Optically-driven switching of a planar nematic liquid crystal cell with parallel rubbing

Varsenik Nersesyan[*1,2,3]

[1] *Electronics and Information Systems Department, Ghent University, Technologiepark 15, 9052 Ghent, Belgium,*
[2] *Center for nano and biophotonics, Ghent University, Technologiepark 15, 9052 Ghent, Belgium*
[3] *Photonics department, Institute for Physical Research of NAS RA, 0203 Ashtarak, Armenia*

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Abstract—This letter reports on the switching of a planar nematic liquid crystal cell with parallel rubbing of the alignment layers, under the application of a voltage, when there is initially an optical field. The voltage application over the liquid crystal in such a cell leads normally to the formation of multiple domains because the two switching directions are equivalent. However, an incident optical field under an angle will locally reorient the director and break the symmetry between the equivalent switching directions. The subsequent application of a voltage pulse amplifies the tilt angle and leads to the formation of a dominant domain, with an order of magnitude larger in size than the optical beam profile. Several switching conditions are demonstrated for different incident angles of the beam. It is shown that the final switching direction of the entire cell is determined by the tilt angle of the optical field. The lensing effects due to the modified director distribution in the domain walls is analyzed qualitatively.

Nematic liquid crystals consist of elongated molecules which are mainly aligned parallel to the so-called director, which leads to optical birefringence. The effective refractive index of the material can be controlled by the application of external electric fields. For liquid crystals with positive dielectric anisotropy ($\Delta\varepsilon>0$) the torque due to an applied electric field tries to align the director parallel with the electric field. On the other hand, the reorientation of the director due to the electric field of an incident laser beam is a well-known optical nonlinear effect [1]. In liquid crystals such nonlinearities are already noticeable for milliwatt powers of an optical beam [2]. Optical reorientation in liquid crystals is commonly used for the generation of spatial optical solitons [3-6].

Recently theoretical and experimental investigations of the joint influence of optical and (quasi-)static electric fields on the orientation of liquid crystal have been demonstrated and discussed in detail by our group [7,8]. We have shown that the reorientation of the director strongly depends on the starting conditions under the influence of a preliminary present optical field and the geometry of the cell. In the experiment described in this paper, anti-parallel rubbing of glass substrates was used, which defined the orientation of director switching in the absence of an optical field.

In this letter, we describe that the case with parallel rubbing (top and bottom towards the same direction) is different because device geometry does not provide a preferential switching direction.

The electric torque related to a static electric field per unit volume for a liquid crystal with director $\vec{\boldsymbol{L}}$ in and static electric field $\vec{\boldsymbol{E_S}}$ is given by:

$$\vec{\Gamma_S} = \varepsilon_0 \Delta\varepsilon \left(\vec{L} \cdot \vec{E_S}\right)\left(\vec{L} \times \vec{E_S}\right), \tag{1}$$

with $\Delta\varepsilon = \varepsilon_\parallel - \varepsilon_\perp$ is the dielectric anisotropy.

Eq. (1) can be averaged for a sinusoidal electric field (with sufficiently high frequency) along the z-axis:

$$\vec{\Gamma_S} = \frac{1}{2}\varepsilon_0 \Delta\varepsilon \left(\vec{L} \cdot \vec{1}_z E_a\right)\left(\vec{L} \times \vec{1}_z E_a\right), \tag{2}$$

where E_a is the amplitude of the ac electric field, $\vec{\boldsymbol{1}}_{\boldsymbol{z}}$ is the unit vector in z direction and $\Delta\varepsilon$ is positive for the material used in our experiments.

Due to rubbing geometry, the director is inhomogeneous with the tilt angle close to 0^o in the center of the cell, and defined by the rubbing pre-tilt (2^0, -2^0) near the boundaries. When an ac voltage is applied and the electric field is in the z direction, the molecules in the bulk can rotate in two ways to align: clockwise or counter-clockwise (within the xz plane). Both directions have an equal probability. Different regions of the cell switch in opposite directions and domain walls are formed between them.

For the uniaxial material we should consider the ordinary and extraordinary refractive indices n_o and n_e respectively. The effective refractive index n_{eff} for a plane wave is given by:

$$n_{eff} = \frac{n_e n_o}{\sqrt{n_o^2 cos^2(\varphi-\varphi_k) + n_e^2 sin^2(\varphi-\varphi_k)}}, \tag{3}$$

where φ and φ_k are the tilt angle of $\vec{\boldsymbol{L}}$ (with respect to x) and the inclination angle of the propagation vector $\vec{\boldsymbol{k}}$ (with respect to z). When $\vec{\boldsymbol{k}} \parallel \vec{\boldsymbol{L}}$, we have $n_{eff} = n_o$, and when $\vec{\boldsymbol{k}} \perp \vec{\boldsymbol{L}}$, we have $n_{eff} = n_e$.

The electric torque related to optical illumination for an optical field with amplitude E_O is given by:

[*] E-mail: vars.nersesyan@gmail.com

$$\overrightarrow{\Gamma_O} = \frac{1}{2}\varepsilon_0(\mathrm{n_e^2} - \mathrm{n_o^2})(\vec{L}\cdot\overrightarrow{E_O})(\vec{L}\times\overrightarrow{E_O}), \qquad (4)$$

For the case of an optical beam incident on a director parallel with x ($\varphi=0$), the torque can be clockwise in the case of (a), counter-clockwise in the case of (b)), as it tries to align the director $\vec{L}$ parallel with the electric field E_o of the laser beam.

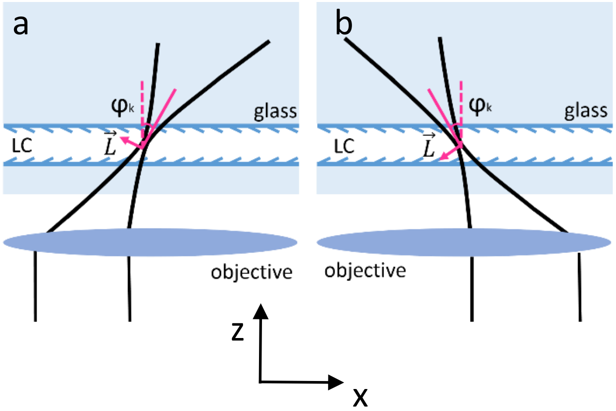

Fig. 1. Illustration of a focused laser beam incident in the liquid crystal cell with parallel rubbing (rubbing towards the right) through a microscope objective, a) with the *k*-vector of the beam having a positive tilt angle φ_k, b) with a negative tilt angle φ_k.

Let us consider the first case when a strong optical beam with tilt angle φ_k (positive or negative with respect to z-axis) enters a planar cell with parallel rubbing (Fig. 1 a, b). The director will slightly reorient due to the electric field of the optical beam. When a voltage above the threshold is applied, the electric torque related to a static electric field in the neighbourhood of the beam will rotate further in the same direction as caused by the optical beam. Near the surfaces the director remains due to the rubbing pre-tilt angle.

In case the laser beam is switched on after the application of the electric field, the influence will be minimal.

The liquid crystal material E7 (Merck) is used because of its relatively large optical anisotropy.

The liquid crystal cell has a thickness of 40 μm and is made of two ITO-coated substrates. The substrates are coated with nylon 6–6, rubbed and glued to each other with the rubbing directions parallel.

Due to the complexity and the sensitivity of the experiment, a Nikon Ti-Eclipse microscope is used together with an AndoriXon+EM-CCD camera to observe the switching of a nematic liquid crystal. For the optical field, an infrared (975 nm) laser beam is used, having a maximal power of 100mW before the microscope objective and linear polarization in the xz plane. The Gaussian laser beam is focused in the middle of the cell by a 60× oil immersion objective. The observation of the cell between parallel polarizers (along x) is done with a CCD camera mounted on the microscope.

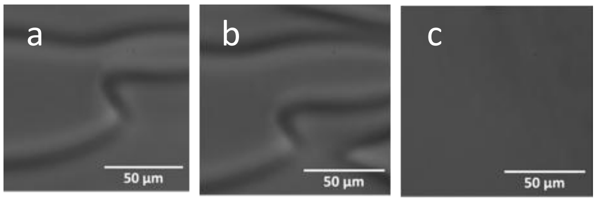

Fig. 2. Microscope transmission images of a planar LC cell, at different times after switching on the voltage (V_P=10V), without illumination: a) 2 s, b) 3 s, c) 6 s.

Figure 2 shows the switching of a planar nematic liquid crystal cell with parallel rubbing of glass substrates. Microscope transmission images are taken at (a) 2 s, (b) 3 s, (c) 6 s after switching on the voltage V_P = 10V. Randomly formed domains are formed and grown until only one domain remains.

Figure 3 illustrates the evolution of the domains in the case of a preliminary present infrared laser beam near the center. Figures (a,b,c), (d,e,f) demonstrate switching voltage conditions of 5V, 8V respectively for a beam power of 50mW and for φ_k = 33°. When the voltage is applied, initially a central (elongated) domain is visible around the position of the incident laser beam (Figs. 3, a,c).

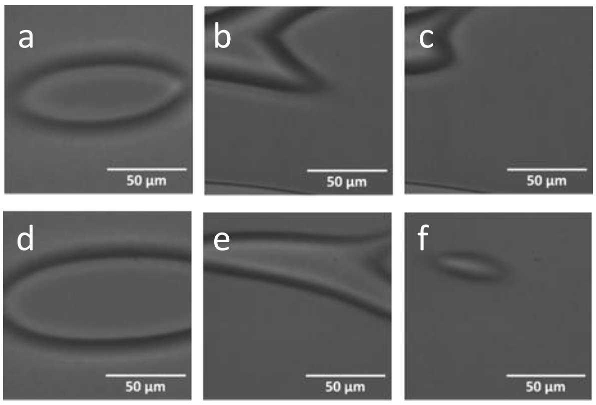

Fig. 3. Microscope transmission images, φ_k = 33°, power of the laser beam 75 mW. Time evolution of the domains due to the beam in the case of different voltage: (a, b, c) V_P=5 V, (d, e, f) V_P=8 V at different time points after switching: a) 2 s, b) 5 s, c) 7 s, d) 3 s, e) 8 s, f) 12 s.

Typically, this domain (and other domains with the same switching direction) enlarges and merges with domains that have the same direction of reorientation. Domains with the opposite reorientation shrink until they disappear completely. To demonstrate this, the cell was moved to image the disappearance of the last domains (Figs. 3 b, c, e, f). Figures 3 c, f visualize the dominance of the domain that was formed in accordance with the laser beam angle φ_k. Figure 4 shows the time evolution of the domains for an incident angle $\varphi_k = 10^o$ for two different powers of the laser beam: 30, 50mW respectively for (a, b) (c, d). It can be concluded that the formation and development of the domain is sensitive to beam parameters such as the angle φ_k and the beam power. In these particular cases (atypical) the domain that is formed by the laser beam does not become dominant, but shrinks (the final director distribution is related to the opposite switching direction).

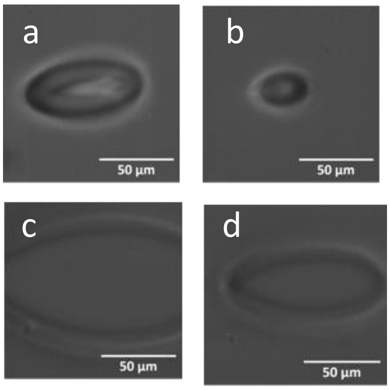

Fig. 4. Microscope transmission images after switching on the voltage (V_a=10 V) when $\varphi_k = 10°$ for two different powers of the laser beam: 30mW, 50mW (before the objective), a) 2 s, b) 4 s, c) 3 s, d) 6 s.

The last set of transmission images in Fig. 5 investigates the role of the direction of incidence, of the laser beam, in particular for opposite angles φ_k (see Fig. 1). Figures 5 a, c are for $\varphi_k = 33^o$ (clockwise rotation). In contrary, Fig. 5 b, d are for negative $\varphi_k = -33^o$ (counter-clockwise rotation). Figure 5 a, b show the growing initial domain near the beam; Figs. 5 c, d show a slowly shrinking domain before disappearing.

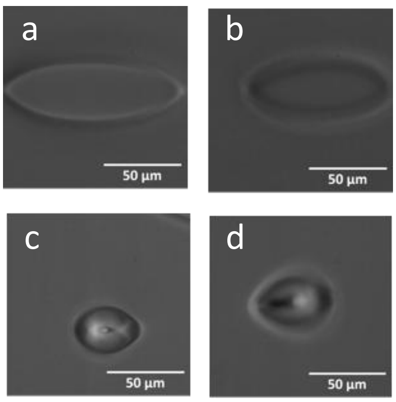

Fig. 5. Microscope transmission images in the case of the IR laser beam of 100 mW power and an angle of (a) $\varphi_k = 33°$, (b) $\varphi_k = -33°$. V_P=10 V, (a, b) expanding domain due to the beam; (c, d) last remaining shrinking domain; a) 3 s, b) 2 s, c) 17 s, d) 15 s.

It is interesting to note the asymmetry of the shrinking domain (and the mirror symmetry between Fig. 5 c, d). It is related to the optical behavior of the domain walls. In fact, the left and right domains have a top/bottom symmetry, but the image depends on the focusing/defocussing properties in relation with the microscope lenses (as illustrated in Fig. 6).

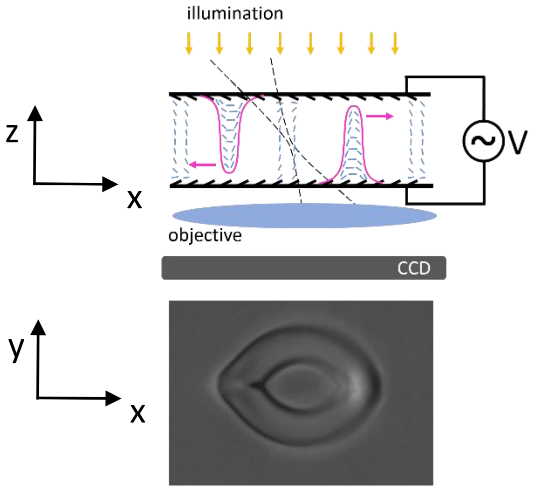

Fig. 6. Illustration of the domain walls in the xz-plane in the case of parallel rubbing and voltage presence. The illumination from the condenser is modulated by the cell and imaged on the CCD camera of the microscope. The domain wall can be related to the lower transmission image in the yx-plane.

The experiments confirm the concept of competitive switching when simultaneous electrical and optical fields are present in the liquid crystal. The domain walls tend to move in order to reduce their length and the associated elastic energy. For the cell with parallel rubbing the motion of the domain wall is mainly in the direction that increases the region around the laser beam.

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