Guided-Wave, Electro-Optic Electric-Field Sensors Utilizing Ti Diffused Lithium-Niobate (Ti:$LiNbO_3$) Channel Waveguides

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ABSTRACT

This paper comprehensively reviews and compares Ti:$LiNbO_3$ integrated optic electric-field sensors, including the asymmetric Mach-Zehnder interferometer (MZI), 1 × 2 directional coupler (DC), and Y-fed balanced-bridge Mach-Zehnder interferometer (YBB-MZI), based on the operating principles, the dc/ac electrical and optical characteristics, and electric-field measurements for each fabricated device, respectively.

Keywords: integrated-optics, electric-field sensor, electro-optic effect, Ti:$LiNbO_3$ channel waveguide,

1. INTRODUCTION

Electro-optic electric-field sensors utilizing Ti:$LiNbO_3$ channel waveguides, being all-dielectric, present several intrinsic advantages compared to their electronic counterparts, such as noise immunity, compact size (a few millimeters), large bandwidth, feasibility of electrode-free operation, and consequently the possibility of operating even in harsh or dangerous environments. The optical fibers and dielectric electro-optic materials also produce minimal field distortion. In this paper we review and compare Ti:$LiNbO_3$ E-field sensors based on the electro-optic effect of lithium-niobate. Three types of E-field sensors were reviewed according to configurations, operating principles, fabrication, dc/ac characteristics, and various experimental results including E-field–sensed RF spectra, and frequency responses. [1]

2. FABRICATION and DEVICE THEORY and STRUCTURES

2.1 Fabrication of Ti:$LiNbO_3$ channel waveguide

The integrated-optic sensors were fabricated on X- or Z-cut $LiNbO_3$ substrate using standard photolithographic technique. Channel waveguides were formed by diffusing a 1050-Å-thick, 7.5μm-wide stripe of titanium film at 1050℃ in wet ambient. The substrate edges were optically polished to allow butt coupling and pig-tailing. A SiO_2 buffer layer ~3000 Å thick was deposited using e-beam evaporation and 99.99% pure SiO_2 pellets to prevent propagation loss caused by the optical absorption of the antenna metal. An aluminium dipole antenna electrode ~5000 Å thick was fabricated to allow sensing of the electric field. [1] Polarization maintaining single-mode and multi-mode optical fibers were attached to the input and output waveguides, respectively.

2.2 Asymmetric Mach-Zehnder Interferometer

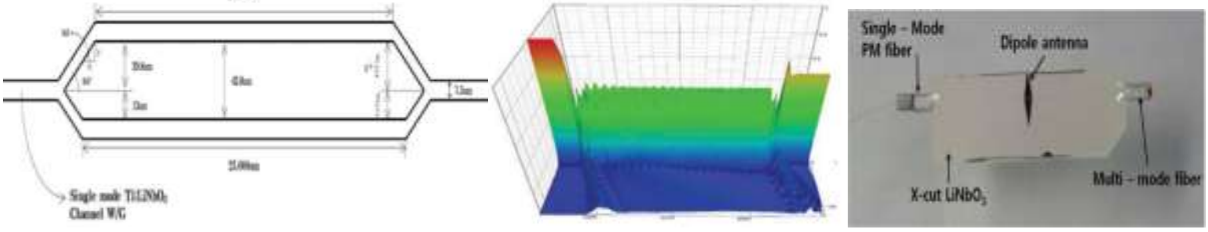

Fig. 1 (a) Schematic diagrams and dimensions, (b) BPM-CAD simulations, and (c) fabricated sensor module of Ti:$LiNbO_3$ asymmetric Mach-Zehnder interferometer.

A configuration of an asymmetric Ti:$LiNbO_3$ Mach-Zehnder interferometer and optical propagation BPM-CAD simulations are shown in Fig. 1. [2] The device was designed to have π/2 phase difference between its two arms through adjusting the path length difference, which makes the sensor have better linearity and sensitivity without a need for external bias to be applied. The device has a 3-dB input splitter and output combiner. The sensed E-field produces phase shifts in the light beam propagating in one of the parallel channel waveguide arms, thereby leading to a net phase shift between two light beams through each channel. When the two light beams recombine at the output combiner, the phase modulation is converted to an amplitude-modulated signal at the same frequency as the sensed E-field. Therefore the light signal amplitude is proportional to the E-field strength.

2.3 1×2 Directional Coupler

A 1 × 2 directional coupler consists of a single-mode Y-junction splitter and a co-directional coupler with two parallel and symmetric waveguide channels. [3] The schematic diagram and its dimensions are shown in Fig. 2. Light is fed in and split into the two symmetric waveguides equally through the Y-junction region. The co-directional coupler guides the two single-mode light beams traveling along the two channels. With no modulating voltage applied, the coupler is set to the 3-dB operating point automatically due to the symmetric structure of the 1 × 2 directional coupler. While a driving voltage is applied through the electrodes over the coupler region, however, light can be coupled from one channel into the other. The 1 × 2 directional coupler modulator has two complementary optical outputs and, in general, is characterized by its interaction length (L), coupling conversion length (lc), and the phase mismatch of the propagation constant (Δβ) between the two arms.

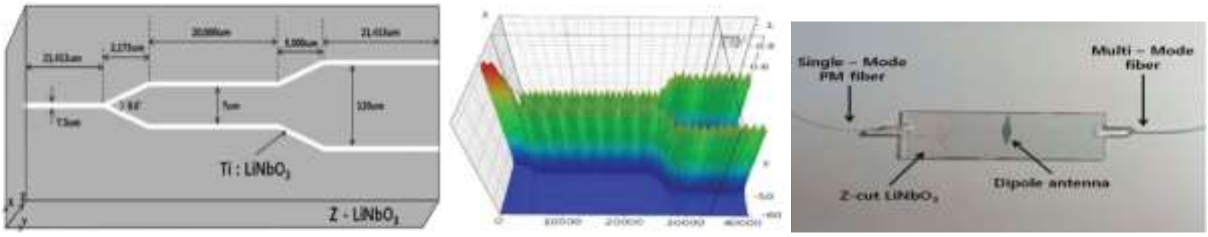

Fig. 2. (a) Schematic diagrams and dimensions, (b) BPM-CAD simulations, and (c) fabricated sensor module of Ti:LiNbO3 1×2 directional coupler.

2.4 1×2 Y-fed balanced bridge Mach-Zehnder interferometer

The YBB-MZI modulator consists of a 3-dB directional coupler at the output and has two complementary output waveguide as shown in Fig. 3. [4] This type of modulator provides a well-defined transfer function for the output optical power versus the detected electric-field intensity and can be automatically biased at the optimum 3 dB operating point due to its symmetrical structure, which offers a more tolerant design in the fabrication process than Mach–Zehnder interferometric modulators or 1 × 2 directional couplers, which are asymmetrical.

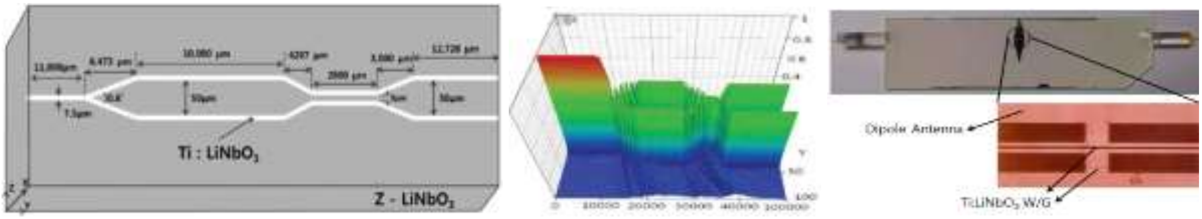

Fig. 3. (a) Schematic diagrams and dimensions, (b) BPM-CAD simulations, and (c) fabricated sensor module of Ti:LiNbO3 1×2 YBB-MZI interferometer.

3. DC/AC CHARACTERISTICS and E-FIELD SENSING

3.1 DC Characteristic Curve

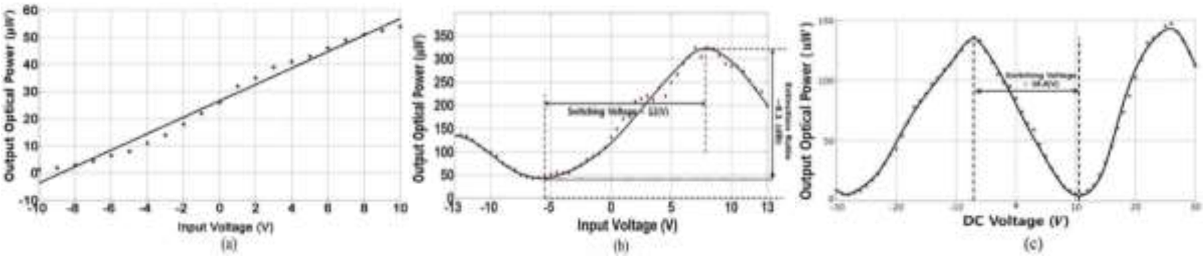

Fig. 5. Measured optical output power intensities versus applied dc voltage of (a) asymmetric Mach-Zehnder interferometer, (b) 1 × 2 directional coupler, and (c) 1 × 2 YBB-MZI interferometer.

3.2 AC Characteristics

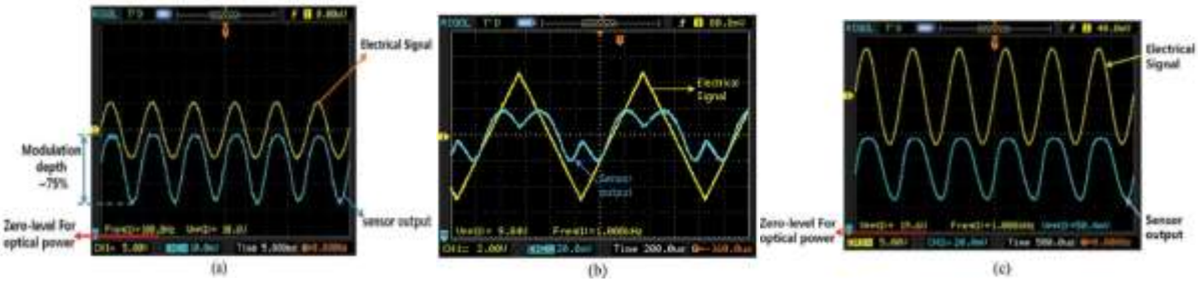

Fig. 6. The 1-kHz ac modulation responses of (a) asymmetric Mach-Zehnder interferometer, (b) 1 × 2 directional coupler, and (c) 1 × 2 YBB-MZI interferometer.

3.3 RF Sensing

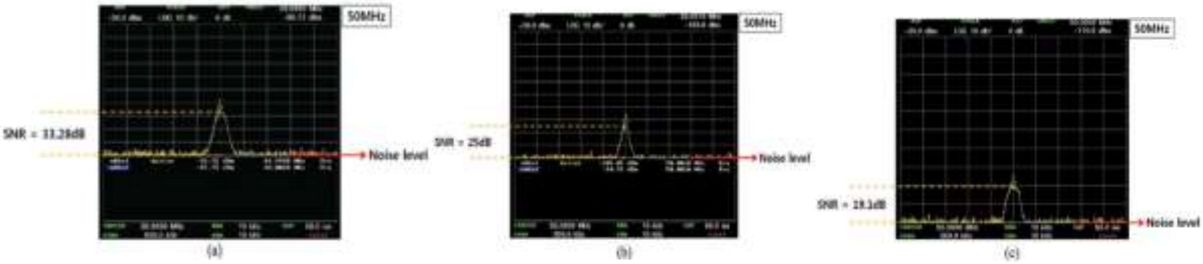

Fig. 7. The RF spectra of 50 MHz RF input signal into the TEM cell with a power level of 100 mW: (a) asymmetric Mach-Zehnder interferometer, (b) 1 × 2 directional coupler, and (c) 1 × 2 YBB-MZI interferometer.

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4. CONCLUSIONS

The ac output characteristics of the asymmetric MZI interferometer show a modulation depth of ~75% at Vπ voltage of ~5.3 V. The minimum detectable electric fields are ~0.28 V/m and ~0.646 V/m, corresponding to a dynamic range of about ~32 dB and ~26 dB at frequencies of 20 MHz and 50 MHz, respectively. A dc switching voltage of ~12 V and an extinction ratio of ~8.1 dB were observed with the 1 × 2 directional coupler. The minimum detectable electric fields are ~0.99 V/m and ~1.67 V/m, corresponding to a dynamic range of about ~29.5 dB and ~25 dB at frequencies of 20 MHz and 50 MHz, respectively. A dc switching voltage of ~16.6 V and an extinction ratio of ~14.7 dB were observed on the 1 × 2 YBB-MZI interferometer. The minimum detectable electric fields are ~1.12 V/m and ~3.3 V/m, corresponding to a dynamic range of about ~22 dB and ~18dB at frequencies of 10MHz and 50 MHz, respectively.

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