European Conference on Optical Communication (ECOC) 2022 © Optica Publishing Group 2022

Low-Loss Ti-diffused $LiNbO_3$ Modulator Integrated with Electro-Optic Frequency-Domain Equalizer for High Bandwidth Exceeding 110 GHz

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Abstract *We propose and demonstrate a low-loss and high-bandwidth lithium niobate modulator integrated with an electro-optic frequency-domain equalizer. The fabricated Ti-diffused lithium niobate modulator has a low optical loss of 5.4 dB, low half-wave voltage of 3.7 V, and high bandwidth exceeding 110 GHz.*

Introduction

The bandwidth of an optical modulator is a important factor that limits the data capacity per channel of optical fiber links. Lithium niobate (LN) modulators have been used in digital coherent links because of their low optical loss and low frequency-chirping modulation. However, the bandwidth of conventional LN modulators is limited to less than 50 GHz. To widen the bandwidth of the modulator, a layered structure, such as a thin-film active layer with a supporting substrate, has been proposed [1]. Owing to the advances in precise wafer-bonding, such as smart-cut or ion-slice, and chemical-mechanical polishing technology, thin-film LN wafers with an LN layer thickness of less than 1 μm are becoming popular in the research area of nonlinear optics, which includes LN modulators [2]. In recent years, thin-film LN modulators with low half-wave voltage and high bandwidth have been reported as a technical approach to optimize both the materials and structure of a device [2-5]. However, thin-film LN remains problematic because of its large optical loss, especially the coupling loss from the device chip to the optical fiber, and the cost of fabrication for industry.

In this study, a high-bandwidth modulator using the photonic-integrated-circuit approach is demonstrated. We propose an electro-optic frequency-domain equalizer (EO equalizer) as a novel method to design the frequency dependence of the modulator response, as shown in Fig. 1. The EO equalizer can be integrated with a Mach-Zehnder (MZ) modulator by modifying the optical waveguides and electrodes, such as using waveguide-crossing. In the case of an x-cut LN modulator with a coplanar electrode for a push-pull drive, the modulation polarity can be reversed with a waveguide-crossing structure.

Traveling-wave Optical Modulator

A traveling-wave modulator is a structure typically used for high-speed modulation. The bandwidth of lumped-electrode modulators is limited by the capacitance of the electrode, whereas the bandwidth of traveling-wave

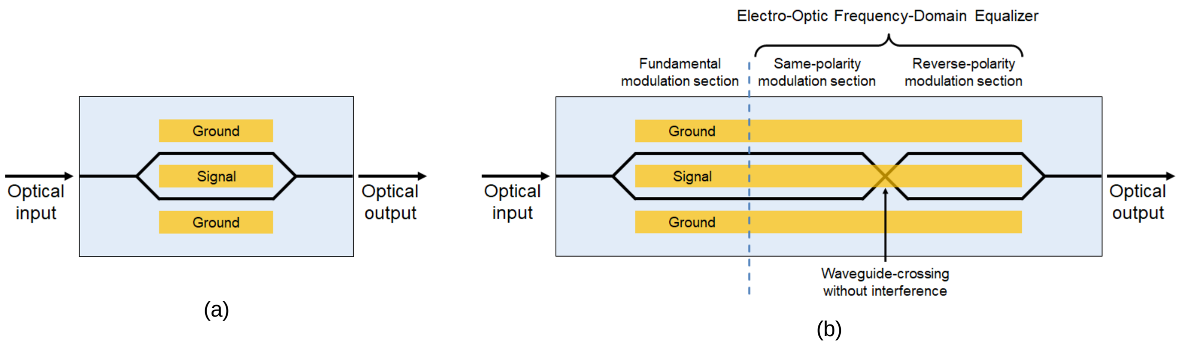

Fig. 1: (a) Conventional $LiNbO_3$ Mach-Zehnder modulator, (b) proposed Mach-Zehnder modulator integrated with electro-optic frequency-domain equalizer

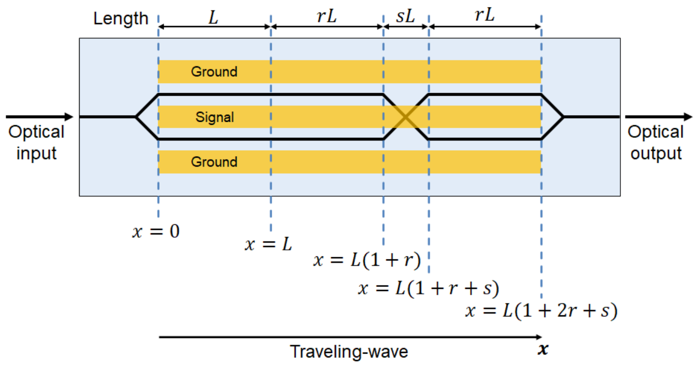

Fig. 2: Structural modelling and electrical signal propagation of a traveling-wave Mach-Zehnder modulator integrated with EO equalizer.

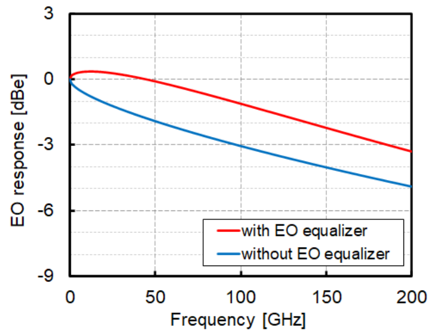

Fig. 3: Numerical calculation of the frequency response of a Mach-Zehnder modulator with and without an EO equalizer.

modulators depends on both the velocity matching and electrical propagation loss of the electrode. The frequency dependence of the modulator caused by the velocity mismatch can be designed to be sufficiently small such that it is negligible by ensuring the velocities of the two waves correspond accurately. Thus, the bandwidth of the traveling-wave modulator is limited by the electrical propagation loss under the velocity-matching condition. The electrical loss consists of conduction loss of the metal electrode and dielectric loss of the dielectric material, including the substrate. Because both of these types of loss increase at higher frequencies, the effective applied voltage at high frequencies is lower than that at low frequencies. Thus, the frequency response of the traveling-wave modulator is determined by the electrical propagation loss.

Electro-Optic Frequency-Domain Equalizer

An EO equalizer can be used to design and tailor the frequency response of traveling-wave modulators. The structure and signal propagation are shown in Fig. 2 to explain the operation principle of the EO equalizer. Here, we consider a voltage signal propagating on a traveling-wave electrode.

$$V(x) = V_0 \exp\{-\alpha_{ele}(f)x\} \tag{1}$$

where V_0 is the input voltage, and α_{ele} is the electrical loss coefficient.

The proposed MZ modulator with the EO equalizer has four modulation sections, as shown in Fig. 2: a fundamental modulation section with a length of L similar to conventional modulators, a same-polarity modulation section with a length of rL, a non-modulation section with a length of sL for polarity inversion, and a reverse-polarity modulation section with a length of rL. By comparing the induced optical phase change of a conventional MZ modulator with a length of L to that of an MZ modulator with the EO equalizer shown in Fig. 2 (under the condition that they have the same voltage signal input), we define the electro-optic relative gain G_{Eq} as follows.

$$G_{Eq}(f) \equiv \left| \frac{\phi_{MZ\ with\ Eq}}{\phi_{MZ}} \right|^2 = \left| \frac{\int_0^{L(1+r)} V(x)\,dx - \int_{L(1+r+s)}^{L(1+2r+s)} V(x)\,dx}{\int_0^L V(x)\,dx} \right|^2 \tag{2}$$

Here, ϕ_{MZ} and $\phi_{MZ\ with\ Eq}$ are the phase changes induced in a conventional MZ modulator and in an MZ modulator with an EO equalizer. Further, r and s indicate the ratio of the length of the fundamental modulation section to the reverse-polarity modulation section and the non-modulation section, respectively. For example, when $r = 1$, $s = 0$, and f is the frequency of the electro-optic 3-dB bandwidth of the MZ modulator without the EO equalizer, then G_{Eq} is calculated to be 1.9 dB. An example of the numerically calculated frequency response is shown in Fig. 3. The frequency response of the conventional MZ modulator without the EO equalizer was calculated using the electrical loss in our previous study [7]. Previously [7], the effective length of the modulator was 5 cm, but the result shown in Fig. 3 was estimated for a length of 1.9 cm. The conventional modulator has a 3-dB bandwidth of approximately 95 GHz, whereas for the modulator with the integrated EO equalizer, the response at 95 GHz improves by 1.9 dB. Thus, the EO equalizer potentially enables the frequency response of the modulator to be tailored by changing both the circuit model and parameters such as the ratio of the length of each section to the electrical loss. Even though the waveguide-crossing-type EO equalizer is explained in detail, several other types of EO equalizers that operate using a 180°-bending waveguide, ferroelectric-domain inversion, polarity-managed capacity-loaded electrode, etc., also exist, as shown in Fig. 4.

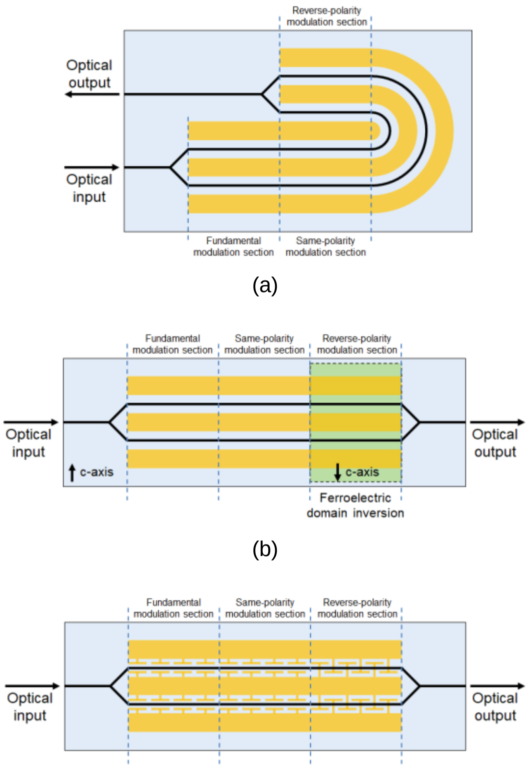

Fig. 4: Different types of EO equalizers: (a) bending waveguide type, (b) ferroelectric-domain inversion type, (c) polarity-managed capacity-loaded electrode type

Experimental Demonstration

We fabricated a Ti-diffused $LiNbO_3$ modulator with an EO equalizer for an experimental demonstration. The device structures are shown in Fig. 5 (a). The substrate was an x-cut LN, and the Mach-Zehnder-interferometer optical waveguide was formed by the thermal diffusion of Ti. The traveling-wave electrode was designed to be more than 20 μm thick to decrease electrical propagation loss. The LN substrate was bonded to a handle wafer after polishing the reverse side to suppress conversion of the electrical mode to a substrate mode at specific frequencies. The length of the fundamental modulation section was 1.9 cm. The device is designed such that $r = 1$ and $s = 1.4$.

The fabricated chip is shown in Fig. 5(b). The optical insertion loss including the on-chip propagation loss and fiber-coupling loss was 5.4 dB, and the half-wave voltage at the direct current was 3.7 V. The small optical loss is attributed to both the low-loss Ti-diffused waveguides and low coupling loss between the waveguides and standard single-mode fibers. Because the measured loss of 5.4 dB is the value resulting from the active alignment of the fiber with the direct butt coupling, we expect the loss to be reduced by using an anti-reflection coating and index-matched fiber bonding. The measured frequency response is shown in Fig. 5(c). The electro-optic S_{21} was significantly broad, and the response at 110 GHz was −0.4 dB. The measured response is in good agreement with the designed values calculated from the measured electrical S_{21} and EO equalizer model.

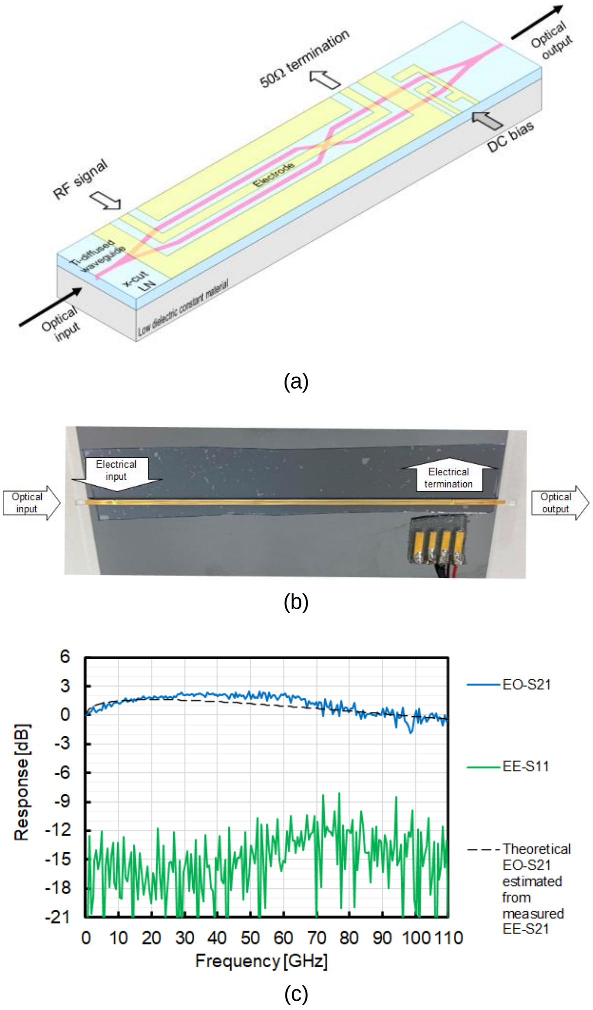

Fig. 5: (a) Structure of Ti-diffused $LiNbO_3$ modulator with EO equalizer, (b) fabricated chip, (c) measured frequency response of the modulator

Conclusion

We demonstrated a high-bandwidth modulator by integrating an EO equalizer. The low-loss high-bandwidth modulator was realized by using the EO equalizer in combination with a Ti-diffused LN modulator. The EO equalizer could potentially be applied not only to Ti-diffused LN modulators but also to other types of modulators such as thin-film LN modulators for ultra-high bandwidth.

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