Up to 360 Gb/s Optical Interconnects with Ultra-high Bandwidth Thin Film Lithium Niobate Modulator

Fan Yang[1], Xiansong Fang[1], Xinyu Chen[1], Yanping Li[1] and Fan Zhang[1,2,*]
[1]State Key Laboratory of Advanced Optical Communication Systems and Networks, Frontiers Science Center for Nano-optoelectronics, Department of Electronics, Peking University, Beijing 100871, China
[2]Peng Cheng Laboratory, Shenzhen 518055, China
[*]Author e-mail address: fzhang@pku.edu.cn

Abstract: We demonstrate ultrahigh-speed optical interconnects with single lane bit rate up to 360Gb/s (120GBaud) PAM-8 signal based on thin film lithium niobate modulator with a 3-dB bandwidth larger than 110GHz.

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1. Introduction

With the growing demand for broadband services, the global network traffic of data centers is increasing exponentially. 25.6Tb/s monolithic integrated circuit network switching device has appeared and served the data centers, which puts demand on optical interconnects for data rates of 400Gb/s/λ [1].

Thin film lithium niobite (TFLN) electro-optic modulators have emerged as a strong candidate for 400G data center interconnects (DCI) since they exhibit high bandwidth and low Vπ while improving the ability of integration. Recently, beyond 200G high speed operations of TFLN modulators were reported. 320Gb/s 16 quadrature amplitude modulation (16-QAM) was demonstrated with an IQ modulator based on TFLN platform with a bit error rate (BER) of 8.4×10-3 [2]. Each Mach-Zehnder modulator (MZM) in the IQ modulator showed a bandwidth of 48GHz [2]. Although coherent systems exhibit high performance, intensity-modulated direct-detected (IM-DD) systems are still more competitive for DCI owing to their simple structure, cost effectiveness and low power consumption. In 2018, a 100GHz TFLN modulator was proposed and supported 210Gb/s eight-level pulse amplitude modulation (PAM-8) [3]. Afterwards, 220Gb/s PAM-4 modulation was achieved based on a 56GHz TFLN MZM with a BER below the 20% hard-decision forward error-correction (HD-FEC) threshold of 1.5×10^{-2} [4]. With digital band-interleaved (DBI) based digital-to-analog converter (DAC) and high-bandwidth receiver [5], 700.4Gb/s line rate probabilistically shaped (PS) 16-QAM signals and 630 Gb/s PS-PAM-16 signals were generated with an 80GHz TFLN modulator and transmitted over 10.2km optically dispersion-compensated single mode fiber. However, optical dispersion compensation also induces more cost and additional link loss. Therefore, high baud rate signals operation with TFLN modulators and transmission without optical dispersion compensation is of great importance.

In this paper, we report short-reach optical interconnects of high baud rate Nyquist shaped PAM-6 and PAM-8 signals by using a TFLN traveling-wave MZM with a 3-dB bandwidth exceeding 110GHz. With Volterra nonlinear equalizer and decision feedback equalizer, we achieve back-to-back (BTB) generation of 360Gb/s (120GBaud) PAM-8 signal and 330Gb/s (110GBaud) PAM-8 signal transmission over 500m SSMF, respectively, with a BER below the 25% SD-FEC threshold of 4×10^{-2} [6]. Our work demonstrates the application for short-reach optical interconnects beyond 300G with TFLN modulators without optical dispersion compensation at C-band.

2. Device characteristic and experimental setup

Fig. 1 shows the microscope image of the ultra-broadband TFLN modulator we fabricated. The modulator works at Mach-Zehnder interferometer configuration. Each arm of the MZM contains a phase modulator of 5 mm length and the two arms are connected by 1×2 multimode interference (MMI) couplers to achieve beam-splitting and beam-combining. The electrodes are made of coplanar waveguide transmission lines. One group of GSG pads are built for a radio frequency (RF) probe to apply the bias voltage and the high-speed driving signals. Another group of GSG pads are terminated with an external 50 Ω load through another probe. Light is coupled in and out of the device by fiber-to-chip edge couplers with a loss of ~6.5dB/facet. The measured half-wave voltage (Vπ) at 5MHz of the device is 4.74 V and the extinction ratio is > 23 dB. Fig. 2(a) shows the measured electro-optic (EO) response of the TFLN MZM, which presents a flat response over the frequency range with a roll-off of ~ 2.5 dB from 10 MHz to 110 GHz.

The experimental setup is shown in Fig. 2(b). At the transmitter, an external cavity laser (ECL) at 1549.93nm is employed as the optical source. Before coupling to the chip, the polarization state of the light is adjusted with a polarization controller (PC). The baseband Nyquist PAM signal is generated by an arbitrary waveform generator (AWG) (Keysight 8199A) operating at 256GSa/s sampling rate and 60GHz bandwidth. After amplified by an EA with 60GHz bandwidth, the electrical signal from AWG is delivered to the modulator through a GSG probe with 110GHz bandwidth. After SSMF transmission, the optical signal is detected with a single-ended 70GHz photodetector (PD) and amplified by an EA with 60GHz bandwidth. Finally, the received signal is captured by a

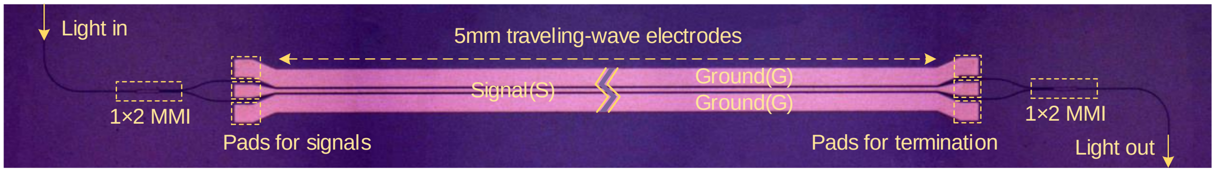

Fig. 1. The Microscope image of the thin film LN travelling-wave MZM. MMI: multimode interference.

real-time digital storage oscilloscope (DSO) (Keysight UXR0594AP) with 256GSa/s sampling rate and 59GHz bandwidth for offline processing. The frequency response of the whole system is measured as Fig. 2(c), which is used for system calibration to pre-compensate the high-frequency roll-off. Moreover, the spectrum components exceeding 60GHz cannot be captured due to the brick wall filtering characteristic of the DSO, which set an upper-bound of 120GBaud for the detected signals in our experiments.

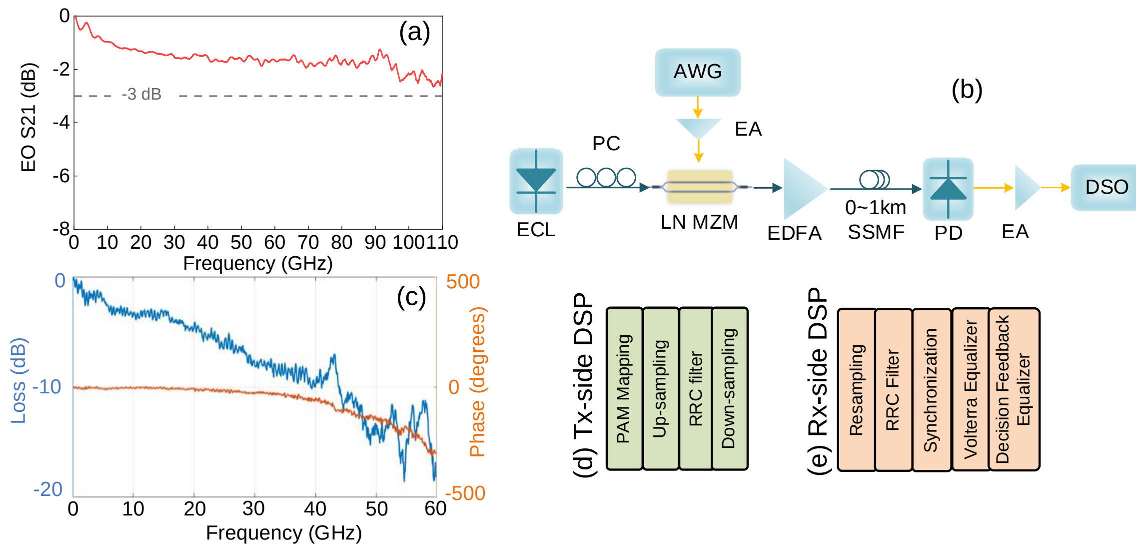

Fig. 2. (a) Electro-optic response of the thin film LN MZM. (b) Experimental setup. (c) The frequency response of the whole transmission system. (d) Transmitter side DSP. (e) Receiver side DSP. ECL: external cavity laser; PC: polarization controller; AWG: arbitrary waveform generator; EA: electrical amplifier; EDFA: erbium-doped fiber amplifier; SSMF: standard single-mode fiber; PD: photodiode; DSO: digital storage oscilloscope. Tx: transmitter; Rx: receiver; RRC: root raised cosine.

The digital signal processing (DSP) stacks are shown in Fig. 2(d)~(e). At the transmitter, the binary bit stream is mapped to PAM-4/6/8 symbols first. After up-sampling, the signal is digitally Nyquist shaped using root raised cosine (RRC) filter with a roll-off factor of 0.01. Then the signal is down-sampled before sending to the AWG. At the receiver, the captured waveform is firstly re-sampled to 2 samples per symbol (SPS), matched RRC filtered, and synchronized. Channel equalization is performed by Volterra non-linear equalization (VNLE). After that, a decision feedback equalizer (DFE) is employed to enhance the performance. Finally, the symbol de-mapping and BER calculation is performed.

3. Experimental results

Fig. 3(a) shows the measured BERs of PAM-8/6/4 signals for different data rates at the BTB scenario. For PAM-8 signals, it can be seen that 360Gb/s and 330Gb/s signals can be achieved below the 25% SD-FEC threshold of 0.04. 300Gb/s and 240Gb/s signals can be achieved below the 20% SD-FEC and the 7% HD-FEC thresholds, respectively. For PAM-6 signals, 300Gb/s and 250Gb/s signals can be achieved below the 20% SD-FEC and the 7% HD-FEC thresholds, respectively. Fig. 3(b) displays the measured BER versus the received power for PAM-8/6 signals at different baud rates.

Fig. 3(c) shows the measured BER versus the transmission distance for PAM-8 signals with different baud rates. Considering the potential of decision feedback equalizer (DFE) to compensate the chromatic dispersion-induced distortions for IM/DD optical systems [7], the combination of VNLE and DFE is employed to enhance transmission performance. 330Gb/s PAM-8 signals can be transmitted below the 25% SD-FEC threshold after 500m transmission, and 300Gb/s PAM-8 signals can be transmitted below the 20% SD-FEC threshold after 1km transmission. Fig. 3(d)~(f) show the measured optical spectra of Nyquist PAM-8/6/4 signals at 0.02nm resolution, respectively, at BTB scenarios with different baud rates. Fig. 3(g)~(i) display typical eye diagrams of PAM-8/6/4 signals after equalization for different baud rates.

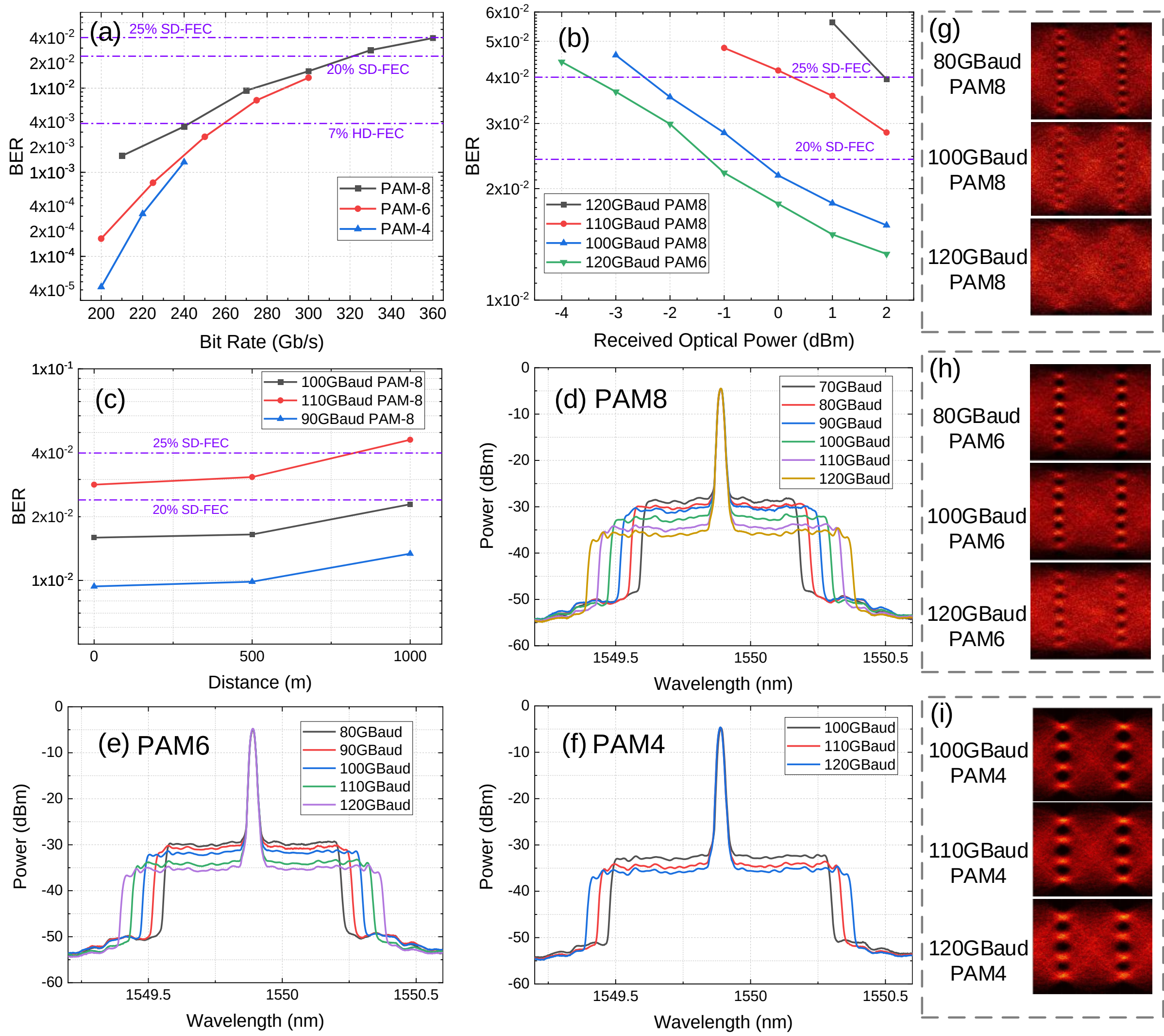

Fig. 3. (a) Measured BERs versus data rates for PAM-8/6/4 signals at BTB. (b) Measured BERs versus the received optical power for PAM-8/6 signals at BTB. (c) Measured BERs versus transmission distance for PAM-8 signals with different symbol rates. (d)~(f) Measured optical spectra of PAM-8/6/4 signals with different symbol rates at BTB. (g)~(i) PAM-8/6/4 reconstructed eye diagrams after equalization.

4. Conclusion

We report high baud rate optical interconnects (up to 120Gbaud PAM-8) with a TFLN MZM with 3-dB bandwidth larger than 110GHz. With the help of Nyquist pulse shaping and post-equalization, 360Gb/s PAM-8 signals at BTB and 330Gb/s PAM-8 signals after 500m SSMF transmission are achieved, respectively, below the 25% SD-FEC threshold. Our work indicates that beyond 300G single lane data rate optical interconnects is possible based on TFLN modulators without optical dispersion compensation at C-band, which has great potential for single lane 400G DCI applications.

5. Acknowledgement

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6. References

[1] M. Zhang, C. Wang, P. Kharel, D. Zhu, and M. Lončar, Optica 8, 652-667 (2021).
[2] M. Xu, M. He, H. Zhang, Z. Li, X. Xiao, S. Yu, X. Cai, et al., Nat. Commun. 11, 3911 (2020).
[3] C. Wang, M. Zhang, X. Chen, M. Bertrand, A. Shams-Ansari, et al., Nature 562, 101–104 (2018).
[4] Y. Zhang, M. Xu, M. He, X. Xiao, S. Yu, et al., ECOC (2019), pp. 1–4.
[5] Xi Chen, Junho Cho, Gregory Raybon, Di Che, K.W. Kim, et al., ECOC (2020), pp.1-4.
[6] S. T. Le, *et al.*, J. Lightw. Technol. 37, 418-424 (2019).
[7] J. Zhou, *et al.*, Opt. Lett. 46, 138-141(2021).