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Single Carrier net 400 Gbit/s IM/DD over 400 m Fiber enabled by Plasmonic Mach-Zehnder Modulator

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Abstract: We demonstrate a 437.1Gbit/s IM/DD link by employing a 178GBd PAM8 signal encoded by a plasmonic MZM. Symbol rates of up to 256GBd and transmission over 400m while maintaining net-rates of >400Gbit/s are successfully demonstrated.

1. Introduction

The everlasting increase in datacenter traffic is currently pushing single carrier line rates. Providers prefer simpler solutions such as intensity modulated direct detection (IM/DD) transceivers [1]. These transceivers should offer highest speeds, small footprint, low driving voltages, as well as integration in current manufacturing processes [2].

Recently, IM/DD demonstrations have, for the first time, reached 400 Gbit/s [3]. These advances were mainly driven by the development of improved digital-to-analog converters (DACs) in addition to modulator improvements [3]. Further advancements are expected with improvements in co-packaged optics and electronics [4]. So far, only thin-film lithium-niobate (TFLN), InP as well as electro-absorption modulators have reached the 400 Gbit/s mark [3, 5, 6]. Most recently, up to 510 Gbit/s net-bitrates have been demonstrated with TFLN modulators using a 200 GBd duooctonary signal. Partial response signaling was employed to cope with bandwidth limitations in the system and has shown to work despite strong bandwidth limitations [7].

To overcome the bandwidth limitations of conventional modulators, plasmonic devices can be employed. Plasmonic modulators, have been shown to operate up to 500 GHz [8] and are therefore an ideal solution for such high-bandwidth applications. Recently net data rates of up to 373 Gbit/s by means of micro-ring resonator modulators (MRR) [9] and up to 363 Gbit/s with Mach-Zehnder modulators (MZM) [10] have been demonstrated. These plasmonic modulators are based on the silicon photonic (SiPh) platform and can therefore seamlessly be integrated into standard SiPh processes for monolithic integration. This promises further improvements through co-packaging [11], enable small footprint [12] and low driving voltages [13], forming an ideal candidate for 400 Gbit/s tranceivers. However a single carrier IM/DD demonstration with plasmonics reaching above 400 Gbit/s is still missing.

In this paper, we demonstrate net bit rates >400 Gbit/s by employing IM/DD schemes enabled by a wideband plasmonic Mach-Zehnder modulator. This was achieved by using a 176 GBd PAM 8 signal, reaching 437.1 Gbit/s while staying below a 25% SD FEC overhead. Symbol rates of up to 256 GBd are shown, and different modulation formats are investigated. In addition, transmission over 400 m standard single-mode fiber is shown, while still reaching net-data rates of 400 Gbit/s. These results are the highest symbol rate and net bitrate demonstrated utilizing plasmonic MZM.

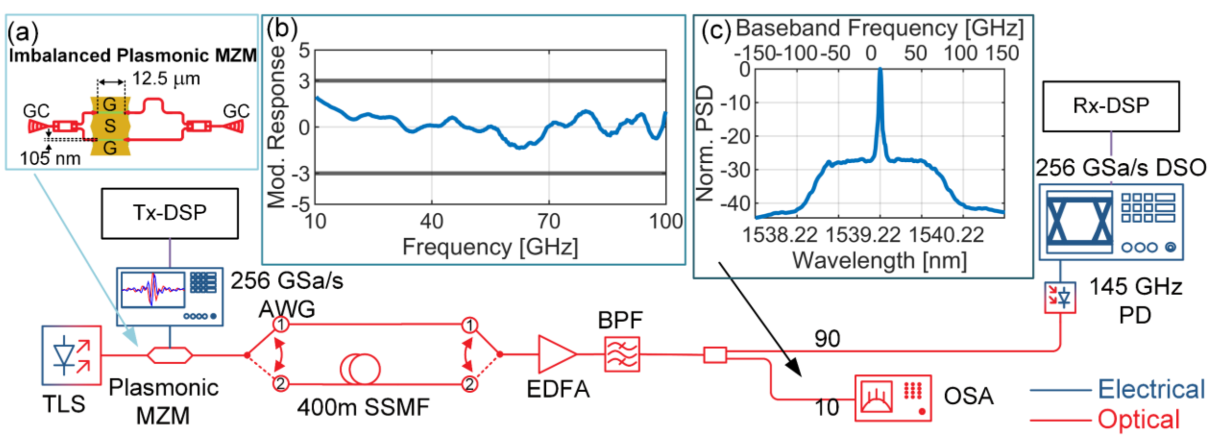

Fig. 1. Experimental setup of the intensity-modulated direct detection link. The schematics of the plasmonic Mach-Zehnder modulator (MZM) can be seen in inset (a), while the measured bandwidth between 10 and 100 GHz is shown in inset (b). After modulation, the optical signal is either transmitted back-to-back to a pre-amplified receiver or via a fiber span of 400 m standard single-mode fiber (SSMF). The spectrum of a 256 GBd PAM 2 signal can be seen in inset (c)

2. Experimental Setup

The experimental setup is shown in Fig. 1. A tunable laser source (TLS) at a wavelength of 1539.22 nm is used to drive the plasmonic MZM at an optical laser power of up to 12 dBm. A 256 GSa/s arbitrary waveform generator (AWG) with an analog bandwidth of 80 GHz is used to drive the MZM. In the transmitter digital-signal processing (DSP), pulse-amplitude modulated (PAM) signals with a square-root-raised cosine shape are generated. The optical signal is then either transmitted through 400 m of standard single-mode fiber or directly back-to-back to the pre-amplified receiver. The pre-amplified receiver structure consists of an erbium-doped-fiber amplifier (EDFA), a 3 nm bandpass filter followed by a 145 GHz PIN photodetector. The electrical signal is sampled by a real-time oscilloscope with an analog bandwidth of 110 GHz and 256 GSa/s. The receiver DSP consists of timing recovery, a T/2 spaced feed-forward equalizer with 151 taps, followed by a third order Volterra equalizer with [55, 15, 15] taps. Lastly, the signal is again filtered by a T-spaced feed-forward equalizer with 1001 taps followed by the symbol decision. Only for the 256 GBd PAM 2 signal, a pattern dependent equalizer with a length of 7 was used to further compensate for low-pass characteristics.

The employed plasmonic MZM, illustrated in Fig. 1(a), was fabricated on Polariton's Plasmonic PIC platform [14]. The demonstated modulator is an imbalanced MZM with a plasmonic slot length of 12.5 µm and a width of 105 nm. Hence, the operation point of the MZM is tuned by selecting the appropriate wavelength. The plasmonic slots are filled with Lightwave Logic's Perkinamine™ chromophore series 3. The devices' fiber-to-fiber losses are 13.75 dB. This includes fiber-to-chip grating coupler losses of 3.1 dB per facet, photonic plasmonic converter losses of 2×0.5 dB, silicon photonic routing losses of 1.3 dB and plasmonic losses of 5.25 dB. The V_{π} of the MZM has been measured to be 7.25 V leading to a $V_{\pi, eq}$ of 3.625 V. As the plasmonic modulator is designed as a high-impedance load, it utilizes twice the 50 Ω voltage leading to the aforementioned $V_{\pi, eq}$. Lastly, the bandwidth of the device was measured between 10 – 100 GHz and is shown in Fig. 1(b). It can be seen that there is no clear drop-off within the measured region.

3. Data Transmission Results

Results for the back-to-back setup can be seen in Fig. 2. Fig. 2(a) shows achievable information rate (AIR) as a function of symbol rate while (b) details the net-data rates. AIR was calculated by using the generalized mutual information (GMI) times symbol rates, while net-data rates were calculated using the respective overhead determined by the normalized GMI (NGMI) thresholds given in [10] times the symbol rate and bits/symbol. This means, that for each measurement the respective NGMI value was calculated and the corresponding FEC overhead applied. In Fig. ***2***(c), the normalized GMI is plotted and the NGMI threshold for the highest 25% FEC overhead is visualized. If the NGMI dropped below the threshold, no net-rate was calculated. In (d), the respective bit-error rate (BER) _as a function of the symbol rate is plotted and two HD FEC thresholds from [10] are visualized. The highest AIR reached

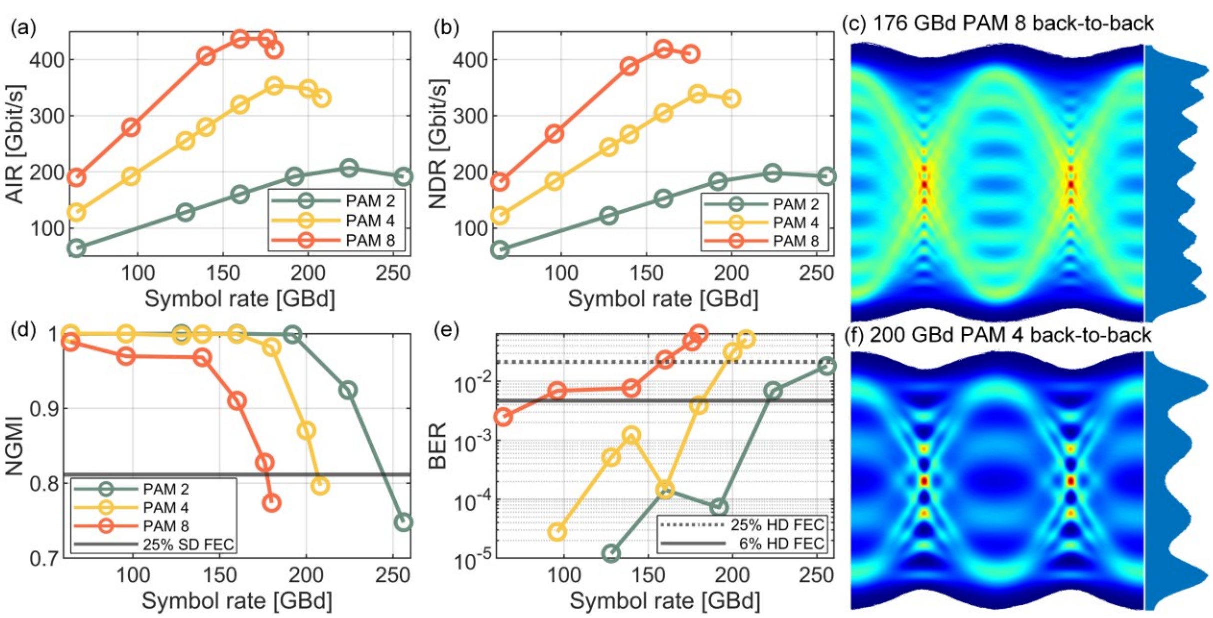

Fig. 2 Back-to-back experimental results are split into 6 subplots. (a-d) Respectively detailing the achievable information rate (AIR), net-data rate (NDR), normalized general mutual information (NGMI) as well as bit-error rate (BER) for the back-to-back measurements. (e-f) Showing the achieved eye-diagrams for the 176 GBd PAM 8 signal reaching the highest AIR and the 200 GBd PAM 4 signal.

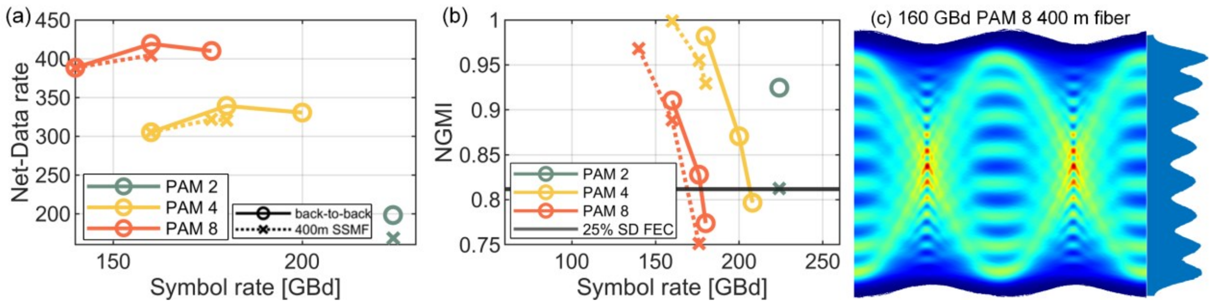

Fig. 3 Comparison between back-to-back and 400 m fiber transmission is detailed in (a & b). Respectively showing the net-data rate and normalized general information (NGMI) for the back-to-back (solid lines) as well as the 400 m fiber transmission (dashed lines). (c) Showing the achieved eye-diagrams for the 160 GBd PAM 8 signal reaching the highest data rate after fiber transmission of 404.5 Gbit/s.

was 437.1 Gbit/s by a 176 GBd PAM 8 signal while reaching a net-data rate of 410 Gbit/s. The eye diagram is visualized in Fig. 2(c). However, the 160 GBd PAM 8 signal reaches an even higher net-data rate of 419.2 Gbit/s. While PAM 4 signals were successfully transmitted up to 200 GBd, the highest net-data rate was achieved with the 180 GBd signal, reaching a net-data rate of 339 Gbit/s. The eye diagram of the 200 GBd signal is shown in Fig. 2(f). The highest PAM 2 signal below the NGMI threshold is the 224 GBd signal, reaching a net-data rate of 198.2 Gbit/s. However, the BER of the 256 GBd PAM 2 signal, stays below the 25% HD-FEC limit also mentioned in [10]. Here the net-data rate was calculated by the overhead determined through the BER threshold and equals 191.5 Gbit/s. The jumps in BER for the PAM 2 as well as the PAM 4 signal, can be explained by an increase in optical input power. Measurements up to 120 GBd PAM 8, 140 GBd PAM 4, and 160 GBd PAM 2 were performed at 8 dBm, while for symbol rates above that, the optical input power to the plasmonic MZM was increased to 12 dBm.

Results for 400 m SSMF transmission are shown in Fig. 3(a-c). Results after 400 m fiber transmission are shown as dashed lines and are compared to the back-to-back results (solid lines). By means of 160 GBd PAM 8 signal, a net-data rate of 404.5 Gbit/s after fiber transmission could be achieved. The 180 GBd PAM 4 signal achieves a net-data rate of 320.6 Gbit/s, while the 224 GBd PAM 2 signal reaches 168.4 Gbit/s.

4. Conclusion

To the best of our knowledge, we demonstrate for the first time a high-speed plasmonic MZM reaching data rates over 400 Gbit/s in an IM/DD link. This has been successfully proven by a single carrier net data rate of 404.5 Gbit/s over 400 m SSMF by employing a 160 GBd PAM 8 signal. This demonstration shows that plasmonic modulators not only offer highest data rates but at the same time offer ideal bandwidth, modulation efficiency on a small footprint. With the ease of integration, they offer a promising solution for future highest-speed transceiver modules. Further improvements in DAC bandwidth, the full potential of the plasmonic platform could be reached.

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