Advances in Ultra-Wideband $LiNbO_3$ Thin-Film Modulators

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Abstract: We review recent advances and design considerations for thin-film lithium niobate (TFLN) modulators with ultra-wide bandwidth and CMOS-compatible voltage, and we discuss how to approach the limits of the electro-optic bandwidth of the TFLN-based modulators. © 2022 The Author(s)

1. Introduction

Network traffic is increasing at an alarming speed, largely driven by bandwidth-hungry applications such as 5G networks, Internet-to-Things (IoT) devices, video streaming, and cloud-based services [1]. To meet the ever-growing demand, cost-efficient optical networks are required for supporting high-speed optical links. High-performance electro-optic modulators are the critical building blocks in high-speed optical links, and they encode high-speed electrical information into an optical carrier with high fidelity. To enable cost-efficient and high-speed optical links, efforts are made to minimize the number of electro-optic (EO) interfaces of parallel lanes, and this is where high-symbol-rate transmission occurs. Under this scenario, a single optical modulator is used to encode high-symbol-rate electrical signals into an optical carrier. Therefore, the bandwidth of future EO modulators plays a crucial role and is expected to exceed 100 GHz. Meanwhile, a small footprint and low driving voltage of the EO modulators are necessary to match the CMOS electronic driving circuitry.

LN external modulators have been widely used in long-haul communication systems. The commercial LN modulator has achieved tremendous success mainly owing to its strong linear (Pockels) EO coefficient (r_{33} = 30.8 pm/V), femtosecond timescale EO response, and chirp-free operation. Furthermore, the low absorption loss (~0.17%/cm at 1.32 μm) [2] and the transparency range (0.4– 5.5 μm) [3] contribute to its success. However, traditional LN modulators are based on ion-diffused or proton-exchange optical waveguides on bulk LN crystals [4]. Such weak-confined waveguides require electrodes to be placed away from them to achieve low metal absorption losses, and thus, low modulation efficiency (typically >10 Vcm). Therefore, traditional LN modulators require a long modulation region (at least 10 cm) to achieve a sub-1V V_π. Moreover, the EO bandwidth runs into a bottleneck (~35 GHz) owing to the high RF loss from the long electrodes. Thin-film lithium niobate (TFLN) platform breaks the deadlock and takes the performance of the modulator to a new level. A critical step in improving the modulation performance is the fabrication of low-loss, highly-confined waveguides in TFLN. Thus, the electrodes can be placed very close to the edge of the waveguides without introducing additional metal absorption losses. Therefore, the interaction between the electric and optical fields is significantly enhanced compared to the legacy LN modulator. Most recently, researchers have demonstrated highly confined submicron waveguides by electron-beam lithography (EBL).

In this paper, we will review the state-of-the-art TFLN modulators that provide an ultrawide bandwidth, and highlight the design advancement in the microwave, optical, and device structure.

2. State-of-the-art and design considerations of ultra-wideband TFLN-based modulators

A remarkable increase in bandwidth in the TFLN platform has been reported in the last three years [5-8]. Low-loss, energy-efficient, high-bandwidth TFLN-based modulators have shown ultra-high symbol rates and net rates both in intensity-modulated direct-detection (IM-DD) and coherent transmission systems. In [9], V_π of 1.4 V and EO bandwidth of 45 GHz were achieved simultaneously using an integrated Mach-Zehnder modulator (MZM) with regular traveling-wave electrode (TWE), according to a BW/V_π of 32 GHz/V, which significantly improved compared to the commercial LN (<10 GHz/V). With a similar device configuration, Yu et al. experimentally demonstrated a hard-decision forward error correction (HD-FEC) of 220 Gbit/s (110 Gbaud PAM-4) [10]. Advanced LN IQ modulators have been demonstrated in [11]. The device demonstrated the lowest on-chip loss (<1.8 dB) among the presented in-phase quadrature (IQ) modulators. The drive voltage was 1.9 V and the EO bandwidth was 48 GHz for a 13-mm device, and these values were 3.1 V and > 67 GHz for a 7.5-mm device. 80 Gbaud error-free QPSK generation, 110 Gbaud QPSK generation, and 80 Gbaud 16 quadrature amplitude modulation (QAM) generation (320 Gbit/s) with a bit-error rate (BER) well below the soft-decision forward error correction (SD-FEC, 4×10^{-2}) was demonstrated.

We must highlight that the keys to achieving ultra-wide modulation bandwidth in the traveling-wave scheme include (a) low microwave propagation loss, (b) propagation speed matching between optical waves and microwaves, and (c) impedance matching among the modulator, the electrical system, and the terminator. Regarding regular traveling-wave electrodes (TWEs), we can realize perfect velocity matching and decent impedance matching through optimization, but the microwave loss is difficult to be further reduced. Thus, it is critical to lower per-unit-length RF attenuation and shorten modulation length, meanwhile maintaining targeting at a CMOS-compatible driving voltage.

The dominant microwave loss (α_m) includes dielectric loss and conductor loss. Dielectric loss is closely related to the substrate material, and conductor loss is highly dependent on electrode design. A delicate TWE scheme that can drastically reduce conductor loss without sacrificing velocity matching and modulation efficiency is the so-called capacitive-loaded CPW (CL-TWE). The center conductor gap and width of the CL-TWEs are much larger than those of the regular CPW, resulting in less current crowding and a significant reduction in αc. Moreover, the protruding periodic T-rails help ensure a high modulation efficiency. On the other hand, replacing the silicon substrate with the air can offer much lower permittivity and intrinsic loss, resulting in a lower dielectric loss. In [12], the microwave loss is greatly reduced to 0.24 dB cm^{-1} $GHz^{-1/2}$ owing to substrate removal. and perfect velocity matching can realize by controlling the depth of the air gap. The fabricated device features a half-wave voltage (V_π) of 1V and an electro-optic response with a 1.4 dB roll-off at 50 GHz at the O-band (Fig. 1. (a)).

Most recently, TFLN-based modulators with low drive voltages and bandwidths beyond 100 GHz have been demonstrated with CL-TWEs and quartz substrates [13]. As shown in Fig. 1. (b), a TFLN-based dual-polarization in-phase quadrature (DP-IQ) integrated with an on-chip polarization rotator and combiner (PRC) has been demonstrated. The device adopted the optimized 23.5-mm-long CL-TWEs for CMOS-level voltage and 110-GHz bandwidth. The high-performance device DP-IQ modulator allows for a record net bitrate of up to 1.96 Tb/s and ultra-low power consumption (1.04 fJ/bit) using a 130 Gbaud probabilistic constellation shaping (PCS-) 400QAM.

For a CMOS-level driving voltage (< 1 V), the TFLN modulator requires a modulation length of 1–2 cm, which is difficult to achieve owing to the fixed r_{33} coefficient. Devices are extremely long to be practically adapted to a compact transceiver package, such as QSFP-DD (quad small form-factor pluggable double density). By employing meander TWE and optical waveguides folded LNOI-based MZM's were found to be effective solutions to reduce the device length while maintaining the overall performance [14]. Most recently, Y. Xue, et al [15] proposed a ring-assisted MZM, featuring a high-quality factor (7.7×10^5), nearly flat EO response up to 67 GHz, and a compact footprint (3.4 mm × 0.7 mm) (Fig. 2). This coupling scheme breaks the photon lifetime limit of the conventional resonant modulator.

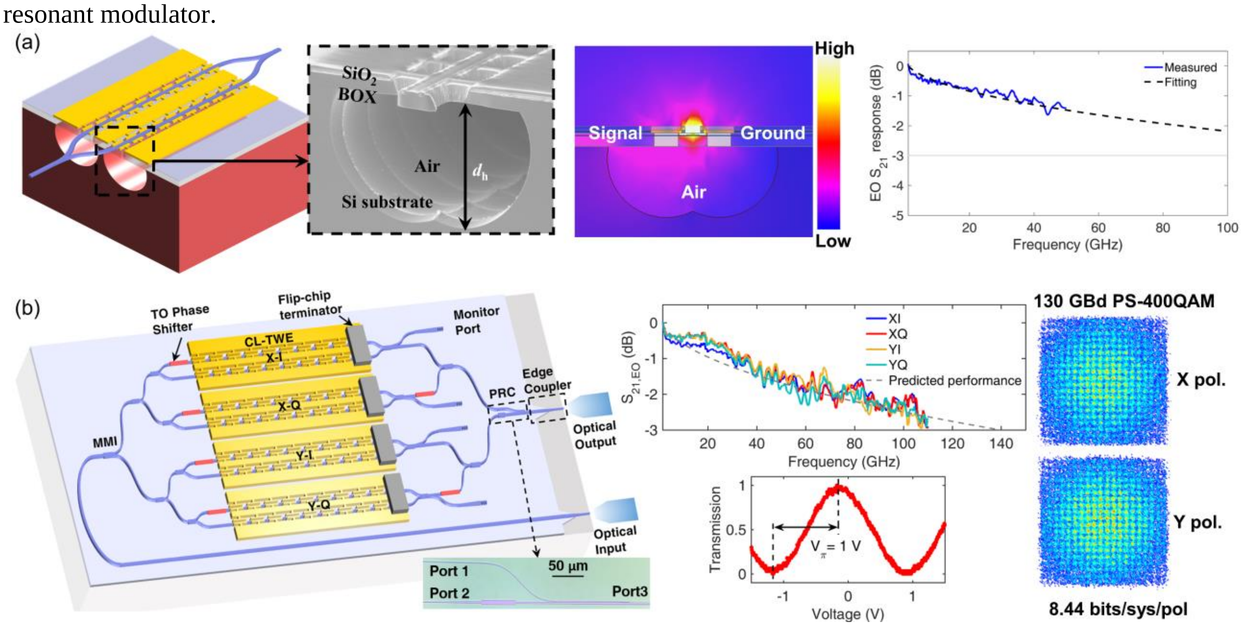

Fig. 1. (a) High-performance MZM based on LN-on-Silicon platform and silicon removal technology [12]. (b) Dual polarization IQ modulator based on LN-on-quartz platform for Tb/s transmission [13].

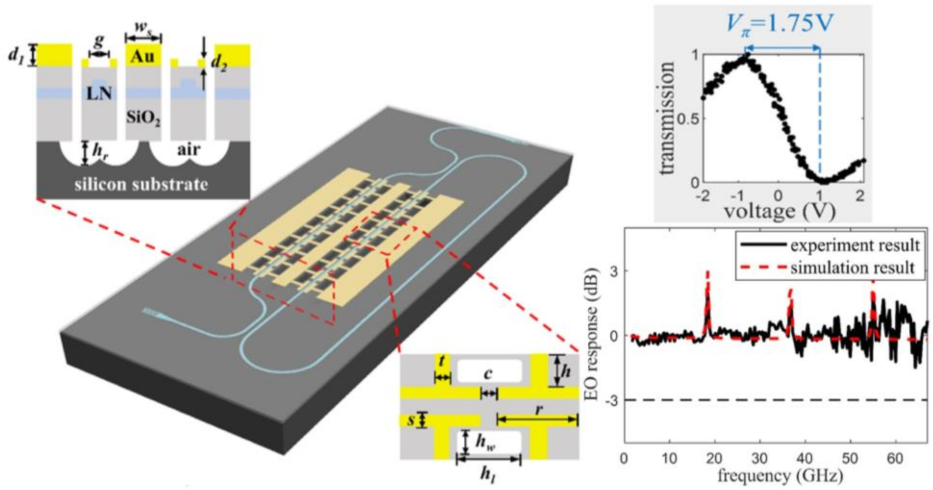

Fig. 2. A ring-assisted TFLN-based MZM feature high Q-factor and wide bandwidth [15].

3. Conclusion and future outlook

TFLN-based EO modulators have verified at least 110 GHz bandwidth and ultra-high speed driverless modulation, making short-reach transmission of a single carrier of 2 Tb/s more practical. Owing to the coefficient of LN is not large enough, the modulation length needs 1-2 cm for a low driving voltage in traveling-wave schemes. Few delicate structures were proposed for a compact footprint and even higher performance. The key to breaking the bandwidth-voltage limit is realizing a more efficient and stronger EO interaction. An alternative is to slow down light waves and microwaves to the same speed, along with new challenges like how to realize less wavelength- and temperature-dependent EO modulation.

4. References.

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