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Silicon Photonics IQ Modulator Targeted for 800ZR Data Center Interconnection

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Abstract *An all-silicon polarization-multiplexed modulator is demonstrated for the first time at 120GBaud-16QAM over 100-km SSMF, achieving per-polarization output power of -18.7dBm and rOSNR of 23.5dB at oFEC BER threshold. A BER of 1.4e-3 was obtained with a 63-GHz scope without sophisticated DSP or optical equalization. ©2022 The Authors*

Introduction

Compared with InP [1] and thin-film lithium niobate (TFLN) platforms [2, 3], silicon photonics (Sipho) has advantages in chip size, volume, and co-packaging capability, which make it competitive for cost-sensitive metro and DCI coherent applications (such as 800ZR [4]). High-baud-rate, high-QAM-order Sipho IQ modulators (IQM) have been demonstrated in recent years [5-7]. A non-segmented Sipho modulator with a 3-dB EO bandwidth of ~34 GHz was reported for 100GBaud-16QAM and 100GBaud-32QAM operations [5]. A bandwidth-broadened Sipho IQM based on a segmented design was reported for 120GBaud-16QAM and 120GBaud-32QAM operations [6]. Nonlinear compensation and optical equalization were employed to optimize modulator's performance [5, 6]. In [7], the authors reported 110GBaud-32QAM and 110GBaud-64QAM transmission over an 80-km SSMF, where the 3-dB EO bandwidth of the Sipho MZM is 28 GHz.

In this paper, we demonstrate an all-silicon polarization-multiplexed IQM with suitable bandwidth, output power, and required optical signal-to-noise ratio (rOSNR) that are close to a real 800ZR transmission link's requirement via a standard open forward-error-correction (oFEC). Compared with previous reports [5-7], a small AC VπL of ~1.9 V*cm in our case enables a compact modulator and thus a wide bandwidth. The non-segmented MZM design has a smooth roll-off of EO S21 and a 3-dB EO bandwidth of 36.8 GHz at a bias of -3 V and 40.5 GHz at a bias of -5 V, respectively. Only the TE-polarization of the dual-polarization IQM chip was tested, due to the limitation of RF probes. For 120GBaud-16QAM, the TE-polarization of the IQM (where the IQM has a 3-dB TE/TM power splitter) outputs -18.74 dBm power at a laser power of 17.25 dBm and achieves a rOSNR of 23.51 dB at the oFEC BER threshold of 2.0e-2 over a 100-km SSMF [8]. Without nonlinear compensation, optical equalization, or using an ultra-wide-bandwidth high-ENOB scope, this demonstration has a great potential to be used in small pluggable transceivers such as OSFP and QSFP-DD for 800ZR data center interconnection.

In addition, we also report BERs of 1.4e-3 and 2.8e-3 for 120GBaud-16QAM operation without and with a 100-km SSMF, respectively. A BER of 2.08e-2 for 120Gbaud-32QAM without a 100-km SSMF was also achieved.

MZM Design and Characterization

Fig. 1(a) compares the electrical S21 of four 4.5-mm long MZM designs, where MZM0 is used in our previous 100-GBaud work [9]. In MZM1, MZM2 and MZM3 designs, we reduce PN junction's series resistance and reduce transmission line's resistive RF loss to broaden the bandwidth for 800-Gbps applications. The electrical S21 of new designs improves across the entire frequency range. Fig. 1(b) depicts the normalized EO S21 of three 2.5-mm long MZM designs. The 3-dB EO bandwidths of the three modulators measured at a bias of -3 V are 36.8 GHz, 37.7 GHz, and 39.2 GHz, respectively. The bandwidths increase to 40.5 GHz, 41.4 GHz, and 44.6 GHz, respectively, with MZMs biased at -5 V.

The IQM discussed in this paper is a part of a COSA (coherent optical sub-assembling) chip. It employs a 2.5-mm long MZM1 design with an AC Vπ of ~7.8 V at a bias of -3 V. The AC Vπ and 3-dB EO bandwidth are plotted at different bias in Fig. 1(c). IQM chips that employ MZM2 and MZM3 designs are under fabrication and will be discussed separately.

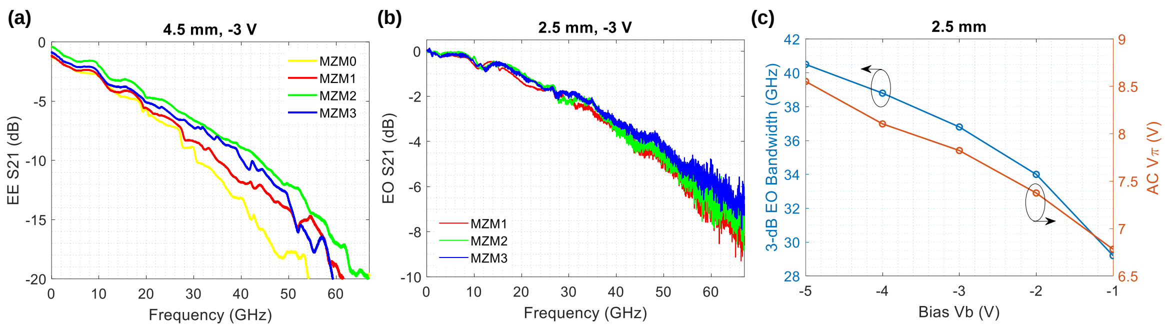

Fig. 1: (a) Electrical S21 of four types of 4.5-mm long MZMs, which are biased at -3 V. (b) EO S21 of 2.5-mm long MZMs, which are biased at -3 V. (c) 3-dB EO bandwidth and AC V_π of 2.5-mm long MZM1 are measured at different bias voltages.

Experimental Setup and Data Transmission

The setup for 120-GBaud experiment is depicted in Fig. 2(a). We start the experiment by skipping the 100-km SSMF first. A Keysight arbitrary waveform generator (AWG) M8199 was operated at 120-GSa/s to generate 1-sample-per-symbol (1-sps) signals. The AWG has a 65-GHz 3-dB analog bandwidth, and an ENOB of 5.5 bits up to ~60 GHz. The MZMs are driven by SHF S804B drivers through a 67-GHz GGB probe. S804B has a 3-dB bandwidth of ~60 GHz, a maximum gain of 22 dB, and a 1-dB compression point of 12 dBm. In the inset of Fig. 2(a), Tx's EO S21 is simulated using tested S-parameters of driver, cables, probes, and MZM. With MZM biased at -3 V, Tx's S21 rolls off to around -13 dB at 60 GHz.

A NeoPhotonics external cavity laser (uITLA) with a <50-kHz linewidth was operated at 193.4 THz and at an output power of 17.25 dBm. The optical chip is fiber-pigtailed and is biased using a DC probe card. Limited by the RF probes, we tested only the TE-polarization of the dual-polarization IQM, which has a 3-dB TE/TM power splitter. The output signal of the IQM was first amplified by an EDFA and then loaded with amplified spontaneous emission (ASE) at the OSNR station. The signal was finally captured using a Keysight optical modulation analyser (OMA) N4391A, which consists of a coherent receiver without trans-impedance amplifiers and a 160-GSa/s real-time scope with a 63-GHz 3-dB bandwidth. Since only TE-polarization was tested, a polarization controller was used to maximize the power of TE at OMA receiver.

Transmitted data are generated offline and loaded to AWG, with a pseudo-random symbol sequence length of 2^15 symbols and a 15-tap time-domain pre-emphasis filter. The offline Rx DSPs include signal synchronization, IQ imbalance and skew compensation, chromatic dispersion compensation, 128-tap 4x2 MIMO adaptive feedforward equalization, carrier frequency/phase recovery, and BER counting.

Fig. 2(b) shows the optical spectra of 120GBaud-16QAM signals under different pre-emphasis conditions, with MZM biased at -3 V. The pre-emphasis is quantified by a pre-emphasis ratio, ranging from 0 (without any pre-emphasis) to 1.0. Without any pre-emphasis, the optical spectrum rolls off to around -17 dB at 60 GHz, whereas it becomes flat-topped (-6 dB at ±60 GHz off center) with a pre-emphasis ratio of 0.7. At a fixed AWG output voltage, a larger pre-emphasis ratio results in a higher peak-to-average power ratio (PAPR), and thus lower IQM output power (Fig. 2(c)). In Fig. 2(c), at a fixed pre-emphasis ratio of 0.7, the output power increases from -22.35 dBm to -18.74 dBm with AWG output increasing from 0.25 Vpp to 0.40 Vpp. On the other hand, rOSNR degrades due to worsened driver's nonlinearity with large AWG output. This can be exemplified by the BER curves in Fig. 2(d), where the noise floor of BER curves goes higher with larger AWG output. The nonlinear behaviour of the driver is also captured by the constellation diagrams. In the inset of Fig. 2(d) where AWG output is set at 0.25 Vpp, a BER of 1.4e-3 was achieved at an OSNR of 30.08 dB and an output power of -22.35 dBm. In comparison, the minimum BER increases to 4.0e-3 when AWG output is set at 0.40 Vpp, even if the OSNR increases to 33.09 dB due to a higher output power of -18.74 dBm. The deterioration of driver's nonlinearity clearly reflects on the rOSNR penalty curves in Fig. 2(e). Here the rOSNRs at the oFEC BER threshold of 2.0e-2 are referenced to the rOSNR for the case of 0.25-Vpp AWG output and a pre-emphasis ratio of 0.7. Fig. 2(e) also illustrates that at a fixed AWG output, the pre-emphasis ratio of 0.7 produces the best rOSNR among the ratios of 0.5, 0.7 and 1.

It is worth noting that 1.4e-3 is the record low BER that a Sipho IQM achieves for 120GB-16QAM, to the authors' best knowledge. This is enabled by a low BER floor, obtained without

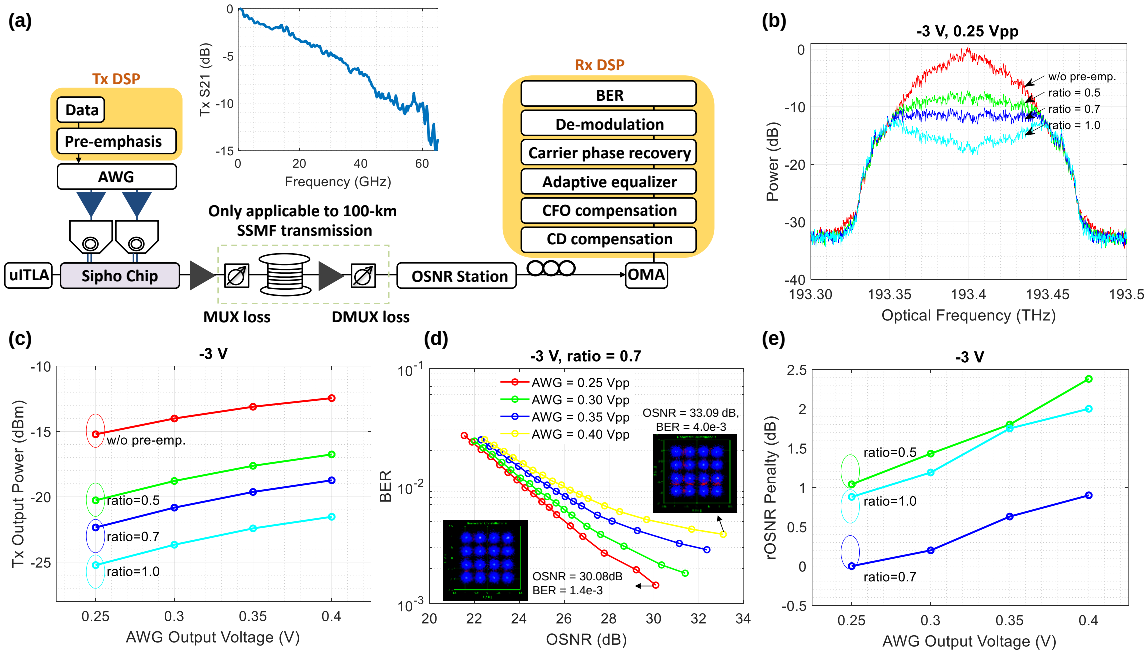

Fig. 2: (a) 120-GBaud experimental setup. The inset is the simulated Tx's EO S21 based on tested S-parameters of each component, with MZM biased at -3 V. (b) Optical spectra of 120GB-16QAM, where different pre-emphasis conditions were applied. (c) The output power is measured with different AWG output and pre-emphasis ratios. (d) BER curves measured under different AWG output. (e) rOSNR at the oFEC BER threshold of 2.0e-2 are measured with different AWG output and pre-emphasis ratios. rOSNR penalty is referenced to the condition of 0.25-Vpp AWG output and a pre-emphasis ratio of 0.7.

nonlinear compensation, optical equalization, or an ultra-wide-bandwidth, high-ENOB OMA.

We further studied data transmission over a 100-km SSMF for two cases. A second EDFA and two VOAs are added (Fig. 2), where the attenuations of the first and second VOAs emulate the DWDM MUX and DEMUX loss, respectively. In Case 1 where we set MZM bias at -1 V, a pre-emphasis ratio at 0.7, and AWG output as 0.25 Vpp, the output power is -22.13 dBm and rOSNRs at the oFEC BER threshold without and with a 100-km SSMF are 22.62 dB and 22.93 dB, respectively (Fig. 3). In Case 2 where we set MZM bias at -3 V, a pre-emphasis ratio of 0.7, and AWG output as 0.40 Vpp, the output power is -18.74 dBm and rOSNRs without and with a 100-km SSMF are 23.26 dB and 23.51 dB, respectively. The 3-dB bandwidth increases to 40.5 GHz when MZM is biased at -5 V, and the power and rOSNR without a 100-km SSMF are -18.61 dBm and 23.69 dB, respectively.

Finally, we also achieved a BER of 2.08e-2 for single-polarization, 120Gbaud-32QAM without a 100-km SSMF, which is below the conventional 20% OH SD-FEC BER threshold of 2.4e-2.

Conclusions

With optimized MZM's bandwidth and Vπ, we demonstrate an all-silicon polarization-multiplexed IQM with a per polarization output power of -18.74 dBm (at 17.25-dBm laser power) and a rOSNR of 23.51 dB at the oFEC BER threshold of 2.0e-2 over a 100-km SSMF for 120GBaud-16QAM. These are equivalent to an output power of -15.74 dBm and rOSNR of 26.51 dB for 120GBuad-16QAM, dual-polarization operation. Without using sophisticated DSP, optical equalization, or a high-bandwidth high-ENOB scope, we report low BERs for 120GBaud-16QAM over a 100-km SSMF, and for 120GBaud-16QAM and 120GBaud-32QAM without a 100-km SSMF. By improving S21 through driver peaking and shorter interconnects, we expect both output power and rOSNR meeting 800ZR requirements.

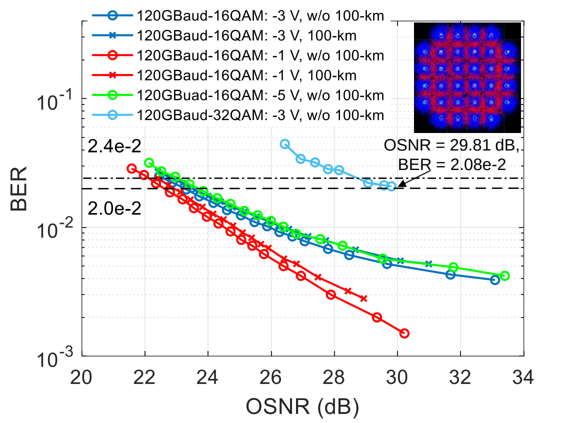

Fig. 3: BER curves obtained with and without a 100-km SSMF. The MZM bias, pre-emphasis ratio, and AWG output are set (blue) as -3 V, 0.7, and 0.40 Vpp, (red) as -1 V, 0.7, and 0.25 Vpp, (green) as -5 V, 0.7, 0.40 Vpp, and (cyan) as -3 V, 0.75, and 0.25 Vpp, respectively. The inset is a constellation diagram of 120GB-32QAM.

References

[1] Y.-W. Chen, K. Kuzmin, R. Zhang, M. Poirier, T. Tomimoto, G. Zarris, R. Moore, C. Chen, W. Wu, J. Huang, M. Boudreau, H. Xu, and W. I. Way, "InP CDM and ICR enabled 128Gbad/DP-16QAM-PS and 120Gbaud/DP-QPSK long-haul transmission," *IEEE Photonics Technology Letters*, vol. 34, no. 9, pp. 471–474, 2022, DOI: 10.1109/LPT.2022.3165484

[2] S. Makino, S. Takeuchi, S. Maruyama, M. Doi, Y. Ohmori, and Y. Kubota, "Demonstration of thin-film lithium niobate high bandwidth coherent driver modulator," in *Proceedings of Optical Fiber Communication Conference*, San Diego, USA, 2022, paper M1D.2, DOI: 10.1364/OFC.2022.M1D.2

[3] M. Xu, F. Pittalà, J. Tang, Y. Zhu, M. He, W. C. Ng, Z. Ruan, X. Tang, M. Kuschnerov, L. Liu, S. Yu, B. Zheng, and X. Cai, "Thin-film lithium niobate DP-IQ modulator for driverless 130 Gbaud 64 QAM transmission," in *Proceedings of Optical Fiber Communication* Conference, San Diego, USA, 2022, paper Th1J.2, DOI:10.1364/OFC.2022.Th1J.2

[4] [Online]. Available: https://www.oiforum.com/technical-work/hot-topics/800g-coherent

[5] S. Zhalehpour, J. Lin, M. Guo, H. Sepehrian, Z. Zhang, L. A. Rusch, and W. Shi, "All-silicon IQ modulator for 100GBaud 32QAM transmissions," in *Proceedings of Optical Fiber Communication Conference*, San Diego, USA, 2019, paper Th4A.5, DOI: 10.1364/OFC.2019.Th4A.5

[6] Z. Zheng, A. Mohammadi, O. Jafari, H. Sepehrian, J. Lin, X. Zhang, L. A. Rusch, and W. Shi, "Silicon IQ modulator for 120 Gbaud QAM," in *Proceedings of European Conference on Optical Communication*, Bordeaux, France, 2021, paper Tu4D.3, DOI: 10.1109/ECOC52684.2021.9605951

[7] E. Berikaa, M. S. Alam, A. Samani, S. Lessard, and D. V. Plant, "Net 1 Tbps/λ transmission over 80 km of SSMF using a single segment SiP IQM with all electronic equalization," in *Proceedings of Optical Fiber Communication Conference*, San Diego, USA, 2022, paper Th4A.5, DOI: 10.1364/OFC.2022.Th4A.5

[8] [Online].Available:https://0201.nccdn.net/1_2/000/000/12d/a26/openroadm_msa-5.0-w-port-digital-specification_20210701.docx

[9] J. Zhou, J. Wang, L. Zhu, and Q. Zhang, "Silicon photonics for 100gbaud", *Journal of Lightwave Technology*, vol. 39, no. 4, pp. 857–867, 2021, DOI: 10.1109/JLT.2020.3009952