

Optical Amplification-Free High Baudrate Links for Intra-Data Center Communications

Oskars Ozolins^{ID}, Senior Member, IEEE, Mahdieh Joharifar^{ID}, Toms Salgals^{ID}, Hadrien Louchet, Richard Schatz^{ID}, Markus Gruen, Thomas Dippon, Benjamin Kruger, Fabio Pittala, Di Che, Yasuhiro Matsui, Yuchuan Fan^{ID}, Member, IEEE, Aleksejs Udalcovs^{ID}, Senior Member, IEEE, Urban Westergren, Lu Zhang^{ID}, Xianbin Yu^{ID}, Senior Member, IEEE, Sandis Spolitis^{ID}, Member, IEEE, Vjaceslavs Bobrovs^{ID}, Sergei Popov^{ID}, and Xiaodan Pang^{ID}, Senior Member, IEEE

(Post-Deadline Paper)

Abstract—The enormous traffic growth sets a stringent requirement to upgrade short-reach optical links to 1.6 TbE capacity in an economically viable way. The power consumption and latency

Manuscript received 21 June 2022; revised 15 September 2022; accepted 1 October 2022. Date of publication 14 October 2022; date of current version 16 February 2023. This work was supported in part by the H2020 ICT TWILIGHT Project under Grant 781471, in part by the Swedish Research Council (VR) Projects under Grants 2019-05197 and 2016-04510, in part by RTU Science Support Fund, in part by the National Key Research and Development Program of China under Grant 2018YFB1801503, and in part by the ERDF-funded RINGO Project under Grant 1.1.1.1/21/A/052. (*Oskars Ozolins and Mahdieh Joharifar contributed equally to this work.*) (Corresponding authors: Oskars Ozolins; Xiaodan Pang).

Oskars Ozolins is with the RISE Research Institutes of Sweden, 164 40 Kista, Sweden, also with the Department of Applied Physics, KTH Royal Institute of Technology, 106 91 Stockholm, Sweden, and also with the Institute of Telecommunications, Riga Technical University, 1048 Riga, Latvia (e-mail: oskars.ozolins@ri.se).

Aleksejs Udalcovs is with the RISE Research Institutes of Sweden, 164 40 Kista, Sweden (e-mail: aleksejs.udalcovs@gmail.com).

Mahdieh Joharifar, Richard Schatz, Yuchuan Fan, Urban Westergren, and Sergei Popov are with the Department of Applied Physics, KTH Royal Institute of Technology, 106 91 Stockholm, Sweden (e-mail: mahdieh@kth.se; rschatz@kth.se; yuchuanf@kth.se; urban@kth.se; sergeip@kth.se).

Xiaodan Pang is with the Department of Applied Physics, KTH Royal Institute of Technology, 106 91 Stockholm, Sweden, and also with the Institute of Communication Technologies Research Center, Riga Technical University, 1048 Riga, Latvia (e-mail: xiaodan@kth.se).

Toms Salgals and Sandis Spolitis are with the Institute of Communication Technologies Research Center, Riga Technical University, 1048 Riga, Latvia, and also with the Communication Technologies Research Center, Riga Technical University, 1048 Riga, Latvia (e-mail: toms.salgals@rtu.lv; sandis.spolitis@rtu.lv).

Vjaceslavs Bobrovs is with the Institute of Communication Technologies Research Center, Riga Technical University, 1048 Riga, Latvia (e-mail: vjaceslavs.bobrovs@rtu.lv).

Hadrien Louchet, Markus Gruen, Thomas Dippon, Benjamin Kruger, and Fabio Pittala are with the Keysight Technologies GmbH, 122051 Böblingen, Germany (e-mail: hadrien.louchet@keysight.com; markus.gruen@keysight.com; thomas_dippon@keysight.com; benjamin.krueger@keysight.com; fabio.pittala@keysight.com).

Di Che is with the Nokia Bell Labs, Murray Hill, NJ 07974 USA (e-mail: di.che@nokia-bell-labs.com).

Yasuhiro Matsui is with the II-VI Incorporated, Fremont, CA 94538 USA (e-mail: yasuhiro.matsui@ii-vi.com).

Lu Zhang and Xianbin Yu are with the College of Information Science and Electronic Engineering, Zhejiang University, Zhejiang Lab, Hangzhou 321004, China (e-mail: zhanglu1993@zju.edu.cn; xyu@zju.edu.cn).

Color versions of one or more figures in this article are available at <https://doi.org/10.1109/JLT.2022.3214722>.

Digital Object Identifier 10.1109/JLT.2022.3214722

in these links should be as low as possible, especially for high-speed computing. This is possible to achieve using high baudrate on-off keying links thanks to a better noise tolerance and a relaxed requirement on linearity for electronics and photonics. In this regard, we demonstrate a 200 Gbaud on-off keying link without any optical amplification using an externally modulated laser with 3.3 dBm of modulated output power operating at 1541.25 nm wavelength. We achieve transmission over 200 meters of single-mode fiber with performance below 6.25% overhead hard-decision forward error correction threshold for each baudrate and all selection of modulation formats. We also show 108 Gbaud on-off keying link with superior performance without decision feedback equalizer up to 400 meters of single-mode fiber. In addition, we benchmark the short-reach optical link with 112 Gbaud four-level pulse amplitude modulation and 100 Gbaud six-level pulse amplitude modulation. For 108 Gbaud on-off keying and 112 Gbaud four-level pulse amplitude modulation, we can achieve an even lower bit error rate.

Index Terms—On-off keying, optical interconnects, pulse amplitude modulation.

I. INTRODUCTION

THE ever-growing internet traffic demands are driving the need for fast development in the intra-Data Center links and high-performance computing (HPC). The main requirement is to scale the Data Center link capacity to 1.6 TbE in an economically viable way [1], [2], [3]. In addition, for high-performance computing, the latency should be as low as possible. With multilevel pulse amplitude modulation (PAM) one can increase the capacity for bandwidth-limited systems. However, that imposes stringent requirements in terms of noise tolerance and linearity for driving electronics and photonics. Due to this drawback, it is worth reviving interest in on-off keying (OOK) for applications in short-reach communication. In that case, the low complexity OOK links should operate at the highest lane rate while still performing below the hard-decision forward error correction (HD-FEC) threshold. Multiple high-performance technologies are required to comply with this stringent requirement [4]. Several optical modulator technologies can provide low-cost and high-performance solutions for high-speed short-reach optical communications [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22]. High-speed silicon ring resonator modulators (RRMs) are an attractive alternative

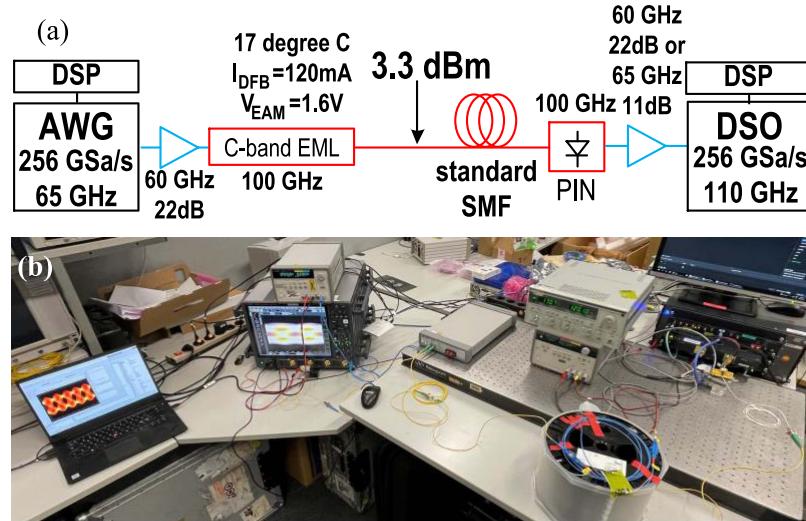


Fig. 1. (a) Experiment setup, and (b) Setup picture.

thanks to their compact size and low energy consumption. The recent demonstration shows up to 128 Gbps OOK [5]. It is possible to extend the transmission distance by utilizing the optical peaking effect and negative chirp. Up to 2 kilometers of data transmission of 100 Gbaud PAM-4 signals with a bit error rate (BER) under the general 7% overhead (OH) HD-FEC threshold has been recently demonstrated [6]. In addition, a plasmonic modulator with a high-speed 2:1 selector has been used to achieve 222 Gbaud OOK transmission over a 120 meter long single-mode fiber (SMF). That shows the application of even smaller modulators. Yet the setup included two erbium-doped fiber amplifiers (EDFA) [7] which increases the power consumption. Higher baudrate has been recently achieved using polybinary modulation [8]. A competing technology, a thin-film lithium niobate Mach Zehnder modulator seems to be viable for building a transmitter for short-reach optical communication thanks to high bandwidth and low driving voltage at the expense of an external laser [9], [10], [11]. Recently a sub 1 Vpp Silicon Photonic MZM was demonstrated [23]. In most of these demonstrations, there have been no widely opened eye diagrams of the highest baudrate OOK shown. On the other hand, one critical point in these transmitters is the ability to integrate a laser source. Recently, an electrically pumped laser transmitter integrated on thin-film lithium niobate has been demonstrated [12]. High-speed integrated externally modulated lasers (EMLs) [13], [14], [15], [16], [17] and directly modulated lasers (DMLs) [18], [19], [20] are, therefore, compelling alternatives enabling up to 200 Gbaud OOK transmission [17]. In an earlier demonstration, a 204 Gbaud OOK transmission over inter-Data Center distances using the C-band EML and optical dispersion compensation based on chirped fiber Bragg gratings has been shown [15]. A 180 Gbaud OOK transmission over intra-Data Center distance using an EDFA was achieved with the same EML [16].

In this article, we extend our recent report on optical amplification-free 200 Gbaud OOK link for intra-Data Center communications [17] with more detailed system characterizations and transmission performance evaluations. To the

best of our knowledge, our experiment is the first EML-based system demonstration of 200 Gbaud on-off keying without any optical amplification with opened-eye diagrams enabling the usage of simple, power-efficient equalization schemes. We demonstrate optical amplification-free 108 Gbaud, 170 Gbaud, 180 Gbaud, 190 Gbaud, and 200 Gbaud OOK link using the EML with 3.3 dBm of modulated output power operating at 1541.25 nm wavelength. The link configuration also supports the transmission of 112 Gbaud PAM4 and 100 Gbaud PAM6. For all modulation formats, we achieve below 6.25% OH HD-FEC threshold of 4.5×10^{-3} . In the case of high baudrate OOK, the superior performance is achieved after 200 meters of single-mode fiber using only a decision feedback equalizer (DFE) with 33 feed-forward taps (FF-taps) and 3 feedback taps (FB-taps). For the 108 Gbaud OOK link the post-equalization is not required to achieve 400 meters link performance below the 6.25% OH HD-FEC threshold. That enables low latency requirements for high-speed computing. For 112 Gbaud PAM4 at ob2b we can achieve an even lower bit error rate that complies with the KP4-FEC threshold of 2.2×10^{-4} .

II. EXPERIMENTAL CONFIGURATION

A. Externally Modulated Laser

The optical transmitter is based on a C-band externally modulated laser that consists of a monolithically integrated distributed feedback laser and traveling-wave electroabsorption modulator (DFB-TWEAM). The component is designed by KTH, fabricated by KTH and Syntune, and packaged by u²t Photonics [24] and [25]. At the output, 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. To increase the optical modulation amplitude, we regulate the case temperature, modulator bias, and driving signal amplitude. The modulator bandwidth is 100 GHz and the passband ripple is lower than 2 dB, indicating its high linearity [26]. That enables the generation of high baudrate multilevel pulse amplitude

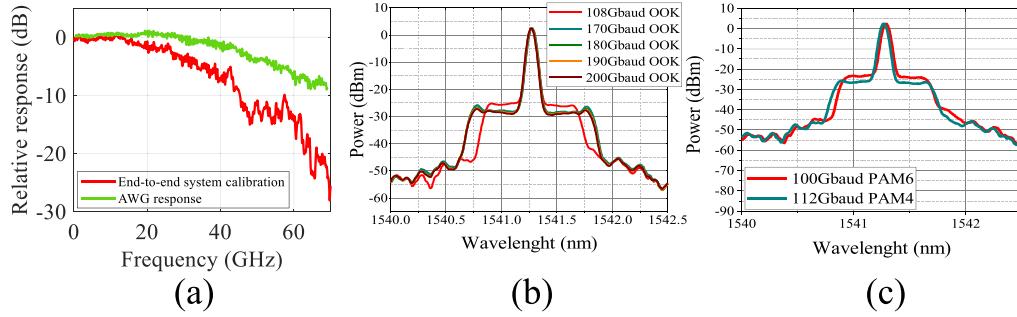


Fig. 2. (a) End-to-end system calibration, and (b) and (c) Optical spectrum at 0.1 nm resolution.

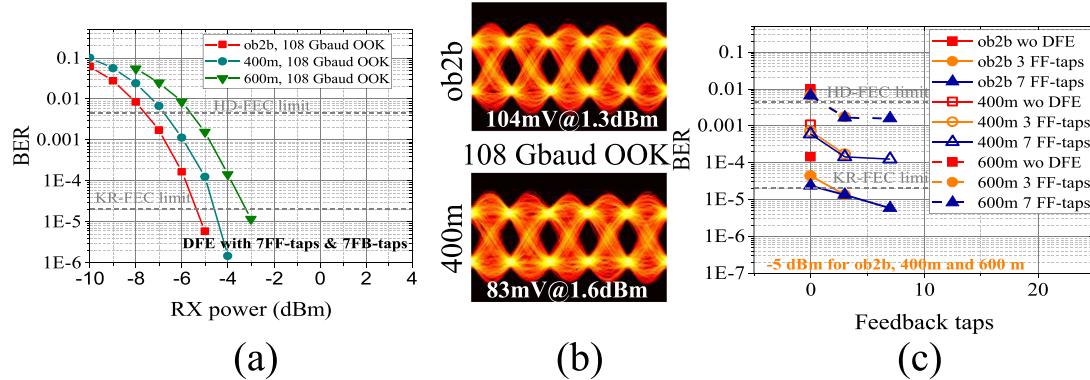


Fig. 3. (a) Bit error rate (BER) Versus received optical power (RX power) For 108 Gbaud OOK with a 7 feed forward taps (FF-taps) And 7 feedback taps (FB-taps) DFE, (b) Eye diagrams (see insets), And (c) BER versus different configurations of post-equalization.

modulation signals. In future designs, the number of modulator sections can be increased to reduce the required electrical voltage swing. That comes at a price of larger insertion loss in the modulator that needs to be compensated with the higher laser power.

B. Optical Amplification-Free Transmission Setup

The optical amplification-free experimental setup is shown in Fig. 1(a). We use developed digital signal processing (DSP) routines to generate the signal in MATLAB. We use a random binary sequence with over 1 million bit-length that is obtained using the Mersenne Twister generator with a shuffled seed number. The sequence is up-sampled and filtered with a root-raised-cosine (RRC) filter with an optimized roll-off factor for each modulation format. 0.01 roll-off factor is used for 170 Gbaud to 200 Gbaud OOK. A higher roll-off factor of 0.02 is used for 108 Gbaud OOK and 112 Gbaud PAM4 modulation formats. In the case of 100 Gbaud PAM6, a 0.15 roll-off factor delivered the best performance. To compensate for the bandwidth limitation in the system a static frequency domain pre-equalization up to 70 GHz is used for all modulation formats. The used response is shown in red in Fig. 2(a). The end-to-end bandwidth includes the cascading effect of electrical amplifiers, optoelectronic components, and adapters. Please observe that the end-to-end system calibration of the optical link follows closely the calibration with just the state-of-the-art Arbitrary Waveform Generator (AWG). To find the best system

performance the response was obtained by using a different number of frequency steps that varies from 700 to 750. Then the pre-equalized signal is loaded into the memory of 256 GSa/s M8199A AWG. The output of the AWG is connected to an electrical amplifier (22 dB gain, 60 GHz bandwidth) to adjust the voltage swing. That is necessary to have enough driving voltage to enhance the extinction ratio of the modulated signal and simultaneously compensate for high-frequency roll-off. We achieved extinction ratio from 4 dB to 5 dB depending on modulates signal bandwidth. The signal was transmitted over 200 meters of the SMF in the case of 170 Gbaud to 200 Gbaud OOK and 100 Gbaud PAM6 modulation formats. For 108 Gbaud OOK and 112 Gbaud PAM4 modulation formats, the 600 meters transmission has been achieved. The dispersion tolerance at the operation wavelength of 1542.25 nm (see Fig. 2(b) and (c)) limits the achievable transmission distance. The chirp of the modulator is low as can be deduced from the symmetric spectrum seen in Fig. 2(b) and (c). The combined effect of chromatic dispersion interaction with chirp is the main impairment in our system. It is worth mentioning that the TWEAM chirp is engineered to a mild degree of pulse chirping at the TWEAM in our implementation. We exploit chromatic dispersion to compress the pulses over the first meters of the link. That allows reducing the effective length of our system which can even become negative [16]. The microwave design of the DFB-TWEAM can be applied to a semiconductor material with a larger bandgap to achieve modulation at operation wavelength in O-band [25], [26]. Then transmission distances over SMF can be significantly improved.

One would require having higher laser power in the modulator due to larger attenuation in the O-band. We obtain 3.3 dBm of modulated optical power at the input of the PIN photodetector (3 dB BW >90 GHz and responsivity = 0.5 A/W), without the insertion loss of a variable optical attenuator (VOA) that is used to adjust the optical signal power. Afterward, the 170 Gbaud to 200 Gbaud OOK signal is amplified by another amplifier (22 dB gain, 60 GHz bandwidth), however, for the 108 Gbaud OOK and PAM signals we use a different electrical amplifier (11 dB gain, 65 GHz bandwidth). For 170 Gbaud to 200 Gbaud OOK, we need a higher voltage swing to compensate for the frequency roll-off in the system to achieve the best performance. We use discrete photodetector and electrical amplifiers in the receiver with 50 Ohm impedance matching to minimize the reflections that can deteriorate signal performance. Then the signal is sampled with 256 GSa/s UXR1104A Infiniium UXR-Serie digital storage oscilloscope (DSO) and processed offline. We are using a typical DSP routine that consists of a low-pass filter (LPF), a timing recovery, a feed-forward equalizer (FFE) or a decision feedback equalizer (DFE), and an error counter. An FFE with a different number of feed-forward taps (FF-taps) and feedback taps (FB-taps) is used to mitigate inter symbol interference (ISI) induced by chromatic dispersion in intensity-modulated direct detection systems where the phase information of the carrier is not available. A DFE with a different configuration of taps is used to mitigate ISI in presence of noise. The actual photo of the setup is given in Fig. 1(b).

III. EXPERIMENTAL RESULTS

In this part, we show optical amplification-free high baudrate link performance for on-off keying and pulse amplitude modulation. We use several forward error correction thresholds for the result analysis. But we compare all modulation formats at a 6.25% OH HD-FEC threshold of 4.5×10^{-3} . We also show the values of the optical power received at the PIN photodetector and voltage at the 256 GSa/s UXR1104A Infiniium UXR-Serie DSO as insets on all the eye diagrams for each modulation format used in the experiment. All eye diagrams correspond to the highest received power and the same DFE configuration as per BER curves.

We evaluate the performance for optical back-to-back (ob2b) and after transmission over 200 meters of single-mode fiber for 170 Gbaud to 200 Gbaud OOK and 100 Gbaud PAM6. We achieve a higher transmission distance with 108 Gbaud OOK and 112 Gbaud PAM4 modulation formats.

A. On-Off Keying

In Fig. 3(a), we show the BER as a function of received optical power (RX_{power}) for 108 Gbaud OOK signal using the DFE with 7 feed-forward taps (FF-taps) and 7 feedback taps (FB-taps). The number of taps in the DFE can be relaxed to 3 FF-taps and 3 FB-taps to achieve performance below the HD-FEC threshold as can be seen from Fig. 3(c) where BER as a function of DFE configuration is shown. We obtain the BER values in Fig. 3(c) at minus 5 dBm of received optical power. That corresponds to a voltage swing of 33 mV for ob2b and around 27 mV after transmission. In addition, for ob2b and after 400 meters

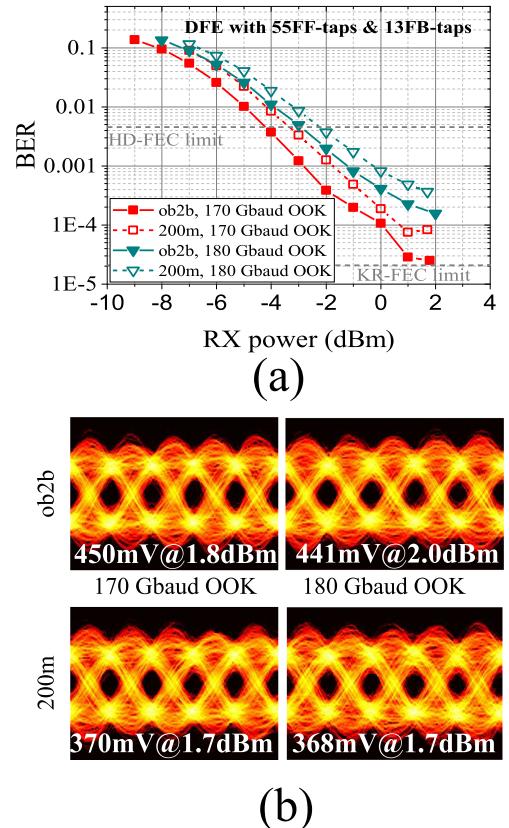


Fig. 4. (a) BER versus RX power for 170 Gbaud and 180 Gbaud OOK with a DFE with 55 FF-taps & 13 FB-taps, and (b) Eye diagrams (see insets for details).

of SMF we can achieve below the HD-FEC threshold without any post-equalization. We use this DFE configuration for the transmission over 600 meters of SMF just to show that there is still a margin on the signal performance. The post-equalization allowed us to achieve signal performance below the KR-FEC threshold of 2.1×10^{-5} . We obtain a 1 dB and 3 dB power penalty after 400 meters and 600 meters of SMF, respectively. It is worth noting that the signal performance without any post-equalization was just above the HD-FEC threshold after transmission over 600 meters of SMF. Eye diagrams after the equalization with the opened eyes are shown in Fig. 3(b).

In Fig. 4(a), we show the BER as a function of RX_{power} for 170 Gbaud and 180 Gbaud OOK signals using the DFE with 55 FF-taps and 13 FB-taps. The number of taps in the DFE can be relaxed to 13 FF-taps and 3 FB-taps for 170 Gbaud OOK and 21 FF-taps and 3 FB-taps for 180 Gbaud OOK (see Fig. 6). We use this configuration to show that there is still a margin on the signal performance. We obtain the BERs below the HD-FEC threshold for both cases: the ob2b and the 200 meters SMF; eye diagrams after the equalization with the opened eyes are shown in Fig. 4(b). We have around a 1 dB power penalty due to transmission over 200 meters of SMF. It is worth noting that the 170 Gbaud OOK signal performance was just above the KR-FEC threshold.

The transmission performance in terms of BER versus RX_{power} for 190 Gbaud and 200 Gbaud OOK signals is shown in Fig. 5(a). We use the DFE with 55 FF-taps and 13 FB-taps to achieve performance below the HD-FEC threshold of 4.5×10^{-3}

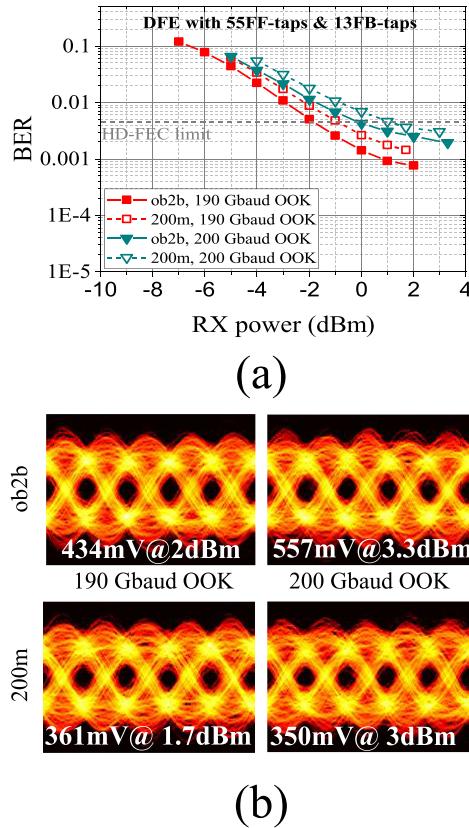


Fig. 5. (a) BER versus RX power for 190 Gbaud and 200 Gbaud OOK with a 55 FF-taps&13 FB-taps DFE, and (b) Eye diagrams (see insets for details).

for ob2b and after transmission over 200 meters of SMF. Eye diagrams after the equalization with the opened eyes are shown in Fig. 5(b). We obtain similar power penalty values for transmission over 200 meters of SMF. The number of taps in the DFE can be relaxed to 21 FF-taps and 3 FB-taps for 190 Gbaud OOK and to 33 FF-taps and 3 FB-taps for 200 Gbaud OOK (see Fig. 6). The 200 Gbaud OOK signal requires post-equalization with at least DFE with 33 FF-taps and 3 FB-taps. That shows that we are using signals that are with bandwidth beyond system response. That requires a post-equalization to achieve significant performance improvement.

A detailed analysis of the DFE impact on the 170 Gbaud, 180 Gbaud, 190 Gbaud, and 200 Gbaud OOK signals quality is provided in Fig. 6. For the 170 Gbaud OOK signal, we achieve below the KR-FEC threshold in the case of ob2b. Fiber dispersion sets a limitation on achievable performance. An FFE is not enough to reduce the bit error rate below the HD-FEC threshold; at least 3 FB-taps are needed in combination with 13 FF-taps for 170 Gbaud OOK, 21 FF-taps for 180 Gbaud and 190 Gbaud OOK, and 33 FF-taps for 200 Gbaud OOK. Adding more FB-taps does not improve the signal quality significantly. These configurations of the post-equalizer bring the signal quality below the 6.25% OH HD-FEC threshold of 4.5×10^{-3} after transmission over 200 meters long optical link where no optical amplification is used thanks to the high output power of the C-band externally modulated laser. Further improvement in the performance can be obtained with short memory length maximum likelihood sequence estimation (MLSE) equalization [3].

B. Pulse Amplitude Modulation

We then extend our system performance evaluation with multilevel PAM signals, which further reflects the characteristics of both the modulation linearity and the SNR. Two PAM configurations, namely, PAM4 and PAM6 are employed for this study. We explore the maximum supportable data rates by the system setup for each modulation format, with BER performance fulfilling the requirement of the 6.25% OH HD-FEC threshold. We also see if the performance can be better and support the KP4-FEC threshold.

Fig. 7(a) shows the BER performance as a function of the RX power for 112 Gbaud PAM4 for both ob2b and after different fiber link lengths. It is observed that for ob2b, the BER can reach below the KP4-FEC threshold at 2 dBm using the DFE with 55 FF-taps and 13 FB-taps. For 112 Gbaud PAM4 and 100 Gbaud PAM6 we only require a post-equalizer with only 3 tap FFE to achieve the performance below the HD-FEC threshold (see Fig. 8). Transmission over 200 meters fiber link results in negligible power penalty compared with the ob2b, though KP4-FEC is not achieved due to limited maximum power of 1.6 dBm in this case. Further increasing the transmission distance to 400 meters introduces about a 0.5 dB penalty due to fiber chromatic dispersion. Finally, we observed an over 3 dB power penalty for the 600 meters transmission case compared with ob2b, whereas the 6.25% OH HD-FEC threshold is still achievable thanks to the sufficient power margin. We obtain approximately a 5 dB power budget for this link. That would not be sufficient for operation in the O-band [27], [28]. The power budget requirement can be met with an improved design of DFB-TWEAM. It is possible to achieve higher output power for the laser design and a higher extinction ratio for the modulator design. Another alternative is to use an integrated optical preamplifier in the receiver e.g., a semiconductor optical amplifier (SOA) instead of a low noise electrical amplification. That allows to amplify the received signal well above the thermal noise floor of the electrical amplifier and may hence provide better receiver sensitivity. On the other hand, an SOA may give pulse distortion due to its fast gain compression and if it is integrated with the detector without any optical bandpass filter in-between, the benefit of optical amplification will be further hampered by broadband spontaneous emission noise. Therefore, a further evaluation is required to quantify the potential benefit. Fig. 7(b) shows the selected eye diagrams after the post-equalizer for 112 Gbaud PAM4 in the case of ob2b and after 200 meters transmission, captured at the highest achievable received optical power values, respectively. One can see that in both cases clear eye openings without any nonlinear distortions are obtained, reflecting excellent characteristics of the system in terms of both SNR and linearity.

Fig. 8(a) shows the BER performance versus RX power for PAM6 signals at 100 Gbaud. Successful transmissions with BER below the 6.25% OH HD-FEC threshold are achieved for both ob2b and after 200 meters of SMF at this baudrate. Less than 1 dB power penalty is observed after the 200 meters transmission, indicating that the system is mainly limited by noise due to the higher required SNR for PAM6. It is also noted that further increasing transmission distance couldn't

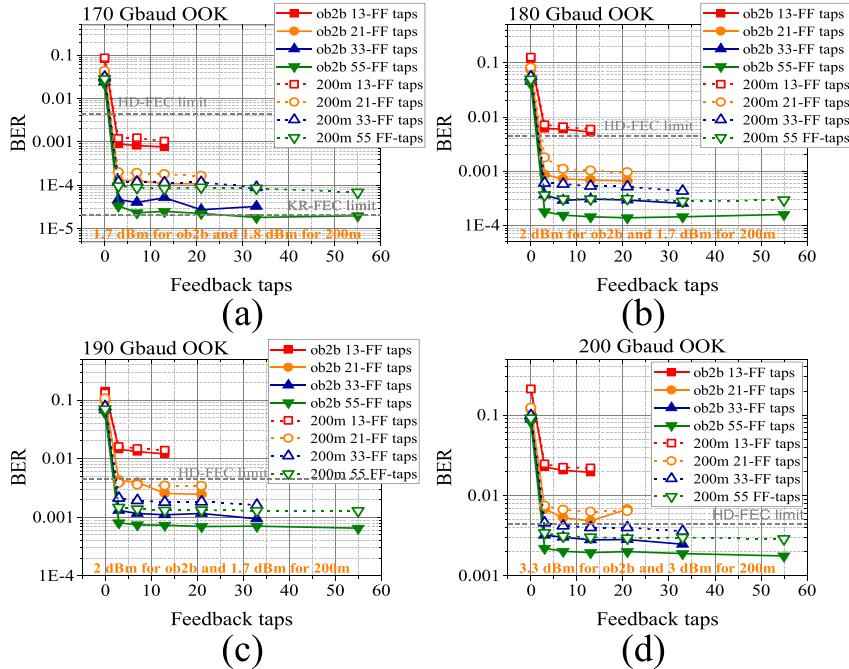


Fig. 6. (a) Bit error rate versus number of taps in decision feedback equalizer for (a) 170 Gbaud OOK, (b) 200 Gbaud OOK, (c) 190 Gbaud OOK, and (d) 200 Gbaud OOK links.

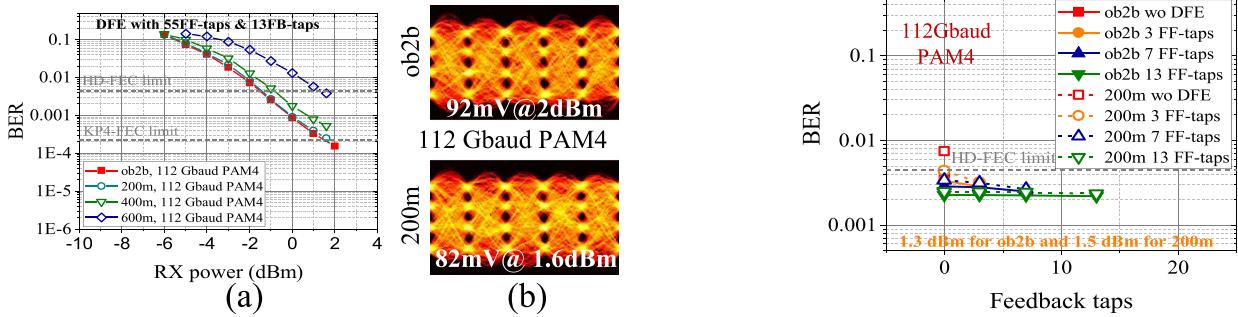


Fig. 7. (a) BER versus RX power for 112 Gbaud PAM4 with a 55 FF-taps&13 FB-taps DFE, (b) Eye diagrams (see insets).

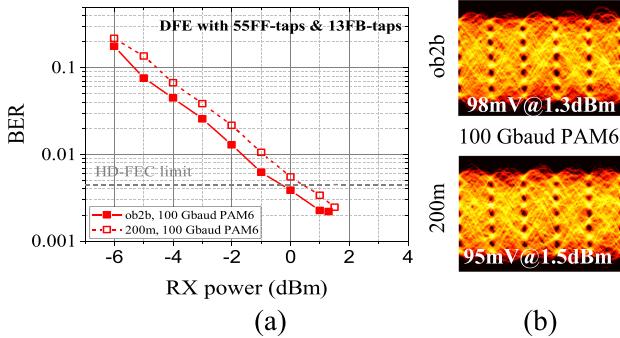


Fig. 8. (a) BER versus RX power for 100 Gbaud PAM6 with a 55 FF-taps&13 FB-taps DFE, (b) Eye diagrams (see insets).

result in below the targeted FEC threshold due to limited received power in this experiment. The eye diagrams for both cases captured at the highest received power are shown in

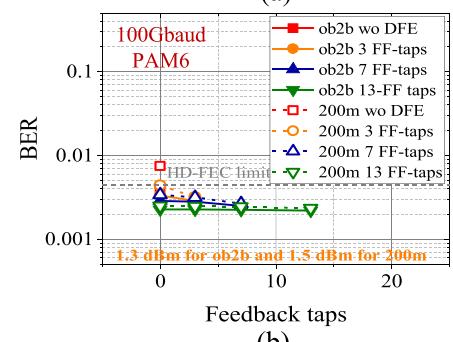
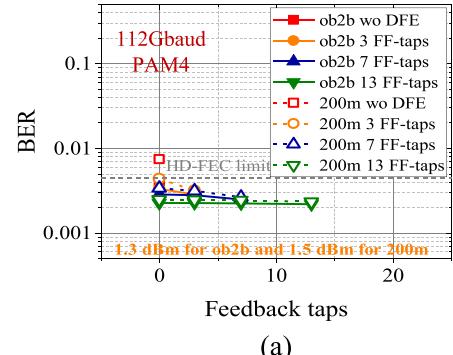


Fig. 9. Bit error rate versus tap numbers of decision feedback equalizer for (a) 112 Gbaud PAM4, and (b) 100 Gbaud PAM6 links.

Fig. 8(b). Like the 112 Gbaud PAM4 cases, negligible nonlinear compressions are observed despite the increased amplitude levels.

Finally, we evaluate the performance of the digital post-equalizers with different complexities for both 112 Gbaud PAM4

and 100 Gbaud PAM6. For PAM4, as shown in Fig. 9(a), the targeted FEC threshold can be achieved even without DFE for ob2b, and the BER after 200 meters of transmission is only slightly above the threshold. Adding a 3-tap FFE is sufficient to bring the BER performance of the 200 meters case below the FEC threshold. This is mainly due to the digital pre-equalization performed at the transmitter side to effectively pre-compensate for the calibrated channel frequency response. The KP4-FEC threshold can be achieved only for the ob2b case when up to 13 tap FFE is used, whereas it is not achievable for the 200 meters case which is limited by received optical power. Similarly, for PAM6, as shown in Fig. 9(b), the targeted HD-FEC threshold can be achieved for ob2b without any DFE, and 3 tap FFE is sufficient to improve the BER performance of the 200 meters transmission case to below the FEC threshold. As the system is mainly limited by noise for higher-order PAM signals, adding up to 13 feedback taps in the DFE configurations only brings limited improvement compared with FFE.

IV. CONCLUSION

We demonstrate amplification-free high baudrate optical links thanks to high output power for the externally modulated laser. The BER performance is well below the 6.25% OH HD-FEC threshold for all modulation formats used in the experiment. We demonstrate a 108 Gbaud OOK optical link without post-equalization with performance below the KR-FEC threshold. We also show a widely opened eye diagram for 200 Gbaud OOK signal after transmission over 200 meters of SMF without any optical amplification using the C-band EML. We benchmark the short-reach optical link with 112 Gbaud PAM4 and achieve performance below the KP4-FEC threshold for ob2b. We note that the microwave design of the DFB-TWEAM can be applied to a semiconductor material with a larger bandgap to achieve modulation at different operation wavelengths. This would require having higher laser power in the modulator due to higher fiber loss in the O-band.

ACKNOWLEDGMENT

We thank Keysight Technologies for the loan of the M8199A Arbitrary Waveform Generator and the UXR1104A Infinium UXR-Series Oscilloscope.

REFERENCES

- [1] M. Spyropoulou et al., “The path to 1Tb/s and beyond datacenter interconnect networks: Technologies, components, and subsystems,” *Proc. SPIE*, vol. 11712, 2021, Art. no. 117120G.
- [2] X. Pang et al., “200 Gbps/lane IM/DD technologies for short reach optical interconnects,” *J. Lightw. Technol.*, vol. 38, no. 2, pp. 492–503, Jan. 2020.
- [3] J. Wei et al., “Experimental demonstration of advanced modulation formats for data center networks on 200 Gb/s lane rate IMDD links,” *Opt. Exp.*, vol. 28, no. 23, pp. 35240–35250, Nov. 2020.
- [4] R. Hersent et al., “160-GSa/s-and-beyond 108-GHz-bandwidth over-2-V_{ppd} output-swing 0.5-μm InP DHBT 2:1 AMUX-driver for next-generation optical communications,” *IEEE Microw. Wireless Compon. Lett.*, vol. 32, no. 6, pp. 752–755, Jun. 2022.
- [5] M. Sakib et al., “A high-speed micro-ring modulator for next generation energy-efficient optical networks beyond 100 Gbaud,” in *Proc. CLEO*, 2021, pp. 1–2.
- [6] D. W. U. Chan et al., “C-band 67 GHz silicon photonic microring modulator for dispersion-uncompensated 100 Gbaud PAM-4,” *Opt. Lett.*, vol. 47, no. 11, pp. 2935–2938, Jun. 2022.
- [7] W. Heni et al., “Ultra-high-speed 2:1 digital selector and plasmonic modulator IM/DD transmitter operating at 222 GBaud for intra-datacenter applications,” *J. Lightw. Technol.*, vol. 38, no. 9, pp. 2734–2739, May 2020.
- [8] Q. Hu et al., “Plasmonic-MZM-based short-reach transmission up to 10 km supporting >304 GBd polybinary or 432 Gbit/s PAM-8 signaling,” in *Proc. Eur. Conf. Opt. Commun.*, 2021, pp. 1–4.
- [9] P. Kharel et al., “Breaking voltage-bandwidth limits in integrated lithium niobate modulators using micro-structured electrodes,” *Optica*, vol. 8, no. 3, pp. 357–363, Mar. 2021.
- [10] D. Che and X. Chen, “Faster-than-Nyquist signaling up to 300-GBd PAM-4 and 570-GBd OOK suitable for co-packaged optics,” in *Proc. Eur. Conf. Opt. Commun.*, 2021, pp. 1–4.
- [11] F. Yang et al., “Monolithic thin film lithium niobate electro-optic modulator with over 110 GHz bandwidth,” *Chin. Opt. Lett.*, vol. 20, no. 2, pp. 1–5, Feb. 2022.
- [12] A. Shams-Ansari et al., “Electrically pumped laser transmitter integrated on thin-film lithium niobate,” *Optica*, vol. 9, no. 4, pp. 408–411, Apr. 2022.
- [13] S. Kanazawa et al., “224-Gbit/s 4-PAM operation of a high-modulation-bandwidth high-output-power Hi-FIT AXEL transmitter,” *Opt. Lett.*, vol. 47, no. 12, pp. 3019–3022, Jun. 2022.
- [14] M. S. Bin Hossain et al., “Partial response O-band EML transmission beyond 300-GBd with a 128/256 GSa/s DAC,” in *Proc. Opt. Fiber Commun. Conf. Exhib.*, 2022, pp. 1–3.
- [15] H. Mardoyan et al., “204-Gbaud on-off keying transmitter for inter-data center communications,” in *Proc. Opt. Fiber Commun. Conf. Exhib.*, 2018, pp. 1–3.
- [16] J. M. Estarán et al., “140/180/204-Gbaud OOK transceiver for inter- and intra-data center connectivity,” *J. Lightw. Technol.*, vol. 37, no. 1, pp. 178–187, Jan. 2019.
- [17] O. Ozolins et al., “Optical amplification-free 200 Gbaud on-off keying link for intra-data center communications,” in *Proc. Opt. Fiber Commun. Conf. Exhib.*, 2022, pp. 1–3.
- [18] Y. Matsui et al., “Low-chirp isolator-free 65-GHz-bandwidth directly modulated lasers,” *Nature Photon.*, vol. 15, no. 1, pp. 59–63, Jan. 2021.
- [19] D. Che et al., “Long-term reliable >200-Gb/s directly modulated lasers with 800GbE-compliant DSP,” in *Proc. Opt. Fiber Commun. Conf. Exhib.*, 2021, pp. 1–3.
- [20] N.-P. Diamantopoulos et al., “>100-GHz bandwidth directly-modulated lasers and adaptive entropy loading for energy-efficient >300-Gbps/λ IM/DD systems,” *J. Lightw. Technol.*, vol. 39, no. 3, pp. 771–778, Feb. 2021.
- [21] M. S. Alam, X. Li, M. Jacques, E. Berikaa, P.-C. Koh, and D. V. Plant., “Net 300 Gbps/λ transmission over 2 km of SMF with a silicon photonic Mach-Zehnder modulator,” *IEEE Photon. Technol. Lett.*, vol. 33, no. 24, pp. 1391–1394, Dec. 2021.
- [22] H. Sato, J. Mao, A. Bannaron, T. Kamiya, G.-W. Lu, and S. Yokoyama, “A 100 Gbaud on-off-Keying silicon-polymer hybrid modulator operating at up to 110 °C,” *IEEE Photon. Technol.*, vol. 33, no. 24, pp. 1507–1510, Dec. 2021.
- [23] E. Berikaa et al., “Net 67 Gbps transmission over 2 km at sub 1 Vpp using packaged silicon photonic MZM,” *IEEE Photon. Technol. Lett.*, vol. 34, no. 21, pp. 1139–1142, Nov. 2022.
- [24] M. Chaciński, U. Westergren, B. Stoltz, L. Thylen, R. Schatz, and S. Hammerfeldt, “Monolithically integrated 100 GHz DFB-TWEAM,” *J. Lightw. Technol.*, vol. 27, no. 16, pp. 3410–3415, Aug. 2009.
- [25] M. Chaciński et al., “ETDM transmitter module for 100-Gb/s ethernet,” *IEEE Photon. Technol. Lett.*, vol. 22, no. 2, pp. 70–72, Jan. 2010.
- [26] O. Ozolins et al., “100 GHz externally modulated laser for optical interconnects,” *J. Lightw. Technol.*, vol. 35, no. 6, pp. 1174–1179, Mar. 2017.
- [27] J. Wei et al., “System aspects of the next-generation data-center networks based on 200G per lambda IMDD links,” in *Proc. SPIE*, vol. 11308, 2020, Art. no. 1130805.
- [28] N. Stojanovic, C. Prodaniuc, L. Zhang, and J. Wei, “210/225 Gbit/s PAM-6 transmission with BER below KP4-FEC/EFEC and at least 14 dB link budget,” in *Proc. Eur. Conf. Opt. Commun.*, 2018, pp. 1–3.