Engineered Thin Film Lithium Niobate Substrate for High Gain-Bandwidth Electro-optic Modulators

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Abstract: This paper reports the demonstration of a high-speed electro-optic modulator in crystal ion sliced thin film lithium niobate (TFLN™). Experimental results indicate potential to realize a 100 GHz TFLN™ modulator at 1550 nm with $V_\pi = 2.5V$.

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1. Introduction

Lithium niobate (LiNbO$_3$) has long been the dominant material for electro-optic modulation in both data transmission and microwave photonic applications, due to its high electro-optic figure of merit, availability in large-area, high quality wafers, and well-developed device fabrication technology. Thinning or machining of the LiNbO$_3$ substrate has been proposed to facilitate velocity and impedance matching and reduce RF loss in traveling wave modulators. This paper reports the evaluation of a high-speed electro-optic modulator in thin-film lithium niobate (TFLN™) on quartz prepared by crystal ion slicing, a technique that produces high-quality, large-area thin films with the same electro-optic properties as bulk crystals. TFLN™ enables high-quality, electro-optic materials to be bonded to RF-friendly substrates such as quartz to produce very wide-band, low-voltage modulator devices. Based on experimental results, it has been shown that TFLN™ enables impedance matched devices exceeding 100 GHz bandwidth at $V_\pi$. Length products about 1/3 that of bulk substrate based designs.

2. Design and Modeling

The modulator device design incorporated a coplanar waveguide structure on a 4-micron thick TFLN™ film bonded to a quartz substrate. Optical waveguides were formed by annealed proton exchange. Both RF and optical modes and the interaction between them were computed using Comsol Multiphysics™ software. The low permittivity quartz substrate enables simultaneous velocity matching, low RF loss and matched impedance. Figure 1 shows the geometry of the device along with the computed RF and optical modes. The electrode geometry of Figure 1 is in contrast to the narrow (8 $\mu$m) and thick (nearly 30 $\mu$m) center electrode designs typically used for bulk lithium niobate modulators. In addition to fabrication simplicity and cost reduction, the wide and thin center electrode has the benefit of eliminating the need for RF launch and termination tapers.

3. Characterization

RF transmission and reflection of a fabricated electrode on a TFLN™ on quartz substrate was measured using a high frequency vector network analyzer. Measurement data is shown in Figure 2. The TFLN™ loss tangent was determined from S21 data to increase from 0.001 at 10 GHz to about 0.007 at 65 GHz. From the reflection spectrum, approximate values for effective index and characteristic impedance at 10 GHz were extracted as $n_m = 2.3 \pm 0.05$ and $Z_0 = 35 \Omega \pm 1 \Omega$, both of which agreed well with simulation results.

The electro-optic response of a fabricated modulator with the geometry of Figure 1 was measured at a wavelength of 1310 nm. DC $V_\pi$ was measured as 1.9V. The $V_\pi$ for a 1550 nm device was measured to be 2.5V. Both values were in close agreement with predicted values, confirming that the TFLN™ films were of bulk crystal quality. The RF electro-optic response at quadrature with the electrical output terminated in 50 $\Omega$ was measured from 0.1 to 40 GHz using a vector network analyzer. Port 2 of the analyzer was attached to the RF amplified
photodetector output. The measurement bandwidth of the system was limited by the 40 GHz bandwidths of the photodetector and low noise RF amplifier. Normalized measurement results are shown in Figure 3 and show good agreement with the modeled response.

4. Optimized Modulator Design

The RF electro-optic measurements confirmed the RF electro-optic performance of the 4 μm TFLN™ on quartz substrate. The next step was to implement a thicker electrode, which would have the dual purpose of improving index match and reducing RF loss. Simulation of the modulator with an electrode thickness of 7 μm and nominal TFLN™ loss tangent of 0.005 yielded a 3 dB e-o-e cut-off exceeding 100 GHz. The optimized TFLN™ modulator design exhibits a Vπ Length product approximately 1/3 that for a bulk substrate based device. The simulated characteristic impedance was only marginally reduced from 40 Ω to 38 Ω at 50 GHz while DC Vπ was maintained at 2.5 V. A device with such thicker electrodes has been fabricated and measurements are in-progress.

5. Conclusions

The RF electro-optic performance of crystal-ion-sliced TFLN™ on a quartz material has been measured. The modulator test device exhibited good impedance matching, velocity matching and low RF loss without the need for the high aspect ratio electrodes typically used for bulk lithium niobate wafer devices. RF electrodes on TFLN™ confirmed the low RF loss tangent of the TFLN™ on quartz structure. Optimization of the electrode thickness is expected to produce a modulator exhibiting a 3 dB e-o-e bandwidth exceeding 100 GHz at a Vπ of 2.5 V at 1550 nm wavelength. TFLN™ on quartz technology opens the possibility of efficient ultra wide-band modulators reaching into the millimeter-wave regime.

6. Acknowledgements

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7. References


8. Distribution Statement

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