200 Gbit/s Transmitter Based on a Spin-on Ferroelectric Waveguide Modulator

Shiyoshi Yokoyama,[1, 2] Jiawei Mao, Futa Uemura, Hiromu Sato, and Guo-Wei Lu,[1,3]
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
3. Division of Computer Engineering, The University of Aizu, Fukushima 965-8580, Japan
E-mail: s_yokoyama@cm.kyushu-u.ac.jp

Abstract: We demonstrate a 200 Gbit/s PAM4 transmitter using a ferroelectric waveguide Mach-Zehnder modulator. It has BER below FEC threshold, drive voltage of 1.3 V_{pp}, and possible reliable operation.

1. Introduction

Recent progress of highly efficient and high-speed electro-optic (EO) modulator technology has received intensive research attentions in microwave photonics and fiber-optic networks. Among the different types of materials used in the modulator, the thin-film EO waveguide offers intrinsic advantages such as a large EO coefficient (r_{33}>100 pm/V), traveling wave modulation, and excellent compatibility with other materials and silicon-on-insulator substrates.

State-of-the-art efficient EO modulators rely on the phase modulation in various types of waveguide structures. Particularly, highlight of the polymer modulators can be impressed due to the advantages in fabrication allowed by the spin-on-preparation technique, which enables various waveguide structures on the silicon-on-insulator substrates. To date, spin-on polymer waveguide modulators have shown outstanding performance such as high data rate transmission, low-power consumption, and easy integration to other substrates. The progress makes the modulator device as one of the few possible solutions to realize over 120 Gbaud high-speed signalization [1]. It meets the critical demand in the emerging optical interconnects for short-reach and data center network. Despite being fast and efficient, reliability issue should be investigated, i.e., stabilities against high-temperature exposure, high-intensity optical signal, humidity exposure, and recycling thermal shock. While progress is significantly being made, careful consideration should be continued to fully address the industrial applications [1], [2]. The heterogeneous integration of strong EO coefficient materials such as ferroelectric epitaxial films is the alternative technique. We have recently prepared the heterogeneous thin-film $LnNbO_3$ and silicon waveguide modulator on insulator and showed the modulation bandwidth of 60 GHz and 200 Gbit/s PAM4 transmission with error-free signal accuracy [3]. However, limited EO activity due to the intrinsic material's Pockels effect (r_{33}=31 pm/V) made it difficult to further improve the driving voltage and smaller foot-print properties. The measured a half-wave voltage (V_π) was 3.2 V using the 8.0 mm-long phase shifter.

The ferroelectric oxides with perovskite phase such as PZT ($Pb[Zi, Ti]O_3$), PLZT($[Pb, La][Zi, Ti]O_3$) and BTO ($BaTiO_3$) exhibit large EO effects and promise to provide the modulator devices with lower driving voltage, lower cost, and more compact footprint properties. Reported EO coefficients are 67 pm/V (PZT) and 342 pm/V (BTO) [4]., [5]. Some of ferroelectric films-on-insulator (FFOI) waveguide modulators have shown great progress in developing the high-frequency modulation. However, achieved speeds of signal have not yet satisfied the values as

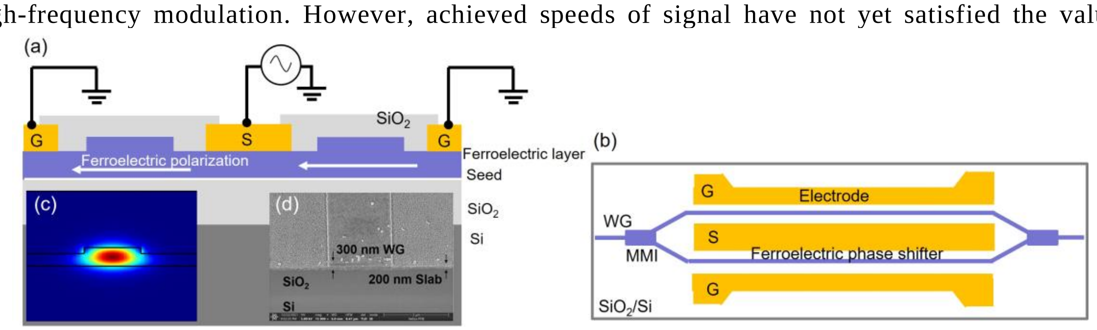


Fig. 1. Schematic diagrams of the FFOI waveguide modulator. (a) Sectional view of the phase shifter part. (b) Top view of the FFOI-MZI modulator. (c) Simulated optical modal distribution in TE mode. (d) The fabricated waveguide (SEM image).

expected in the current telecommunications technologies. There are several fabrication techniques to obtain FFOI, such as sputtering, pulse laser deposition, and molecular beam epitaxy. Among these methods, the spin-on technique via sol-gel chemical reaction is the quick and cost-effective way. In this study, we utilize the spin-on technique using precursor sol-gel solutions to obtain FFOI substrates and fabricate waveguide modulators. We measured effective EO coefficient of around 200 pm/V and half-wave voltage length ($V_{\pi}{\cdot}L$) product smaller than 1.0 V·cm in a Mach-Zehnder interferometer (MMI) waveguide modulator. The high-speed transmission measurements were performed up to 100 Gbaud, thus we measured 100 Gbit/s OOK and 200 Gbit/s PAM4 modulation signals.

2. High-speed FFOI waveguide modulator

2.1. Preparation of Epitaxially Grown FFOI waveguide

The preparation of the FFOI, for example PZT thin film, is as follow. The substrate is a commercial Si wafer with a 3-μm thick thermal oxide SiO_2. The surface of SiO_2/Si was chemically modified with an atomic seed layer, which promotes the crystallization of PZT in desired atomic lattice orientation. After deposition of the PZT film by the spin-coating technique, the substrate was heated using a rapid thermal annealing system at elevated temperatures under O_2 atmosphere. The spin-coating and rapid thermal annealing process were repeated several times to obtain a desired film thickness of 300 nm. We confirmed the out-of-plane x-ray diffraction (XRD) signal attributed to the (100) and (200) lattice plane, which means that the c-axis of the PZT crystal is perpendicular to the substrate while the a-axis and b-axis are distributed in the plane. The FFOI of PLZT and BTO can be prepared in similar way.

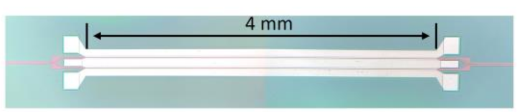
2.2. Waveguide Design and Fabrication

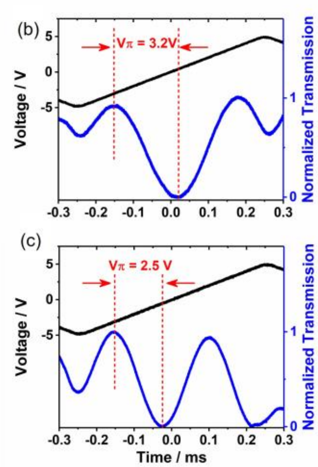
Figures 1(a) and (b) show the schematic diagrams of the phase shifter waveguide. The ridge waveguide structure is employed to have the single mode confinement. The simulated TE_0 mode distribution is shown in Fig. 1(c), where the optical modal is tightly confined in the PZT ridge due to the large refractive index contrast (n_{SiO2}=1.44, n_{PZT}=2.40). According to the designed structure to maintain the fundamental transverse (TE_0) mode, the waveguide was prepared as the ridge height and ridge width of 100 nm and 1.6 μm, respectively, as shown in the SEM picture of Fig. 1(d). We used the MMI splitters to prepare the MZI modulators. The phase shifter length is 4.0 mm (Fig. 2(a)). Electrodes are placed on both sides to apply a transverse modulated electric field, and the TE optical mode is preferred in this configuration. Final process is the DC electric poling, where we applied an electric field of 15 V/μm via the electrode microstrip lines at elevated temperatures.

2.3. Device Measurement

Since our PZT waveguide has a large transmission window, the modulator performed both C-band and O-band modulations. Figures 2(b) and (c) show the typical EO responses at the wavelength of 1550nm and 1310nm, respectively. We obtained the $V_{\pi}{\cdot}L$ products of 1.3 V·cm and 1.0 V·cm at 1550 nm and 1310 nm, respectively. It is interesting to compare the $V_{\pi}{\cdot}L$ of PLZT to PZT. As expected, PLZT modulator had smaller $V_{\pi}{\cdot}L$ properties due the larger effective EO coefficients. From the measure of $V_{\pi}{\cdot}L$, we estimate the effective EO coefficients of r_{eff}=86 pm/V and 198 pm/V for PZT and PLZT, respectively. Measure of details for BTO waveguide is under investigation.

(a)





(d) π-voltage length product ($V\pi \cdot L$) and r_{eff}-factor

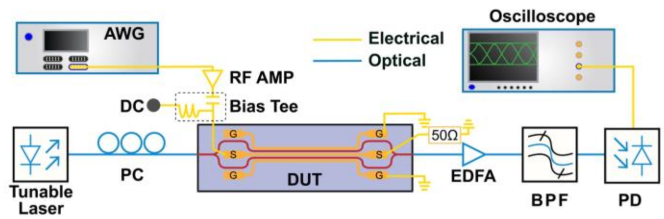
	PZT		PLZT	
Wavelength	1550 nm	1310 nm	1550 nm	1310 nm
$V_{\pi}{\cdot}L$	1.3 V·cm	1.0 V·cm	0.88 V·cm	0.48 V·cm
r_{eff}	86 pm/V		198 pm/V	

Fig. 2. Electro-optic properties of the FFOI waveguide modulator. (a) Photo picture of the fabricated MZI modulator. (b) The measured EO response at the wavelength of 1550 nm. (c) The measured EO response at the wavelength of 1310 nm. (d) EO properties of PZT and PLZT MZI modulators.

2.4. High speed modulation

Figure 3(a) represents the experimental setup for testing the high-speed serial data modulation. The CW light from the laser with the wavelength of 1550 nm is modulated by applying the electric driving singles. EO (Pockel’s effect) intensity modulators generally exhibit excellent EO linearity, which makes them suitable for multilevel modulation such as PAM4. To evaluate the feasibility of our modulator for high-data-rate operation, we applied an electrical signal and verified the modulation rate at data transfer speeds as high as 200 Gbit/s PAM4. A four-level electrical signal with a pattern length of 2^{11}-1 was produced using an arbitrary waveform generator (AWG, M8194A Keysight), as a digital-to-analog converter, at a sampling rate of 120 GSa/s. The electrical signal was amplified by a linear broadband amplifier (S804B, SHF) to 1.3 V_{pp}. The optical signal was received by a 70 GHz signal photodetector (PD XPDV3120R, Finisar) after passing through an Er-doped fiber amplifier (EDFA) and a band-pass filter (BPF), and then, fed to an oscilloscope (DCA86116C and UXR1102A, Keysight) for eye-pattern generation and BER analysis. Figure 3(b) show the measured eye patterns for OOK and PAM4. A clear eye opening was obtained after the standard offline process using the feed-forward equalizer and transmitter distortion eye closure quaternary. The BER analysis revealed low BERs of 2.5×10^{-4} for 160 Gbit/s and 7.1×10^{-4} for 200 Gbit/s PAM4.

(a)



(b)

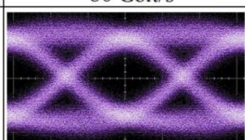
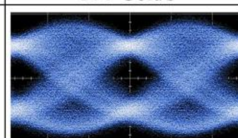
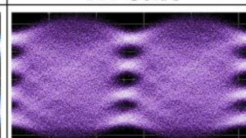
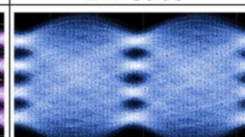
	80 Gbit/s	100 Gbit/s	160 Gbit/s	200 Gbit/s
Eye pattern				
BER	2.2×10^{-9}	3.7×10^{-7}	2.5×10^{-4}	7.1×10^{-4}

Fig. 3. High-speed signal generation by FFOI waveguide modulator (PZT). (a) Experimental setup for OOK and PAM4 transmissions. (b) Measured eye patterns and BERs.

3. Conclusion

We have demonstrated a 100 Gbit/s OOK and 200 Gbit/s PAM4 transmitter using FFOI waveguide modulators. The thin ferroelectric oxide films were prepared on the standard SiO_2/Si wafers. Thus, a wide variety of waveguide structures can be prepared to construct the designed waveguide modulator. The measured effective EO coefficient of our modulator was increased up to 200 pm/V, which enabled to prepare a relatively short phase-shifter modulator. Error-free operation was successfully demonstrated and confirmed the BER below FEC threshold. Since the ferroelectric oxides used in the fabricated modulators have chemical and physical stabilities, the measured results show considerable promise for the reliable efficient modulator applications with low driving-voltage and high bandwidths.

Acknowledgements

This work was supported in part by MEXT under Grant JP19H00770; in part by JST under Grant JPMJMS2063; in part by NICT under Grand 02101.

References

[1] G-W. Lu, et al., “High-temperature-resistant silicon-polymer hybrid modulator operating at up to 200 Gbit s^{-1} for energy-efficient datacentres and harsh-environment applications,” Nat. Comm., **11**, 4224 (2020).

[2] H. Sato, et al., “A 100 Gbaud on-off-keying silicon-polymer hybrid modulator operating at up to 110°C,” IEEE Phot. Tech. Lett., **33**, 1507 (2021)

[3] J. Mao, et al., “Heterogeneous silicon-on-lithium niobate electro-optic modulator for 100-Gbaud modulation,” APL Photonics (2022).

[4] K. Alexander, et al., “Nnonophotonic Pockels modulators on a silicon nitride platform,” Nat. Comm., **9**, 3444 (2018).

[5] S. Abel, et al., “Large Pockels effect in micro- and nanostructures barium titanate integrated on silicon,” Nat. Mater., **18**, 42 (2019).