Advanced Photonics Congress (BGPP, IPR, NP, Networks,
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Integrated, Thin Film, High Bandwidth Modulators for 5G Wireless Communication Systems

Andrew J. Mercante,[1] Shouyuan Shi,[1] Peng Yao,[2] and Dennis W. Prather[1]
[1]Electrical and Computer Engineering Department, University of Delaware, Newark, DE 19716, USA
[2]Phase Sensitive Innovations, Inc., 51 East Main Street, Newark, DE 19711, USA
dprather@udel.edu

Abstract: This paper's focus is on a standalone crystal ion sliced (CIS) lithium niobate phase modulator. Simulated and experimental results are shown; indicating functionality across the entire millimeter wave spectrum (DC to 305 GHz). © 2018 The Author(s)

OCIS codes: (130.3120) Integrated optics devices; (160.3730) Lithium niobate;.(230.4110) Modulators

1. Introduction

With 5G wireless communications spanning into the millimeter wave region of the electromagnetic spectrum, RF systems are being challenged to span broader bandwidths. While such systems can consist of multiple, banded, subsystems, this comes at the expense of increased size, weight, and power requirements. An ideal solution would be to have a single system that accommodates such wide operational bandwidths in an economical as well as energy and spectrally efficient way. For this reason, this paper will introduce an RF-Photonic phased array system that operates over ultra-broad bandwidths that accommodates the emerging 5G spectral ranges. In particular, the enabling photonic device is a wideband electro-optic (EO) modulator that is used to up-convert RF signals directly at the RF front-end, or antenna element. In so doing, the received RF signal becomes a sideband on an optical carrier that can be subsequently processed using simple optical lens. This technique has been shown to provide extreme RF signal fidelity, unlimited beam-bandwidth product (BBP), and the ability to implement multi-user MIMO.

The key to the up-conversion process is the development of a wide bandwidth EO modulator. Herein we present the development of a crystal-ion-sliced (CIS) Lithium Niobate modulator that is suitable for commercially manufacturing. The substrate consists of a 700 nm thick *x*-cut $LiNbO_3$ device layer, affixed to a 500 µm thick quartz handle wafer via a 2 µm thick PECVD SiO_2 intermediate bonding layer. Shallow rib waveguides are formed by reactive ion etching (RIE) are utilized for guiding a single transverse electric (TE) optical mode, which are immediately adjacent to electroplated Au coplanar waveguides (CPWs) that support the modulating RF mode.

An illustration of the fabricated device's cross-section is shown in Fig.1. The values for h_{Au}, h_{etch}, h_{slab}, w_{bottom}, and $w_{top;}$ are 1.86 µm, 160 nm, 540 nm, 1.8 µm, and 1.1 µm, respectively. Not shown in Fig.1 are signal width, and interaction region length; their respective values are 9.3 µm, and 1 cm.

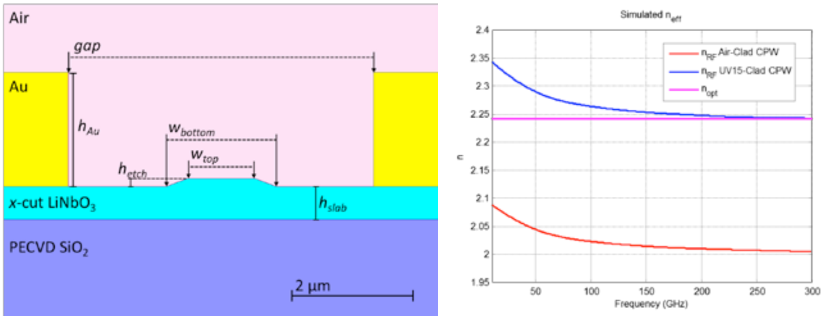

Figure 1: Illustration of device cross-section (left). Simulated indices of the fabricated device (right)

2. Index Matching

One of the more important aspects of device design in a broadband $LiNbO_3$ modulator is the index matching between the RF and optical modes in the context of a traveling wave device. This has been previously addressed in bulk devices [1] and mechanically thinned devices [2], but not in the context of a CIS device [3]. If the indices are not adequately matched the broadband functionality can be severely limited [4,5]. In such a travelling wave $LiNbO_3$ phase modulator an optimal device will have the group velocity of the optical waveguide matched the phase velocity of the RF waveguide so that the two remained phase-aligned as they co-propagate down the axis of the modulator.

The simulated RF index (n_{RF}), and optical index (n_{opt}) values are extracted from HFSS and Lumerical models, respectively, of the aforementioned device. The low dielectric constant of the quartz handle makes it difficult to match n_{RF} to n_{opt}. Consequently, at higher frequencies, e.g., 110 GHz the simulated n_{RF} is equal to ~2 and will reduced the operational bandwidth. To achieve broadband operation, the effective RF index must be increased. A proven method for increasing n_{RF} is to clad the modulator's interaction region within a higher index material, preferably a material with low RF loss such as UV15 adhesive [6]. By adding a UV15 cladding layer to the HFSS model, the simulated n_{RF} at 110 GHz increases from ~2 to ~2.22. Also, by increasing the cladding layer thicknesses from 10 µm to 100 µm , simulations show little variation in n_{RF}. However, the effect on the simulated optical group index according to Lumerical simulations is a decrease from 2.261 to 2.244, which also helps to match modal indices. The simulated results, shown in Fig. 1, suggest that by coating the interaction region in UV15 the index mismatch can be reduced from 0.26 to 0.02 at 110 GHz. We experimentally demonstrate that this holds true.

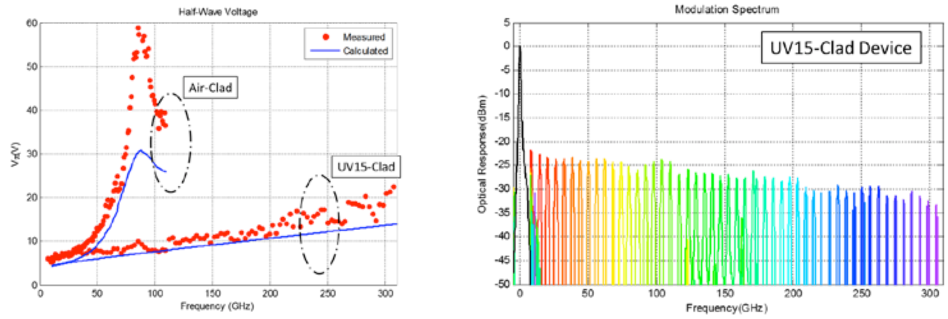

Figure 2: Half-wave voltages (left) and upper half of the modulation spectrum (right).

3. Characterization

Measured and calculated values for half-wave voltage as a function of modulation frequency $V_\pi(f)$ are presented in Fig. 2. The measured half-wave voltage data was extracted from the sideband data [7] in Fig. 2. The calculated data is based on simulated modal overlap, simulated effective indices, and CPW attenuation. CPW attenuation was measured to 110 GHz and extrapolated to higher frequencies. The CPW possesses an input impedance of ~50 Ω. The optical portion of the modulator is characterized by coupling polarization maintaining single mode fibers to the end facets of the rib waveguide. Optical waveguide propagation loss of ~7 dB/cm is measured via cutback method. This result is comparable to propagation losses in the literature for dry etched ridge waveguides [8]. Although, through refined processing techniques similar devices have reported propagation loss as low as 0.4 dB/cm [9].

4. Conclusion

The design, fabrication, characterization and application of broadband CIS modulators for 5G wireless communication system was presented. To the best of our knowledge, this is the first broadband CIS $LiNbO_3$ modulator having a measured frequency response upto and beyond 300 GHz. A cladding procedure was presented that raises the RF effective index to match that of the optical effective index, thereby yielding broadband performance. Use of sub-micrometer thick $LiNbO_3$ on insulator allows for electrode design that makes this the most efficient $LiNbO_3$-based traveling wave modulators and their integration with RF phased array antennas makes them well suited to address the emerging needs of emerging 5G applications.

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