Domain inverted electrode-free $LiNbO_3$ sensor for high voltage measurements

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1. Introduction

In the last few 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. Conventional electric field meters normally use conductive parts, which can interfere with the field to be measured, and are very sensitive to electromagnetic noise. Moreover, frequency bandwidth limitation and 50-Ω characteristic impedance in the case of RF waveguide sensors limits the scope of applicability of such technology. Electro-optic (EO) devices present several advantages compared to their electronic counterparts such as noise immunity, the feasibility of electrode-free operation, and consequently the possibility of operating even in harsh or dangerous environments.

So far, several configurations of EO sensors have been proposed, mostly based on waveguide interferometers [1] or bulk polarization/phase rotation in a piezoelectric crystal [2]. This second approach is based on polarization or phase measurements which require interrogation systems that are rather expensive to implement and may present long-term stability issues. On the contrary, waveguide based sensors directly translate the electric field value into an optical power variation, thus simplifying the interrogation system and potentially lowering the costs. In this context, Mach-Zehnder interferometers are employed for their sensitivity. However, they require additional metal electrodes and controlled biasing to work properly. To overcome some limitations, schemes without any conductive parts based on ferroelectric poling of the two interferometer arms have been proposed [3]. Alternative designs are based on Bragg grating in $LiNbO_3$ [4] or cutoff modulators with dummy electrode structure [5]. Field intensities measurable with the aforementioned approaches are typically below the fields present in some installations, like electric plants or railways electric network where very bulky sensors need to be employed [6].

2. Device design

The scheme of the proposed device is sketched in fig. 1.

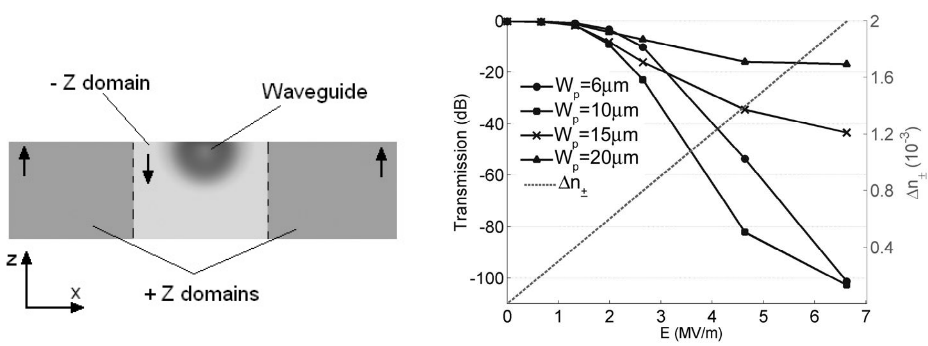

Fig. 1: Left: Proposed cross-section of the electric field sensor.PE waveguide is centered in the domain inverted region Right: Transmitted power vs. external field after 10mm propagation for different poling region widths

A proton exchange (PE) y-propagating waveguide in z-cut $LiNbO_3$ is designed to be near cutoff at the working wavelength (λ=1550 nm) and centered in a domain inverted region. The waveguide has a width of 6 μm and a depth of 4 μm, where the vertical profile was assumed to be half-gaussian with an index step of 0.01. The application of an external electric field parallel to the z axis of the device leads to an increase of the refractive index in the central inverted domain, while a decrease in the external ones. Thus, the index difference change $\Delta n_\pm$ between positive and negative domains is given by:

$$\Delta n_\pm = 2 \cdot \frac{n_e^3}{2} r_{33} E \,, \qquad (1)$$

where E is the intensity of the external applied electric field, n_e=2.14 and r_{33}=30.8 pm/V are respectively the refractive indices and the electro-optic coefficient along the z-axis. From eq. (1) we estimate that we are able to induce index changes of $\Delta n_{\pm} = 6.5 \cdot 10^{-3}$ for electric fields of 20 MV/m, while keeping the external field below the coercive field of $LiNbO_3$ along z-axis (E_c= 21.4 MV/m). In order to find the optimal configuration, we simulated with a BPM software the behavior of the sensor under variation of the width of the central poled region (W_p=6, 10, 15, 20 μm). In fig.1, we also report the optical power in the waveguide mode after a fixed propagation length L=10 mm versus the external electric field applied. From these results we see that the best sensitivity is obtained for a poling region width W_p=10 μm.
Moreover, in fig. 2 we show the evolution of the optical power in the waveguide along the propagation. These simulations suggest that the sensor may be optimized for a specific electric field range by reducing the overall length to target for very intense field while increasing it for weaker fields. A multi-layer dielectric mirror could be deposited on one sensor face in order improve the sensitivity and allow the device to work in reflection.
A waveguide below cutoff can also be used to achieve AC operation. For such device a positive or negative electric field would increase or decrease respectively the transmitted power. In this case the poling length and pattern could be optimized to improve the linearity and dynamic range of the response.

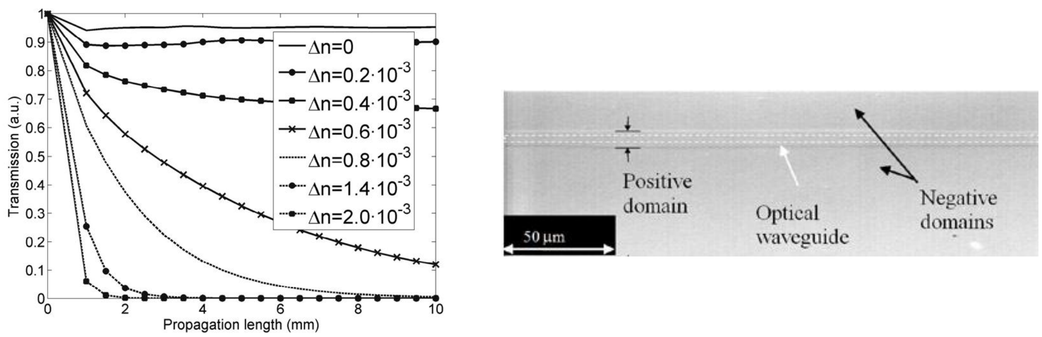

Fig. 2: Left: Evolution of the optical field along propagation direction for different values of index change induced by external electric field. Right: Domain inverted regions revealed by HF differential etching

3. Fabrication

The device was fabricated starting from the domain inversion by electric field poling. To this aim a 3.3 μm-thick layer of resist AZ4533 was spun on the z- face and was used as an insulator layer after patterning and baking at 140ºC for 1 hour. The inverted domains were then revealed via differential etching in hydrofluoric acid for alignment purposes. The final difference between z+ and z- domains was around 90 nm. Fig. 2 shows the poled domains and illustrates the position of the waveguides in their center. According to our simulations, the etching step is not affecting the optical mode even in the presence of the external electric field. Waveguide mask was aligned with the center of the inverted regions and a 200-nm-thick aluminum mask layer was deposited by lift-off technique. Waveguides were fabricated by 30 minutes PE in molten benzoic acid with a subsequent annealing step of 11 hours at 360ºC. The aluminum mask was then removed and the sample was diced and the faces were end polished.
Preliminary measurements confirm the simulation results and the possibility to measure electric fields as high as 20 MV/m. More details on the characterization and results will be presented at the Conference.

References

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