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System-level Characterization of High-Speed Silicon Photonics Travelling Wave Mach-Zehnder Modulators

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Abstract— We present a comprehensive system-level characterization of silicon photonics (SiP) C-band and O-band traveling-wave Mach-Zehnder modulators (TWMZMs) implemented using imec silicon photonics process design kit (PDK). This work focuses on evaluating the performance limits and application suitability of these TWMZMs for high-speed optical interconnects. Using the C-band TWMZM, we demonstrate optical amplification-free transmission of 256 Gbaud (net 241 Gb/s) on-off keying (OOK), 150 Gbaud (net 291 Gb/s) pulse amplitude modulation with 4 levels (PAM4), 128 Gbaud (net 301 Gb/s) PAM6, and 95 Gbaud (net 268 Gb/s) PAM8 signals over 100 meters of standard single-mode fiber (SMF), achieving a 6.25% overhead hard decision-forward error correction (HD-FEC) threshold. With optical amplification, the same modulator supports data rates of 175 Gbaud (net 329 Gb/s) PAM4, 145 Gbaud (net 341 Gb/s) PAM6, and 112 Gbaud (net 316 Gb/s) PAM8. For the O-band TWMZM, we achieve rates up to 224 Gbaud (net 210 Gb/s) OOK and 140 Gbaud (net 263 Gb/s) PAM4 transmission over 500 meters of SMF. We perform detailed analysis of both TWMZM performance in 200 Gb/s per lane scenarios as defined by the IEEE 802.3dj Task Force. Our results show that both modulators meet defined requirements with a simple 13-tap feed-forward equalizer (FFE). We also assess the thermal performance of the C-band TWMZM across multiple operating conditions. These results demonstrate the potential for high-performance, DR and FR-compliant 200 Gb/s per lane transceivers based on SiP TWMZMs with minimal DSP requirements, and mark significant progress toward enabling 400 Gb/s per lane transceivers using conventional SiP technologies.

Index Terms—Silicon Photonics, Mach-Zehnder Modulator, Optical Interconnects, 400 Gb/s per lane, IEEE 802.3dj, Data Center Interconnects.

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I. INTRODUCTION

Increased demand for Artificial-Intelligence (AI) compute power introduces new challenges for data center interconnects. As integration density and energy efficiency are primary concerns, Silicon Photonics (SiP) is a compelling platform for scalable and cost-effective implementation. The SiP ring-resonator modulators (RRM) are an excellent solution for high-density AI interconnects [1], offering outstanding energy efficiency and a small footprint, despite lower bandwidth and high thermal sensitivity. The RRM offers an excellent solution for short-reach intra-rack communication [2]. On the other hand, for inter-rack communication, higher-performance technology would be preferred to increase data transmission rates per lane. One could use Thin-Film-Lithium-Niobate or Indium Phosphide; however, the use of the same SiP platform would simplify implementation workflows and ensure cost-efficiency. Electro-absorption modulators (EAM) and Mach-Zehnder modulators (MZM) in SiP both have high-bandwidth and high-extinction ratio. Despite superior bandwidth and higher energy-efficiency, SiGe EAMs [3] are currently unsuitable for mass deployment due to a limited operational window and high self-heating, resulting in low output optical powers. Recent demonstration includes gross 448 Gb/s at 25% overhead (OH) Soft-decision (SD) forward-error correction (FEC) limit and 425 Gb/s at 6.25% OH hard-decision FEC (HD-FEC) threshold using optical amplification, short pseudo-random bit sequences (PRBS15) and reference clock between transmitter and receiver [4]. On the other hand, SiP MZMs offer differential drive that can improve the signal-to-noise ratio (SNR) significantly which makes them primary candidates for enabling higher data rates and reach despite

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lower bandwidth and energy efficiency than EAMs. In recent years, an extraordinary amount of research is being focused on developing better SiP MZMs [5-15]. Since the demonstration of 200 Gb/s pulse amplitude modulation with 6 levels (PAM6) [5] at 20% OH SD-FEC threshold, there has been lot of interest in pushing SiP MZM technology to 400 Gb/s per lane. The SiP MZM with 30 GHz bandwidth [6] has demonstrated successful operation at 2 μm wavelength, paving way for an increase of operational windows. It has been shown that codesign and cointegration of driver and SiP MZM can significantly increase the bandwidth and reduce power consumption, demonstrating 224 Gb/s PAM4 [7] and 200 Gb/s on-off keying (OOK) [8] at 20% OH SD-FEC. O-band SiP MZM [9] demonstrated the first 300 Gb/s net data transmission rate over 2 km of single mode fiber (SMF) using probabilistically shaped PAM8. Recently, SiP MZMs achieving 336 Gb/s PAM8 [10] and 414 Gb/s PAM8 [11] has been reported, however lack of quantitative figures e.g., bit error rate measurements, limits comparison of these reports to state-of-the-art. There are several approaches to increasing the bandwidth of SiP MZM. It has been shown that enhancement of MZM with micro-capacitors [12] allows for an increase bandwidth by 35%, while maintaining similar $V\pi \times L$, demonstrating 240 Gb/s 4-level amplitude-shift-keying (ASK-4) transmission at 7% OH HD-FEC threshold. Alternatively, the concept of a compact (124 μm long) slow-light modulator [13] has been proposed to extend bandwidth beyond 110 GHz. While it allows record-high bandwidth, it requires high driving voltages due to $V\pi$ being ~ 78.0 V. On the other hand, one could use indium-tin oxide (ITO) for electrode materials [14] to enable beyond 110 GHz bandwidths, while maintain reasonable $V\pi$ values. First 400 Gb/s per lane gross transmission rate with refined slow-light MZM (249 μm length, 90 GHz bandwidth, ~ 33 V $V\pi$) was recently demonstrated [15] and Bidirectional

gated recurrent unit (bi-GRU) was used for equalization at 7% OH HD-FEC with 8 parallel channels. While advancements of SiP MZMs lately have been tremendous, it is still unclear how practical these improvements are. The majority of research uses optical amplifiers, compensating not only coupler loss but also modulator losses, and neglecting nonlinear effects like two-photon absorption (TPA). Furthermore, some demonstrations use reference clock and short PRBS. Additionally, some results are reported with high overhead FEC or without FEC, making it difficult to evaluate readiness for practical implementation. To address this gap we extend our work [16], [17] with detailed analysis of operation of traveling wave Mach-Zehnder modulator (TWMZMs) in C-band and O-band. Comparison of latest high-speed demonstrations with SiP MZMs can be seen in Table 1.

In this paper, we review recent high-speed demonstration (net rates are given in Table 1) using SiP Mach-Zehnder modulators including our record optical amplification-free transmission [17] of 256 Gb/s OOK, 310 Gb/s PAM4, and 320 Gb/s PAM6, as well as amplified [16] 350 Gb/s PAM4, 362.5 Gb/s PAM6, and 336 Gb/s PAM8 transmission using C-band TWMZM. In this paper, we present a comprehensive system-level characterization of C-band and O-band traveling-wave Mach-Zehnder modulators (TWMZMs) implemented using the standard imec iSIPP50G silicon photonics platform. This work focuses on evaluating the capabilities and limitations of TWMZMs for next-generation optical interconnects. We show O-band TWMZM achieving 224 Gb/s OOK and 280 Gb/s PAM4 transmission. Additionally, we demonstrate modulator operation in accordance with IEEE 802.3dj for net 200 Gb/s per lane scenarios using O-band and C-band TWMZM and evaluate performance in high-temperature scenarios up to 85°C. Lastly, we demonstrate a virtual differential measurement method

TABLE I
RECENT HIGH-SPEED DEMONSTRATIONS OF SiP MACH-ZEHNDER MODULATORS

Type	$V\pi L$, $V \times \text{cm}$	Length, mm	Bandwidth, GHz	Gross Data Rates	Net Data Rates	Opt. amp.	Ref.
TWMZM	1.6	1.5	22.5	200 Gbps PAM6 @ 20%SD-FEC	167 Gbps PAM6	EDFA	[5]
Folded MZM	1.9	3.74	56	224 Gbps PAM4 @ 20% SD-FEC	186 Gbps PAM4	EDFA	[7]
Dual-drive MZM	1.8	1.0	70	200 Gbps OOK @ 20% SD-FEC	167 Gbps OOK	EDFA	[8]
TWMZM	1.4	2.5	47	305 Gbps PS-PAM8@ 20% SD-FEC	305 Gbps PS-PAM8	PDFA	[9]
TWMZM	1.1	3	44	336 Gbps PAM8 @ n.a.	n.a	PDFA	[10]
TWMZM (O-band)	n.a.	n.a.	60	414 Gbps PAM8 @ n.a.	n.a	-	[11]
TWMZM	3	4	61	240 Gbps ASK4 @ 7% HD-FEC	224 Gbps ASK4	EDFA	[12]
SL-MZM	0.97	0.124	110	112 Gbps OOK @ 20% SD-FEC	93 Gbps OOK	EDFA	[13]
SL-MZM	0.82	0.25	90	400 Gbps PAM4@ 7% HD-FEC	374 Gbps PAM4	EDFA	[15]
TWMZM (C-band)	2	1.5	42	256 Gbps OOK@ 6.25% HD-FEC 310 Gbps PAM4@ 6.25% HD-FEC 320 Gbps PAM6@ 6.25% HD-FEC 285 Gbps PAM8@ 6.25% HD-FEC	241 Gbps OOK 291 Gbps PAM4 301 Gbps PAM6 268 Gbps PAM8	-	This work
TMMZM	2	1.5	42	256 Gbps OOK@ 6.25% HD-FEC 350 Gbps PAM4@ 6.25% HD-FEC 362.5 Gbps PAM6@ 6.25% HD-FEC 336 Gbps PAM8@ 6.25% HD-FEC	241 Gbps OOK 329 Gbps PAM4 341 Gbps PAM6 316 Gbps PAM8	EDFA	This work
TWMZM	2.3	1.5	34	224 Gbps OOK@ 6.25% HD-FEC 280 Gbps PAM4@ 6.25% HD-FEC	210 Gbps OOK 263 Gbps PAM4	PDFA	This work

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enabling higher SNR for differential device measurements. We note that for all measurements no clock forwarding between transmitter and receiver was used to ensure real-world conditions.

The paper is organized into four sections. Section 1 discusses the state-of-the-art for SiP MZMs. Section 2 discusses design parameters of C-band and O-band TWMZM and investigates the opto-electrical performance of components. Section 3 investigates transmission system achievable performance as well as performance in net 200 Gb/s per lane scenarios and different temperature conditions. Finally, Section 4 concludes the study.

II. DEVICES AND EXPERIMENTAL SETUP

The devices investigated in this work are based on the standard imec iSIPP50G process design kit (PDK) fabricated within the imec iSIPP50G multi-project wafer (MPW) run [18], [19]. Consequently, the focus of this paper is on TWMZM experimental characterization and system-level performance evaluation under high-speed transmission conditions. The stack includes SOI optical frontend with passive devices and PN-junction modulators (3 dopant concentration levels for each polarity), and backend with tungsten plugs and microheaters, 2 layers of copper metallization and aluminum pads for probing or wire-bonding. For both C-band and O-band, the TWMZM phase shifter length is 1.5 mm, resulting in $V\pi L$ of 2 V $\times$ cm and 2.3 V $\times$ cm at -2V bias, respectively. Detailed design considerations and doping levels, together with analysis, are reported in [20]. One can see the TWMZM PIC in Fig. 1.

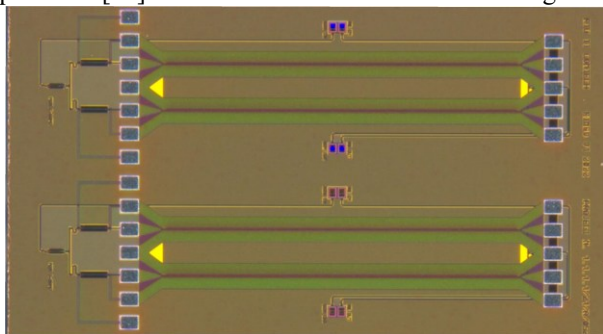


Fig. 1. O-band and C-band TWMZM

Each modulator arm has a tunable phase shifter to control the modulation point of the modulator at the desired wavelength.

A. Device description

We received 63 dies from our MPW run and we sampled 5 dies from different locations for bandwidth and insertion loss measurement. No bandwidth changes were observed across 5 sites; however, the die from the middle of the wafer possessed ~ 1 dB lower insertion loss compared to samples from the outer circle of the wafer. We performed optical-optical and electro-optical characterization using Keysight Integrated Photonics test station, consisting of O/C band tunable lasers (Keysight N7776C), power meter (Keysight N7745), and 67 GHz Lightwave component analyzer (Keysight N4373E). Measured C-band MZM bandwidth at different reverse bias conditions can be seen in Fig. 2.

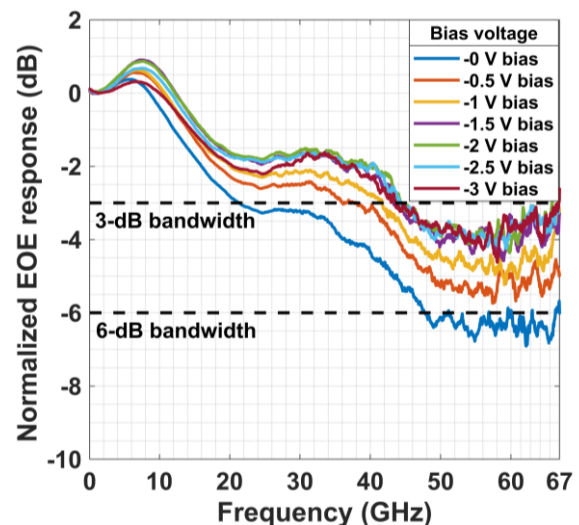


Fig. 2. C-band TWMZM normalized EO bandwidth

As shown in Fig. 2, with an increase of reverse bias, the 3-dB bandwidth of the modulator increases, caused by lower PN-junction capacitance at higher reverse bias. Unbiased C-band TWMZM 3-dB bandwidth is 21 GHz, while increasing reverse bias to -3 V increases it to 44 GHz. At the same time, we can see that the 6-dB bandwidth is beyond 67 GHz, enabling high transmission rates. One can observe ripples, which can be caused by velocity mismatch or electrode design; however, due to the limited footprint of MPW, we were not able to place structures for pad capacitance de-embedding, RF loss, and velocity mismatch calculations, which would allow us to evaluate the impact of these factors on TWMZM bandwidth. C-band TWMZM insertion loss and insertion loss of reference waveguide of the same length are depicted in Fig. 3.

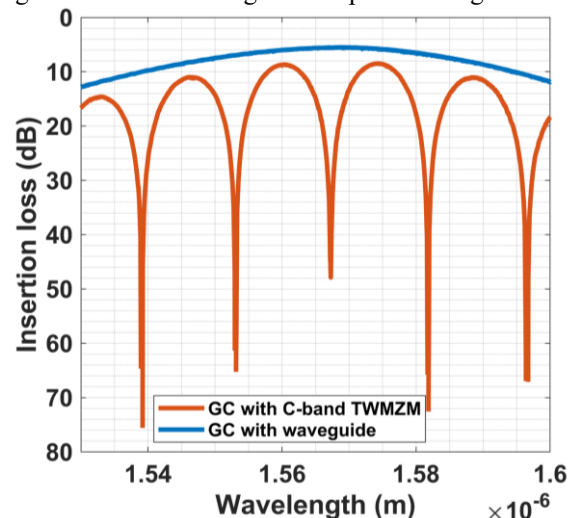


Fig. 3. C-band TWMZM and reference waveguide insertion loss (inc. grating couplers)

From Fig. 3, one can see that at 1570 nm, the insertion loss of the reference structure is 5.6 dB, where 4.6 dB comes from grating couplers (2.3 dB per facet). The modulator itself introduces an additional 3 dB, resulting in a total on-chip loss of 8.6 dB when the modulator is biased at maximum. Measured O-band MZM bandwidth at different reverse bias conditions can be seen in Fig. 4.

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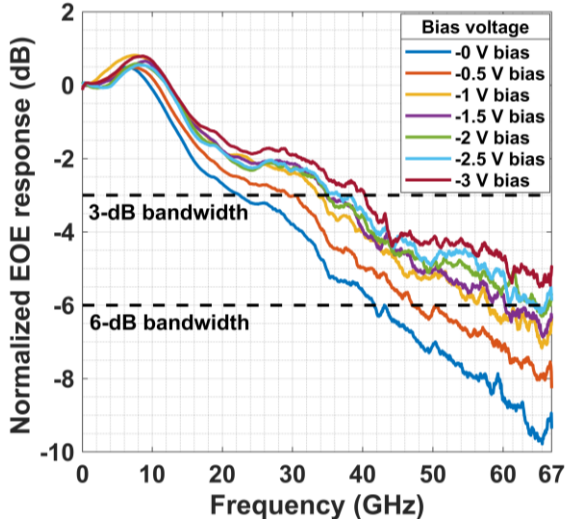


Fig. 4. O-band TWMZM normalized EO bandwidth

We can see from Fig.4 that reverse bias has an impact on modulator's 3-dB bandwidth. Unbiased O-band TWMZM 3-dB bandwidth is 22 GHz, while increasing reverse bias to -3 V increases it to 42 GHz. Measured 6-dB bandwidth is beyond 67 GHz. O-band TWMZM insertion loss and the insertion loss of the reference waveguide of the same length are depicted in Fig.5.

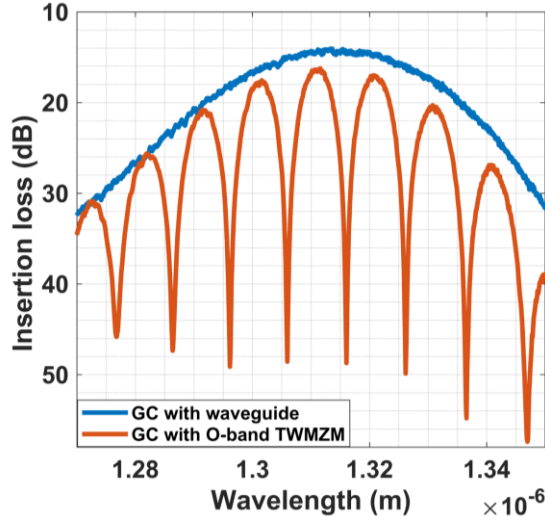


Fig. 5. O-band TWMZM and reference waveguide insertion loss (inc. grating couplers)

From Fig.5, one can see that at 1310 nm, the insertion loss of the reference structure is 14.5 dB, where 10.2 dB comes from grating couplers (5.1 dB per facet). The modulator introduces an additional 2 dB, resulting in total on-chip loss of 16.5 dB at maximum transmission.

B. Large-signal experimental setup

We perform a large signal test for TWMZM modulators to investigate their performance. We tested C-band TWMZM in optical-amplification-free mode and with EDFA to investigate the impact of optical amplification on a real system. A performance investigation of O-band TWMZM was done with PDFA due to the significant impact of TPA and large insertion loss of the chip. The achieved speeds using large signal measurements are shown as gross bitrate. The large signal experimental setup is depicted in Fig.6.

The signal bit sequences are generated offline in MATLAB from a random binary sequence of >1 million bit-length obtained using the Mersenne Twister generator with a shuffled seed number. The obtained bit sequence is first digitally up-sampled to 4 samples per symbol, pulse-shaped with root-raised-cosine (RRC) filter with roll-off factors of 0.6 for OOK, 0.5 for PAM4 and PAM6, and 0.4 for PAM8, and down-sampled to 256 GSa/s to match the sampling rate of the arbitrary waveform generator (AWG, Keysight M8199B). The virtual differential drive for the TWMZM is achieved by applying a 2.7 V_{pp} output voltage swing from each of two AWG channels and adjusting skew between channels. The approach can be transferred to a single-ended device using a balun [21]. Both modulators are reverse-biased using a 110 GHz bias-tee (SHF BT110R) at -2.5 V to ensure higher bandwidth operation. Signal and bias are applied to the modulators using a 67-GHz ground-signal-ground-signal-ground (GSGSG) RF probe, with integrated tips for adjusting the left/right arm of the modulator by heating. Due to the limitation of the probe station, we are forced to use a 400 mm long cable between the AWG and the probe. Single optical fiber probes are coupled at 2 μm height and 8° angle to minimize insertion loss. The output power of the tunable laser was set to 15.5 dBm (Cobrite DX1) at 1568 nm and to 19.4 dBm (Keysight N7776C-013) at 1311.4 nm. Wavelength is optimized to match minimal grating coupler insertion loss. For C-band TWMZM, we observed additional nonlinear loss of 0.7 dB at 15.5 dBm input power. In optical-amplification-free measurement, the resulting optical power on a 70-GHz PIN photodiode (PD) is 2.3 dBm. To investigate the

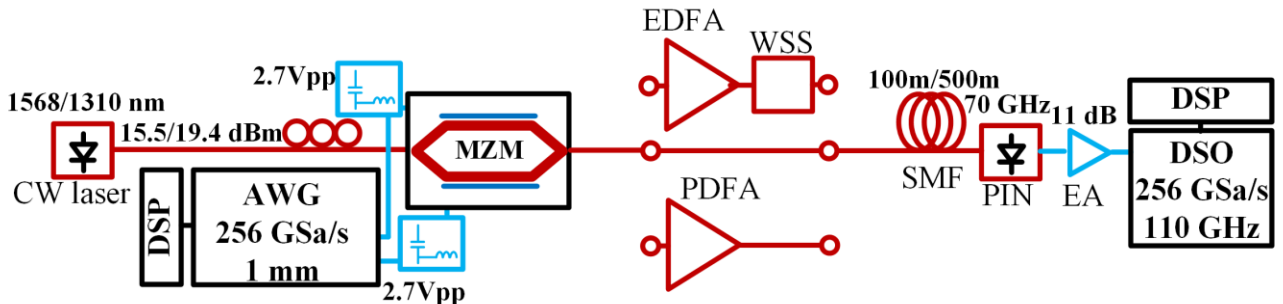


Fig. 6. Experimental setup for C-band and O-band TWMZM testing.

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impact of optical-amplification in the system, a modulated signal is delivered to an EDFA, which is set to 14.5 dBm output optical power to overcome grating coupler and waveguide losses in TWMZM. An amplified spontaneous emission (ASE) noise is then filtered using a wavelength-selective switch (Coherent WaveShaper, WSS) with an insertion loss of 5 dB, resulting in up to 8 dBm optical signal on a 70-GHz PIN photodiode (PD). In the case of O-band TWMZM we used PDFA due to very high nonlinear loss. While the expected power on PD should be close 0 dBm, we observed additional loss of 3.7 dB caused by TPA. Therefore, we used PDFA to achieve reasonable power levels on PD. In this case, we limited our received power to 5 dBm to avoid excessive ASE impact on PD due to the lack of O-band band-pass filter. The signal from the PD was then fed into a 110-GHz real-time digital storage oscilloscope (DSO, 256 GSa/s, Keysight UXR1104A). No clock or marker forwarding from the AWG to the DSO was used to ensure real-world conditions. Offline signal processing included matched filtering, timing recovery, and down-sampling based on maximum variance[22], followed by a half-spaced decision-feedback equalizer (DFE) with varying feed-forward (FF) and feedback (FB) taps. Bit error rate (BER) performance is counted after the offline demodulation by comparing the demodulated bitstream to the transmitted bitstream.

III. RESULTS AND DISCUSSION

In this section, we investigate transmission link at highest gross rate (net rate can be seen in Table 1) for on-off keying and pulse amplitude modulation. We investigate the impact of temperature on the transmission system at different transmission rates for temperatures from 25°C to 85 °C. We compare the system performance of optical-amplification-free against a system with optical amplification to determine the trade-off for testing. Additionally, we investigate both TWMZM's performance in a net 200 Gb/s per lane scenario in accordance with IEEE 802.3dj requirements. We evaluate the performance for optical back-to-back (ob2b) and after transmission over 100 meters (m) and 500 m of SMF for the most analyzed data transmission rates. We show eye diagrams at the highest received power and the same DFE configuration as per the BER curves. Lastly, we investigate the impact of virtual differential signaling compared to the conventional approach.

A. C-band TWMZM performance

Firstly, we investigated C-band TWMZM achievable performance in the optical-amplification scenario. In Fig. 7, we show the BER as a function of received optical power (RX_{power}) for 212.5 Gb/s, 224 Gb/s, and 256 Gb/s OOK signals using the DFE with 21 FF-taps and 21 FB-taps for ob2b and after transmission over 100 m and 500 m SMF.

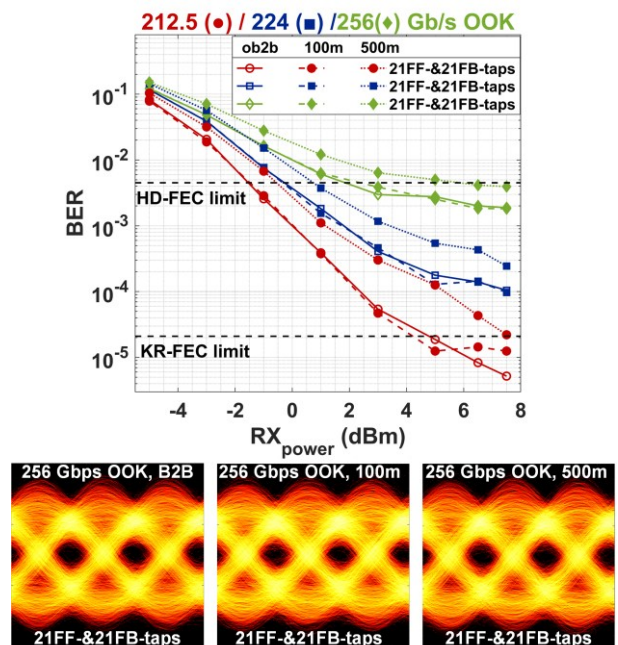


Fig. 7. BER versus RX_{power} for OOK signals and Eye diagrams (see insets for details).

One can see that reaching the 6.25% OH HD-FEC threshold requires RX_{power} of 2 dBm (5 dBm) for 256 Gb/s, 0 dBm (1 dBm) for 224 Gb/s, and -1.5 dBm (-0.5 dBm) for 212.5 Gb/s OOK signals after transmission over 100 m (500 m) SMF fiber. We can observe that there is no dispersion power penalty in the case of 100 m transmission, however, after transmission over 500 m SMF dispersion power penalty is 1 dB for 212.5/224 Gb/s OOK signals and 3 dBm for 256 Gb/s OOK signals. For 212.5 Gb/s OOK signal, we managed to reach the KR-FEC threshold of 2.1×10^{-5} for ob2b and after transmission over 100 m of SMF. We demonstrate eye diagrams for 256 Gb/s OOK as insets for Fig. 7. One can see that the eye diagrams are open, which signifies the excellent performance of the transmission system.

In Fig. 8, we show the BER as a function of RX_{power} for 320 Gb/s, 340 Gb/s and 350 Gb/s PAM4 signals using the DFE with 99 FF-taps and 99 FB-taps for ob2b and after transmission over 100 m SMF. One can see that reaching the 6.25% OH HD-FEC threshold requires RX_{power} of 2.5 dBm for 320 Gb/s, 5 dBm for 340 Gb/s, and 7.5 dBm for 350 Gb/s PAM4 signals. We demonstrate eye diagrams for 350 Gb/s PAM4 as insets for Fig. 8.

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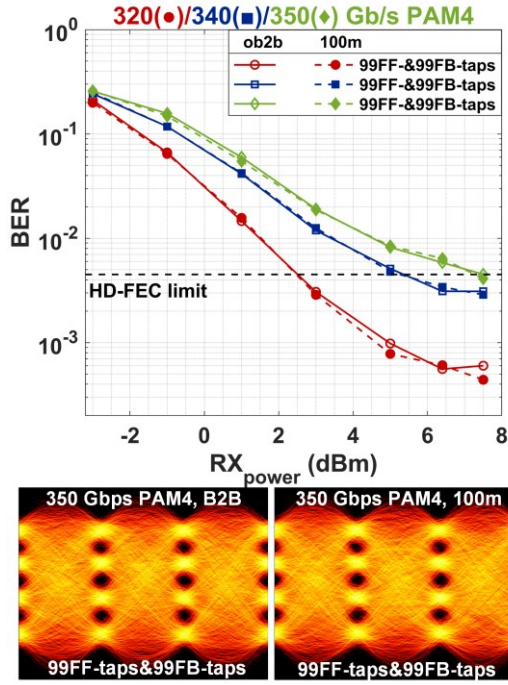


Fig. 8. BER versus RX_{power} for PAM4 signals and Eye diagrams (see insets for details).

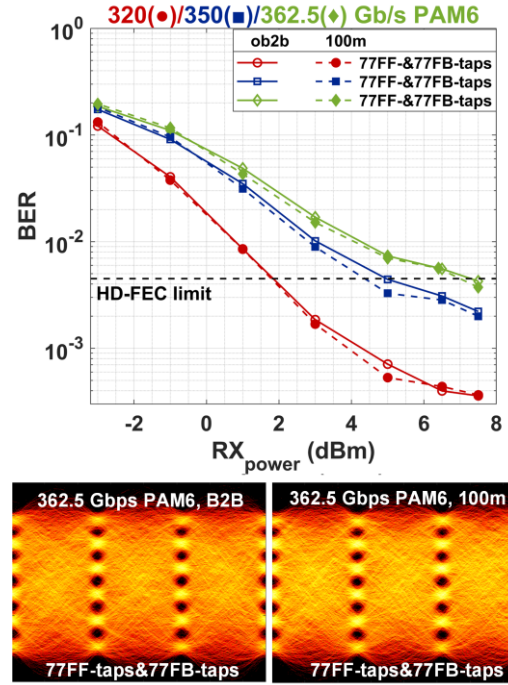


Fig. 9. BER versus RX_{power} for PAM6 signals and Eye diagrams (see insets for details).

In Fig. 9. we show the BER as a function of RX_{power} for 320 Gb/s, 350 Gb/s and 362.5 Gb/s PAM6 signals using the DFE with 77 FF-taps and 77 FB-taps for ob2b and after transmission over 100 m SMF.

One can see that reaching the 6.25% OH HD-FEC threshold requires RX_{power} of 2 dBm for 320 Gb/s, 5 dBm for 350 Gb/s, and 7.5 dBm for 362.5 Gb/s PAM6 signals. We demonstrate eye diagrams for 362.5 Gb/s PAM6 as insets for Fig. 9.

In Fig. 10. we show the BER as a function of RX_{power} for 300 Gb/s, 318.75 Gb/s and 336 Gb/s PAM8 signals using the DFE with 55 FF-taps and 55 FB-taps for ob2b and after transmission over 100 m SMF.

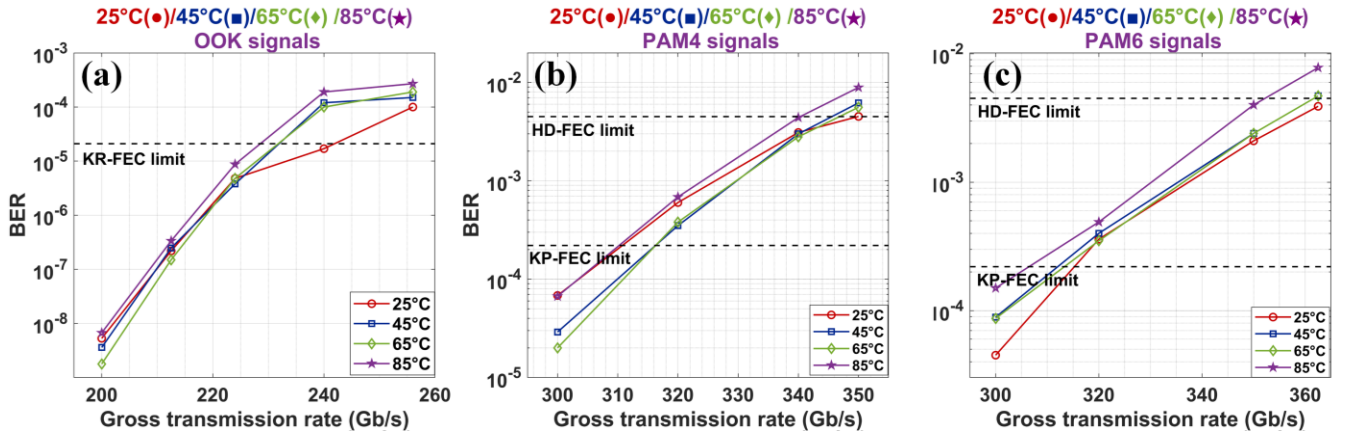


Fig. 11. Temperature impact at different gross transmission rates for (a) OOK, (b) PAM and (c) PAM6 signals

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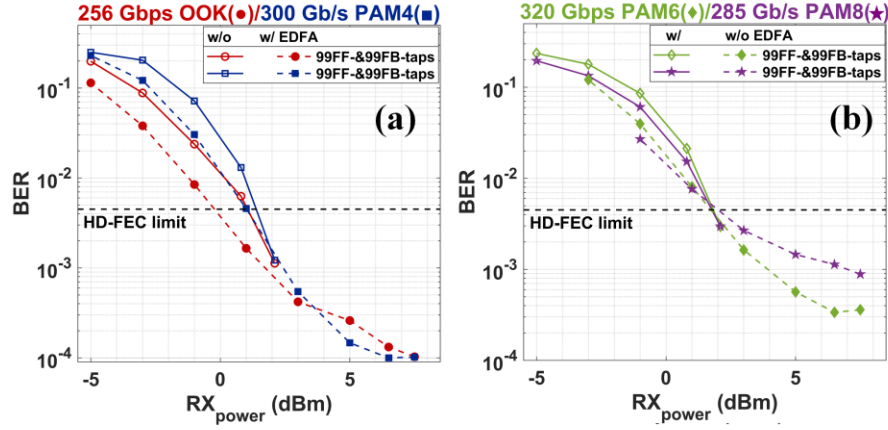


Fig. 12. C-band TWMZM performance comparison for (a) optical-amplification-free (w/o EDFA) and (b) optical amplification (w/ EDFA) scenarios

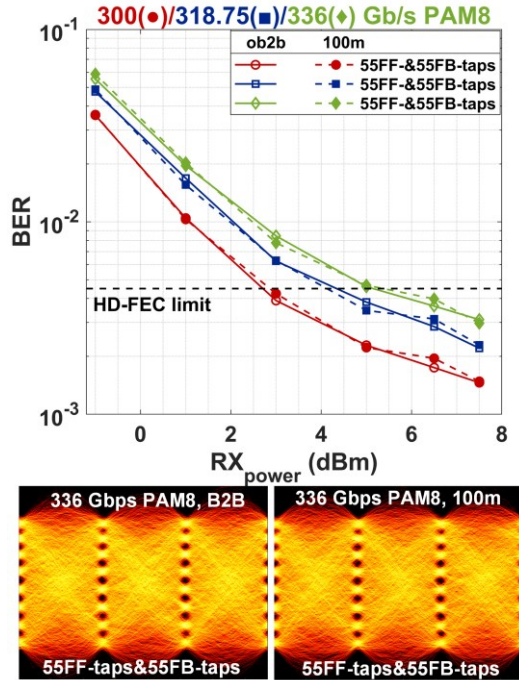


Fig. 10. BER versus RX_{power} for PAM8 signals and Eye diagrams (see insets for details).

One can see that reaching the 6.25% OH HD-FEC threshold requires RX_{power} of 3 dBm for 300 Gb/s, 4.5 dBm for 318.75 Gb/s, and 5 dBm for 336 Gb/s PAM8 signals. We demonstrate eye diagrams for 336 Gb/s PAM8 as insets for Fig. 10.

In Fig. 11 (a-c), we show the BER as a function of gross transmission rate at 25°C, 45°C, 65°C, and 85°C temperatures at maximum RX_{power} using the DFE with 99 FF-taps and 99 FB-taps after transmission over 100 m SMF. Fig. 11(a) shows OOK signal measurements at different temperatures. In this case, we used estimated BER values for 200 and 212.5 Gb/s OOK signals as the counted error was low and didn't have enough statistical significance. We can observe that at lower data rates, there is a very small difference between BER performance; however, with the data rate increase, we see that modulator performance at 85°C deteriorates slightly. In Fig.11(b) one can

see PAM4 performance at different temperatures. We can see that there is little difference between 45°C and 65°C measurements, however, we can see that modulator performance at 85°C is worse. In Fig.11(c) one can see PAM6 temperature dependence. We observe little difference between 25°C to 65°C temperatures, however 85°C shows performance degradation of TWMZM. From Fig.11. we can see that C-band TWMZM can operate at temperatures up to 65°C without significant degradation, however, at 85°C one might have to account for degradation when designing links based on SiP TWMZM.

B. System analysis with and without EDFA

We compared the achievable performance of the C-band TWMZM in an optical-amplification-free configuration with its performance at the same data rate when optical amplification was employed (see Fig. 12). To authors best knowledge, these are the highest achieved optical-amplification-free data transmission rates on a conventional SiP modulator and the first demonstration of optical-amplification-free transmission of net 300 Gb/s using SiP modulator [17]. In Fig.12(a-b). one can see 256 Gb/s OOK, 300 Gb/s PAM4, 320 Gb/s PAM6 and 285 Gb/s PAM8 transmission in optical-amplification-free scenario without and with EDFA. We can see that the use of EDFA allows us to achieve higher RX_{power} levels on PD, however, we can see that BER curves for both scenarios are always crossing close to 2 dBm RX_{power} levels. Transmitted signals in system with EDFA are approaching BER at powers above 5 dBm, however in case of optical-amplification-free system we don't observe saturation. It would be necessary to extend received optical power to 8 dBm in an amplification-free scenario to determine whether saturation comes from PD, however, that was not possible due on-chip loss and lack of higher power C-band laser. One can see, that for PAM signals, difference between scenarios is smaller, as EDFA introduces penalty to SNR, and higher-order signals are more susceptible to SNR reduction.

C. O-band TWMZM performance

We investigated the achievable performance for O-band

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TWMZM. In Fig. 13, we show the BER as a function of RX_{power} for 200 Gb/s, 212.5 Gb/s, and 224 Gb/s OOK signals using the DFE with 99 FF-taps and 99 FB-taps for ob2b and after transmission over 500 m SMF.

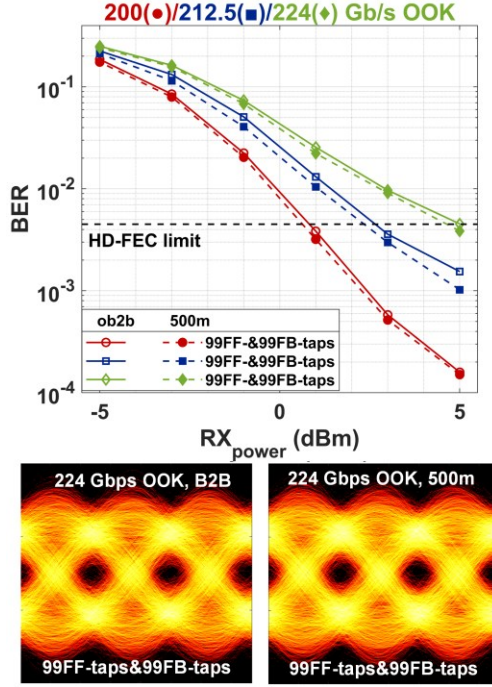


Fig. 13. BER versus RX_{power} for OOK signals and Eye diagrams (see insets for details).

One can see that reaching the 6.25% OH HD-FEC threshold requires RX_{power} of 1 dBm for 200 Gb/s, 3 dBm for 212.5 Gb/s, and 5 dBm for 224 Gb/s OOK signals after transmission over 500 m SMF fiber. We demonstrate eye diagrams for 224 Gb/s OOK as insets for Fig. 13.

In Fig. 14, we show the BER as a function of RX_{power} for 224 Gb/s, 256 Gb/s and 280 Gb/s PAM4 signals using the DFE with 99 FF-taps and 99 FB-taps for ob2b and after transmission over 500 m of SMF.

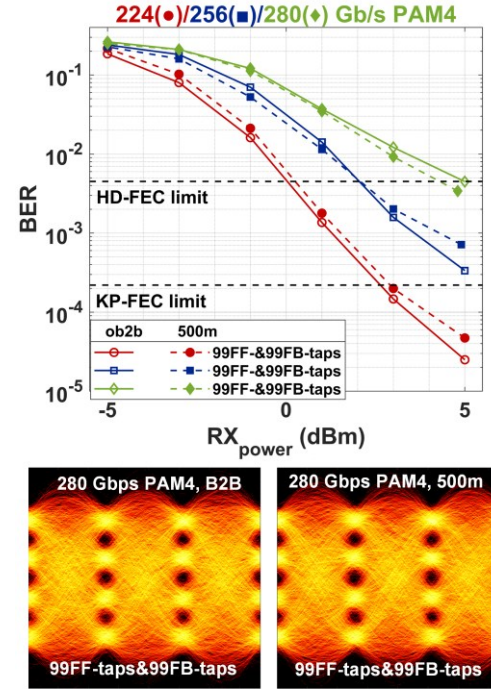


Fig. 14. BER versus RX_{power} for PAM4 signals and Eye diagrams (see insets for details).

Reaching the 6.25% OH HD-FEC threshold requires RX_{power} of 0 dBm for 224 Gb/s, 2 dBm for 256 Gb/s, and 5 dBm for 280 Gb/s OOK signals after transmission over 500 m SMF fiber. For a 224 Gb/s PAM4 signal, we reached the KP-FEC threshold of 2.2×10^{-4} for ob2b after transmission over 500 m of SMF at 3 dBm RX_{power} . We demonstrate eye diagrams for 280 Gb/s PAM4 as insets for Fig. 14.

D. Net 200 Gb/s per lane performance

Several realization scenarios for net 200 Gbps per lane are proposed by IEEE 802.3 dj Taskforce. DR reach is proposed to be realized using one FEC [23], namely FECo, with a pre-FEC threshold of 2.4×10^{-4} at 212.5 Gbps lane rate, however, for FR proposed scheme consists of two concatenated FECs, where FECi requires a pre-FEC BER of 4.85×10^{-3} at 226.785 Gbps

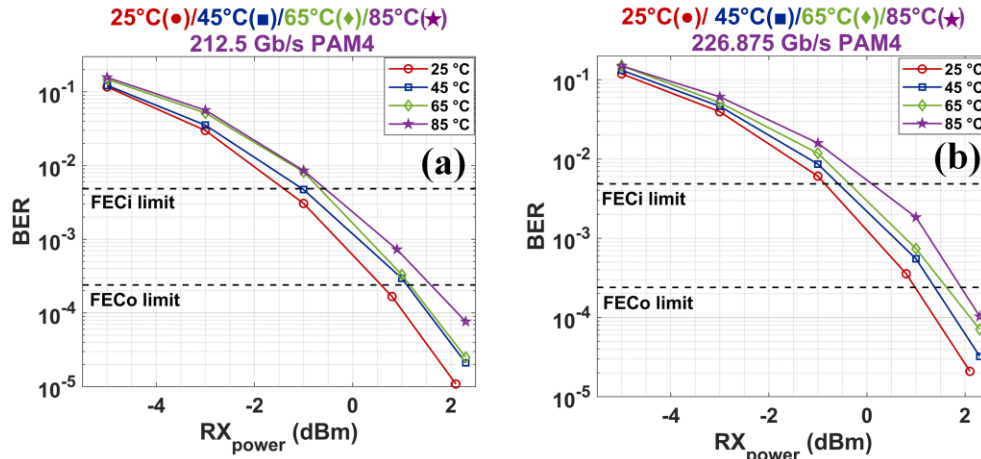


Fig. 16. Temperature impact on C-band TWMZM at (a) 212.5Gb/s and (b)226.785 Gb/s PAM4

line rate. Relaxing FEC requirements gives additional power

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budget margin and enables earlier adoption; however, it comes at a cost of up to 280 ns of latency per hop [24] and increased line rate.

We evaluate the operation of both C-band and O-band TWMZM in accordance with this specification. In case of C-band TWMZM, we limit the test setup to optical-amplification-free to give closer conditions to field application.

We demonstrate the BER as a function of RX_{power} for 212.5 Gb/s and 226.875 Gb/s PAM4 signals using C-band TWMZM for ob2b and after transmission over 100 m/500 m SMF in Fig.15.

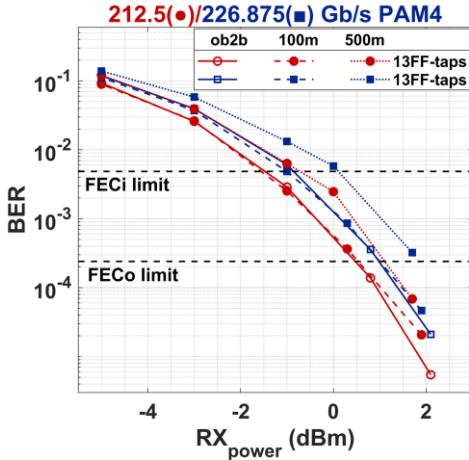


Fig. 15. C-band TWMZM BER versus RX_{power} for 212.5 Gb/s and 226.875 Gb/s PAM4 signals.

One can see from Fig.15 that it requires 0.5 dBm of RX_{power} for 212.5 Gb/s PAM4 to reach FECo limit for ob2b and 100 m transmission, and 1 dBm for 500 m transmission. In the case of 226.875 Gb/s PAM4, -1 dBm is required to reach the FECi limit for ob2b and 100 m transmission, and 0 dBm is required for 500 m transmission. We can see that in case of C-band TWMZM, we can extend the power margin by 1.5 dB for 100 m reach scenarios and 1 dB for 500 m scenarios at the expense of additional latency.

In Fig.16(a-b). one can see BER as a function of RX_{power} for 212.5/226.875 Gb/s using C-band TWMZM in ob2b case at different temperatures. Same 13 FF-tap FFE equalizer was

used. One can see that for 212.5 Gb/s (Fig.16. (a)), when compared to 25°C, the power penalty is 0.5 dB for 45°C, 0.55 dB for 65°C and 1 dB for 85 C at FECo threshold. For 226.875 Gb/s (Fig.16. (b)) power penalty is 0.3 dB for 45°C, 0.5 dB for 65°C, and 1 dB for 85 C at the FECi threshold. While at 85°C power penalties are identical, for lower temperatures one could gain even more margin when operating the modulator at 226.875 Gb/s compared to 212.5 Gb/s.

BER as a function of RX_{power} for 212.5 Gb/s and 226.875 Gb/s PAM4 signals using O-band TWMZM for ob2b and after transmission over 500 m SMF is depicted in Fig.17

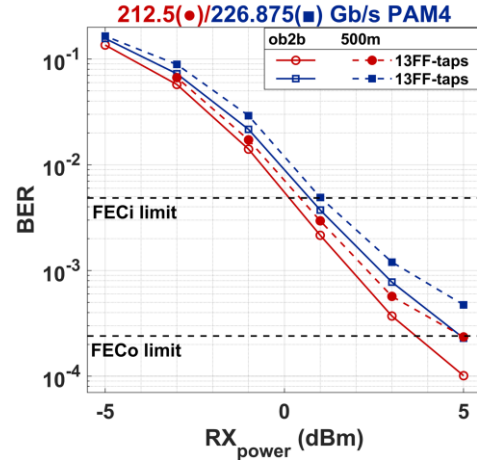


Fig. 17. O-band TWMZM BER versus RX_{power} for 212.5 Gb/s and 226.875 Gb/s PAM4 signals.

From Fig.17. we can observe that it requires 5 dBm of RX_{power} for 212.5 Gb/s PAM4 to reach FECo limit, and only 1 dBm of optical power for 226.875 Gb/s PAM4 to reach FECi limit. In this case, going to larger overhead FEC would extend power margin by 4 dB using O-band SiP TWMZM at expense of additional latency. This might be crucial for early scaling if SiP 200 Gb/s per lane links.

E. Impact of virtual differential channel

Lastly, it is important to discuss virtual differential channel method used for enhancing the SNR of measurement equipment. While this method is important to achieve higher transmission rates, this also allows to achieve higher signal

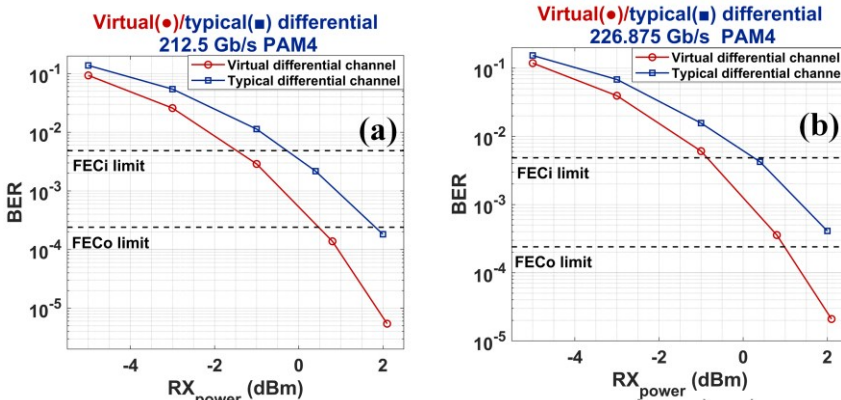
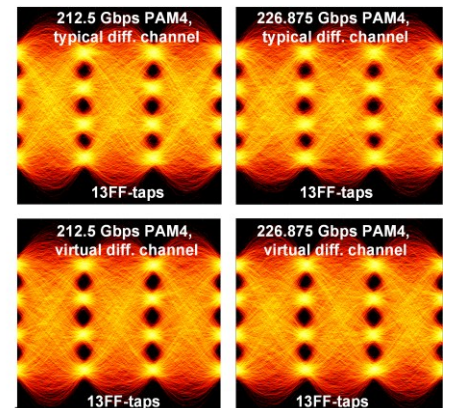


Fig. 18. Comparison of typical vs. virtual differential channel for (a) 212.5 Gb/s and (b) 226.875 Gb/s PAM4 signaling. (Eye diagrams shown as insets)



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quality at lower transmission rates, allowing a more thorough analysis of modulator limitations. One can see a comparison between typical differential and virtual differential generation for 212.5 Gb/s and 226.875 Gb/s generation in an optical-amplification-free system in Fig.18 (a-b). In the case of typical generation using AWG, one digital-analog-converter (DAC) drives a differential amplifier to obtain opposite polarity signals to drive the modulator. In case of virtual differential channel, we take negative output from another AWG channel, that has different DAC. As noise of both DACs are uncorrelated, it provided up to 3 dB SNR gain (theoretical), allowing us to achieve better signal quality. We can see, that the use of virtual differential signaling allows us to reduce BER from 2×10^{-4} to 6×10^{-6} for 212.5 Gb/s PAM4 (Fig.18 (a)) and from 4×10^{-4} to 2×10^{-5} for 226.875 Gb/s PAM4 (Fig.18 (b)). Eye diagrams for all cases are shown in Fig.18. as insets.

IV. CONCLUSIONS

We presented a comprehensive system-level characterization of C-band and O-band silicon photonics traveling-wave Mach-Zehnder modulators implemented using the standard imec iSIPP50G platform. We show optical amplification-free transmission of 256 Gbaud (net 241 Gb/s) OOK, 150 Gbaud (net 291 Gb/s) PAM4, 128 Gbaud (net 301 Gb/s) PAM6, and 95 Gbaud (net 268 Gb/s) PAM8 signals over 100 m of SMF at 6.25 % OH HD-FEC threshold using C-band TWMZM. We show the same modulator achieving 175 Gbaud (net 329 Gb/s) PAM4, 145 Gbaud (net 341 Gb/s PAM6), and 112 Gbaud (net 316 Gb/s) PAM8 if optical amplification is used. We show O-band TWMZM achieving up to 224 Gbaud (net 210 Gb/s) OOK and 140 Gbaud (net 263 Gb/s) PAM4 transmission over 500 m SMF.

Additionally, we investigate 200 Gb/s per lane scenarios defined by IEEE 802.3 dj Taskforce and demonstrate that our modulators can reach required FECi and FECo limits for ob2b and after 500 m transmission over SMF with 13 FF-taps FFE. We investigate the temperature performance of C-band TWMZM in multiple scenarios. This paves the road for high-performance C-band/O-band DR and FR compliant 200 Gb/s per lane transceivers based on SiP TWMZM with simple DSP as well as closes the gap to 400 Gb/s per lane transceivers using conventional SiP technologies.

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