200 GBd Electro-optic PLZT Modulator for O-band Transmission

Shiyoshi Yokoyama,[1, 2] Yuexin Yin,[1] Sahar Alasvand Yazdani,[1] Hiromu Sato,[1] and Guo-Wei Lu,[1,2]

1. Institute for Materials Chemistry and Engineering, Kyushu University, Fukuoka 816-8580, Japan
2. Department of Molecular and Material Science, Kyushu University, Fukuoka 816-8580, Japan
E-mail: s_yokoyama@cm.kyushu-u.ac.jp

Abstract: We demonstrate a 200 GBd modulation using a ferroelectric film-on-insulator (PLZT) modulator. The 2.5 mm-long phase shifter efficiently facilitated modulation, achieving error-free O-band transmission over a 2.0 km distance. © 2024 The Author(s)

1. Introduction

In recent years, data traffic has surged dramatically due to the growing use of bandwidth-intensive applications, including high-resolution streaming media, B5G technologies, cloud computing services, and IoT. This surge has placed increased demands on fiber communication networks. This surge is fueled by a continuous influx of newly emerging and largely unexpected digital applications and services. Increasing attention has been given to the realization of Terabit Ethernet for Tbit/s network applications. To achieve single-channel Tbit/s transmission rates, efforts are being directed toward increasing channel symbol rates and employing advanced coherent modulation techniques, such as differential quadrature amplitude phase-shift keying [1]. Another approach is optical time-division multiplexing, combined with efficient demultiplexing at the receiver, which also enhances transmission via all-optical signal processing [2]. While these high line rates can be achieved through advanced modulation formats, there is ongoing effort to further expand electronic bandwidth. Generating high-symbol-rate electronic signals is advantageous because any modulation fundamentally relies on a single electrical-to-optical modulation with one optical carrier. In recent years, extensive research has been conducted to push electrical symbol rate generation well beyond 200 Gbaud, a development expected to support the next generation of coherent fiber transmissions [3, 4]. More recently, advancements have enabled electrical bandwidth operations exceeding 150 GHz by using digital band interleaved (DBI) digital-to-analog converters (DACs) [5] or electrical mixers based on indium phosphide (InP) double heterojunction bipolar transistors [6]. These innovations have facilitated modulations at symbol rates of 216 Gbaud and 314 Gbaud, achieving signaling rates of over 500 Gbit/s using a single Mach-Zehnder interferometer modulator. Such developments are critically important for high-density optical processing, particularly for optical interface technologies required in data centers, which demand more stringent technical specifications. However, despite these improvements in high-symbol-rate generation, the available electro-optical (EO) devices capable of handling high frequencies are limited by the scarcity of suitable materials and device options. There is an urgent need to explore more efficient modulation devices that are fully compatible with high-bandwidth electronics.

2. High-speed PLZT waveguide modulator

2.1. Efficient EO modulator prepared in a ferroelectric crystal-on-insulator.

Our approach focuses on utilizing strong ferroelectrics in waveguide modulators, specifically incorporating a ferroelectric crystal-on-insulator structure. This hybrid structure offers significant advantages in terms of drive voltage, bandwidth, high-speed signaling, and compact fabrication. The potential of such modulators has already been demonstrated with recently developed thin-film lithium niobate (TFLN) modulators, which have shown promising results in high-line-rate transmissions. Nevertheless, the electro-optic (EO) coefficient of around 31 pm/V in TFLN devices limits the potential for enhancing modulation efficiency, especially when attempting to further minimize device size. To address this, we have chosen the ferroelectric crystal $Pb(La)[Zr, Ti]O_3$ (PLZT) for its high EO coefficient, around 200 pm/V, and its excellent optical transparency at fiber communication wavelengths. In our feasibility study of the PLZT modulator, we achieved modulation rates up to 172 Gbaud [7, 8]. However, the efficiency of high-speed modulation was hindered by RF power attenuation within the CPW line. The main contributors to the electrical losses were conductor losses, which varied with frequency, and substrate losses, which remained constant regardless of frequency. To overcome these limitations, we redesigned and optimized the phase shifter section of the PLZT modulator to support modulation rates up to 200 Gbaud. Although recent advancements in high-symbol-rate electronic signal generation could further increase signaling speeds, that aspect is beyond the scope of this study. All experiments were conducted using a simple intensity-modulated direct detection system.

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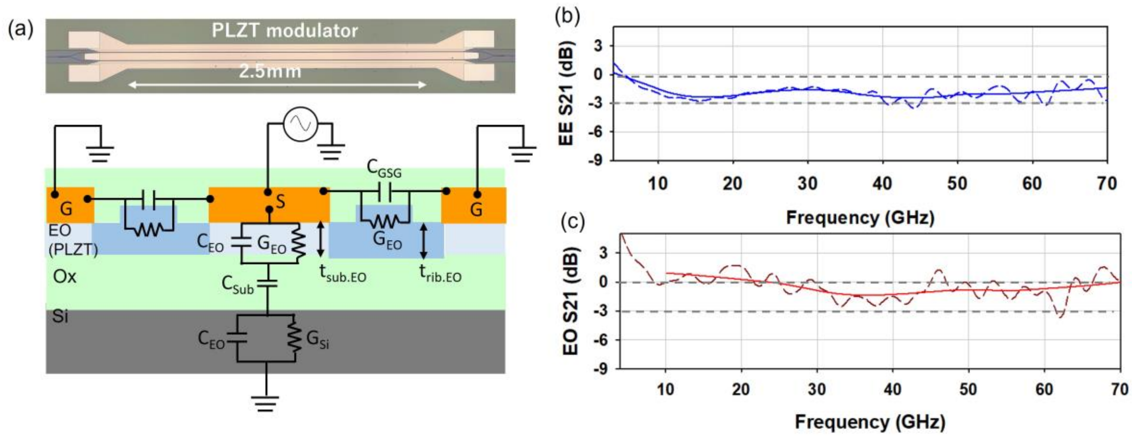

Fig. 1. Frequency response of the PLZT modulator. (a) Photograph and sectional view of the phase shifter part. (b) RF power attenuation of the CPW line at different frequencies. (d) EO frequency response of the PLZT modulator.

2.2. Electrical element of the phase shifter and optimization

Figure 1(a) presents a cross-sectional schematic of the CPW section of the PLZT modulator, along with the electrical elements contributing to the overall impedance. The waveguide was designed to concentrate the optical electric field around the optical mode core within PLZT, ensuring efficient EO modulation. Metal electrodes, consisting of a signal line and a ground plane with an aluminum thickness of 0.8 µm, were deposited across the waveguide core. Since PLZT has a large dielectric constant (~1300), the elements in the layer play a significant role, which consequently affects the RF power attenuation. Therefore, the thickness of the PLZT layer (200nm) beneath the electrodes was adjustable to optimize the signal-to-substrate capacitance. Finally, as shown in Fig. 1(b), we measured RF attenuation frequency response exhibiting minimal roll-off, less than 2.0 dB at 70 GHz. Additionally, the measured EO modulation frequency response is shown in Fig. 1(c), showing a roll-off of less than 3 dB between 10 and 70 GHz. The PLZT modulator is configured with a MZI structure using MMI splitters. The phase shifter length was 2.5 mm, and PM fiber was connected to the waveguide edge, guiding laser light to the modulator. Given that the EO coefficient of PLZT is approximately 195 pm/V, the modulator achieved a $V_{\pi}L$ value of 5.8 V·mm at a wavelength of 1310 nm.

2.3. 200 GBd modulation of the PLZT modulator

We investigated the feasibility of using the PLZT modulator for high-speed transmission by generating a 200 GBd OOK signal (200 Gbit/s line rate). For the OOK transmission, a PRBS electrical signal generated by an 80 GHz AWG (Keysight M8199B) was applied to the PLZT modulator. A linear 100 GHz driver was used to adjust the voltage swing to approximately 300 mV_{pp}. To detect the generated OOK signals, the optical output was amplified using a Pr-doped fiber amplifier. A high-speed digital communication analyzer oscilloscope (Keysight DCA-X N1000A and N1046A) and a 100 GHz photodetector module (Fraunhofer HHI) were used for signal detection and analysis during the experiments. The measurement setup is shown in Fig. 2(a), and the measured eye patterns at 200 GBd are presented in Fig. 2(b) and 2(c). The eye patterns are compared without and with applying 8-tap feedforward equalization (FFE) within the digital communication analyzer. In Fig. 2(e), the bit error ratios (BER) at various symbol rates are shown. The estimated BERs without FFE remained below the threshold for soft-decision forward error correction (SH-FEC) even at a symbol rate as high as 200 GBd. With FFE post-processing, signal fidelity improved by more than two orders of magnitude. The EO response of the current PLZT modulator, driven by the Pockels effect, shows a linear correlation between electrical and optical power. When operating the PLZT modulator with PAM4 modulation at a symbol rate of 182 Gbit/s, BERs below the FEC threshold were achieved for a 2.0 km fiber transmission at a wavelength of 1310 nm. Notably, the EO modulation during these PAM4 signaling test was limited by the bandwidth and electric linearity of our testing equipment.

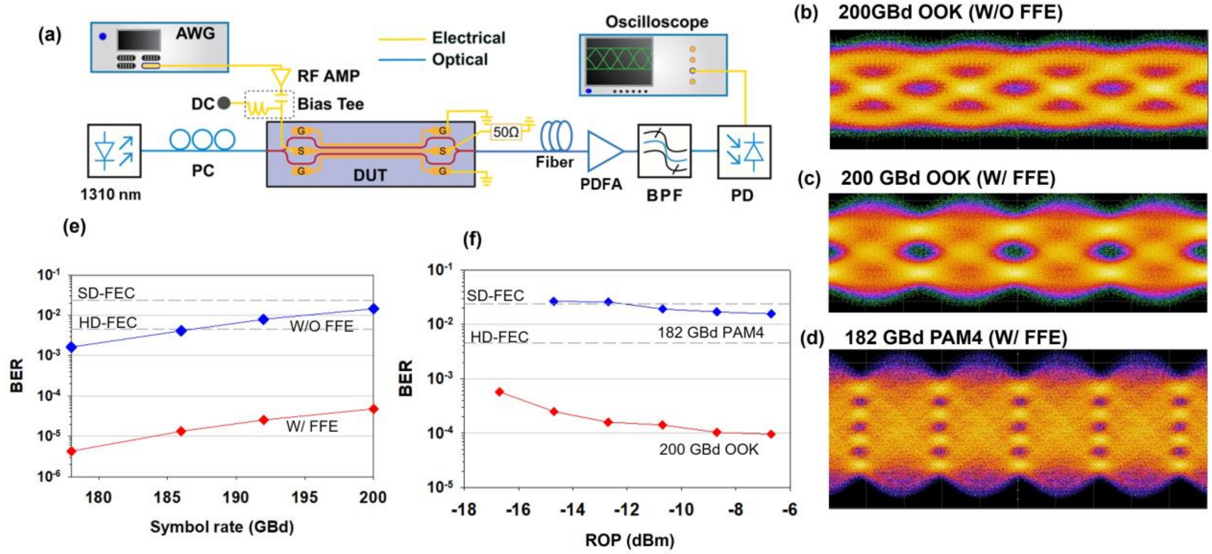

Fig. 2. High-speed signal generation by PLZT modulator. (a) Experimental setup for OOK and PAM4 transmissions. (b, c) Measured eye patterns obtained from OOK signals at 200 GBd without FEC and FFE (tap=8). (d) PAM4 signal at 182 GBd. (e) BER values at different OOK signals for symbol rates of 178-200 GBd. (f) O-band 2 km-long fiber transmission of 200 GBd OOK and 182 GBd PAM4.

3. Conclusion

We have demonstrated a high-speed OOK and PAM4 transmitter using PLZT waveguide modulators. The CPW line in the modulator was specifically designed and fabricated to enhance its bandwidth capability beyond 70 GHz. The strong EO effect of PLZT enables a particularly efficient and compact phase-shifter modulator, outperforming traditional crystal-based modulators. Error-free operation was achieved, with BERs below the FEC threshold. These results highlights the potential of PLZT modulator for reliable, efficient applications, offering both low driving-voltage and high bandwidth performance.

Acknowledgements

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