Generation and transmission of 160-Gbaud QPSK Coherent Signals using a Dual-Drive Plasmonic-Organic Hybrid I/Q modulator on Silicon Photonics

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Abstract: We report on coherent transmission of beyond 100 GBd signaling based on plasmonic technology. Using dual-drive plasmonic-organic-hybrid I/Q modulator on silicon photonics platform, we demonstrate the successful transmission of 160-GBaud QPSK and 140-GBaud 16QAM modulations.

1. Introduction

The need for capacity in fiber optic transmission systems is growing steadily [1]. To realize optical transceivers with high symbol rates, improved device technology and elaborate modulation formats are needed. The cost, energy consumption, and size of these strategic components are of course key elements in the development of future solutions. To increase the speed and bandwidth of data, current components such as Analog-Multiplexer (AMUX) circuits [2-5], high-speed drivers [6], and various Mach-Zehnder Modulator technologies [7-12] are the cornerstone of high-speed single-carrier transmission. Focusing on coherent technologies, 200 GBd symbol rate transmission per wavelength modulated with dual polarization probabilistically shaped 64-QAM has recently been demonstrated using bandwidth interleaving techniques at the transmitter with in-phase/quadrature (I/Q) thin-film LiNbO3 modulators showing up to 100 GHz bandwidth [8]. Another alternative for wide E/O bandwidth modulators is plasmonic organic-hybrid (POH) Mach–Zehnder modulator (MZM) on silicon photonics (SiPh) which provide extremely high bandwidth, far above 100 GHz [9]. In that respect, several record experiments in intensity modulation and direct detection (IM/DD) have been performed using POH modulators at 222-Gbaud OOK modulation format [10] and 304-Gbaud Polybinary modulation schemes [11]. Further, a first coherent IQ experiment with plasmonic modulators has been performed at 100-Gbaud QPSK but with a single-ended drive for each arm [12].

In this paper, we show for the first-time coherent measurements in I/Q POH-MZM dual-drive at a high data rate up to 160-Gbaud. Relying on an arbitrary waveform generator running at 256 GS/s and 60 GHz drivers, we assess the performance of our dual-drive POH I/Q modulator as a function of the symbol rate and demonstrate successful back-to-back transmission of QPSK signals up to 160-GBaud and 16-QAM at 140-GBaud with Nyquist pulse shaping.

2. Dual-Drive Plasmonic IQ modulator and Experimental Setup

The dual-drive plasmonic IQ modulator consists of two nested plasmonic dual-drive Mach-Zehnder modulators [10,13]. The MZMs are fabricated on the silicon photonic platform. A schematic of this device is shown in Figure 1(a). Basic photonic functionalities such as routing, and splitting are performed using standard silicon photonics components while plasmonic phase modulators [14] are complementing this established platform. This way, high-speed electro-optic modulators with an electro-optic bandwidth exceeding 500 GHz [9], and an optical bandwidth reaching from below 1300 nm to above 1600 nm [15] are added to silicon photonics. In such a high-speed plasmonic modulator, light from a silicon photonic feeding waveguide is coupled to a sub-wavelength-wide plasmonic slot, where the mode interacts with an organic electro-optic material [16]. When an electrical signal is applied across the plasmonic slot, the refractive index of the organic electro-optic material is changed exploiting the Pockels effect. This allows to linearly encode the electrical driving signal onto the phase of the mode propagating along the 15-µm-

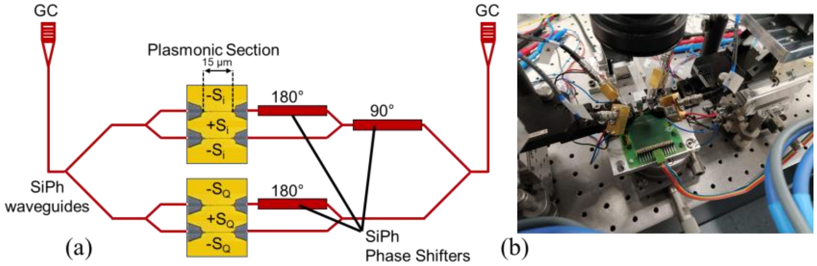

Fig.1: (a) Schematic of POH IQ MZM in dual drive cofiguration; (b) Setup picture.

long plasmonic waveguide, before it is coupled back to silicon photonics. In order to translate the phase modulation into an amplitude modulation, two plasmonic phase modulators are integrated into a silicon photonic Mach-Zehnder interferometer in a push-pull configuration. To achieve both phase- and amplitude modulation, two MZMs are integrated in a "parent" silicon photonic Mach-Zehnder interferometer. The two MZMs as well as the parent MZI are implemented in a balanced configuration. The operating points of the MZMs as well as the IQ bias are adjusted using standard silicon photonic phase shifters. The two MZMs are operated in the Null point, the IQ bias is adjusted to 90°. The silicon photonic phase shifters are wire-bonded to a PCB board for adjusting the biases, while the high-speed differential signals were fed to the plasmonic MZMs using 67 GHz RF probes. The plasmonic modulator section occupied less than 2 x 100 µm x 120 µm.

The differential drive IQ modulator feature 17.9 dB fiber-to-fiber losses, a static extinction ratio exceeding >50 dB, and a Vπ of < 8 V. Note that for driving the plasmonic dual-drive MZM, a 50Ω source needs to provide only Vπ /4 (< 2 V here) to switch the modulator from the on- to the off-state [13].

We can see in Figure 2 the description of our experimental transmission setup. The light from an external cavity laser at λ=1555.7nm is coupled to- and from the IQ modulator using SiPh fiber-to-chip grating couplers (GCs) and polarization maintaining fibers. Two input bit streams are produced by an arbitrary waveform generator (AWG) running at 256 GSa/s with 65 GHz analog bandwidth, generating two random bit sequences. In order to generate the up to 160-GBaud QPSK and 140-GBaud 16-QAM signals for the transmitter part, we operate four high-speed linear Drivers (SHF827) with high-frequency RF probes for the signal applied to the inputs of the POH IQ MZM (See Figure 1(b)). These linear drivers have a 3-Vppd linear-output-swing with a bandwidth in excess of 66GHz.

To assess the transmission performance, we send the generated signal from the transmitter under test either to our back-to-back testbed or to 3x100 km of SMF. In the back-to-back scenario, the signal is directly sent to an Erbium-doped fiber amplifier (EDFA) followed by a 2nm optical filter to filter out of band ASE noise A variable optical attenuator (VOA) is used to adjust the input power for optimum performance of the commercial 70-GHz bandwidth balanced photodiode (PD) of our coherent receiver. The signal polarization is adjusted before entering the coherent mixer. The detected signals from the balanced photodiodes are then sampled and stored by a Keysight Infiniium Digital Storage Oscilloscope (DSO) with 113 GHz bandwidth operating at 256 GS/s.

2. Results and discussion

We first measured the transmission performance in back-to-back of QPSK (resp. 16-QAM) signaling by varying the symbol from 100-GBaud to 160-GBaud (resp. 80-GBaud to 140-GBaud) by steps of 20-GBaud. To process the stored waveforms, we applied standard digital signal processing (DSP), followed by signal-to-noise (SNR) measurement. The DSP consists of matched filtering, timing recovery, T/2-spaced blind equalizer using CMA+RDE equalizer, phase recovery, T/2-spaced LMS equalizer, nonlinear pattern with pattern length of 7 and T-spaced LMS. Fig. 3(a) shows the evolution of the measured SNR as a function of baudrates for QPSK and 16-QAM modulation formats as well as the received signal constellation after DSP at each baudrate. Fig.3(b) depicts the eye diagram

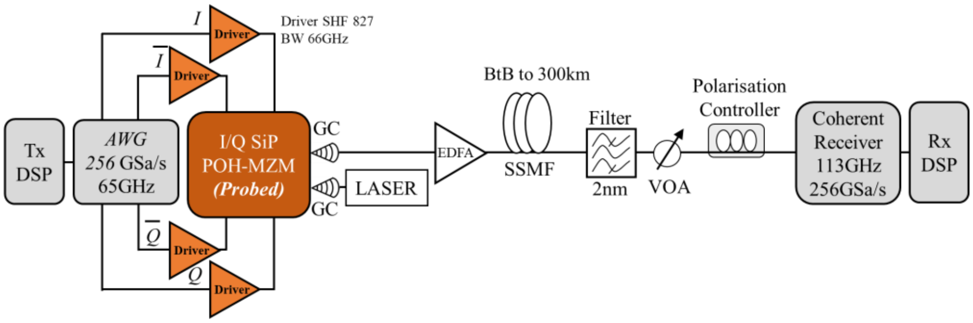

Fig. 2: Experimental setup for the optical transceivers generating in back-to-back and transmission.

obtained after performing the offline DSP at 140-GBaud for 16-QAM and 160-GBaud for QPSK, the latter exhibiting a clear eye opening. For both formats, the SNR decreases similarly in Fig.3(a) when increasing the baudrate. For instance, at 120-GBaud the 3dB SNR penalty compared to 100-Gbaud is the same for QPSK as for 16-QAM signal. Above 120-GBaud, the SNR decreases more steeply attributed to the limited bandwidth of the drivers, photodiodes, and AWG. However, the performance remains higher than the FEC limit [17] up to 160-Gbaud for QPSK format and 140-Gbaud for 16-QAM format.

Finally, we assess the transmission performance of 120-GBaud 16-QAM along our transmission line made of 3 spans of SMF separated by EDFAs. As depicted by the eye diagrams in Fig.3(c), the 120-GBaud 16-QAM signaling achieved SNRs of 15.4 dB, 14.5 dB, and 13.7 dB for 100 km, 200 km and 300 km respectively, showing only a slight penalty compared to the optical back-to-back.

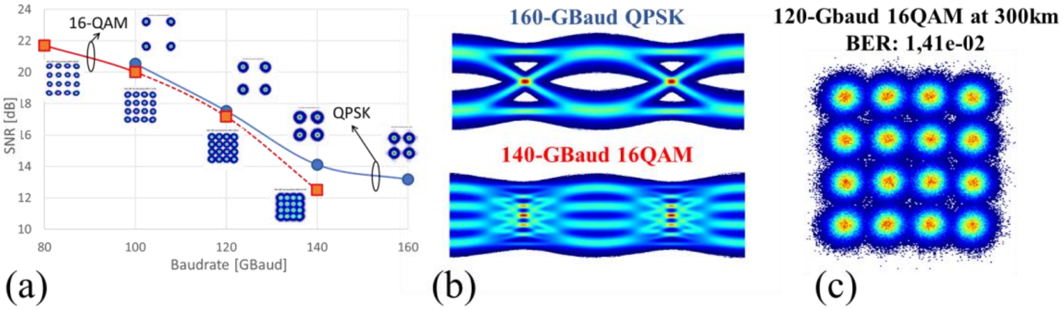

Fig. 3: (a) Performances in back-to-back for QPSK and 16-QAM modulation formats vs baudrates, (b) Eye diagrams at the receiver, and (c) eye diagrams of 120-GBaud 16-QAM signals after 100, 200, 300km transmission.

4. Conclusion

We demonstrate for the first-time, to the best of our knowledge, a high-speed data rate optical coherent transmitter at 160-GBaud QPSK and 140-GBaud 16-QAM using a dual-drive plasmonic-organic hybrid I/Q modulator on silicon photonics platform. The POH technology is approaching the requirements imposed by the industry in the field of high-speed coherent systems, establishing itself as an alternative solution for MZM technologies.

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6. References

[1] P. J. Winzer and D. T. Neilson, "From Scaling Disparities to Integrated Parallelism: A Decathlon for a Decade," in Journal of Lightwave Technology, vol. 35, no. 5, pp. 1099-1115, March 2017.

[2] M. Nakamura, et al., "High Symbol-Rate Signal Optimization for Long-Haul Transmission Systems over 1-Tbps/λ Net-Data Rate", in Proc. ECOC, Bordeaux, France, Sep. 2021, paper We3C1.1.

[3] R. Hersent et al., "Analog-Multiplexer (AMUX) circuit realized in InP DHBT technology for high order electrical modulation formats (PAM-4, PAM-8)," 2020 23rd International Microwave and Radar Conference (MIKON), 2020, pp. 222-224, doi: 10.23919/MIKON48703.2020.9253772.

[4] K. Schuh, et al., " High-speed IM/DD transmission with analog (de-)multiplexers," in Proc. ECOC, Bordeaux, France, Sep. 2021, paper We1C1.1.

[5] M. Nagatani et al., "An Over-110-GHz-Bandwidth 2:1 Analog Multiplexer in 0.25-μm InP DHBT Technology," 2018 IEEE/MTT-S International Microwave Symposium - IMS, 2018, pp. 655-658, doi: 10.1109/MWSYM.2018.8439317.

[6] R. Hersent et al., "Design, modelling and characterization of a 3-Vppd 90-GBaud over-110-GHz-bandwidth linear driver in 0.5-μm InP DHBTs for optical communications," 2021 IEEE BiCMOS and Compound semiconductor Integrated Circuits and Technology Symposium (BCICTS), 2021.

[7] F. Pittalà et al., "220 GBaud Signal Generation Enabled by a Two-channel 256 GSa/s Arbitrary Waveform Generator and Advanced DSP," 2020 European Conference on Optical Communications (ECOC), 2020, pp. 1-4, doi: 10.1109/ECOC48923.2020.9333130.

[8] X. Chen, et al., "Transmission of 200-GBaud PDM Probabilistically Shaped 64-QAM Signals Modulated via a 100-GHz Thin-film LiNbO3 I/Q Modulator," in Optical Fiber Communication Conference (OFC) 2021, P. Dong, J. Kani, C. Xie, R. Casellas, C. Cole, and M. Li, eds., OSA Technical Digest (Optical Society of America, 2021), paper F3C.5.

[9] M. Burla et al. "500 GHz plasmonic Mach-Zehnder modulator enabling sub-THz microwave photonics." APL Photonics 4.5 (2019): 056106. https://doi.org/10.1063/1.5086868

[10] 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," Journal of Lightwave Technology, (Volume: 38, Issue: 9, May1, 1 2020) Page(s): 2734 - 2739, DOI: 10.1109/JLT.2020.2972637

[11] Q. Hu, et al., "Plasmonic-MZM-based Short-Reach Transmission up to 10km Supporting >304 GBd Polybinary or 432Gbit/s PAM-8 Signaling," in Proc. ECOC, Bordeaux, France, Sep. 2021, paper Th3C1-PD2.4.

[12] W. Heni, et al. "Plasmonic IQ modulators with attojoule per bit electrical energy consumption". Nat Commun 10, 1694 (2019).

[13] B. Baeuerle, et al. "120 GBd plasmonic Mach-Zehnder modulator with a novel differential electrode design operated at a peak-to-peak drive voltage of 178 mV." *Optics express* 27.12 (2019): 16823-16832.

[14] A. Melikyan, et al. "High-speed plasmonic phase modulators." Nature Photonics 8.3 (2014): 229-233.

[15] C. Haffner, et al. "Harnessing nonlinearities near material absorption resonances for reducing losses in plasmonic modulators." Opt. Mat. Express 7.7 (2017).

[16] Heni, Wolfgang, et al. "Silicon–organic and plasmonic–organic hybrid photonics." ACS photonics 4.7 (2017): 1576-1590.

[17] H. Bissessur, et al, "Real-Time Unrepeatered C-Band Transmission of 30.5 Tb/s over 276.4 km and 29.45 Tb/s over 292.5 km," *OFC*, 2021, pp. 1-3.