

Light controlled phase shifter for optofluidics

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We report the light-induced control of optical phase shift by a liquid crystal cell made with LiNbO₃:Fe crystals as substrates. We show that a phase shift of a few π s can be easily reached for two orthogonal polarizations due to liquid crystal reorientation driven by the photovoltaic electric field originated in the substrates. This effect is exploited to get all-optical switching with a contrast of about 80%, by 2 s pump pulse. © 2016 Optical Society of America

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Optofluidics merging microfluidic technology with optics holds great promise of providing highly innovative methods for sensing devices related to a wide range of applications such as biomedical analysis, pollution detection and security [1]. A primary goal is achieving the ability of integrating in a single chip a complete optics laboratory equipped with all the necessary devices, starting with the laser source and ending with the light detectors. For this reason, it becomes very important to develop any possible active or passive optical device based on a proper material suitable for a microfluidics platform. To this aim, it is important to investigate the capabilities of different materials to be used as supporting substrates for this technology. Besides the more popular PDMS, recently, lithium niobate has also been proposed to exploit the properties of this material to obtain optical sensing in an optofluidic platform [2]. In particular, the photovoltaic effect of lithium niobate has been successfully used to manipulate particles and actuate droplets inside a microfluidic device realized on an iron-doped lithium niobate (LiNbO₃:Fe) substrate [3,4].

One open issue in optofluidic systems concerns the difficulty in applying external electric fields, which makes it tricky to use conventional liquid crystal based spatial light modulators. Therefore, the exploitation of lithium niobate based platforms to get all-optical devices working as optically addressed spatial light modulators (OASLMs) could be a solution.

It is known that doping lithium niobate with iron significantly enhances the photovoltaic response, thanks to the increased concentration of donor (Fe²⁺) and acceptor (Fe³⁺) ions inside the material. The photovoltaic effect consists in

the appearance of a photo-induced current, which is generated upon illumination according to the scheme: $\text{Fe}^{2+} + h\nu \leftrightarrow \text{Fe}^{3+} + e^-$. The subsequent charge distribution that takes place inside the crystal gives rise to an electric field with values up to 10^5 V/cm in saturation, depending on the dopant concentration and on the reduction degree (i.e., the ratio between Fe²⁺ and Fe³⁺ ions) of the material. The electric field associated with the photovoltaic current is defined as photovoltaic field [5].

When two LiNbO₃:Fe crystals are used as substrates in a liquid crystal (LC) cell in the proper configuration, the photovoltaic fields in each substrate give rise to a field between the two substrates. Such an optically generated electric field induces reorientation of the LC director with a consequent phase shift of the propagating light, thus giving rise to a nonlinear optical effect. A similar approach was proposed by Evans *et al.* in 2006 [6], where the onset of the photovoltaic effect was reported. In that Letter, the authors discuss the transmission properties of such a cell due to a superposition between the photovoltaic effect and the two-beam coupling originated by the photorefractive properties of the crystals. This is obtained by choosing the crystal c-axis oriented along the beam propagation direction and focusing the pump beam on the cell. This system is similar to the ones that couple a photoconductive material with liquid crystal such as in optically addressed light valves, also investigated to enhance the nonlinear response of liquid crystals through the modulation of the surface charges [7].

Here we show that by using an LC cell with z-cut LiNbO₃:Fe crystal substrates and a single unfocused pump beam for homogeneous illumination, a light-induced control of the phase shift can be easily achieved in a time range of a few seconds, corresponding to an induced optical anisotropy Δn of about 0.1, making negligible any contribution originated by photorefractive nonlinearities of the LiNbO₃:Fe crystals. We exploit this effect to get all-optical switching of the transmitted signal with a contrast ratio of 80%. The absence of electric contacts for the application of the external electric field makes this effect very interesting for applications in optofluidic platforms based on lithium niobate.

The LC cell is obtained by using two z-cut LiNbO₃:Fe thin crystals (900 μm) as substrates. They were obtained by a boule of lithium niobate doped with iron ($c_{\text{Fe}} = 18.9 \times 10^{18} \text{ cm}^{-3} = 0.1\%$ mol) grown at the University of Padua by using the Czochralski technique. The crystals used in this Letter present

a reduction degree of about 0.02 ± 0.01 . The two substrates were rubbed with a cotton tissue before cell assembling to obtain planar LC cells. The investigated cell thicknesses were 6 and 13 μm , as determined by Mylar spacers. The used LC is the nematic pentylcyanobiphenil 5CB (by Nematel) inserted into the cell by capillarity. The good planar alignment of the final samples was checked under a polarizing optical microscope. Cells were irradiated by the green line of an Ar+ laser ($\lambda = 514 \text{ nm}$) at normal incidence, with a beam diameter on the sample of about 1.5 mm. In this configuration, light propagates along the c -axis of both $\text{LiNbO}_3:\text{Fe}$ crystals and, being linearly polarized parallel to the cell rubbing direction, it does not undergo any phase shift due to the crystals birefringence. As mentioned, light irradiation produces an electric field in the region filled by LC. The effect of the light-induced electric field on LC is to reorient the director, thus producing a smooth transition from planar to homeotropic configuration. This reorientation produces, in turn, a phase shift on the light propagating through the cell that can be measured by a pump-probe technique, as described in [8]. A sketch of the experimental set up is shown in Fig. 1.

The probe beam originates from a low-power He-Ne laser counter propagating with respect to the green pump beam and linearly polarized to form an angle of 45° with the rubbing direction. The probe light transmitted by the sample is divided by a polarizing beam splitter into two beams: one polarized parallel and the other perpendicular to the first polarizer placed before the sample. The two signals have been detected as a function of the exposure time. In this way, the induced phase shift is determined from the ratio between the intensities I_\perp and I_\parallel of the two beams, according to the expressions [8]

$$\phi = N\pi + 2 \tan^{-1} \sqrt{\frac{I_\perp}{I_\parallel}} \quad \text{if } N = 0, 2, 4, \dots,$$

$$\phi = (N + 1)\pi + 2 \tan^{-1} \sqrt{\frac{I_\perp}{I_\parallel}} \quad \text{if } N = 1, 3, 5, \dots,$$

where the integer N represents the number of extrema (maxima and minima in the curves I_\perp and I_\parallel vs t). The pump power was 177 mW, corresponding to an intensity on the sample of about 10 W/cm^2 , and the exposure time was 10 s. Higher intensities and/or longer exposure times produce spurious oscillations of the probe signals, probably due to the photorefractive response of the substrates.

Figure 2 shows the two transmitted probe signals as a function of the exposure time, for a 13 μm thick cell.

The signal shows the typical oscillations observed when a planar sample, in the same geometry as the one used in the

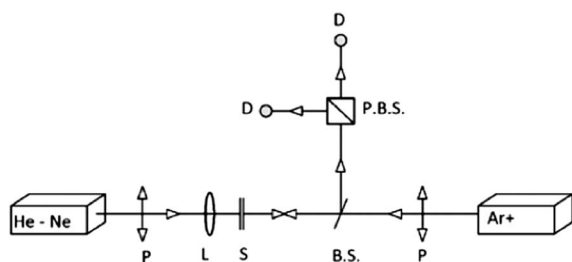


Fig. 1. Experimental setup. P, polarizers; L, lens; S, sample; B.S., beam splitter; P.B.S., polarizing beam splitter; D, detectors.

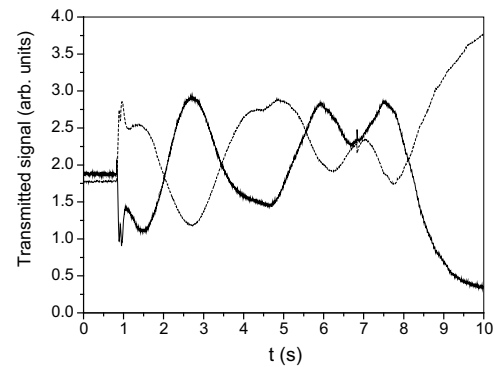


Fig. 2. Transmitted probe signal with polarization parallel (dashed line) and orthogonal (solid line) to that of the probe beam incident on the cell.

experiment, is submitted to an increasing voltage, where each additional peak corresponds to an increase of π of the phase shift between the two waves. The final situation corresponds to almost uniform director alignment perpendicular to the substrates, thus allowing transmission of the signal parallel to the incoming polarization. The perfect symmetry of the two curves is expected from the increasing reorientation of the liquid crystal director. It is worth remarking that the curves shown in Fig. 2 cannot be as symmetric and “clean” as those obtained in the classical measurement of the phase shift in a liquid crystal conventional cell, where the transmitted signal is detected vs the externally applied voltage [8]. Here the transmitted signal is detected as a function of the exposure time, and the shape of the oscillations is affected by the relationship between this parameter and the photovoltaic voltage across the cell.

We remark that an “empty” cell made only by the two crystal substrates shows flat I_\perp and I_\parallel signals for 10 s of irradiation demonstrating that any nonlinear response originated by photorefractive occurring inside the crystals is negligible in this time scale.

Figure 3 reports the phase shift calculated from data of Fig. 2. Thinner cells exhibit a lower maximum phase shift. It is well known that the induced phase shift is related to the induced optical anisotropy Δn through the relation [9] $\Delta\phi = (2\pi/\lambda)d\Delta n$. It is remarkable that from data of Fig. 3 one gets a maximum index modulation $\Delta n_{\text{max}} \cong 0.1$, which is higher than the one achievable with a photorefractive crystal [2,10], thus confirming the main role played by LC director reorientation induced by the photovoltaic field.

We remark that the maximum phase shift is closely related to the quality of cell alignment. We believe that a further optimization of the cell preparation would produce higher values of $\Delta\phi$.

It is worth mentioning that “ordinary” cells made by ordinary glass substrates showed no response, ruling out any contribution from the direct effect of light on the LC.

This light-induced reorientation can be efficiently exploited to obtain all-optical switching of the transmitted beam by using the same pump probe configuration described above. The probe beam is again polarized at 45° with respect to the rubbing direction, and the red light transmitted by the cell is polarized orthogonally to the incident one. Due to the initial planar configuration of the cell, this situation corresponds to maximum transmittance. When the cell is irradiated with the pump beam,

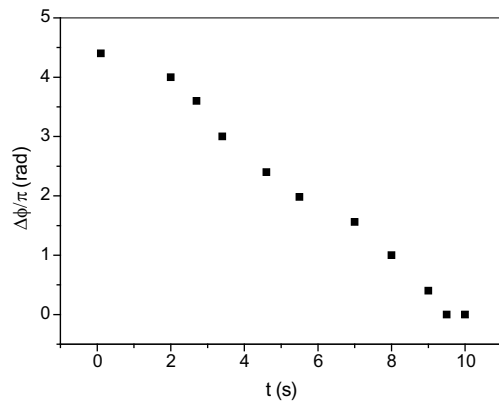


Fig. 3. Induced phase shift as a function of the irradiation time.

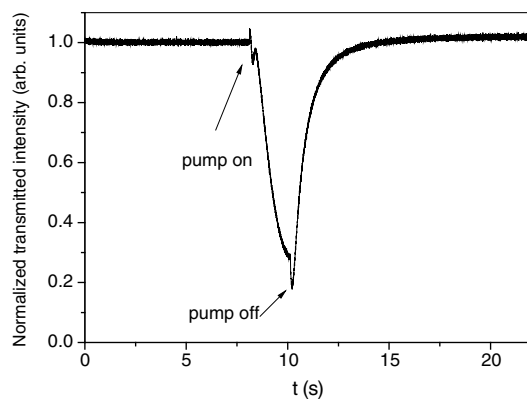


Fig. 4. Transmitted probe intensity under 2 s pump irradiation.

the transmittance of red light decreases to a minimum value in times depending on the LC rotational viscosity and dielectric anisotropy and on the value of the electric field generated by the LiNbO₃:Fe substrates during light irradiation. Figure 4 shows the probe transmitted light during pump irradiation of a 13 μm cell.

The exposure time is 2 s. Both the switch-on and switch-off times are of the order of 1 s. (The specific values are 1.4 s and 0.75 s, respectively.) Faster switch-on times have been measured in a certain number of cells, the minimum observed value being 50 ms for a 6 μm cell where, however, the contrast ratio between on/off states was lower than that reported in Fig. 4.

The reason for such a wide distribution of switch-on times is not clear yet, even if small differences in the reduction degree, present in the used LiNbO₃:Fe substrates, can affect the crystal response and change to a certain extent the behavior of different cells. However, the observation of response times down to 50 ms, demonstrates the possibility of improving the speed of the obtained optical switching.

The parameters governing the switch-off time are fixed by the kind of LC used (fixing the sample temperature), according to the relation [9]

$$\tau_{\text{off}} \cong \frac{\gamma d^2}{K \pi^2},$$

where γ , d , and K are the LC rotational viscosity, the cell thickness, and the elastic constant, respectively. On the contrary, those affecting the switch-on time follow the relation [11]

$$\tau_{\text{on}} \cong \frac{\gamma}{\epsilon_0 |\Delta\epsilon| E^2},$$

where ϵ_0 and $\Delta\epsilon$ are the vacuum dielectric permittivity and the dielectric anisotropy of the LC, and E is the modulus of the electric field created in the cell by the two photovoltaic substrates. The latter is not fixed by the particular kind of LC used and can be tailored a little bit. In principle, it can be increased by acting on the dopant concentration of the substrates and on the reduction degree, but at the expense of the maximum cell transmission. Moreover, a higher pump intensity with respect to that used in this Letter, should lead to a square dependence of the photovoltaic current on the intensity itself [12] and, thus, to the possibility of enhancing the photovoltaic field by increasing I .

In conclusion, we reported the light-induced control of optical phase shift by a liquid crystal cell made with LiNbO₃:Fe crystals as substrates. We have shown that a phase shift of a few π s can be easily reached between two orthogonal polarizations due to liquid crystal reorientation driven by the photovoltaic electric field originated in the substrates. We have also demonstrated that such an effect can lead to all-optical switching of the transmitted signal with contrast of about 80%. These results look promising to realize all-optical devices to be integrated in platforms exploiting lithium niobate as a substrate for optofluidic circuits.

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