A Highly Compact Thin-film Lithium Niobate Modulator with Low Half-wave Voltage

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Abstract: Meandered thin-film lithium niobate modulators with capacitively loaded travelling-wave electrodes are demonstrated. Interdigitated T-rails are employed for reversed electric field, resulting in 1.08 V half-wave voltage and 3-dB bandwidth beyond 50 GHz for 8-mm-long devices.

1. Introduction

High-speed electro-optic modulators are key components in optical communications and interconnections. The explosive growth of data traffic in the 5G network and beyond has put forward more stringent requirements for modulation bandwidth and power consumption of modulators. Lithium niobate has been considered an ideal electro-optic material with large electro-optic coefficient. However, traditional lithium niobate modulators require a large footprint of serval centimeters for reduced half-wave voltage V_π [1,2]. The high confinement optical waveguide formed by dry etching of thin film lithium niobate (TFLN) allows for reduced electrode gap and half-wave voltage length product [3-10], and large modulation bandwidth is also guaranteed by adjusting the thickness of buried silica bonding layer for velocity matching.

In order to realize directly driving by CMOS circuits, V_π has been targeted to around 1 V, which ensures ultra-low power consumption and operation without an electrical amplifier [8]. Modulator with V_π as low as 1.3 V has been proposed [6], though at the expense of a long modulation length of 2.4 cm, which is not conducive to high-density integration and compact transceiver package. Folded TFLN modulators are expected to reduce V_π while maintaining a small device footprint by multiplying the modulation length. However, phase modulation will be offset by the reversed electric field after folding the electrodes. Poled TFLN waveguide [7] and heterogeneous crossed silicon waveguide [8] are implemented to accumulate the phase shift, but they suffer from complicated device fabrication procedure, as additional poling or heterogeneous integration processes are involved.

Here we report a highly compact meandered TFLN modulator based on specially designed capacitively loaded travelling-wave electrodes (CL-TWEs). CL-TWEs have proved efficient in breaking the voltage-bandwidth limits in TFLN modulators [9,10]. Here we further expand its application in the meandered TFLN modulator with interdigitated T-rails to ensure reversed electric field for light travelling in the opposite direction, thus allowing cumulated phase modulation in the folded waveguides. A highly compact meandered TFLN modulator with a footprint less than $8 \times 1.3\ \mathrm{mm}^2$ has demonstrated a half-wave voltage as low as 1.08 V, and 3-dB electro-optic bandwidth over 50 GHz.

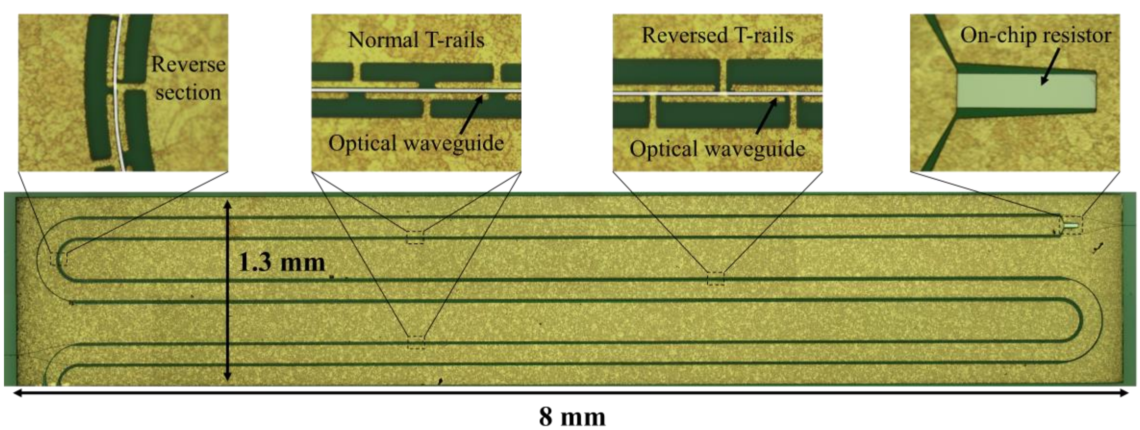

Fig.1. Microscope photos of the fabricated TFLN modulator

2. Device structure

The proposed modulator is shown in Fig. 1, which is based on 600 nm X-cut TFLN on quartz substrate. The adoption of quartz substrate and CL-TWEs helps reduce microwave loss and achieve velocity matching for improved voltage-bandwidth performance [9,10].

The width and the height of the TFLN ridge waveguide are designed to be 1 μm and 200 nm, respectively. A 600-nm-thick silica layer is deposited on the partially-etched TFLN waveguides, so as to suppress the optical absorption loss caused by the narrow-gap T-rails and the electrodes over the entering and exiting Y-branches. T-rails with a narrow gap of 2 μm are placed on both sides of the TFLN waveguides for reduced voltage length product, and the resulting optical absorption loss is estimated to be under 0.05 dB/cm. On the other hand, the optical absorption due to the cross top electrodes over the Y-branches is under 0.5 dB/cm.

As shown in Fig. 1, the modulator consists of three 7-mm-long straight modulation sections, connected by curved waveguides. By employing interdigitated T-rails in the central modulation segment, the electric field in TFLN waveguide remains the same direction after folding, thus leading to cumulated phase shift. Based on the calculated overlap between the electric and optical fields, the voltage-length product is estimated to be 2 V·cm assuming 90% T-rail duty cycle.

The CL-TWEs are optimized for broadband operation. The period of the T-rails is set to 50 μm to extend the microwave cut-off frequency [10]. The signal electrode width and unloaded electrode gap are adjusted to ensure velocity matching with the light wave while maintaining a characteristic impedance close to 50 Ω, and their optimized values are taken to be 120 μm and 30 μm for central modulation segment with reversed T-rails, 130 μm and 20 μm for modulation segments on both sides, respectively. Such a wide signal electrode helps reduce ohmic losses due to the skin effect of gold electrodes, which dominates the microwave loss up to 50 GHz, thus improving the bandwidth of the modulator. A 50 Ω on-chip terminal resistor is included at the end of the CL-TWEs to facilitate the high frequency electro-optic response characterization.

3. Fabrication and characterization

The meandered TFLN modulators are fabricated with 600-nm-thick X-cut TFLN on quartz provided by NanoLN. The optical waveguides, including straight waveguides, 180 degree bents, and Y-branches, are defined by electron beam lithography (EBL) and Ar-based dry etching. Then a 600-nm-thick silica layer is deposited over the partially etched TFLN by plasma enhanced chemical vapor deposition (PECVD). The 50 Ω thin-film NiCr resistor is prepared by a lift-off process. Finally, the CL-TWEs are patterned by contact UV lithography and thickened to 1.5 μm by electroplating.

Lensed fibers are used for coupling the light into and out of the modulator. The fiber-to-fiber insertion loss is measured as 14 dB, which consists of 2 dB on chip loss and 12 dB coupling loss. The on-chip loss is calculated from the optical transmission loss of 0.9 dB/cm determined by the Fabry–Pérot (F-P) fringes. On the other hand, the high coupling loss of 6 dB/facet is caused by mode-field mismatch, which can be reduced by adopting a mode field converter [11].

The extinction behaviour of the modulator measured at 10 MHz is plotted in Fig. 2 (a). An extinction ratio beyond 15 dB is recorded, and a half-wave voltage of 1.08 V is extracted, corresponding to a voltage-length product of 2.27 V·cm, in fair agreement with the predicted value. In comparison, the half-wave voltage for a meandered modulator without reversed T-rails is 3.18 V, confirming the effectiveness of reversed T-rails in reducing V_π. The microwave S-parameters of the CL-TWEs are measured by a Rohde&Schwarz ZNA50 vector network analyser (VNA) and microwave probes. As shown in Fig. 2 (b), the 6-dB roll off in the microwave transmission S_{21} is beyond 50 GHz. The extracted microwave index shows an excellent match with the light wave (n_g ~ 2.26). The electro-optic response measured with a high-speed photodetector (u^2t XPDV2120R) is also plotted in Fig. 2 (b). The 3-dB electro-optic modulation bandwidth is beyond 50 GHz.

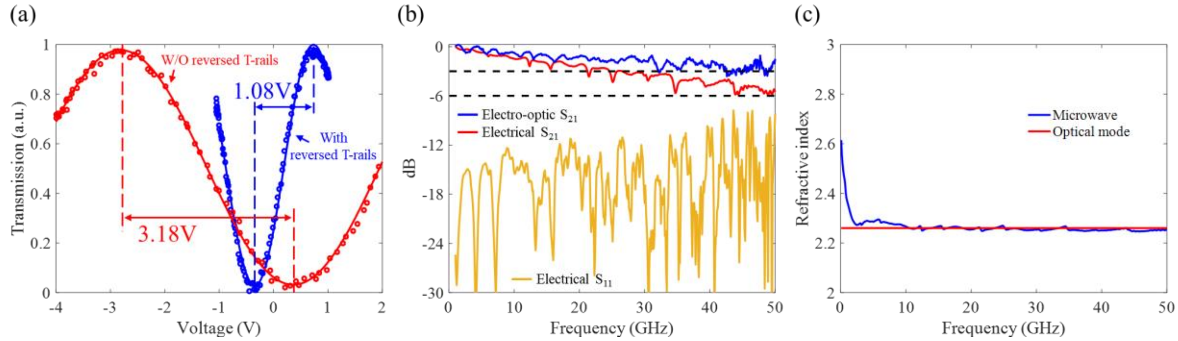

Fig.2. (a) Extinction behavior of modulators with and w/o reversed T-rails. (b) Microwave S-parameters and electro-optic response of the TFLN modulator. (c) The extracted microwave refractive index.

4. Conclusions

By employing CL-TWEs with interdigitated T-rails, the equivalent modulation length is multiplied for a meandered TFLN modulator. The highly compact modulator with a footprint less than 8×1.3 mm^2 exhibits a low half-wave voltage of 1.08 V, together with a 3-dB electro-optic modulation bandwidth beyond 50 GHz. The device shows the potential for direct CMOS driving and is promising for high capacity optical communications.

5. Acknowledgements

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