Thin-Film Lithium Niobate Modulator for a Flat Frequency-Response over 110 GHz Bandwidth with Integrated Electro-Optic Frequency-Domain Equalizer

Yuya Yamaguchi[1], Pham Tien Dat[1], Naokatsu Yamamoto[1], Kouichi Akahane[1], Atsushi Kanno[1,2], Tetsuya Kawanishi[1,3]
[1]National Institute of Information and Communications Technology, 4-2-1, Nukuikitamachi, Koganei, Tokyo, Japan
[2]Nagoya Institute of Technology, Gokiso-cho, showa-ku, Nagoya, Aichi, Japan
[3]Waseda University, 3-4-1, Okubo, Shinjuku, Tokyo, Japan
yamaguchi@nict.go.jp

Abstract: We demonstrated an optical modulator with an ultra-flat frequency-response over 110 GHz by using a thin-film lithium niobate platform and the integration of an electro-optic frequency-domain equalizer. The half-wave voltage was 2.4 V, and we measured an extinction ratio exceeding 40 dB.

1. Introduction

High baud-rate modulation serves as a solution to achieving substantial data transmission capacity without increasing the number of parallelized channels [1, 2]. While the complexity of the setup can remain relatively straightforward, the challenge lies in ensuring that the components constituting the transceiver function effectively across a wide bandwidth. Optical modulators play a crucial role in the transmitter by converting electrical signal into optical ones. These modulators, alongside digital-to-analog (DAC) converters acting as signal sources, are dominant components imposing limitations on the system's bandwidth. Although frequency-domain equalization through digital signal processing can mitigate the frequency dependence of these components, it necessitates high-performance DACs with characteristics like high resolution, broad bandwidth, high output power in high-frequency domains. In practice, the performance of DACs is constrained by inherent limitations. Therefore, improving the performance of the modulator is crucial to maximize the capacity of the communication links.

Lithium niobate (LN) is a prominent material for optical modulators. Notably, LN exhibits substantial Pockels effect, endowing it with capability for highly efficient and linear modulation. Moreover, its high transparency in the C-band wavelength underscore its potential for low-loss modulators. However, its high dielectric constant poses a challenge for achieving large bandwidth in a traveling-wave configuration. To address this limitation, a structural optimization was proposed in the form of thin-film LN on insulator. This innovation offers a solution to mitigate the impact of the high dielectric constant, leading to the development of modulators with large bandwidth and low half-wave voltage requirements [3–6]. Additionally, we introduced an electro-optic frequency-domain equalizer (EOFDE) that has the capacity to broaden the 3-dB bandwidth, taking a circuit diagram approach. As a previous work, we demonstrated a 3-dB bandwidth exceeding 110 GHz by integrating the EOFDE with a titanium-diffused lithium niobate modulator [7]. In this paper, we present an ultra-flat frequency response extending over 110 GHz by using a fabricated thin-film LN modulator integrated with EOFDE.

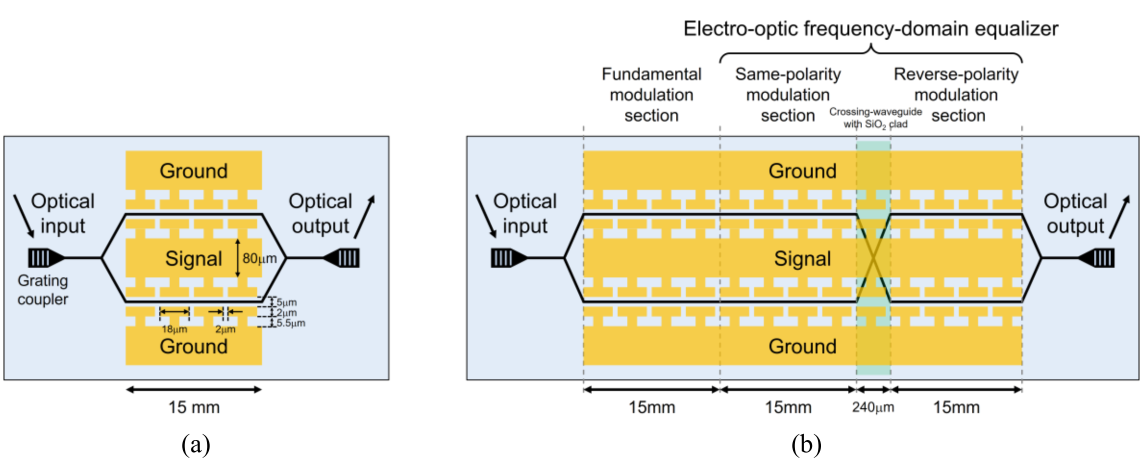


Fig. 1. Structure of thin-film LN modulator without EOFDE (a) and integrated with EOFDE (b)

2. Device Design and Fabrication

The structure of the fabricated devices is shown in Fig. 1. To compare the impact of EOFDE integration, we fabricated modulators integrated with and without the EOFDE. The device consists of grating couplers, 1×2 MMI couplers for Mach-Zehnder (MZ) interferometer, and a capacity-loaded traveling-wave electrode (CLTWE), among other components. The CLTWE was employed to achieve velocity matching by controlling the effective refractive index for modulating microwaves. In an effort to reduce the half-wave voltage, the gap of the CLTWE was set at 5 µm. Additionally, we designed the electrode to be 1.2 µm thick to minimize microwave losses and enhance the 3-dB bandwidth. The cross-sectional structure at modulation section is summarized in Fig. 2. The length of the modulator without EOFDE was 25 mm in total, which included a modulation section of 15 mm. In the modulator integrated with EOFDE, the fundamental modulation section, same-polarity modulation section, and reverse-polarity modulation section each spanned 15 mm, resulting in a total electrode length of approximately 45 mm.

Regarding the fabrication process, we prepared a wafer comprising an 800-nm x-cut LN layer on a SiO_2 (Quartz) substrate. Optical rib-waveguides were formed through electron-beam lithography and dry etching. Subsequently, we sputtered an SiO_2 buffer layer in areas where the optical waveguides made contact with the electrodes to prevent any optical absorptions. The electrode was formed via a lift-off process that included both photo lithography and electron-beam evaporation of gold. Finally, an overclad layer with an optimized thickness was deposited to ensure precise velocity matching. The picture of the fabricated device is shown in Fig. 3.

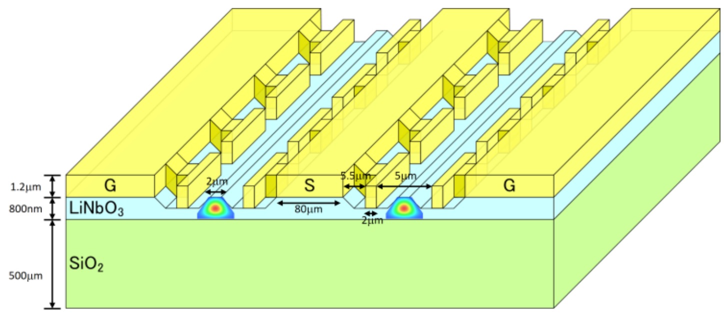


Fig. 2. Cross-sectional structure at modulation section

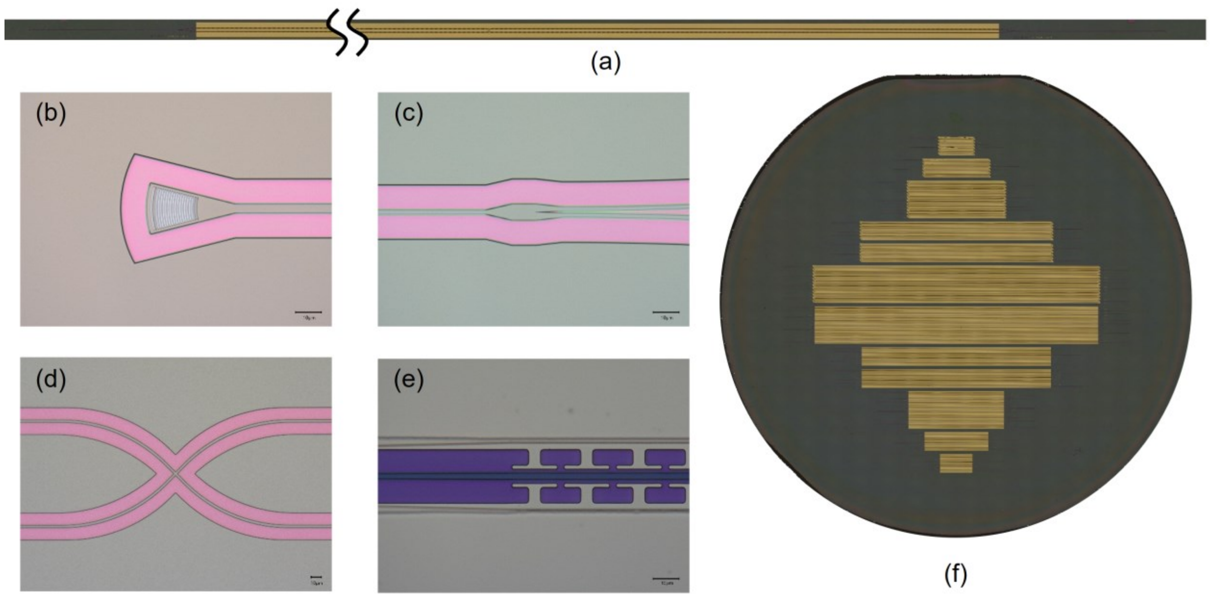
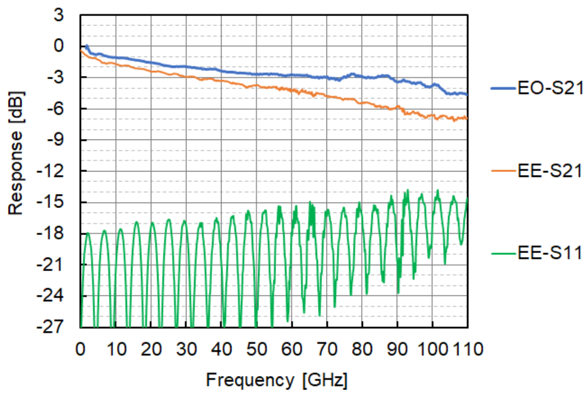


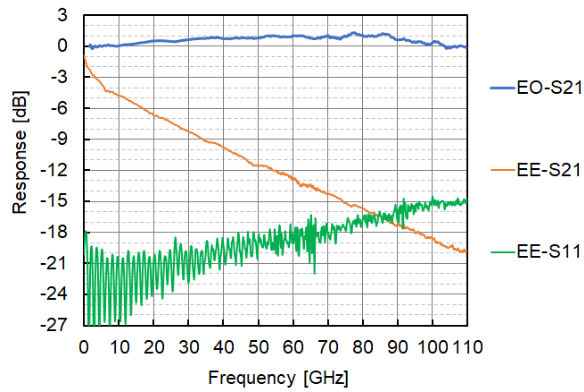
Fig. 3. Pictures of the fabricated device: (a) MZM chip, (b) grating coupler, (c) 1×2 MMI coupler, (d) cross-waveguide in EOFDE, (e) modulation section, (f) wafer after cleanroom process

3. Performance Evaluation

We used angle-polished fibers for optical input and output, connecting them to the grating coupler, and utilized 150-µm-pitch GSG RF-probes for electrical signaling. The optical coupling loss at the grating coupler was 8.2 dB/facet. We measured the performance of both the standard MZ modulator, featuring a 15-mm modulation length, and the modulator integrated with EOFDE. For the standard MZ modulator, the optical loss was 18.5 dB, with an estimated



(a)



(b)

Fig. 4. Measured electro-optic S21, electrical-electrical S21 and S11 of the modulator without EOFDE (a) and integrated with EOFDE (b)

16.4 dB attributed to coupling loss and an additional 2.1 dB arising from on-chip loss. The half-wave voltage was 2.4 V. The electro-optic S_{21} (EO-S21), electrical transmittance S_{21} (EE-S21), and electrical reflectance S_{11} (EE-S11) are shown in Fig. 4 (a). Owing to the low electrical loss of the thick CLTWE, the 3-dB EO bandwidth measured approximately 70 GHz. Regarding the modulator integrated with EOFDE, the optical loss was 19.6 dB, with 16.4 dB attributed to coupling loss and 3.2 dB from on-chip loss. The half-wave voltage remained consistent at 2.4 V. The optical loss increase resulting from the integration of EOFDE was found to be small, estimated at just 1.1 dB in the comparative analysis. The enhancement of frequency response by the EOFDE was experimentally confirmed, as shown in Fig. 4 (b). Notably, the measured EO-S21 remained flat within a 1.5-dB range over 110 GHz bandwidth, underscoring the efficacy of the EOFDE. Furthermore, when we examined the modulation curve of the MZ modulator at low frequencies, the results, as depicted in Fig. 5, closely aligned with the theoretical sinusoidal response, and the extinction ratio was approximately 50 dB.

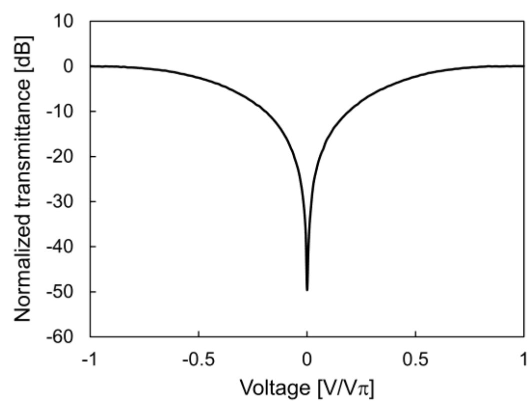


Fig. 5. Modulation curve measured at low frequency

4. Conclusion

An ultra-flat frequency-response modulator was demonstrated using the thin-film LN and EOFDE integration technologies. The measured 3-dB EO bandwidth extending over 110 GHz holds significant promise for its application in next-generation optical fiber communication, potentially supporting modulation rates exceeding 200 Gbaud.

Acknowledgement

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References

[1] G. Raybon et al., Journal of Lightwave Technology, **32**, 824-831, 2014.
[2] X. Chen et al., Journal of Lightwave Technology, **35**, 411-417, 2017.
[3] G. Poberaj et al., Laser & Photonics Reviews, **6,** 488-503, 2012.
[4] V. E. Stenger et al., in Proc. ECOC 2012, Tu.3.E.4.
[5] P. Kharel et al., Optica, **8**, 357-363, 2021.
[6] M. Xu et al., Optica, **9**, 61-62, 2022.
[7] Y. Yamaguchi et al., Journal of Lightwave Technology, **41**, 3883-3891, 2023.