Lateral Light Propagation in SSFLC Devices and Thermal Optical Nonlinearities

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Optical nonlinearities in ferroelectric liquid crystals are investigated experimentally by launching a laser beam laterally into a surface stabilized ferroelectric liquid crystal cell. Our set-up allows measuring both the propagation of the beam inside the cell and the changes induced in the liquid crystal layer. The first is possible due to scattering of light in the liquid crystal layer and the latter by using polarization microscopy. The observed effects are related to thermal optical nonlinearities.

Keywords Optical nonlinearity; lateral light propagation; surface stabilized ferroelectric liquid crystal cells

Introduction

Liquid crystals are partially ordered fluids, in such way that molecules are oriented along a certain direction. These materials are widely used nowadays in flat panel displays because of their extraordinary electro-optical properties. They also exhibit a number of optical nonlinearities with different origin. These nonlinear effects can be divided into two types: electronic and nonelectronic nonlinearities [1]. The electronic nonlinearities are very fast and are similar to nonlinear effects in other materials originating from a perturbation of the electronic wave functions of the molecules. The nonelectronic nonlinearities affect the temperature, molecular orientation, density, . . . of the liquid crystal and they are in general much slower, but require an optical power which is substantially lower.

In nematic liquid crystals these nonelectronic nonlinearities are well investigated and are mainly focused on the generation of holographic gratings [2]. Here, the light travels through the liquid crystal cell as in a display, perpendicular to the glass plates (i.e. transverse light propagation). In this work light travels laterally in the cell, so parallel to the glass plates. This configuration was used to generate spatial solitons in nematic liquid crystals using either thermal or reorientational nonlinear effects. In the thermal case, the soliton can be captured in an isotropic channel [3] or due to thermal indexing [4]. In the other case molecules are reoriented by the electric field of the light and this way it is possible to generate solitons of several millimeters with a few milliwatts of light power [5, 6]. The generation of these solitons is unfortunately very slow [7].
In ferroelectric liquid crystals (FLCs) or in general smectic materials these nonlinear effects are not well investigated. The lateral configuration was already used to investigate switching of a laser beam by using double refraction [8] or by changing the coupling between waveguides [9], but in these cases obviously no nonlinearities are used. Reorientational nonlinearity has been theoretically described [10] and experimentally observed [11] in smectic liquid crystal cells in the transverse situation. But for the lateral case, to our best knowledge, only theoretical predictions have been done on the possible nonlinear effects [12]. Therefore we present in this contribution the first experimental results for lateral light propagation and this work can be seen as a first step in understanding the optical nonlinear effects occurring in FLC cells. The final aim is the generation of spatial optical solitons in FLC cells either via reorientational or thermal optical nonlinear effects.

Fabrication of Cells and Experimental Set-Up

The cells are made using conventional technology for making LCDs [13]. Two glass plates with each a transparent conductor layer (ITO) and an alignment layer (nylon6) are glued together using glue mixed with spacers to insure a homogeneous thickness. No spacers are deposited outside the glue as the laser beam can be deflected when encountering a spacer ball. The glue pattern is such that the cell has a clean open entrance for injecting a laser beam while appropriate filling holes are available (Fig. 1). The cell has anti-parallel rubbing and the rubbing direction makes an angle of 22.5° with respect to the entrance. Using the FLC Felix 017–000 from Clariant (see Table 1 for properties) we were able to fabricate a Surface Stabilized Ferroelectric Liquid Crystal cell (SSFLC). The cell has some zig-zag defects due to the chevron structure [14]. At the entrance of the cell a lot inhomogeneities are present, but this is hard to avoid due to the air-LC interface, inhomogeneity of the alignment layer at the sides, etc.

When cooling down from the isotropic temperature, in the SmA phase the molecules are aligned along the rubbing direction. Cooling down further to the SmC* phase, the molecules tilt away from the rubbing direction, giving rise to two stable states. Roughly speaking (by assuming a cone angle of 45°) we can state that in one stable state, the molecules are aligned along the y-direction. In the other stable state the molecules are at 45° with respect to the y-direction. The reason why we chose to investigate this specific situation will be explained further.

![Figure 1](image)

**Figure 1.** A liquid crystal cell consists of two glass plates glued together with a FLC in between. Laser light can be injected in the cell from the left side.
The experimental set-up shown in Fig. 2 allows to inject a laser beam into the fabricated cells. A Nd:YAG laser is used with a wavelength of 1064 nm and a maximal power of 500 mW. A 40X objective is used to focus the Gaussian beam to a small spot with a waist of approximately 3 µm. The light traveling inside the cell can be observed due to scattering in the LC. Therefore another microscope objective in combination with a CCD camera is used, allowing us to record the trajectory of the beam inside the cell.

On the other hand it is also possible to achieve a polarizing microscope image of the region of the cell where the beam is present. For this we use a collimated light beam from a Xe lamp which is traveling through the cell. Crossed polarizers are used with a direction making an angle of respectively $\theta$ and $\theta + 90^\circ$ with respect to the y-direction. The image is again recorded by an objective lens and a CCD camera. In this way it is possible to observe the changes inside the cell caused by the optical nonlinearity.

![Figure 2. Experimental set-up. A laser beam is injected in the cell by means of a microscope objective. The cell can be placed in a temperature-controlled heating stage (not shown).](image)
Figure 3. Image of the laser beam inside the cell for different voltages, namely (a) $-2 \, \text{V}$ and (b) $+2 \, \text{V}$. The different propagation angle is an effect of double refraction.

Results

In general coupling light into a thin layer is technologically (due to *e.g.* vibrations) and theoretically more difficult than coupling into a thick layer. However, to achieve a SSFLC cell with little defects and good bistability it is best to keep the thickness as small as possible. This is because the helix has to be unwound by surface forces [15]. After testing several FLCs for different cell configurations we concluded that the Felix 017-000 material was a good choice as we could achieve a relatively uniform and homogeneous cell for a thickness of 6 $\mu\text{m}$. The low spontaneous polarization and large helical pitch is obviously related to this. For this thickness we could couple an acceptable amount of light into the cell. Fig. 3 shows the propagation of the laser beam inside the cell. The images are respectively for $-2 \, \text{V}$ and $+2 \, \text{V}$. The beam propagation clearly changes due to changes in the molecular orientation. The change in beam direction is caused by the effect of double refraction [8].

The initial idea was to achieve a nonlinear reorientational effect in the cell, namely to reorient the molecules by the electric field of the light. In order to reduce the absorption of the laser light in the liquid crystal and consequently also the heating of the liquid crystal, we used a laser in the near infrared [16]. To achieve a reorientational effect we tried the following procedure. The polarization direction of the laser light is oriented along the $y$-axis. After application of a square wave, *i.e.* consequently applying $+V$ and $-V$, with $V$ above the threshold voltage and the frequency sufficiently low, we removed the voltage or we applied a square wave below the threshold. We did it in a way such that the molecules remained in the state with an approximate angle of 45$^\circ$ with respect to the $y$-direction. This angle is chosen because the torque on the molecules due the electric field of the light is maximum for 45$^\circ$ between the direction of polarization and molecules [1]. With this nonlinear effect it might be possible to reorient the LC director in this cell and the reorientation we aimed for was a director reorientation on the smectic cone from the 45$^\circ$ orientation to the orientation along the $y$-direction. In this way the index of refraction increases for the $y$-polarized beam and self-focusing can be expected.

At an optical power of 400 mW there was a strong nonlinear effect visible, shown in Fig. 4. The first two images (a) and (b) show that indeed there is a difference between the low and the high optical power, proving the presence of a nonlinearity. An extra attenuator was placed in front of the CCD camera to avoid saturation of the CCD image. The third picture (c) shows the transmission image and demonstrates that the molecular orientation is changed in a region with an elliptic shape. The lighter region near the cell entrance is due to a slightly different molecular orientation as mentioned earlier.

The dark spot in Fig. 4.b is presumably caused by the appearance of an isotropic region in the LC, which means that the effect would be thermal. Due to the heating of the laser
beam the LC goes to the isotropic phase and this isotropic region appears near the focus of the Gaussian beam, where the intensity is maximum. In the isotropic phase, the scattering of light is quasi zero, which explains the dark spot.

The best proof comes from the transmission measurements. Changing the orientation of the crossed polarizers (the angle \( \theta \) in Fig. 2) has no effect on the central region in Fig. 4.c: it always remains black. Also by changing the voltage over the cell, the central region remains black. These observations indicate that there is a transition to the isotropic phase and that the observed effects are not of reorientational nature but thermal.

Figure 5 schematically depicts what is happening in the cell. The central temperature is higher than the clearing point and the central region is isotropic. The shells around it are the lower temperature phases, respectively the nematic and SmA phase.

The previous measurements were done at room temperature. If indeed the effects are thermal, measuring at higher temperatures, closer to the transition temperatures, should increase the effects. Therefore a hot stage was incorporated into our set-up and measurements were carried out at higher temperature, keeping the other parameters constant. In Fig. 6

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**Figure 4.** Image of the laser beam inside the cell, (a) for an optical power of 4 mW and (b) for an optical power of 400 mW. (c) Transmission image for 400 mW.

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**Figure 5.** Schematic drawing of the appearance of different phases in the cell as it is observed in Fig. 4(c) (left) and schematic representation of the temperature inside the cell (right).
transmission measurements are shown for the cell heated to a temperature of 55°C. These figures clearly show that the size of the different phase regions is much larger (note the different scale in Figs. 3 and 4) and the different regions are clearly visible due their different response to an applied voltage. The SmA phase can be identified by its independence on voltage. To identify the nematic phase we compare the zero voltage situation (Fig. 6.c) with the situation in Fig. 6.d where we apply a 10 V square wave (the orientation of nematic molecules reacts to the square of the electric field, not on the sign of the voltage). Between the central isotropic region and the SmA region we can see a small shell lighting up and this can be considered as the nematic region. This nematic region is much smaller than the SmA region, which is most likely due to the shape of the temperature gradient (Fig. 5).

While absorption in the liquid crystal is smaller by using near-infrared light [16], the absorption in the ITO increases (see for example [17]) and the absorption coefficient of the ITO is substantially larger than the one of the liquid crystal. Also the double waist of the optical beam (6 µm) is equal to the cell thickness so the heating of the liquid crystal is most likely due to absorption of light in the ITO. The absorption and thermal heating could be further reduced by putting a low index, low absorbing buffer layer on top of the ITO such as SiOx. On the other hand, thermal optical nonlinearities can be useful, since they are able to generate spatial solitons in nematics. But reorientational spatial solitons are more easily controllable (electrically).

Conclusions

SSFLC cells were fabricated with a thickness of 6 µm which combined few defects and sufficient incoupling of light. The transmission and scattering measurements on these cells clearly demonstrate optical nonlinear effects. The experiments show that the effects are related to thermal optical nonlinearities and that there is a phase transition. This means that it was not possible to trigger a reorientational nonlinearity but that the thermal nonlinearity
is the dominating effect for our configuration. Further experiments are planned for other configurations to investigate the relation between the different optical nonlinear effects.

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