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200 Gb/s Unamplified IM/DD Transmission over 20-km SMF with an O-band Low-Chirp Directly Modulated Laser

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Abstract *200 Gb/s IM/DD transmission over 20-km SMF is demonstrated without any optical amplifiers, achieving BER below the 6.25%-overhead HD-FEC limit, enabled by a broadband and high-power DML with low-complexity digital equalizations. ©2022 The Author(s)*

Introduction

Next-generation 800 Gb/s or 1.6 Tb/s datacom optical modules will be soon needed, considering the bandwidth-scaling pace of switches for data center networks and the already-ongoing deployment of 400 Gb/s optical modules. Single lane data rates of 200 Gb/s will be desirable to reduce the lane count and footprint [1]. Main technical considerations for 200 Gb/s/lane technologies towards development include sufficient bandwidth from the optoelectronics, adequate power budget to support up to DR and LR applications, limited footprint and power consumption from the components and digital signal processing (DSP) ASICs, and bounded latency from the forward error correction (FEC) coder/decoder. In recent years, many intensity-modulation and direct-detection (IM/DD) transmission demonstrations supporting over 200 Gb/s single-lane rates have been reported [2]. Among these works, different types of enabling broadband optoelectronic components are employed, including monolithically integrated transmitters such as electro-absorption modulated lasers (EML) [3-7] or directly modulated lasers (DML) [8], and external modulator-based transmitters such as silicon-photonic- [9], plasmonic- [10], or thin-film Lithium Niobate- (TFLN) [11] Mach-Zehnder modulators (MZM). Most of these encouraging results reported on over 200 Gb/s IM/DD transmissions are, however, achieved with the assistance of optical amplifiers or complex DSP algorithms. Digital equalizers of over hundred-tap memory lengths, nonlinear equalizers based on 2nd or 3rd-order Volterra series, or artificial neural networks (ANN) are often employed to combat the bandwidth (BW) limit and other linear/nonlinear system impairments. Moreover, many of these demonstrations were benchmarked against the high-coding gain soft/hard-decision FEC code limit with large overhead (OH), which introduces unrealistically large complexity and latency for datacom applications. As we are approaching standardization and practical development, it is extremely challenging to simultaneously meet the stringent requirements of high-bandwidth and sufficient power budget while maintaining low cost, low complexity, and low latency. Lately, a 200 Gb/s transmission over 10-km single-mode fiber (SMF) with a high-power DFB+R laser was successfully demonstrated with 800G compliant DSP, achieving bit error rate (BER) performance below 7% HD-FEC and KP4-FEC limit with long-term stability [12]. Yet, the system-level performance limit of such lasers remained to be further explored with higher-speed electronics and longer transmission distances.

In this paper, we report on a 200 Gb/s O-band IM/DD system enabled by a 70-GHz-class directly-modulated DFB+R laser, simultaneously meeting the strict requirements of the power budget of 20-km SMF transmission without any optical amplification or high-complexity nonlinear digital equalization techniques, achieving BER performance below 6.25% OH HD-FEC limit. To the best of our knowledge, this is the first experimental demonstration of 200 Gb/s IM/DD transmission fulfilling these practical requirements simultaneously, carrying on the momentum of developing high-baud rate IM/DD

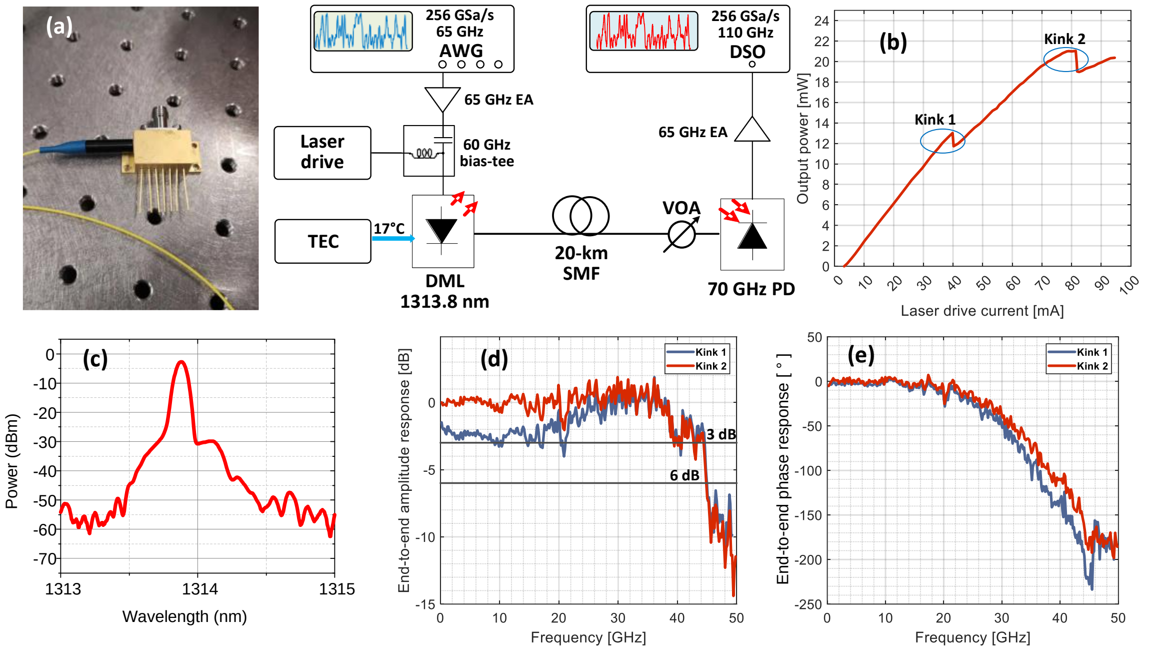

Fig. 1: Experimental setup. (a). A photo of the packaged DFB-R laser. (b). The P-I curve of the DFB-R laser with two kink points where mode hops occur. (c). Optical spectrum at the laser output modulated with 106 Gbaud PAM4 signal operating at bias point before kink 2. (d). Characterized end-to-end system amplitude response up to 50 GHz at two bias points around kink 1 and kink 2. (e). Corresponding end-to-end system phase response up to 50 GHz.

solutions for beyond 400 Gb/s datacom applications.

Experimental setup

Figure 1 shows the experimental setup and measured components and system characteristics. The DML used in this experiment is a packaged module of a recently reported 70-GHz-class DFB+R laser [13], a photo of which is shown in Fig. 1 (a). 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 DL effect enhances the differential gain and reduces the laser chirp, thus enhancing the DML BW. The PPR effect resonantly amplifies the modulation sidebands by exploiting the presence of the side modes. The in-cavity FM-AM conversion results in a high-pass response effect. The laser is driven with an external bias-tee where the bias current and the broadband modulation signal combine. An arbitrary waveform generator (AWG, Keysight M8199A) of 256 GSa/s sampling rate and up to 65 GHz bandwidth is used to generate the modulation signals. The DML is operated at 17°C, and its P-I curve is shown in Fig. 1 (b). Two kink points are observed with increased laser drive current where the output power drops due to mode hops. As the DL and the PPR effects are maximized before the kinks, the laser bandwidth is optimized by operating close to the kink points. In the experiment, optimal bias points were found around 8-9 mA before the kinks, as biasing the laser too close to the kinks may cause instability and lead to unwanted mode hops. Figure 1 (c) shows the optical spectrum of the laser output modulated with 106 Gbaud PAM signal when biasing at 71 mA, close to kink 2. After transmission over 20-km G.652 SMF, the signal is received by a 70 GHz photodiode (PD) before being amplified and captured by a 256 GSa/s real-time digital storage oscilloscope (DSO, Keysight UXR1104A) with 110 GHz bandwidth. No optical amplifiers are used before or after the fiber transmission. Figure 1 (d) and (e) show the characterized end-to-end amplitude and phase response, including the AWG, DML, PD, DSO, and all electrical components in between, measured close to the two kink points, respectively. One can observe that a more flattened amplitude response and a smoother phase response are obtained when biasing the laser close to kink 2 compared with kink 1. Therefore, we keep the laser operating close to kink 2 during the transmission measurements. Transmitter-side static pre-equalizations are performed to flatten the response up to 45 GHz based on the pre-calibration.

Experimental results

Three modulation formats, namely NRZ, PAM4, and PAM6, are evaluated towards the maximum

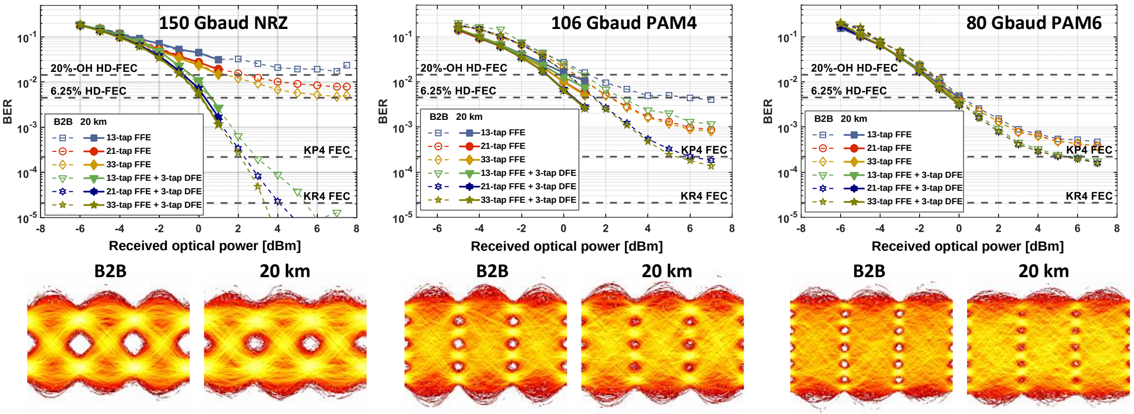

Fig. 2: Measured BER results as a function of received optical power at the PD for 150 Gbaud NRZ, 106 Gbaud PAM4 and 80 Gbaud PAM6 signals before and after 20-km SMF transmissions. Six different digital equalization configurations are shown for each tested case. Selected eye diagrams of the equalized signals at the receiver for each test case at respective highest achievable received optical power are shown.

achievable data rates with this setup, with BER upper-bounded by the 6.25% OH-HD-FEC limit of 4.5×10^{-3}, and the complexity of DSP bounded to symbol-spaced decision-feedback equalizers (DFE) with a total number of taps below 50. Figure 2 shows the measured BER performance as a function of the received optical power at the PD for all three modulation formats. For NRZ, limited by its bandwidth, only up to 150 Gbaud symbol rate was successfully achieved after the 20-km SMF transmission. 13-tap FFE + 3-tap DFE is sufficient to compensate for the inter-symbol interference (ISI) and suppress the high-frequency noise enhancement to achieve below the 6.25%-OH HD-FEC limit. For PAM4, we achieved up to 106 Gbaud symbol rate with 21-tap FFE + 3-tap DFE after the 20-km SMF. Lastly, the transmission of up to 80 Gbaud PAM6 is supported with this experiment configuration, and only 13-tap FFE is required to achieve a BER below the corresponding FEC limit. Clear tendencies can be observed by comparing the three modulation formats at their maximum data rate. From NRZ to PAM6, due to reduced signal bandwidth, the impact of DFE taps becomes less significant due to reduced high-frequency noise enhancement. Meanwhile, an increased BER floor can be observed due to higher requirements on SNR with increased amplitude levels. Selected eye diagrams for all tested cases at the highest achievable optical power are also shown in Fig. 2. Excellent modulation linearity and noise characteristics of the DML are verified as there are no amplitude compressions at high-level modulation formats, despite that no nonlinear equalizers are employed.

Conclusions

System demonstration of 200 Gb/s IM/DD transmissions over 20-km SMF is achieved without any optical amplifiers or complex nonlinear digital equalizers, benchmarked against the 6.25%-OH HD-FEC limit. Key enabling technologies are the high-power, low-chirp, and broadband directly-modulated DFB-R laser and the high-speed electronics to generate and detect high-baud rate signals. This demonstration can be considered a solid case for carrying on the momentum of IM/DD technologies for the beyond 400 G datacom solutions.

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References

[1] X. Pang, O. Ozolins, R. Lin, L. Zhang, A. Udalcovs, L. Xue, R. Schatz, U. Westergren, S. Xiao, W. Hu, G. Jacobsen, S. Popov and J. Chen, "200 Gbps/Lane IM/DD Technologies for Short Reach Optical Interconnects," *Journal of Lightwave Technology*, vol. 38, no. 2, pp. 492-503, 2020, DOI: 10.1109/JLT.2019.2962322.

[2] J. Wei, T. Rahman, S. Calabro, N. Stojanovic, L. Zhang, C. Xie, Z. Ye and M. Kuschnerov, "Experimental demonstration of advanced modulation formats for data center networks on 200 Gb/s lane rate IMDD links," *Opt Express*, vol. 28, no. 23, pp. 35240-35250, 2020, DOI: 10.1364/OE.409905.

[3] O. Ozolins, L. Zhang, A. Udalcovs, H. Louchet, T. Dippon, M. Gruen, X. Pang, R. Schatz, U. Westergren,

S. Xiao, S. Popov and J. Chen, “100 Gbaud PAM4 link without EDFA and post-equalization for optical interconnects,” in *Proc. ECOC*, 2019, p. Th.2.A.3.

[4] S. Kanazawa, H. Yamazaki, Y. Nakanishi, T. Fujisawa, K. Takahata, Y. Ueda, W. Kobayashi, Y. Muramoto, H. Ishii and H. Sanjoh, “Transmission of 214-Gbit/s 4-PAM signal using an ultra-broadband lumped-electrode EADFB laser module,” in *Proc. OFC*, 2016, p. Th5B.3.

[5] H. Taniguchi, S. Yamamoto, Y. Kisaka, S. Kanazawa, T. Yoshimatsu, Y. Isikawa and K. Mizuno, “800-Gbps PAM-4 O-band Transmission through 2-km SMF using 4λ LAN-WDM TOSA with MLSE Based on Nonlinear Channel Estimation and Decision Feedback,” in *Proc. ECOC*, 2021, p. We1C1.3.

[6] M.S.B. Hossain, J. Wei, F. Pittal, x00E, N. Stojanovi, x, S. Calabr, x00F, T. Rahman, B. G, x00F, cherer, T. Wettlin, C. Xie, M. Kuschnerov and S. Pachnicke, “402 Gb/s PAM-8 IM/DD O-Band EML Transmission,” in *Proc. ECOC*, 2021, p. We1C1.4.

[7] O. Ozolins, T. Salgals, H. Louchet, M. Joharifar, R. Schatz, M. Gruen, T. Dippon, B. Krüger, D. Che, Y. Matsui, Y. Fan, A. Udalcovs, L. Zhang, X. Yu, S. Spolitis, V. Bobrovs, S. Popov and X. Pang, “Optical Amplification-Free 200 Gbaud On-Off Keying Link for Intra-Data Center Communications,” in *Proc. OFC*, 2022, p. Th4A.6.

[8] N.P. Diamantopoulos, H. Yamazaki, S. Yamaoka, M. Nagatani, H. Nishi, H. Tanobe, R. Nakao, T. Fujii, K. Takeda, T. Kakitsuka, H. Wakita, M. Ida, H. Nosaka, F. Koyama, Y. Miyamoto and S. Matsuo, “Net 321.24-Gb/s IMDD Transmission Based on a >100-GHz Bandwidth Directly-Modulated Laser,” in *Proc. OFC,* 2020, p. Th4C.1.

[9] M. Jacques, Z. Xing, A. Samani, X. Li, E. El-Fiky, S. Alam, O. Carpentier, P.-C. Koh and D.V. Plant, “Net 212.5 Gbit/s Transmission in O-band With a SiP MZM, One Driver and Linear Equalization,” in *Proc. OFC*, 2020, p. Th4A.3.

[10] Q. Hu, R. Borkowski, Y. Lefevre, F. Buchali, R. Bonk, K. Schuh, E.D. Leo, P. Habegger, M. Destraz, N.D. Medico, H. Duran, V. Tedaldi, C. Funck, Y. Fedoryshyn, J. Leuthold, W. Heni, B. Baeuerle and C. Hoessbacher, “Plasmonic-MZM-based Short-Reach Transmission up to 10 km Supporting >304 GBd Polybinary or 432 Gbit/s PAM-8 Signaling,” in *Proc. ECOC*, 2021, p. PD2.4.

[11] 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. ECOC*, 2021*,* p. PD1.6.

[12] D. Che, Y. Matsui, R. Schatz, G. Raybon, V. Bhatt, M. Kwakernaak and T. Sudo, “Long-Term Reliable >200-Gb/s Directly Modulated Lasers with 800GbE-Compliant DSP,” in *Proc. OFC*, 2021, p. F3A.3.

[13] Y. Matsui, R. Schatz, D. Che, F. Khan, M. Kwakernaak and T. Sudo, “Low-chirp isolator-free 65-GHz-bandwidth directly modulated lasers,” *Nature Photonics*, vol. 15, no. 1, pp. 59-63, 2020, DOI: 10.1038/s41566-020-00742-2.