# High Baudrate Short-Reach Communication

Oskars Ozolins[1,2,3*], Toms Salgals[3,8], Hadrien Louchet[4], Mahdieh Joharifar[2], Richard Schatz[2], Di Che[5], Yasuhiro Matsui[6], Markus Gruen[4], Thomas Dippon[4], Fabio Pittala[4], Benjamin Krüger[4], Yuchuan Fan[1,2], Aleksejs Udalcovs[1], Urban Westergren[2], Lu Zhang[7], Xianbin Yu[7], Sandis Spolitis[3,8], Vjaceslavs Bobrovs[3], Sergei Popov[2], Xiaodan Pang[2,1,3*]
[1] RISE Research Institutes of Sweden, 16440 Kista, Sweden
[2] Department of Applied Physics, KTH Royal Institute of Technology, 106 91 Stockholm, Sweden
[3] Institute of Telecommunications, Riga Technical University, 1048 Riga, Latvia
[4]Keysight Technologies GmbH, Böblingen, Germany
[5]Nokia Bell Labs, Murray Hill, NJ 07974, United States
[6]II-VI Incorporated, Fremont, CA 94538, United States
[7]College of Information Science and Electronic Engineering, Zhejiang University, and Zhejiang Lab, Hangzhou, China
[8]Communication Technologies Research Center, Riga Technical University, 1048 Riga, Latvia
Author e-mail address: oskars.ozolins@ri.se, xiaodan@kth.se

***Abstract**: We demonstrate a 200 Gbps IM/DD link without any optical amplification using C-band externally modulated laser with 3.3 dBm of modulated output power and O-band directly modulated laser with 7.3 dBm of modulated output power.*
***Keywords:** on-off keying, externally modulated lasers, directly modulated lasers, optical communication*

## I. Introduction

Highly challenging requirements are set for optical links by the ever-growing internet traffic demands for high-performance computing (HPC) and the Data Centers. Scaling the link capacity to 800 GbE or even 1.6 TbE in an economically viable way is the key [1]. Single lane data rates of 200 Gbps are desirable to reduce the lane count and footprint [2]. In addition, high-speed computing has stringent requirements when it comes to low latency and loss. Multilevel pulse amplitude modulation (PAM) can be used to increase the capacity for bandwidth limited components but sets stringent requirements in terms of linearity and noise tolerance for driving electronics and photonics. Therefore, it is worth considering the on-off keying (OOK) for this type of short-reach communication. In recent years, an increasing number of demonstrations showing 200 Gbps per single lane in the intensity modulation direct detection (IM/DD) systems have been reported [3]. Promising alternatives enabled by broadband optoelectronic components are demonstrated, including monolithically integrated transmitters such as externally modulated lasers (EML) [4-8] or directly modulated lasers (DML) [9,10], or InP Mach Zehnder Modulators (MZM) [11], or electrically pumped laser transmitter on thin-film Lithium Niobate (TFLN) platform [12], and external modulator-based transmitters such as silicon-photonic modulator [13], plasmonic modulator [14,15], or TFLN Mach-Zehnder modulator (MZM) [16,17]. Optical amplifiers or complex digital signal processing (DSP) algorithms increase the energy consumption and limit the practical applicability.

In this paper, we demonstrate a 200 Gbps IM/DD link without any optical amplification using a C-band EML [18,19] having 3.3 dBm of modulated output power and an O-band DML [20] having 7.3 dBm of modulated output power. We achieve below the 6.25% overhead (OH) hard-decision forward error correction (HD-FEC) threshold of $4.5\times10^{-3}$ after transmission of 200 Gbaud OOK and 108 Gbaud PAM4 over 200 meters of single-mode fiber (SMF) with EML and after transmission of 150 Gbaud OOK and 106 Gbaud PAM4 over 20 km of SMF with DML. We used only a decision feedback equalizer (DFE) with 33 feed-forward taps (FFT) and 3 feedback taps (FBT).

## II. Experimental Setup

Figure 1 shows the experimental setups. We are looking at two different components to build the optical transmitter and generate the high baudrate signals in C-band and O-band, respectively. We generate the signal using the developed digital signal processing (DSP) routines in MATLAB. We use a random binary sequence of >1 million bit-length obtained using the Mersenne Twister generator with a shuffled seed number. Next, the sequence is up-sampled and filtered with a root-raised-cosine (RRC) filter having a different roll-off factor after optimization. Frequency domain pre-equalization up to 70GHz for the EML setup and up to 50 GHz for the DML setup is used to compensate for bandwidth limitation in the system. The link responses are shown in Fig.2(a). Please observe that the response of the end-to-end system calibration of the optical links follows closely the calibration with just the Arbitrary Waveform Generator (AWG). We load the pre-compensated signal into the 256 GSa/s M8199A AWG. The output of the AWG is connected to an electrical amplifier (22 dB gain, 60 GHz bandwidth for the EML setup, and 11 dB gain, 65 GHz bandwidth for the DML setup). For the DML setup, we were limited by the maximum allowed voltage to the component. We mainly need to compensate for high-frequency roll-off and have 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 traveling-electroabsorption modulator (DFB-TWEAM) [18]. At the output, we obtain 3.3 dBm of modulated optical power at 17 degrees Celsius when the TWEAM

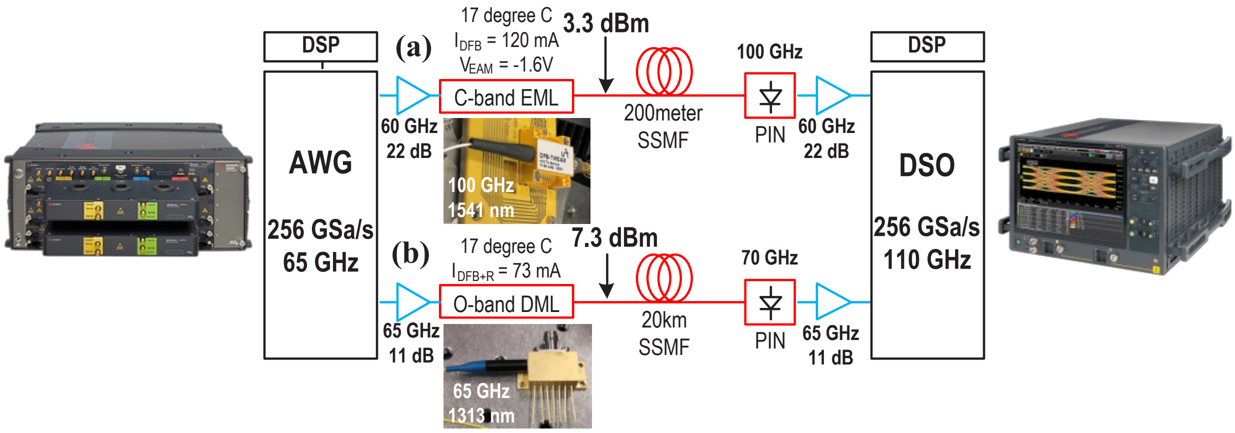


Fig. 1. Experimental setup for high baudrate short-reach communication with (a) EML, (b) DML and (c) setup picture.

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 70 GHz-class DFB+R laser [20]. 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 the bias current and the broadband modulation signal combine. At the output, 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 200 meters of SMF in the EML setup. The dispersion tolerance at the operation wavelength of 1541 nm (see the modulated signal optical spectrum in Fig.2(b)) 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 (see the modulated signal optical spectrum in Fig.2(c)). At the input of the PIN photodetector (3 dB BW >90 GHz and responsivity=0.5 A/W for 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, in the EML setup, the OOK signal is amplified by another amplifier (22 dB gain, 60 GHz bandwidth), however, for the PAM4 signal we use a different electrical amplifier (11 dB gain, 65 GHz bandwidth). The latter one is used in the DML setup after the PIN photodetector. 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.

## III. Results and Discussions

We use the 6.25% overhead (OH) hard-decision forward error correction (HD-FEC) threshold of $4.5\times10^{-3}$ for the result analysis. We evaluate the signal performance for optical back-to-back (ob2b) and after transmission over 200 meters of single-mode fiber for the EML setup and 20 km of SMF for the DML setup. Figure 2 shows the end-to-end system calibration responses for the EML and DML setups as well as optical spectrums for different modulation formats.

In Fig. 3(a), we show the bit error rate (BER) as a function of received optical power ($RX_{power}$) for 106 Gbaud and 108 Gbaud PAM4 signals using the DFE with 33 feed-forward taps (FFT) and 3 feedback taps (FBT). We obtain the BERs below the HD-FEC requirements for both the ob2b and the 200 meters SMF for the EML setups and 20 km for the DML setup. The eye diagrams after the equalization at ob2b with the opened eyes are shown in Fig. 3(b). The required optical power to achieve HD-FEC is smaller for the EML setup, but still, there is more optical power margin in the DML setup. In Fig. 3(c), we show the BER as a function of $RX_{power}$ for 150 Gbaud and 200 Gbaud OOK signals using the same DFE configuration. We achieve a higher baudrate with the EML setup even though we see an error floor. Again, we obtain a better optical power margin for the DML setup. Both results set the highest achieved OOK rates for the IM/DD systems

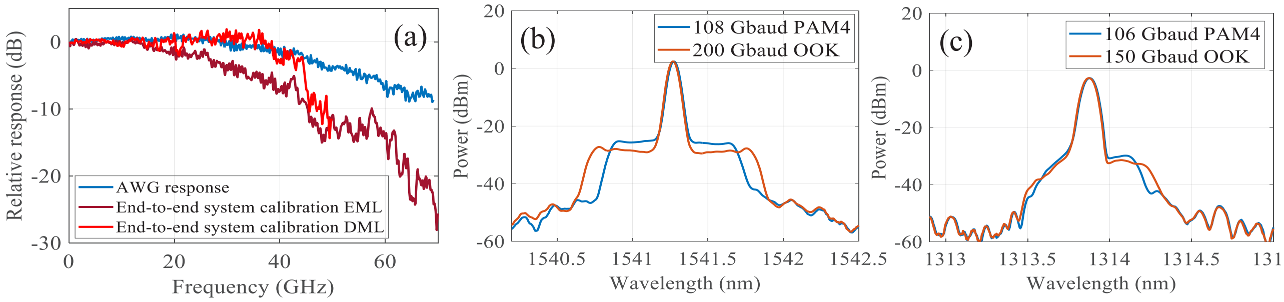


Fig. 2. (a) End-to-end system calibration for high baudrate short-reach communication, (b) optical spectrum for the EML modulated with 108 Gbaud PAM4 and 200 Gbaud OOK, and (c) optical spectrum for the DML modulated with 106 Gbaud PAM4 and 150 Gbaud OOK.

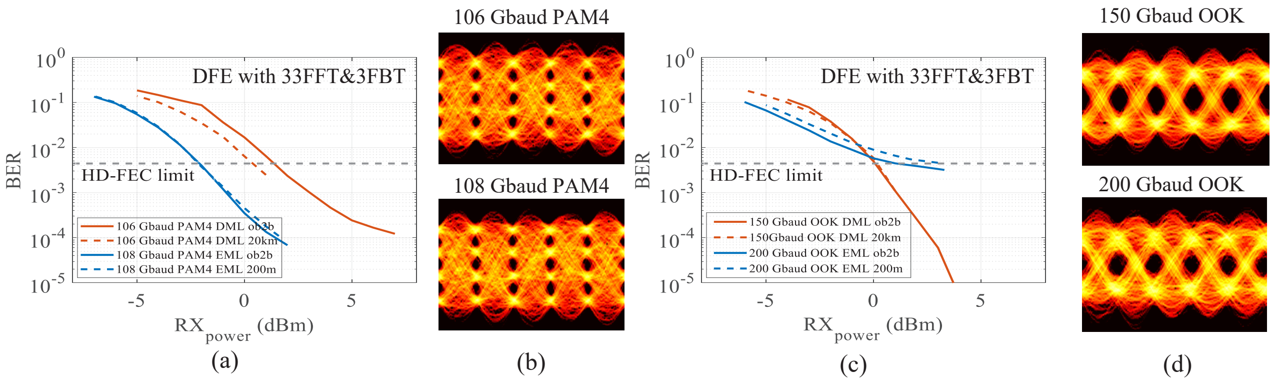


Fig. 3. (a) BER versus RX $_{power}$ after DFE for 106 Gbaud PAM4 with DML and 108 Gbaud PAM4 with EML, (b) eye diagrams for ob2b (c) BER versus RX $_{power}$ after DFE for 150 Gbaud OOK with DML and 200 Gbaud OOK with EML, and (d) eye diagrams for ob2b.

without any optical amplification and simple DSP. That enables low latency requirements for high-speed computing.

## IV. Conclusions

We demonstrate a 200 Gbps IM/DD link without any optical amplification using C-band EML and O-band DML. In the case of EML, we managed to transmit 200 Gbaud OOK signals over 200 meters of SMF without any optical amplification. The O-band DML has higher output power and benefits from the low fiber dispersion of around 1.3µm, enabling 20 km transmission. Both transmitters support the transmission of a single lane data rate of 200 Gbps.

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