



Light-induced electric field generated by photovoltaic substrates investigated through liquid crystal reorientation



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ABSTRACT

Liquid crystal reorientation is exploited to analyze the electric field generated by light irradiation in iron-doped lithium niobate crystals. The evaluation of the strength of this light-induced field is based on the measurement of the phase shift induced in a probe light beam by a liquid crystal cell built with two z-cut iron-doped lithium niobate crystals as substrates. Then, the field profile has been determined starting from a Gaussian-like surface charge density following the model described in the text. The director profile corresponding to the modelled electric field is in good agreement with the director reorientation evaluated experimentally by means of the light-induced phase shift. This investigation gives a new approach to study the effects based on the photovoltaic response of lithium niobate crystals. Moreover, the characterization of the electric field optically generated inside the LC layer is highly desirable in view of the realization of new all-optical devices to be integrated in optofluidic platforms.

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1. Introduction

It is well known that iron-doped lithium niobate ($\text{LiNbO}_3:\text{Fe}$) is able of producing a bulk photovoltaic effect with resulting electric fields up to 10^5 V/cm [1]. The effect is due to an asymmetrical potential associated to this material upon illumination, which causes photoexcited electrons to move in a preferential direction. This flow of electrons gives rise to a photocurrent and to a subsequent charge density producing an electric field in the illuminated region, known as photovoltaic field, as sketched in Fig. 1.

It has been recently shown [2–4] that the charge separation associated to the photovoltaic effect in $\text{LiNbO}_3:\text{Fe}$ can be successfully exploited to optically induce a static electric field in properly designed liquid crystal cells, which is able to reorient the molecular director. The peculiarity of the effect lies in the absence of external contacts and on the possibility to have a full control of the electric field in the cell by light. The absence of electric contacts for the application of the external electric field, makes this effect very interesting in view of the realization of novel optical devices for applications in optofluidic platforms based on lithium niobate.

In view of these possible applications, it is interesting to

characterise the electric field optically generated inside the LC layer. To this purpose, we prepared several cells based on photovoltaic substrates with different iron content. In this way we got different amounts of induced phase shift and we were able to calculate the expected electric field inside the LC cell. Then, we derived the electric field profile starting from a surface charge density of Gaussian shape, both in 2 and 3 D. The expected director profile has also been calculated.

Since the results of this investigation do not depend on the presence of the LC in between the two photovoltaic substrates, the modelled electric field profile can be useful for all the applications of lithium niobate crystals based on their photovoltaic properties, as for example trapping and manipulation of particles due to electro- or dielectrophoretic forces generated by the photovoltaic field on the surfaces of lithium niobate crystals [5–7].

2. Experimental details

The LC cells were built by using two z-cut $\text{LiNbO}_3:\text{Fe}$ thin crystals (900 μm average thickness) as substrates. Crystals were obtained by a boule of lithium niobate doped with iron grown at the University of Padua by using the Czochralski technique. The growth direction was along the z axis (that corresponds to the c-axis) of the material, with a pulling rate of 2 mm/h. After the growth, the

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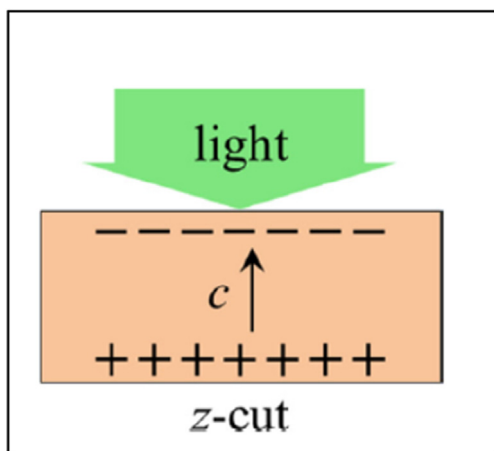


Fig. 1. Sketch of the light induced charge separation in z-cut LiNbO₃ crystals.

LiNbO₃:Fe boule was poled in air atmosphere at 1200 °C in order to obtain single domain crystals. By means of High Resolution X-Ray Diffraction measurements the crystalline quality of the material was checked to be compatible with commercial crystals and the boule was oriented along the three main crystallographic axes. The main faces of the samples are perpendicular to the z-axis. In these crystals the iron dopant is mainly in its 3+ valence state. In order to increase the concentration of Fe²⁺ some samples were submitted to a thermal treatment at 500 °C in a gas mixture of Ar (98%) + H₂ (2%), thus promoting the incorporation of electrons in the material and consequently the reduction of Fe³⁺ ions into Fe²⁺. Several crystals with different iron molar concentration and different reduction degree have been used. The molar concentration of iron was 0%, 0.02%, 0.01%, 0.05% and 0.1%.

Before using them for assembling liquid crystal cells, LiNbO₃:Fe crystals were functionalized with a bath of sulphuric acid and hydrogen peroxide. This makes the crystals surfaces hydrophilic thus allowing the coating with Poly-vinyl-alcohol, the usual surfactant used to obtain planar LC cells. Then each couple of crystals were rubbed with a cotton tissue, in order to obtain planar alignment of the LC molecules. Cell thickness, controlled by Mylar spacers and measured by means of spectroscopic techniques, is in the range (18 ± 5) μm. The LiNbO₃:Fe – based LC cells were then filled with the nematic pentylcyanobiphenil 5CB (from Nematel) inserted by capillarity. The good planar alignment of the final samples was checked under polarizing optical microscope.

Cells were irradiated with an Ar ion laser (λ = 514 nm), impinging at normal incidence. This pump beam was linearly polarized parallel to the cell rubbing direction. In this configuration light propagates along the c-axis of both LiNbO₃:Fe crystals and so it does not undergo any phase shift due to the crystals birefringence. Pump power was fixed at 177 mW and the diameter of the beam on the sample was 1.5 mm. Exposure time varied between 10 and 60 s depending on the time needed by the LC cells to reach a new stable director configuration.

It is worth remarking that the temperature rise in our LiNbO₃:Fe crystals is expected to be very low in the used experimental conditions. This is due to the low reduction degree R of the used substrates (R is defined as the ratio between Fe²⁺ and Fe³⁺ ions). This ratio never exceeds unity and is generally much lower than this value. Temperature increase of some tenths of K has been observed for reduction degrees one or two orders of magnitude higher and for irradiation times on the order of several minutes.

As mentioned, the charge separation associated to the photovoltaic effect in the two LiNbO₃:Fe substrates, gives rise to an electric field in the region filled by the liquid crystal, which

produces a smooth transition from planar to nearly homeotropic configuration. The resulting phase shift induced on the light propagating through the cell can be measured by a pump-probe technique [8].

The probe beam was given by a low power He-Ne laser (λ = 633 nm), counter propagating with respect to the green pump beam and linearly polarized at 45° with respect to the cell rubbing direction. This beam is focused on the sample at the centre of the pump spot. The probe light transmitted by the sample is divided by a polarizing beam splitter into two beams: one polarized parallel (I_{||}) the other perpendicular (I_⊥) to the first polarizer placed before the sample.

3. Results

Details on the phase shift measurements have been reported in previous papers [3,4]. Here we show an example of the typical cell response as a function of the irradiation time, in terms of induced phase shift (Fig. 2). This latter is a signature of director reorientation inside the LC cell.

Data related in Fig. 2 are related to one of the cells giving the best results in terms of obtained phase shift. Data obtained with all the analysed cells are listed in Table 1. For further information we also report the photovoltaic field calculated for each LiNbO₃:Fe crystal starting from the measured photocurrent, as described in Ref. [9]. As a general trend, the induced phase shift increases with iron concentration and with the photovoltaic field inside the cell substrates. Worthy of note, increasing iron concentration up to 1% produces a decrease of the measured phase shift (data not shown). This is not surprising since it is known that for high dopant concentrations additional phenomena occurring during light irradiation in LiNbO₃:Fe crystals can lead to a decrease of the maximum photovoltaic field [10], which explains the decrease of the phase shift measured inside the LC layer. Worthy of note, the optical properties of LiNbO₃ crystals are very sensitive to the intrinsic defects due to Li/Nb substitution, as reported in Ref. [11]. Such an analysis is however outside the scope of the present study, which is mainly devoted to the characterization of the electric field generated in the region occupied by the LC layer.

Deriving the induced optical anisotropy Δn by means of the usual relation [12] $\Delta\phi = (2\pi/\lambda)L\Delta n$, being λ the wavelength of the light propagating through the cell and experiencing the phase shift and L the cell thickness, one gets $\Delta n_{\max} \cong 0.19$. This is the

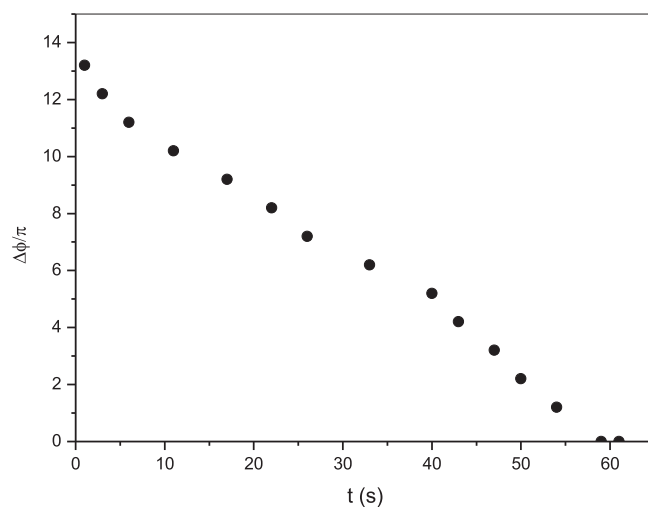


Fig. 2. Induced phase shift as a function of the exposure time, for a cell with 0.1% iron molar concentration.

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