256 GBd Single-Carrier Transmission over 100km SSMF by a Plasmonic IQ Modulator

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Abstract *A plasmonic IQ modulator is used to demonstrate 160 GBd 64QAM with achievable data-rates of 774 Gbit/s in a single-carrier back-to-back experiment. Over a 100 km fibre link it achieves 256 GBd 4QAM and 160 GBd 16QAM with rates of 410 and 600 Gbit/s. ©2023 The Author(s)*

Introduction

In order to keep track with the ever-growing demand for cloud services such as augmented and virtual reality, artificial intelligence and video streaming, standards for optical interconnects are increasing the line rates from 400 Gbit/s, to 800 Gbit/s and 1.6 Tbit/s [1]. A key element in realizing transceivers that offer such data-rates are optical IQ modulators that offer large electro-optical bandwidths at lowest power. A variety of promising modulator technologies have demonstrated high-speed modulation beyond 160 GBd. In particular, silicon photonics [2], indium phosphide [3], gallium arsenide [4], plasmonics [5] and thin-film lithium niobate [6, 7] have been identified as contenders for future 1.6 Tbit/s transceivers.

In this paper, we show optical coherent transmission of up to 256 GBd enabled by a dual-drive plasmonic IQ modulator. Single polarization line-rates of 960 Gbit/s with achievable data-rates of 774 Gbit/s are shown. All data has been encoded by an AWG with drive voltages of 0.77 V_{pp} (measured for a 250GBd signal), including cable losses. In addition, transmission over 100 km is shown for both 4QAM 256 GBd and 16QAM 160 GBd reaching 410 Gbit/s and 600 Gbit/s, respectively.

Device: Dual-Drive Plasmonic IQ modulator

The dual-drive plasmonic IQ modulator was fabricated on Polariton's *Plasmonic PIC* platform [8]. These modulators have been shown to operate up to 500 GHz [9]. In this work, a dual-drive plasmonic IQ modulator featuring two nested differential Mach-Zehnder modulators and three thermo-optical phase shifters to control the operation points was used. Each Mach-Zehnder arm consists of two plasmonic phase shifters, where the optical signal is coupled via photonic plasmonic converters to and from 10-µm-long plasmonic waveguides slots with widths of 100 nm. The plasmonic slots are filled with Lightwave Logic's Perkinamine™ chromophore series 3 (Perkinamine™ 3 is a trademarked proprietary chromophore electro–optic organic material developed by Lightwave Logic). The devices fibre-to-fibre losses are 17.8 dB. This includes fibre-to-chip grating coupler losses of 2.9 dB per facet, photonic plasmonic converter losses of 2×0.5 dB, silicon photonic routing losses of 4.2 dB and plasmonic losses of 5.8 dB. The individual MZM of the device exhibited a $V_{\pi,\mathrm{eq.}}$ of 4 V ±0.1 V measured across a 50 Ω load. The plasmonic IQ modulator is designed as a high-impedance load, utilizing twice the 50 Ω voltage. Note, that the modulator is configured in a differential drive configuration, therefore the differential 50 Ω-matched sources need to provide 2 V_{pp} to switch the Mach-Zehnder from the off- to the on-state [10].

Experimental Configuration

The experimental setup of the demonstrator is illustrated in Fig. 1. It comprises an optical coherent transmitter (Tx), an optional 100 km standard single mode fibre (SSMF) span to emulate a DC interconnect and an optical coherent receiver (Rx). Key components of the transmission link constitute the 256 GSa/s digital-to-analogue and analogue-to-digital (ADC) converters and the differential-driven plasmonic IQ modulator with a 3-dB bandwidth of >100 GHz.

In the optical Tx, the electrical data signal is mapped onto an optical carrier (1542 nm) by means of the optical dual-drive plasmonic IQ modulator. The electrical data signal has been generated by a DAC with an analogue bandwidth of 80 GHz, 8 bits vertical resolution. The nominal single-sided driving voltage after 30 cm of coaxial cables are V_{pp} of 0.77 V for a 250 GBd signal. The devices were probed with RF probes rated for use up to 67 GHz. After the optical Tx, the data signal is amplified by an erbium-doped fibre amplifier and the bandwidth limitations of the

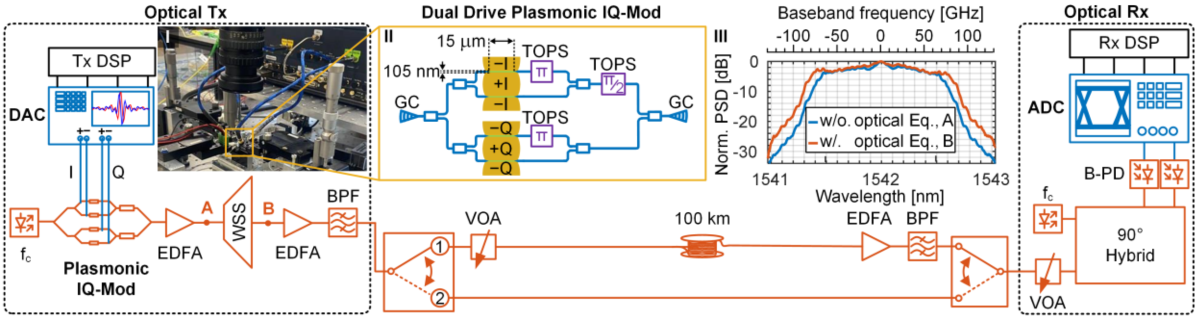

Fig. 1: Experimental configuration of the coherent transmission link. In the optical transmitter (Tx), a data signal is mapped to an optical carrier f_c by means of a dual-drive plasmonic IQ modulator (IQ-Mod). After equalization by an optical filter to compensate for the bandwidth limitations of the electrical Tx, the signal is amplified and either (1) propagates through 100 km fiber span or (2) is directly fed to the coherent receiver. Inset I: Picture of the electro-optical test setup; inset II: schematic of plasmonic IQ-Mod in in dual-drive configuration; inset III: Normalized optical power spectral density (PSD) as measured by an optical spectrum analyzer (Res: 0.016 nm) for signals without and with optical pre-emphasis. GC: grating coupler; TOPS: thermo-optical phase shifter;

electrical Tx (DAC and RF cables) are compensated by a programmable wavelength selective switch (WSS). The response of the AWG is compensated for frequencies up to 80 GHz. After a second EDFA, the optical data signal is either (1) transmitted through 100 km fibre-span, or (2) directly fed to the optical coherent receiver. Here, the optical data signal is down-mixed to baseband by a local oscillator (f_c), a 90° optical hybrid and a pair of 100 GHz balanced photodetectors (B-PD).

Afterwards, the signal is captured by a 256 GSa/s real-time oscilloscope with an analogue bandwidth of 110 GHz and a vertical resolution of 10 bits. Finally, the signal is evaluated by an offline digital processing stage consisting of an optional dispersion compensation, timing recovery, 1x1 constant modulus algorithm, a carrier recovery, a T/2-spaced feedforward least-mean square algorithm, and either a maximum-a-posterior or a Volterra equalizer.

Results

For the optical-back-to-back setup the optical equalization was applied up to 80 GHz. The results of the back-to-back measurements can be seen in Fig 2. The plot shows the achievable information rate (AIR), AIR is calculated by multiplying the general mutual information (GMI) times the symbol rates. Symbol rates of up to 256 GBd were achieved employing a 4QAM modulation format. All of this has been achieved while staying under a 20% SD-FEC [11]. While staying under a HD-FEC up to 200 GBd. The highest AIR could be achieved using a 64QAM 160 GBd modulation format reaching up to 774 Gbit/s.

However, the highest AIR below a 20% SD-FEC coding as seen in Fig 2(b) was achieved by employing a 192 GBd 16QAM signal reaching 645 Gbit/s. All measurements were performed with an optical laser power of 6 dBm, except for higher order modulation formats above 140 GBd a laser power of 11 dBm was used. The DSP chain for these measurements consisted of timing recovery, 1x1 constant modulus algorithm to filter out any remaining lowpass from the transmitter electronics as well as receiver B-PD, a carrier recovery, a T/2-spaced feedforward

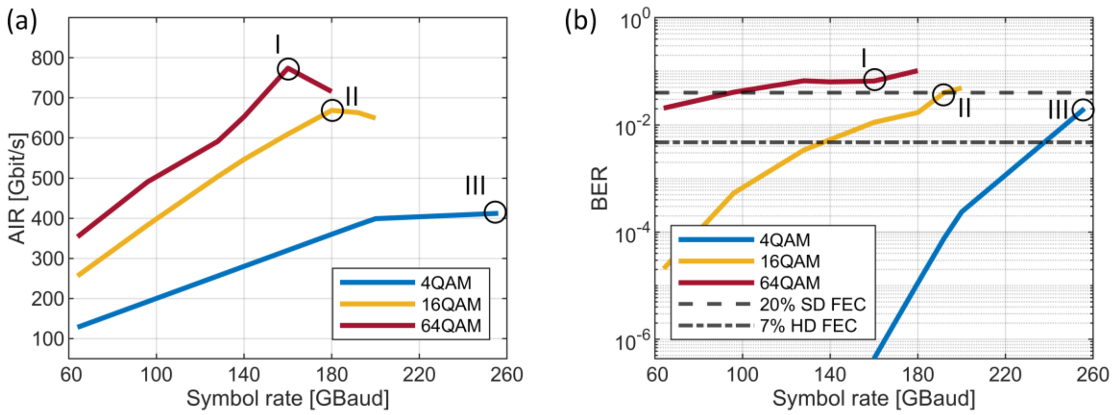

Fig. 2: Showing achievable information rate (AIR) and bit-error rate (BER) over symbol rate. (a) The achievable information rate vs symbol rate for 4QAM 16QAM and 64QAM modulation formats. (b) The corresponding BER for the different modulation formats and symbol rates. For completeness HD-and SD-FEC limits are shown

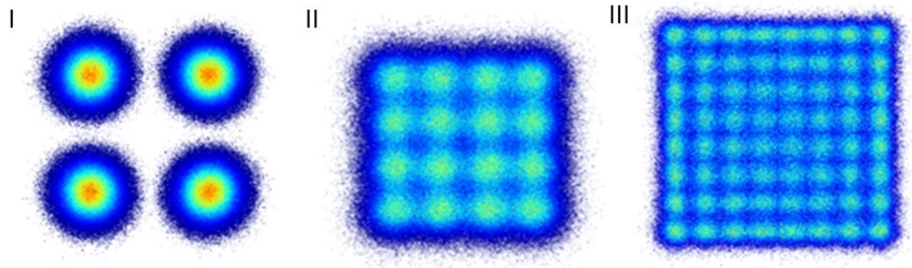

Fig. 3. Constellation diagrams corresponding to the data points I, II and III of Fig 2.

least-mean square algorithm, a Volterra equalizer and a T spaced feedforward least-mean square algorithm followed by the symbol decision. Where T represents the symbol time.

In order to measure the performance in a transmission scenario a fibre link of 100 km SSMF was introduced. Fibre losses were compensated by an EDFA at the receiver. Fig 4 shows the constellations of (a) a 256 GBd 4QAM signal and (b) a 160 GBd 16QAM signal. For the 256 GBd 4QAM measurements optical equalization up to 100 GHz was applied. The launch power into the loop was varied to find the perfect launch power as can be seen in Fig. 4. All measurements were performed with a laser power of 9 dBm fed into the plasmonic modulator. Comparing the performance of the 160 GBd 16QAM signal and 256 GBd 4QAM after 100 km of fibre versus back-to-back shows small variations of 10% in AIR. This can be attributed to the higher laser power. After 100 km of SSMF the highest achievable data rates were 410 Gbit/s for the 256 GBd 4QAM signal and 599 Gbit/s for the 160 GBd 16QAM signal. Both staying below the 20% SD-FEC threshold.

The DSP chain for these measurements consisted of dispersion compensation, timing recovery, 1x1 constant modulus algorithm to filter out any remaining lowpass from the transmitter electronics as well as receiver B-PD, a carrier recovery, a T/2-spaced feedforward least-mean square algorithm, a maximum-a-posterior equalizer and a final T spaced least-mean square algorithm followed by the symbol decision.

Conclusion

We demonstrate for the first time, to the best of our knowledge, a high-speed optical coherent transmitter with symbol rates of up to 256 GBd using a dual-drive plasmonic IQ modulator. The presented IQ modulator can be further extended to a dual-polarization IQ modulator to double the data rate per wavelength, by adding components from the standard silicon photonics library like polarization rotator/combiner, and edge couplers. Future improvements in power handling and system optimization should improve achievable OSNR and therefore enable operation beyond 1.6 Tbit/s.

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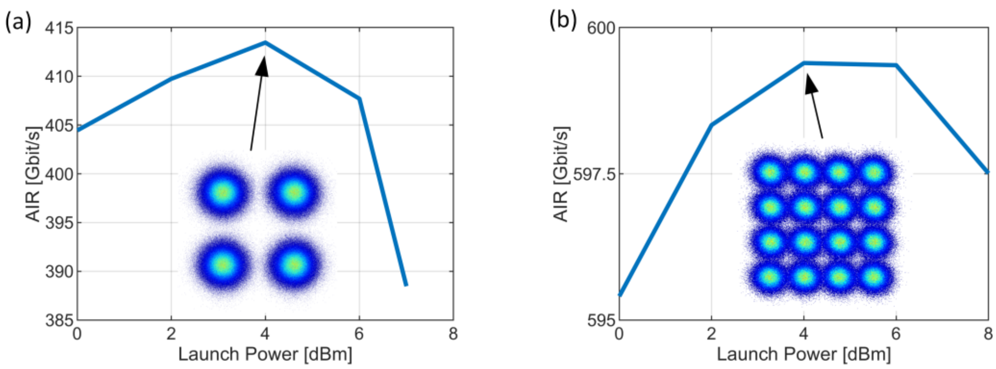

Fig. 4: Effect of launch power into the 100 km SSMF fiber spool versus AIR. (a) Constellation diagram of a 256 GBd 4QAM signal after 100 km fibre transmission achieving up to 413 Gbit/s, (b) Constellation diagram of a 160 Gbaud 16QAM signal after 100 km fibre transmission. Both times an optimum launch power of 4 dBm is observed.

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