Single-Wavelength and Single-Photodiode 700 Gb/s Entropy-Loaded PS-256-QAM and 200-GBaud PS-PAM-16 Transmission over 10-km SMF

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Abstract *We demonstrate the transmission over 10.2-km SMF of intensity-modulated and direct-detected (IM-DD) signals at record 700.4 Gb/s line rate and record 538.8 Gb/s net rate with entropy loaded PS-256-QAM signals, and 200-GBaud PS-PAM-16 signals with 650 Gb/s line rate and 484.5 Gb/s net rate.*

Introduction

Despite coherent systems offering high sensitivity and high spectral efficiency, conventional intensity-modulated direct-detected (IM-DD) systems remain an important option for transmission distances of tens of kilometers or less [1-9]. An IM-DD system requires only one intensity modulator or a directly modulated laser for signal modulation and one single-ended photodiode (PD) with a single analog-to-digital converter (ADC) for detection. The digital signal processing (DSP) for IM-DD systems is also simpler compared to that for coherent systems. High-speed IM-DD systems have recently generated a line rate of up to 554-Gb/s (a net information rate of 460.9 Gb/s) and transmitted over 22 km of optically dispersion-compensated standard single-mode fiber (SMF), achieved by entropy loading and probabilistically shaped (PS) quadrature amplitude modulation (QAM) formats[5]. With single carrier modulation, 516 Gb/s line rate (400 Gb/s net rate) was achieved with PS pulse-amplitude modulation (PAM)[6]. A review of high-speed IM-DD system demonstrations is shown in Fig. 1.

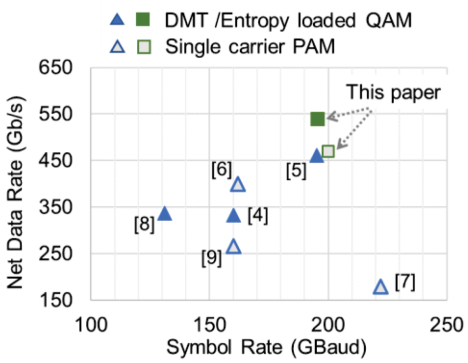

Fig. 1 Review of high-speed IM-DD demonstrations.

In this paper, by further optimizing our digital-band-interleaved (DBI) based digital-to-analog converter (DAC)[10] and pairing it with an ultra-high speed low V_π modulator (Fig.2), we demonstrate a record 700.4-Gb/s line rate and record 538.8-Gb/s net rate IM-DD signal transmitted over 10.2-km optically dispersion-compensated single mode fiber (SMF), which exceeds the previous IM-DD record net data rate[5] by 17%. We also demonstrate a 200 GBaud PS-PAM-16 transmission with line rate of 630 Gb/s and net rate of 484.5 Gb/s, which exceeds the net rate of previous PAM IM-DD net rate record[6] by 21%.

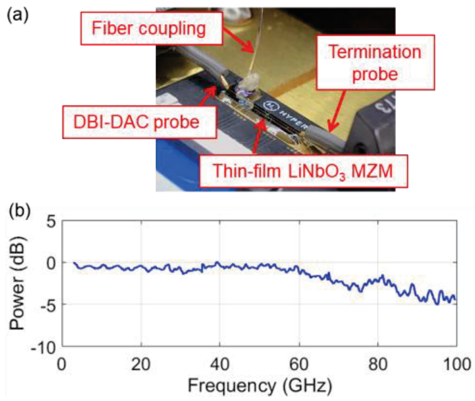

Fig. 2 (a) Setup of the thin-film $LiNbO_3$ MZM modulator; (b) measured combined bandwidth of a RF cable, a RF probe, and the modulator.

Experimental setup

The experimental setup of our IM-DD transmission is shown in Fig. 3. As seen, the optical transmitter consists of an external cavity laser (ECL), an intensity modulator, and a DBI-DAC. The laser has a linewidth of ~100 kHz and is operating at 1550.1 nm. The laser is amplified by an erbium-doped fiber amplifier (EDFA), and the input optical power to the modulator is 23.1 dBm. The intensity modulator is a thin-film $LiNbO_3$ Mach-Zehnder modulator (MZM)[11, 12]. The MZM RF electrode is 1-cm long and has a V_π of ~ 2.4 V (measured at 1 GHz). Optical input and output are packaged with fiber as shown in Fig. 2

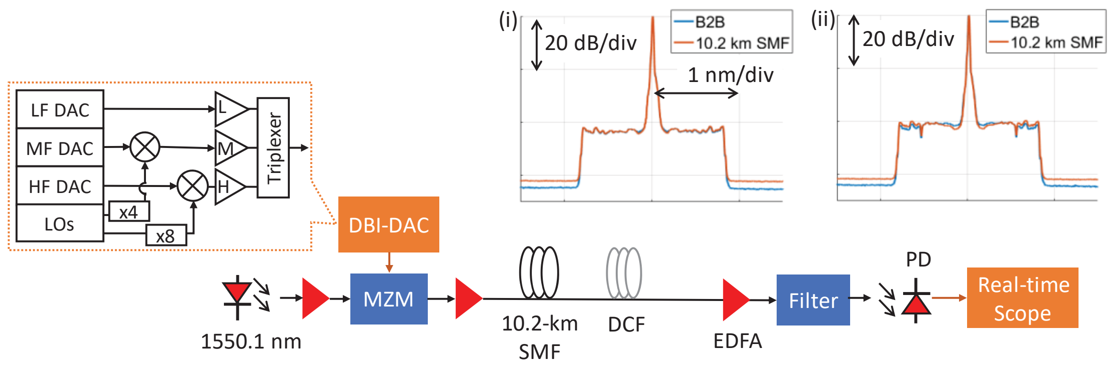

Fig. 3 Experimental setup for the IM-DD transmission. The insets show the optical spectra at back-to-back and after 10.2-km SMF for (i) 200 GBd PS-PAM-16 signal, and (ii) entropy loaded PS-256-QAM signal.

(a). The RF signal is added via a 100-GHz RF probe. The measured combined frequency response combining a short RF cable, the probe, and the modulator is shown in Fig. 2 (b). The response is measured with our calibrated 100-GHz RF signal and 100-GHz photodiode (PD). The insertion loss of the modulator is 11 dB which is dominated by the loss from the on-chip grating couplers. The modulator is driven by a DBI-DAC operating at a sampling rate of 264 GSa/s with a 102-GHz analog bandwidth. The DBI-DAC consists of three baseband 28-nm CMOS DACs (low-frequency/LF, medium-frequency/MF, and high-frequency/HF, shown as an inset to Fig. 3) with ~ 35 GHz bandwidth per CMOS DAC. A detailed description of the DBI-DAC can be found in Ref.10. The RF signal that is driving the MZM has a peak-to-peak voltage of ~ 1.0 V. The MZM is biased at its quadrature position. The modulated light is amplified by an EDFA. The transmission fiber is a 10.2-km SMF with a loss of 0.2 dB/km and a dispersion of 17 ps/km/nm at the signal wavelength. Dispersion-compensation fiber (DCF) with a dispersion of -172 ps/nm is used for optical dispersion compensation. (Alternatively, the system could be operated near the fiber's dispersion-zero around 1300 nm, as in Ref. 2.) The optical power launched into the SMF is 8.7 dBm. After fiber transmission, the signal is filtered by an optical filter with a passband bandwidth of 250 GHz. The filter is a wavelength selective switch, which also functions as a gentle pre-emphasis filter for compensating the PD bandwidth limitation (peaking at 100 GHz with maximum 2 dB pre-emphasis). The received signal is down-converted to the electrical domain via a 100-GHz single-ended PD. The optical input power entering the PD is 9.5 dBm. The down-converted signal is then sampled by a 256-GSa/s 113-GHz real-time scope followed by offline DSP.

Modulation Format and DSP

We apply two modulation formats i) entropy loaded PS-256-QAM signal; and ii) single carrier 200 GBaud PS-PAM-16 signal. The entropy loaded signal is for maximizing the data rate and it consists of two digital bands. We split the available frequencies into two bands because our HF electrical amplifier (c.f. Fig.3) has a higher noise figure which results in lower signal-to-noise ratio (SNR) on frequencies beyond ~ 68 GHz. More specifically, the lower frequency band (DC to 66.76 GHz) carries a 66.1 GBaud PS-256-QAM, and the higher frequency band (68 GHz to 99.9 GHz) carries a 31.6 GBaud PS-256-QAM signal. The entropy (the constellation shaping factors β) of the two bands are adjusted according to the channel SNR. Root-raised-cosine (RRC) filters with 1% spectral roll-off are applied to limit the bandwidth. As digital sub-banding and entropy loading is a relatively advanced format for IM-DD systems, we also apply a simpler format which is 200-GBaud PS 16-ary PAM (PS-PAM-16). There are ~ 0.5 million random symbols used to form each of the transmitter patterns.

Regarding the forward error correction (FEC), we use a rate-0.7932 (26.07% overhead) concatenated FEC coding which consists of a spatially-coupled low-density parity-check (SC-LDPC) inner code of rate 0.8 and a rate-0.9915 hard-decision Bose-Chaudhuri-Hocquenghem (BCH) outer code to remove potential error floors [13]. The required normalized generalized mutual information (NGMI) for the FEC is $NGMI^* = 0.845$.

At the receiver, the entropy loaded two digital bands are processed individually. Each band is digitally filtered, down-converted to baseband, and equalized by a least mean square (LMS) equalizer operating at 2x oversampling. The four LMS filters for the two bands have 731 and 351 taps (both are ~ 5.5 ns). This is because our DBI-DAC is built from discrete components, and relatively long filters are needed to compensate the distortions and reflections along the RF chain. The 200 GBaud PS-PAM-16 signal uses an LMS filter with 2201 taps (~ 5.5 ns). About 9,000 symbols are used for pre-convergence followed by blind equalization. Only the blindly recovered data are used for NGMI calculation. The NGMI is calculated from ~ 2 million symbols. For the entropy loaded signal, the overall NGMI for the two bands is calculated as $NGMI = 1 - (\sum_{i=1}^{2} B_i H_i - \sum_{i=1}^{2} B_i GMI_i)/\sum_{i=1}^{2} B_i m$, where i denotes the sub-band index, GMI_i is measured from the received constellation, B_i is the symbol rate, H_i is the entropy and calculated as $2(1+\beta_i)$, and $m = \log_2 256$.

Results and Discussions

The measured NGMIs and their corresponding net data rate are shown in Fig. 4. At back-to-back, the entropy loaded PS-256-QAM signal yields entropy $H = 7.4\ bits/sym$ (β=2.7) for the lower frequency band (band 1) and $H = 7\ bits/sym$ (β=2.5) for the higher frequency band (band 2). The measured NGMI is 0.8472. For 10.2 km transmission, the entropy drops slightly to $7.26\ bits/sym$ (β=2.63) and $7.18\ bits/sym$ (β=2.49) for the 2 bands due to the increased optical noise (c.f. Fig.3). Under the PAS coding structure [14], we have γ = 0.1728 for PS-256-QAM with code rate of 0.7932. For QAM signals, the line rate and net rate can be calculated as $R_{Line} = 2(1+\beta)r_c$ and $R_{info} = 2(\gamma+\beta)r_c$ where r_c is the symbol rate [15]. Therefore, the aggerate line rate at back-to-back is 710.3 Gb/s [=(2*(1+2.7)*66.1+2*(1+2.5)*31.6)], and the net rate is 548.7 Gb/s [=(2*(0.1728+2.7)*66.1 + 2*(0.1728+2.5)*32)]. After the 10.2 km transmission the line rate is 700.4 Gb/s and the net rate is 538.8 Gb/s. The received digital spectrum and the recovered constellations after 10.2 km transmission is shown in Fig. 5 (a) and (b). The corresponding constellations SNRs are 18.3 dB and 17.6 dB.

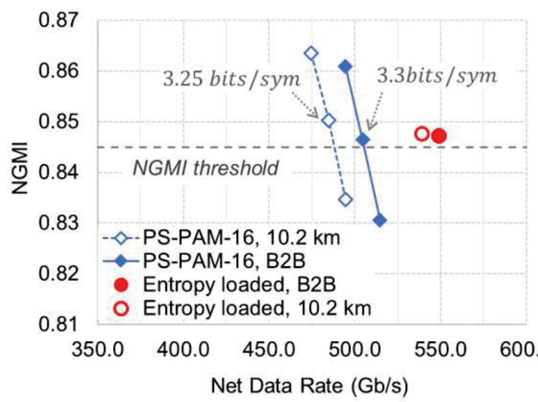

Fig. 4 Measured NGMI as a function of net data rate, for the 200 GBaud PS-PAM-16 IM-DD signal.

For the 200-GBaud PS-PAM-16 signal, we adjust the entropy from 3.2 bits/sym to 3.4 bits/sym (β from 2.2 to 2.4) to find the maximum net data rate. The results are shown as blue curves in Fig. 4. As seen, the highest data rate at back-to-back and 10.2 km are achieved at entropy of 3.3 bits/sym and 3.25 bits/sym. For PS-PAM signals, the line rate and net rate can be calculated as $R_{Line} = (1+\beta)r_c$ and $R_{info} = (\gamma+\beta)r_c$. For PS-PAM-16, we have γ = 0.1728. Therefore, the line and net rate for back to back is 660 Gb/s [=200*(1+2.3)] and net rate is 494.5 [=200*(0.1728+2.3)]. Similarly, we can calculate the line and net rates after 10.2 km as 650 Gb/s and 484.5 Gb/s. The received digital spectrum after 10.2 km is shown in Fig. 6 (a). The recovered amplitudes and the histogram of the amplitudes are shown in Fig. 6 (b) and (c). The corresponding SNR is 17.0 dB. It is worth noting that although our PS-PAM-16 with β=2.25 delivers only slightly higher net data rate as uniform PAM-8, PS-PAM-16 offers shaping gain. The discussion of how much shaping gain PS-PAM could bring to a particular IM-DD system is out of this paper's scope and relevant discussions can be found in e.g. Ref. 16.

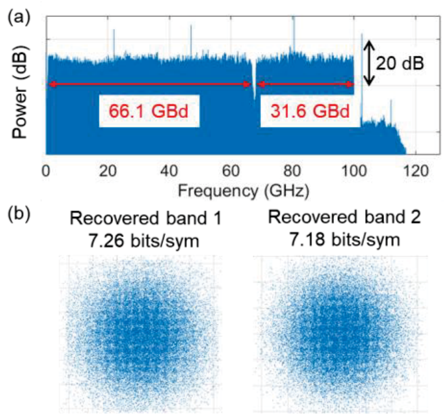

Fig. 5 Entropy loaded PS-256-QAM signal after 10.2 km (a) spectrum; (b) recovered constellations.

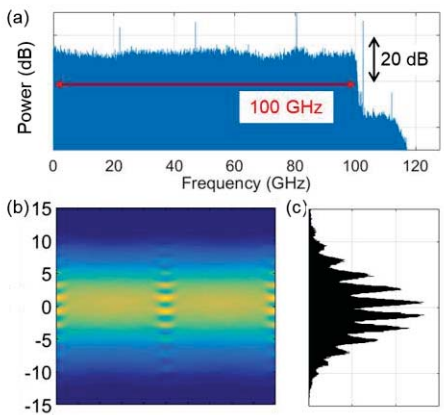

Fig. 6 200 GBaud PS-PAM-16 signal (3.25 bits/sym) after 10.2 km (a) spectrum; (b) recovered eye diagram; (c) histogram (linear scale) of the amplitudes.

Conclusions

We demonstrated IM-DD transmission over 10.2-km SMF at a record 700.4-Gb/s line rate and a record 538.8-Gb/s net rate. This exceeds the previous record for single-wavelength single-PD IM-DD transmission [5] by 17%.

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