JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. 8 No 3, 03011(4pp) (2016)

ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том 8 № 3, 03011(4cc) (2016)

Formation of the Electric Field Distribution in Thin Electro-Optic Layers for Precision Correction their Optical Characteristics

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(Received 20 April 2016; published online 03 October 2016)

A method of making given field distribution within thin electro-optical layers by using narrow band electrodes placed at the same electric potential. A formula for electric field intensity produced by a single band electrode is obtained. Electric field modeling for different band electrode configurations is undertaken. It was shown, by applying piezoresponse force microscopy, that in case of highly inhomogeneous field the polarization of lithium niobate electro-optical film persisted only in the area above the band electrode.

Keywords: Lithium niobate, Electro-optical structures, Piezoresponse force microscopy, Computer simulations.

DOI: 10.21272/jnep.8(3).03011 PACS numbers: 77.80.Dj, 68.55. – a, 77.55.H –

1. INTRODUCTION

Electrooptics and electro-optic effect find widespread application in most diverse devices such as Pockels and Kerr cells, electro-optic modulators [1, 2]. Most of the existing electro-optic devices are made on the basis of single-crystalline bulk materials and significantly fewer of them are made on the basis of film materials. Nevertheless, electro-optic films with given optical axis orientation and spontaneous polarization vector nonreversing [3, 4], which are integrated in thin-film multilayer structures, including gradient ones [5], can be a fine alignment tool for optical cavities of moderate- and high-precise laser gyroscopes, optical narrow band-pass filters, phase shifters and other advanced. Managing effect is obtained due to precise modifying the reflex index of electro-optic films or layers by applying external electric field. At that, the correction of optical path can be performed within the accuracy of a few angstroms.

Electrical intensity needed to modify refraction index in lithium niobate films several hundreds nanometers thick up to ~ 1,5-3 % for optical elements fine adjusting, must 10^5-10^6 V/cm.

Here we report the possibility of making an electric field with given intensity in thin layers of lithium niobate or any other material with electro-optical effect by applying a system of electrodes placed on the substrate and at the same potential and using an electrode out of operational structure, at infinite, as a second potential. The results of field distribution modeling depending on electrode size-shape factor and experimental studies are introduced.

2. MODEL DESCRIPTION

Create a given distribution of the electric field in the thin film of lithium niobate is possible by means of thin electrode system under the same potential. Another potential to be supplied with the freeform electrode located at a distance much greater than the film thickness. Create a given distribution of the electric field in the thin film of lithium niobate is possible by means of thin electrode system under the same potential. Another potential to be supplied with the freeform electrode located at a distance much greater than the film thickness.

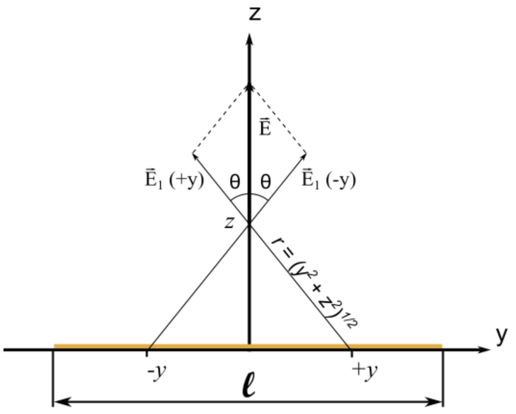
Consider the distribution of the electric field generated by a single thin conductive strip width (m) and length (l).

On the perpendicular at a distance z from the origin, located in the center of the strip, the electric field strength, calculated by integration over m and l (Figure 1), is given by:

$$E = \frac{2\Delta\varphi}{m\left(1 + \ln\frac{2z_{max}}{m}\right)} * arctg\,\frac{m}{2z} \qquad (1)$$

,

where z_{max} – distance to the second electrode provided $z_{max} >> m$, $\Delta\varphi$ – potential difference between electrodes, as well as the condition $m >> l$.



(a)

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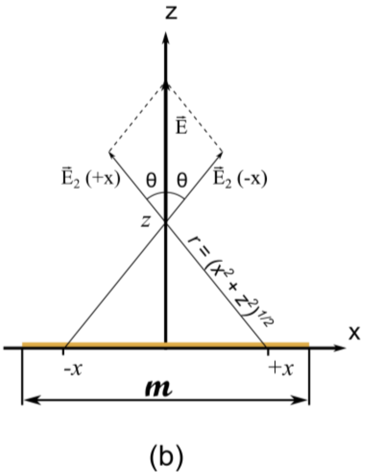

Fig. 1 – Determination of the field at the point with coordinate z, generated elements dx and dy with coordinates $+y$, $-y$ (a) and the $+x$, $-x$ (b)

The electric field generated by the conductive strip at a distance r_0 from the origin in the direction of α was calculated according to the scheme shown in Figure 2.

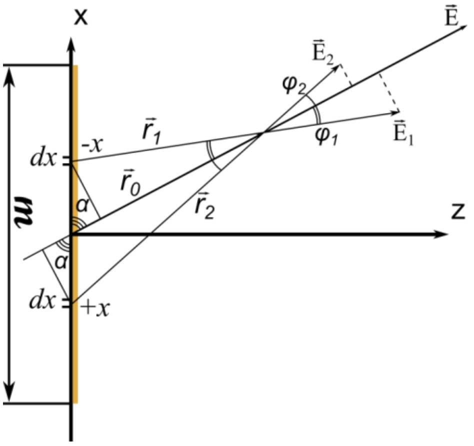

Fig. 2 – Determination of resulting electric field that created by two elements with area of dx and coordinates of $+x$ and $-x$ in direction α at the distance of r_0 from origin

After integration and some transformations, we obtain Eq (2):

$$\vec{E} = \frac{U}{m\left(1+\ln\frac{2z_{max}}{m}\right)} \cdot \left[|\sin\alpha| \left\{ arctg\left(\frac{\frac{m}{2} - r_0\cos\alpha}{r_0|\sin\alpha|}\right) + arctg\left(\frac{\frac{m}{2}+r_0\cos\alpha}{r_0|\sin\alpha|}\right)\right\} + \frac{\cos\alpha}{2}\ln\left|\frac{\left(\frac{m}{2}\right)^2 + r_0 m\cos\alpha + r_0^2}{\left(\frac{m}{2}\right)^2 - r_0 m\cos\alpha + r_0^2}\right|\right]. \quad (2)$$

3. COMPUTER SIMULATION

Using the equation (2), computer modeling was carried out distribution of the electric field created by any number of strip electrodes arranged at an arbitrary distance from each other.

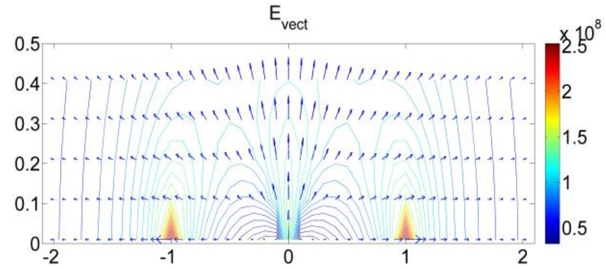

Fig. 3 – The vector distribution of the electric field E, V/m generated by a single stripe electrode with width of 2 μm

Vector distribution of electric field, which formed by single strip electrode is presented at the Fig. 3. We used the following parameters of electrodes for simulation: the width of electrode – 2 μm, voltage – 1000 V, distance from external electrode 1 cm.

One can achieve high homogeneity of electric field by varying width of strips and distance between the mas it shown at Fig. 4. The simulation was made for 10 electrodes with width of 400 nm, distance between strips of 400 nm, voltage of 1000 V and distance from external electrode of 1 cm. Here electric field is almost constant (approx. 10^6 V/m) at the distance of 300 nm and more from the strip electrodes.

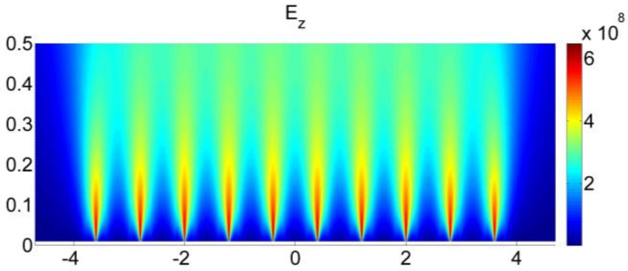

Fig. 4 – Projection of electric field E, V/m to z axis. The plot is calculated for 10 strips with width of 400 nm and distance between electrodes of 400 nm

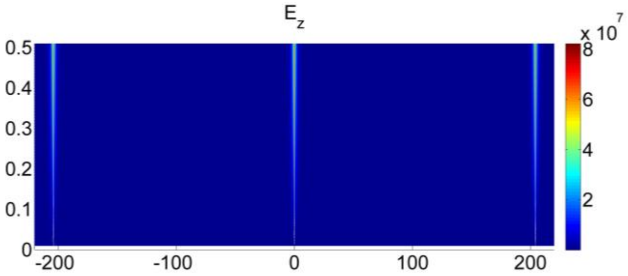

Fig. 5 – Projection of electric field E, V/m to z axis. The plot is calculated for 3 strips with width of 4μm and distance between electrodes of 200 μm

In order to verify mathematical model we calculated electric field of 3 electrodes with a width of 4μm with and a distance of 200 μm between electrodes. The distance from an external electrode and applied voltage were 1 cm and 1000 V, correspondingly (high inhomogeneity of electric field distribution), Fig. 5. Accordingly to this distribution samples for experiments were prepared.

4. EXPERIMENTAL DETAILS

The $LiNbO_3$ films 200 nm thick were deposited on

Al_2O_3 substrate (with pre-coated gold stripe electrodes) by RF magnetron sputtering of the single-crystalline target in Ar/O = 1 atmosphere and under the working pressure of 0.6 Pa. After sputtering process the films were annealed in a furnace at 700 °C for two minutes. The electrodes have a width of 4 μm, a length through the sample, the distance between the electrodes was 200 μm, the system of plane-parallel electrodes had dimensions of 14 × 14 mm (Fig. 6).

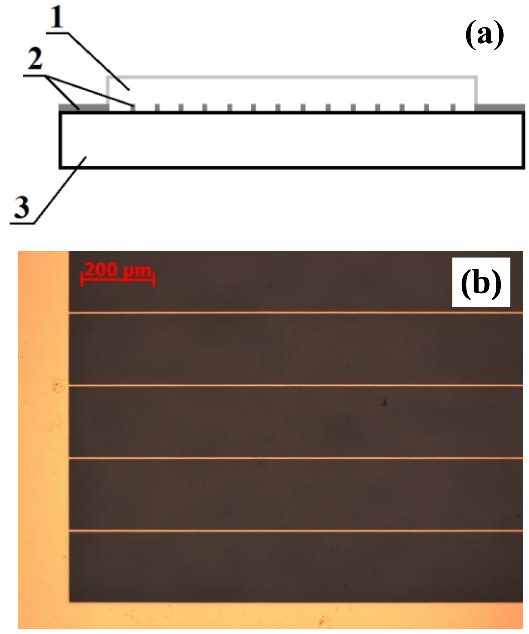

Fig. 6 – Schematic representation (1 – $LiNbO_3$, 2 – Au electrodes, 3 – Al_2O_3 substrate), photo image (b) of the EO structure based on $LiNbO_3$ thin films

The surface morphology, ferro- and piezoelectric properties of the LN thin films were characterized by the piezoresponse force microscopy using commercial scanning probe microscopes MFP-3D (Asylum Research) and NTEGRA Prima (NT-MDT) with Asyelec Ti/Ir coated conductive probes (Asyelec-01, Asylum Research, USA). Out-of-plane PFM images (OOP-PFM) of the samples were obtained by applying AC voltage (5V peak-to-peak) with the frequency around 300 kHz.

5. RESULTS

The surface morphology of the $LiNbO_3$ film synthesized on Al_2O_3 substrate include a single electrode as shown in Fig. 7a. OOP-PFM image obtained simultaneously with the topography image are shown in Fig. 7b. As known, PFM can to used to characterize the polarization states in the ferroelectric materials. The maximum piezoelectric response (negative value a signal or dark contrast) observed in the film with the lower electrode area, and this signal is uniform over the entire length of the electrode, which implies that the polarization vector in this area is directed toward the upper interface. Outside this area the OOP-PFM signal has a zero piezoresponse.

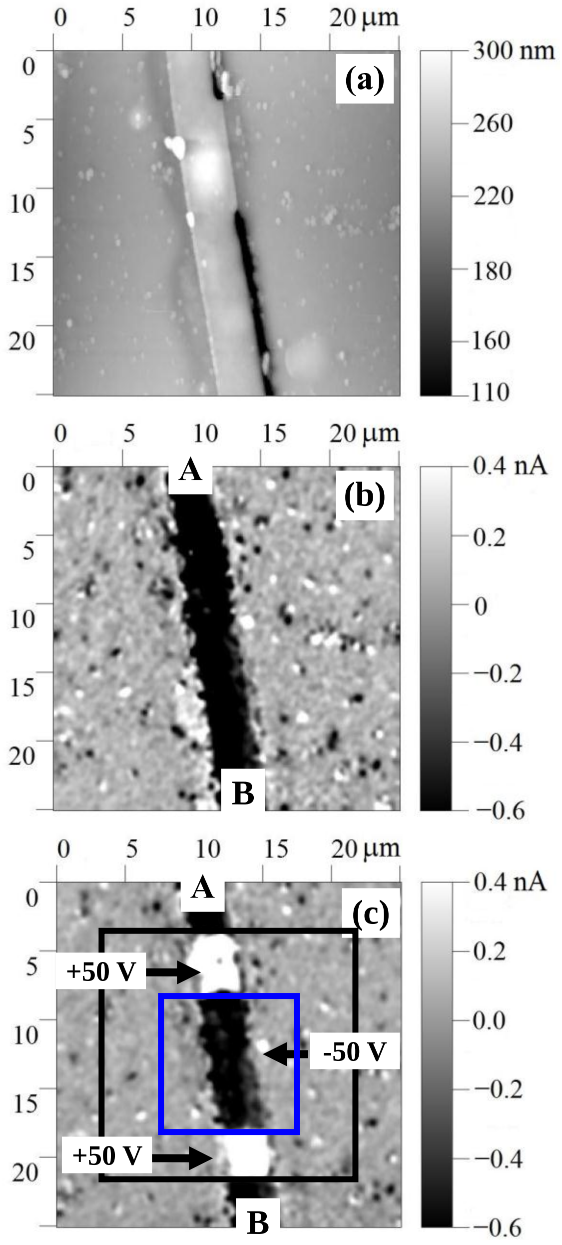

Fig. 7 – Topography (a), OOP-PFM image before (b) and after poling experiment (c) of LN heterostructure

To confirm the presence of the ferroelectric properties of the investigated heterostructures based on $LiNbO_3$, a series of experiments on the local polarization of the surface at DC voltage (Fig. 7c). Since the cantilever in scanning probe microscope in a contact mode plays the role of the upper electrode during the scanning process, it is possible to supply a DC voltage to subsequent visualization a remnant piezoelectric response. After applying an outside 18 × 18 μm^2 square with + 50 V voltage and an inside 8 × 8 μm^2 square with – 50 V, a large OOP-PFM contrast is observed (Fig. 7c). The structure «box-in-box» (or remnant piezoelectric response) characterized of the local polarization switching effect under a DC voltage. However, as can be seen from Fig. 7c polarized only part of the film, which "lies" on the lower gold electrode. Outside electrode ($LiNbO_3$ on sapphire) the poling area do not appear, since the density of the lines of force arising under the cantilever during the polarization is considerably smaller than the electrode area.

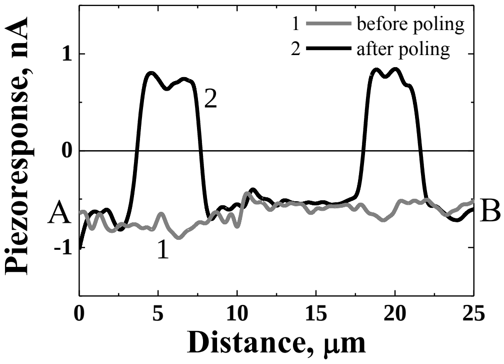

Fig. 8 – OOP-PFM image before (curve 1) and after poling experiment (curve 2) of LN heterostructure along line AB in Fig. 2b, c

Fig. 8 shows the profiles of OOP-PFM piezoelectric response signal before and after polarization, conducted along the lines "A-B" indicated on scans Fig. 7b, c. The level of the remnant signal for the piezoelectric response poled at + 50 V by absolute values compare with the original piezoelectric response, which demonstrates the effect of the full polarization switching under the influence of a DC voltage applied to the cantilever. When a voltage of – 50 V is "recovery" values piezoelectric response to the original state. It is worth noting that the poling area is stable over time and does not disappear after a few hours of uninterrupted scanning.

6. CONCLUSIONS

In summary, the electric field produced by a single electrode strongly inhomogeneous and reaches a maximum value immediately above this electrode in the perpendicular direction. In this case, the vertical component of the electric field rapidly decreased from right and left edges of electrode consistent with some experimental observations. Experimentally is observed that the piezoresponse value (polarization of the ferroelectric film) is stable only in the film area located directly above the bottom electrode. At the same time, the simulation shows that at a sufficient distance from the electrode along the *z*-axis of the electric field becomes uniform. The distance at which the electric field increases uniformity decreases with decreasing width of the electrode.

ACKNOWLEDGEMENT

The research was financially supported by the Federal Target Program “Investigation and Engineering in High-Priority Lines of Development of Science and Technology in Russia for 2014-2020” (unique project identifier RFMEFI57814X0071, contract no. 14.578.21.0071)

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