Error-Free 108 Gbps On-Off Keying Link for Optical Interconnect Applications

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Abstract *We demonstrate an error-free 108 Gbps OOK link using a C-band externally modulated laser with 3.3 dBm of modulated output power and an O-band directly modulated laser with 7.3 dBm of modulated output power. This paves the way forward for high-speed optical interconnects without FEC. ©2022 The Author(s)*

Introduction

Technologies for electrical links face serious challenges to scale the bandwidth in an energy-efficient manner. This is especially critical when high bandwidth density, low latency, and high reach are required. Digital processing performance can scale the compute possibilities per unit area. However, the useful compute power is limited by the ability to transmit digital signals to processing units with enough I/O bandwidth [1]. Therefore, we require low complexity optical links operating at the highest lane rate of on-off keying while still being error-free. Several technologies are required to enable this stringent requirement. Several optical modulator technologies provide low-cost solutions for high-speed optical interconnects [1-4]. However, high-speed silicon ring resonator modulators (RRMs) have recently emerged as an attractive alternative thanks to their compact size and low energy consumption by demonstrating up to 128 Gbps on-off keying (OOK) [3]. Integration of laser source is of critical importance in this type of transmitter. High-speed integrated externally modulated lasers (EMLs) [6] and directly modulated lasers (DMLs) [7] are, therefore, interesting alternatives enabling up to 200 Gbps OOK transmission [8].

In this paper, we demonstrate error-free 108 Gbps OOK transmission over standard single-mode fiber (SMF) using C-band externally modulated laser and O-band directly modulated

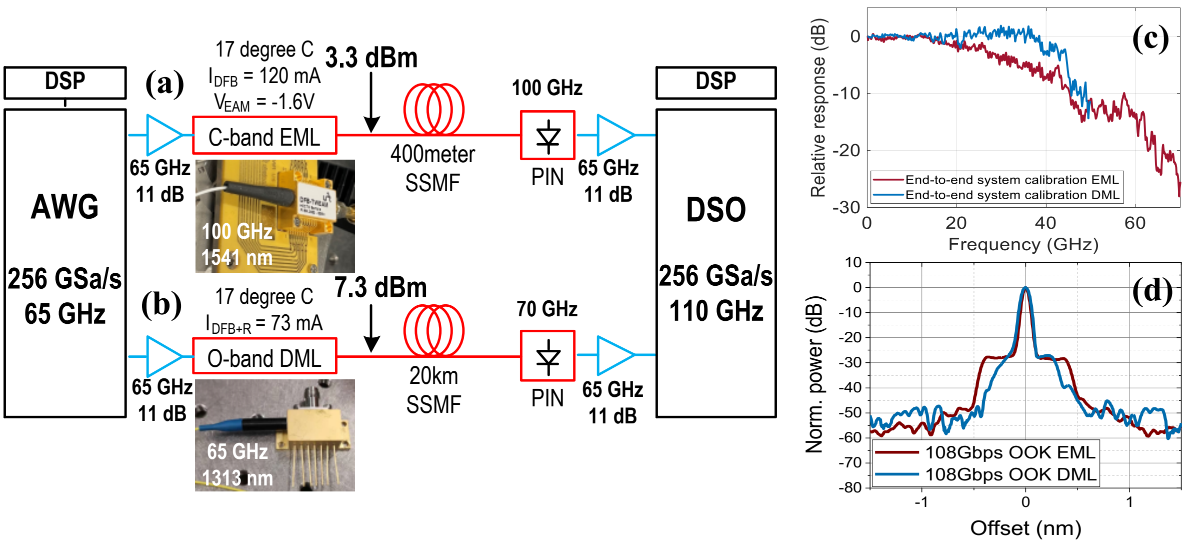

Fig. 1: Experimental setup for 108 on-off keying optical link using (a) EML and (b) with DML; (c) end-to-end system calibration; (d) normalized optical spectrum.

laser. We compare both the counted and estimated bit error rate (BER) performance for both links. We use a technique called importance sampling to estimate the BER [9]. This demonstration paves the way forward for high-speed optical interconnects without forward error correction (FEC).

Experimental Setup

Figure 1 shows the experimental setup. We built a transmitter for 108 Gbps on-off keying link with high bandwidth components in C-band and O-band. We use an externally modulated laser with 100 GHz of bandwidth in the C-band (1541 nm) and a directly modulated laser with 65 GHz of bandwidth in the O-band (1313 nm). The digital signal is generated in MATLAB using in-house developed digital signal processing (DSP) techniques. We use the Mersenne Twister generator with a shuffled seed number to generate the >1 million bit-length random bit sequence. We up-sample the sequence. Then we filter it with a root-raised-cosine (RRC) filter having a different roll-off factor after optimization depending on the available bandwidth in the system. To compensate for bandwidth limitations in the system, we use a frequency domain pre-equalization built in the transmitter. The end-to-end responses before equalization (up to 70 GHz in the case of the EML and up to 50 GHz for the DML) are shown in Fig. 1(c). Then we load the pre-compensated signal to a 256 GSa/s M8199A Arbitrary Waveform Generator (AWG). The output of the AWG is connected to an electrical amplifier (11 dB gain, 65 GHz bandwidth). The amplifier is required to compensate for high-frequency roll-off and has enough driving voltage to enhance the extinction ratio of the modulated signal. The C-band EML consists of a monolithically integrated distributed feedback laser and a traveling-wave electroabsorption modulator (DFB-TWEAM) with 100 GHz bandwidth [6]. We obtain 3.3 dBm of modulated optical power at 17 degrees Celsius when the TWEAM is biased at minus 1.6 volts and the DFB is driven by 120 mA of current. The O-band DML is a packaged module of a recently reported 65 GHz DFB+R laser [7]. The modulation performance of the laser is enhanced by three key effects, i.e., the detuned loading (DL) effect, the photon-photon resonance (PPR) effect, and the in-cavity frequency modulation (FM) - amplitude modulation (AM) conversion. The laser is driven with an external bias-tee where we combine the bias current and the broadband modulation signal. We obtain 7.3 dBm of modulated optical power at 17 degrees Celsius when the DFB+R laser is driven at 73 mA. The signal was transmitted over 400 meters of SMF in the EML setup. The dispersion tolerance at the

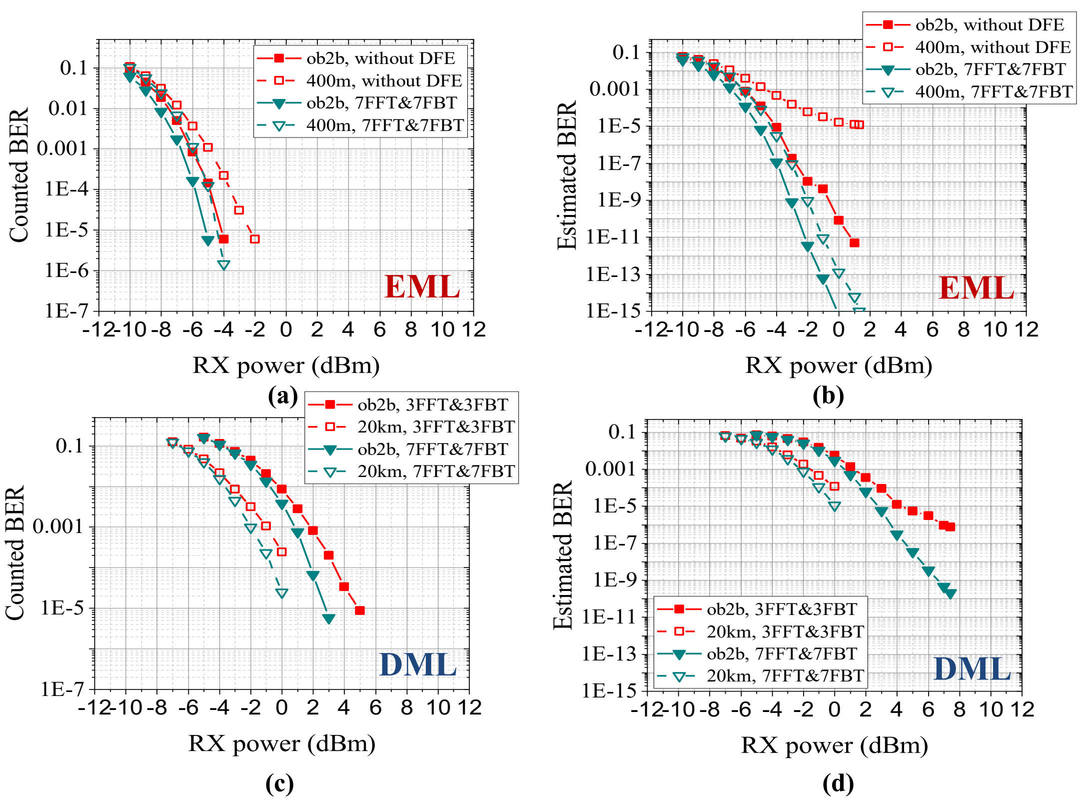

Fig. 2: Bit error rate versus received optical power for 108 Gbps OOK link; (a) counted and (b) estimated BER without and with 7FFT&7FBT DFE for the EML setup; (c) counted and (d) estimated BER with 3FFT&3FBT and 7FFT&7FBT DFE for the DML setup.

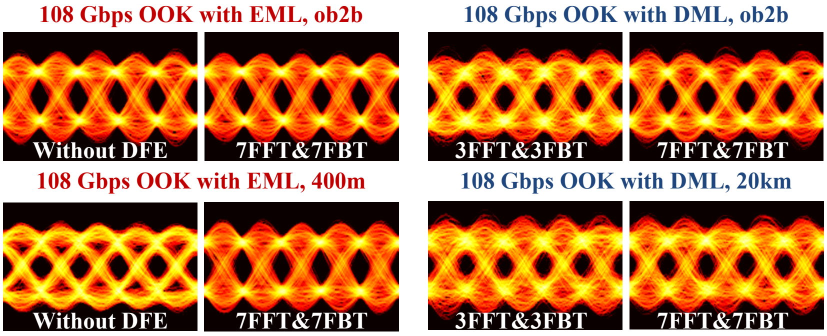

Fig. 3: Eye diagrams for 108 Gbps OOK link without and with 7FFT&7FBT DFE for the EML setup and with 3FFT&3FBT and 7FFT&7FBT DFE for the DML setup.

operation wavelength of 1541 nm limits the achievable transmission distance. In the DML setup, we managed to transmit over 20 km of SMF thanks to the operating wavelength of 1313 nm. For the application of on-chip optical interconnects the dispersion would have a negligible impact. The transmission distance difference in the experiment is not the main factor. With these demonstrations, we would like to show that there is enough optical power to compensate for channel loss. We also show the normalized optical spectrums in Fig.1(d). At the input of the PIN photodetector (3 dB BW >90 GHz and responsivity=0.5 A/W for the EML setup and 3 dB BW >70 GHz and responsivity=0.45 A/W for the DML setup), we obtain 3.3 dBm (EML) and 7.3 dBm (DML) of modulated optical power without the insertion loss of a variable optical attenuator (VOA) that is used to adjust the optical signal power before the PIN photodetector. Afterward, the OOK signal is amplified by another electrical amplifier (11 dB gain, 65 GHz bandwidth). Then the signal is sampled with 256 GSa/s UXR1104A Infiniium UXR-Serie digital storage oscilloscope (DSO) and processed offline using a typical DSP routine, consisting of a low-pass filter (LPF), a timing recovery, a decision feedback equalizer (DFE), and an error counter.

Results and Discussions

We evaluated the signal performance for optical back-to-back (ob2b) and after transmission over 400 meters of SMF for the EML setup and 20 km of SMF for the DML setup, giving a similar chromatic dispersion for both links. In Fig. 2, we show the bit error rate as a function of received optical power (RX power) for 108 Gbps OOK signals. We show both counted and estimated BER for the EML and the DML setups. We used 840 000 symbols for BER counting. We use importance sampling techniques [9] to estimate systems performance beyond the capabilities of BER counting. We obtain error-free transmission in counted BER measurements for both transmitters. The EML setup exhibited a lower required optical power than the DML setup for a certain BER. Error-free transmission using counted BER was achieved for both transmitters. However, in the case of the estimated BER measurements, we see an error floor without DFE in Fig. 2(b). We can gain from using the DFE with 7 feed-forward taps (FFT) and 7 feedback taps (FBT). In the case of the DML setup, a low complexity DFE with 3FFT and 3 FBT is required in both measurements to achieve error-free transmission. An increase in the DFE taps does not provide significant improvement. That demonstrated that the final solution can be realized with low complexity equalization. The eye diagrams at ob2b and after transmission with the opened eyes are shown in Fig. 3. These results demonstrate that 108 Gbps optical interconnects with low complexity equalization can be realized using either EML or DML.

Conclusions

We demonstrate two low complexity 108 Gbps OOK optical links for optical interconnect applications based on either a C-band EML or an O-band DML. In both cases, the error-free transmission was achieved at similar accumulated chromatic dispersion. This is a significant milestone for next-generation energy-efficient high-speed optical interconnects with low-cost optical modulators. That paves the way for low complexity short-reach optical interconnects.

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