$LiNbO_3$ integrated optical probe for high-voltage electric field sensing

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***Abstract*— We present a novel high-voltage optical probe in $LiNbO_3$. A near-cutoff waveguide is centered on a domain inverted region covered with a thin sheet of $LiNbO_3$. DC electric fields up to 20MV/m can be measured.**

Keywords-component; high-voltage optical sensors; ferroelectrics

I. INTRODUCTION

Lithium Niobate ($LiNbO_3$) is one of the most popular materials used in integrated optics because of its electro-optic, nonlinear optical, photorefractive, acoustic and acousto-optic properties [1]. For example, it is used in high speed electro-optic modulators for broadband communication systems [2], wavelength converters [3], and frequency doublers [4]. In addition to telecom applications, thanks to its high dielectric strength and electro-optic properties, $LiNbO_3$ is also used for electric field sensing [5-7]. In the last years, the need for intense electromagnetic field sensing technology has widely increased playing a critical role in various scientific and technical areas, especially in the power industry and in the electromagnetic compatibility (EMC) measurements. So far, several configurations of EO sensors have been proposed, mostly based on waveguide interferometers. In this context, Mach-Zehnder interferometers are employed for their sensitivity. However, they require a tightly controlled biasing to work properly and are very difficult to be operated in very intense electric field.

Recently, new designs for integrated modulators, have been proposed [8] leveraging the micro- and nano-structuring of thin sheets of $LiNbO_3$. Thin sheets are usually directly bonded to a different material or to another $LiNbO_3$ substrate. The use of waveguides at cut-off was proposed for modulation in the field of optical communications [9] and sensing [10]. In this work, we propose an integrated optical probe for high voltage DC fields that can measure electric fields up to 20 MV/m. The novel design leverages a combination of an optical waveguide near cutoff, domain inversion and bonding of thin sheet of $LiNbO_3$ to increase the sensitivity of the device.

II. DEVICE PRINCIPLE AND EXPERIMENTAL RESULTS

The device is sketched in Fig.1. An annealed proton exchange (APE) waveguide near cut-off is fabricated in Z-cut $LiNbO_3$ and centered in a domain inverted region. Another z-cut $LiNbO_3$ substrate is then bonded at room temperature on top of the waveguide, having opposite orientation of the ferroelectric domain. The application of an external electric field parallel to the z axis of the device produces a refractive index change $\Delta n_{\pm}$ between positive and negative domains given by

$$\Delta n_{\pm} = 2 \cdot \frac{n_e^3}{2} r_{33} E$$

where E is the intensity of the external electric field along the z-axis, n_e=2.14 and r_{33}=30.8 pm/V are the refractive index and the electro-optic coefficient along the z-axis, respectively. As a consequence the optical mode will broaden so that, after a sufficient propagation length, a loss is produced due to a mode-profile mismatch of the guided modes in the transition from the active (poled waveguide area) to the passive (unpoled waveguide) region.

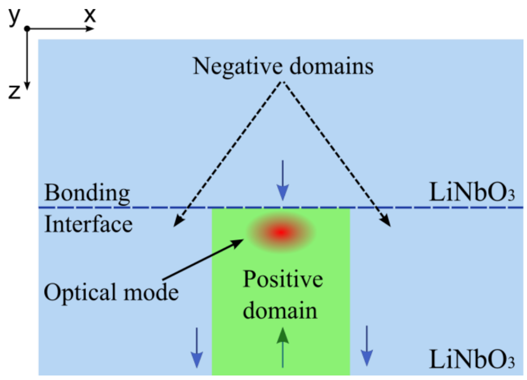

Fig. 1 Cross-section schematic of the optical probe.

The presence of the top layer, apart from enhancing the mode broadening, also contributes to avoid surface depolarization effects that reduce the sensitivity in this type of sensors and can become particularly significative for strong electric fields. Moreover, being made of the same material it avoids discontinuity in the dielectric constant of the sensor and also allow for a very strong and robust bonding.
Taking into account that the electric field across the electro-optic crystal is given by

$$E=V/d$$

where V is the voltage applied to the sensor and d the crystal thickness; it is possible to increase the voltage sensing range by thinning down the substrate. For this reason, to reduce the total thickness, after bonding two 500 μm substrates, we thinned down the top $LiNbO_3$ to 15 μm achieving a total thickness of 520 μm (Fig. 2).

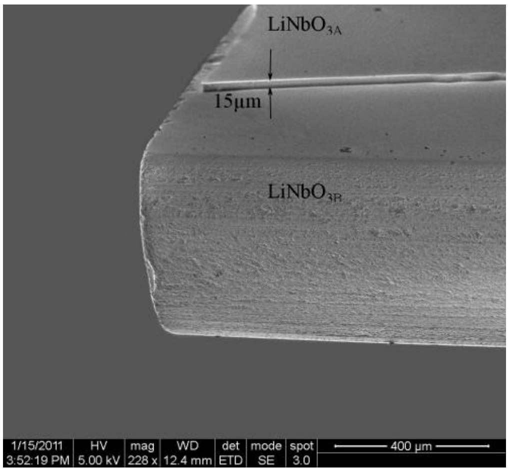

Fig. 2 SEM image of thin plate $LiNbO_3$ bonded on another $LiNbO_3$ substrate

We tested the device as sketched in the schematics of Fig. 3 and the transmission values against different electric fields are plotted in Fig. 4. DC fields up to 2kV/mm, corresponding to an applied voltage of 1040V, were measured. The minimum detectable field is extrapolated to be 14V/mm (7.3 V). The maximum measurable field is limited to the lithium niobate coercive field (20 kV/mm).

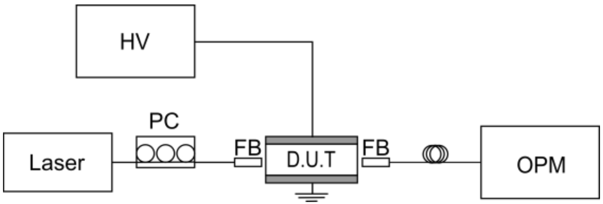

Fig. 3 Block diagram of the dc test setup. HV: high voltage power supply. PC: polarization controller. FB: fiber block. D.U.T.: device under test. OPM: optical power meter.

To improve the sensitivity at lower intensities of the electric field, experiments employing lock-in amplifier techniques are ongoing and will be presented at the conference.

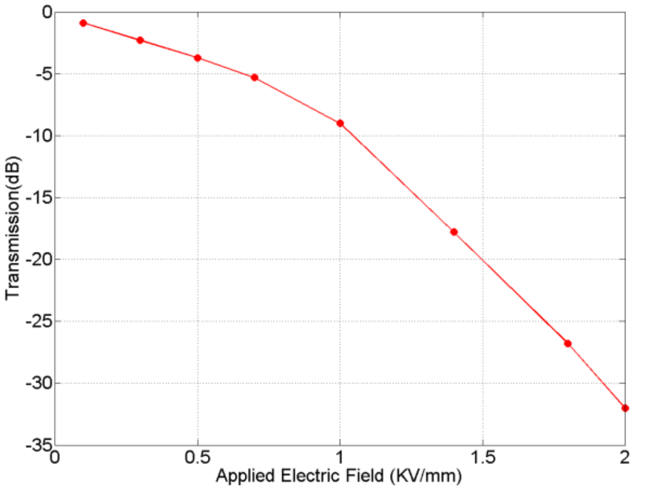

Fig. 4 Experimental results of dc—measurement for a waveguide of 3.5 μm width. The active (poled) length is 10 mm.

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