach the KP-FEC (2.26×10^{-4}) limit [11] at around 2.5 dBm after transmission. The 500-m SMF

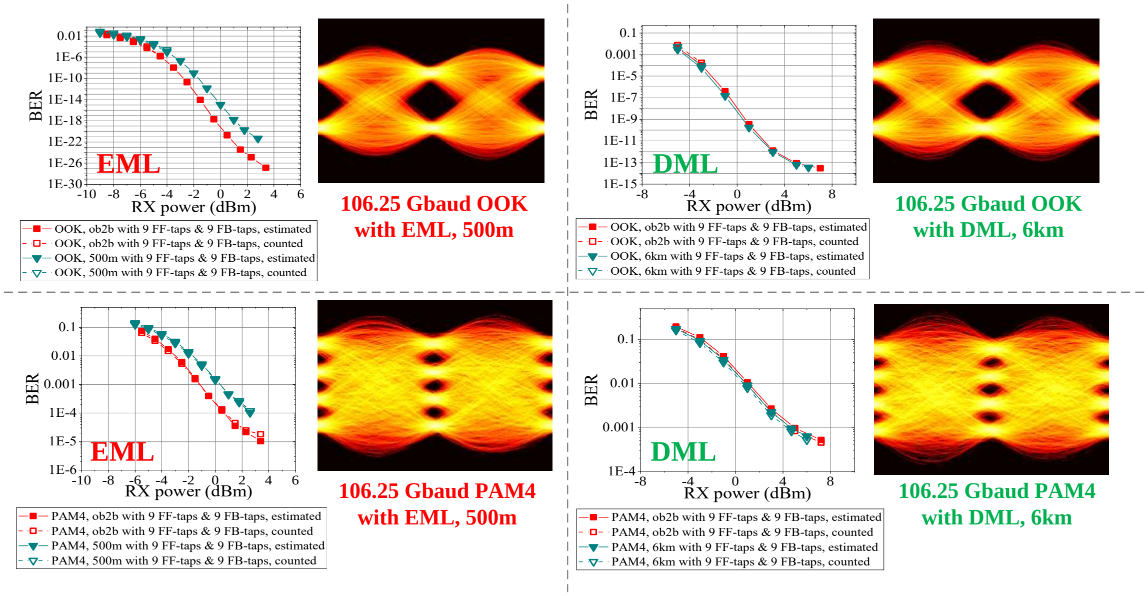

Fig. 2. BER results as a function of received (Rx) optical power for both 106.25 Gbaud NRZ-OOK and PAM4 for both the EML and the DML configurations, respectively. For each case the counted BER and estimated BER are shown to cover the full power sweep range. Selected eye diagrams at highest Rx power level after transmission are shown for all cases.

introduces around 2-dB sensitivity penalty due to the high CD coefficient in the C-band. On the contrary, negligible CD-induced penalty is observed for the O-band DML transmitter case, however, due to the limited transmitter SNR and modulation nonlinearities, KP-FEC was not reached with the low-complexity DFE of 9-FF taps and 9-FB taps. Selected eye diagrams for both modulation formats with both transmitter types after transmissions are also shown in Fig. 2. Clear eye openings can be observed in call test cases. Negligible nonlinear compression is shown for the EML-based PAM4 signal, whereas slight compression in the upper- and lower-levels can be observed for the DML case. In summary, both transmitters show good potential to support the low-complexity optimal-amplifier-free single-lambda 2×100Gigabit Ethernet applications.

4. Conclusion

We demonstrated 106.25 Gbaud NRZ-OOK and PAM4 short-reach transmissions with two types of integrated transmitters, namely, a C-band EML and an O-band DML. We show that both transmitters can fulfill the requirements of supporting optical-amplifier-free interconnects with low-complexity equalizations and low-latency FEC options. These results pave the way for energy-efficient short-reach optical interconnects for (2×)100 Gigabit Ethernet applications.

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