Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713926090

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Online publication date: 06 August 2010

To cite this Article Jagemalm, Pontus , Hermann, David Sparre , Komitov, Lachezar and Simoni, Francesco(1998) 'Opto-thermal reorientation of nematics with two-fold degenerate alignment', Liquid Crystals, 24: 3, 335 — 340
To link to this Article: DOI: 10.1080/026782998207136
URL: http://dx.doi.org/10.1080/026782998207136

LIQUID CRYSTALS, 1998, VOL. 24, NO. 3, 335–340

Opto-thermal reorientation of nematics with two-fold degenerate alignment

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(*Received 9 July 1997; accepted 22 September 1997*)

The preferred direction of alignment of the liquid crystal molecules in nematics with two-fold degenerate alignment can be affected substantially by changing the temperature or by applying an electric field. As a result, an almost in-plane switching of the molecules occurs. Here, we report an opto-thermal reorientation effect in a nematic with two-fold degenerate alignment due to a local heating of the liquid crystal by a high power laser beam. The mechanism of this phenomenon is discussed. The opto-thermal reorientation of the molecules makes it possible to visualize the temperature distribution in the illuminated cell and some applications can be foreseen.

1. Introduction

The anchoring of liquid crystal molecules to solid substrates is an important factor in liquid crystal displays since it defines the type and stability of the liquid crystal alignment and has a strong impact on the display performances. One of the major requirements for displays is that the liquid crystal alignment must be stable and temperature independent in the whole operating range. However, as shown recently, if the alignment is two-fold degenerate [1–3], the preferred direction of alignment is indeed temperature dependent [3], and this then has a negative impact on the liquid crystal display performances. Therefore, two-fold degenerate alignment is regarded as inconvenient for conventional display applications. However, we may try to take advantage of the temperature dependence of the azimuthal angle of the preferred direction using opto-thermal reorientation (OTR). For instance we found, for this type of alignment, a temperature induced almost in-plane reorientation of the director which may reach, depending on the SiO_x evaporation angle and the liquid crystal material, a value of about 80 degrees. When the cell is being viewed between crossed polarizers this thermo-optic effect results in a substantial change of the optical appearance of the sample.

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In this paper we report the results of our study on opto-thermal reorientation of the molecules in a nematic cell with two-fold degenerate alignment due to local heating by the laser beam, and discuss some possible device applications.

2. Experimental

2.1. *Experimental set-up*

The experiments were performed using conventional cells of the sandwich type, consisting of two parallel glass substrates. The cell thickness was kept at 6 μm by evaporated SiO_x spacers and glue which was cured by UV hardening. The glass substrates were ITO coated (200 Å) soda lime glass from Baltracon (Z20) with a protective layer of SiO_2 (200 Å) and of 1·1 mm thickness. The alignment layer, consisting of a SiO_x layer of 200 Å thickness (measured along the surface normal), was evaporated obliquely on top of the ITO layer on the inner surfaces of the cell substrates. The SiO_x deposition took place at room temperature and in high vacuum (10^{-7} mbar, SiO Balzers BAK600). The set-up and functions inside the vacuum chamber were very similar to those that Janning [4] originally used, where the central component was a calibrated quartz oscillator that measured the thickness of the growing SiO_x layer. For surface orientation with a pretilt, the most uniform alignment was reached in a cell with the two glass plates

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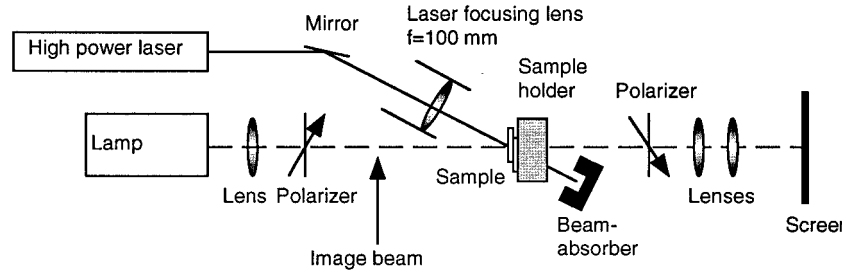

Figure 1. The set-up for the experiment with the high power laser beam.

assembled with the evaporation directions antiparallel to each other. The cells were filled with the liquid crystal E7 (from Merck) in the isotropic phase and then allowed to cool slowly into the nematic phase. Extra attention has to be given to the filling process since the selection of molecular orientation seems to depend strongly on this process [5].

Before inserting the cells in the high power laser beam set-up, they were characterized for the temperature dependence of the director azimuthal angle. To do this the cells were placed in a Mettler FP52 hot stage, which controls the temperature within $\pm 0{\cdot}1$°C, and the hot stage was in turn attached to the turntable of a polarizing microscope. The azimuthal angle of the director was then easily determined from the extinction position between crossed polarizers. An ordinary light table equipped with crossed polarizers is helpful in selecting cells with only one of the two two-fold directions, which is the same as saying that we want one single domain to cover all the cell area.

The experimental set-up is shown in figure 1. The sample was mounted on a stage so that it could be rotated around the sample normal, enabling the determination of the laser-induced radial distribution of the director azimuthal angle. An image light beam and a lens projection system were used to visualize the cell texture upon a screen. The cell was observed between crossed polarizers and an ordinary camera was used to take pictures of the projected image. To avoid stray light from the high-power laser beam, all components had to be well screened. The angle of incidence, which as usual is defined as the angle between the laser beam and the sample normal, was minimized, but still it was possible to see two spots where the laser beam hit the sample. The incoming beam was linearly polarized in the plane of incidence, defined by the laser beam and the sample normal. How tightly the laser beam was focused onto the sample could be varied by moving an $f = 100$ mm lens with respect to the sample position. After passing the sample, the laser beam was absorbed in a non-reflecting cavity. We used a continuous-wave Ar^+-ion laser with a maximum output of 5 W at the single wavelength $\lambda = 514{\cdot}5$ nm.

2.2. *Experimental results*

In cells with a two-fold degenerate alignment produced by oblique evaporation of SiO_x, the azimuthal angle of the preferred direction of alignment shows a temperature dependence [3]. In accordance with these previous studies we have measured the temperature dependence in the cells used in this study and found a behaviour here represented by the typical plot shown in figure 2. The effect of increasing temperature is that the molecules reorient themselves from initially lying close to the evaporation plane to approach gradually the direction perpendicular to the evaporation plane, i.e. the azimuthal angle φ reaches $\sim 90°$. This temperature-induced anchoring transition can change the preferred direction of alignment through more than 80° (see figure 2). The cells used in this experiment had SiO_x aligning layers evaporated at $\alpha = 74°$ which gives the highest possible reorientation with temperature for the investigated material E7. As the director azimuthal angle increases, the pretilt from the substrate decreases from about 20° close to the evaporation plane or nearly zero for $\varphi \approx 90°$ [3].

The aim of the present study was to use the temperature-induced reorientation described above by controlling the temperature of the liquid crystal material

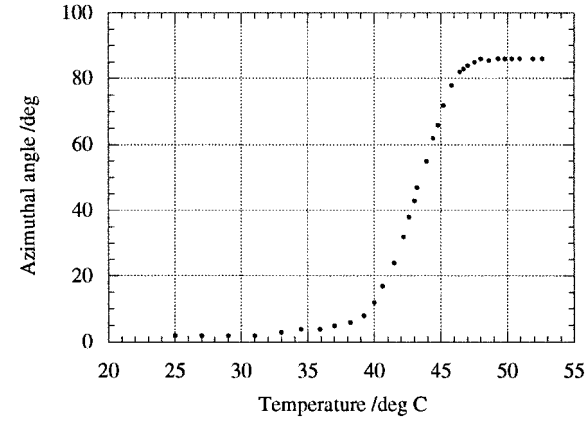

Figure 2. The azimuthal angle of the director as a function of temperature in a cell filled with E7 and with SiO_x aligning layers evaporated at $\alpha = 74°$. The values were measured upon cooling from the isotropic phase.

with a high power laser beam and thereby change the optical properties of the cell. After characterizing the cell in the polarizing microscope it was inserted in the set-up for the high power laser beam as shown in figure 1. The sample was rotated so that its optic axis made 45° with the crossed polarizers. First, the area where the laser beam hits the sample was heated at maximum power for a short time and then stabilized at an optical power of 2·4 W. The influence of the local heating on the liquid crystal alignment is shown in figure 3.

Consider the circular pattern with concentric rings in figure 3. In the centre the temperature is higher than the isotropic–nematic (I–N) phase transition temperature and due to the lack of birefringence the crossed polarizers give extinction. Moving outwards in the circular pattern from the I–N transition border, the director reorients as the temperature decreases. At some halfway position the director orientation, and thus also the optic axis, coincides with the polarization direction of one of the polarizers which then yields a black ring (extinction). The spot where the laser beam impinges on to the sample can be seen as a small green area. As is evident from figure 3, the extension of the beam ($w \sim$ beam radius $\approx 0{\cdot}1$ mm) is in this case much less than the characteristic length ($l \approx 4$ mm) over which the reorientation of the nematic director occurs.

The temperature gradient inside the sample can naturally be spread over a larger radial distance by heating the sample and the sample holder. Then it should also be possible to get a wider radial range over which the thermal reorientation occurs. This was realized as shown in figure 4 where the ambient temperature was raised to about 35°C (compare also with figure 2).

If the laser power is decreased or the laser beam radius is increased at constant power, then the temperature in the central area can be lowered to below the transition temperature for the I–N phase transition. This means that we avoid the isotropic area in the centre and just use the reorientation effect in the nematic phase. As an example, with a less tightly focused beam than used above, we were able to achieve an 80° reorientation of the director in a circular area of about 0·9 mm radius, then completely covered by a 5 W laser beam. Of course, a temperature gradient occurs outside the illuminated area, but with successively smaller temperatures as the distance from the centre increases and, as a consequence, the reorientation decreases. We should also expect a temperature gradient following the gaussian intensity distribution for the laser beam itself. At this stage however, it was difficult to obtain the temperature distribution in the area covered by the beam due to the strong scattering of the laser light. The achieved alignment could be observed just after switching the laser beam off, but with a short relaxation time to lower temperatures and hence a quick reorientation effect; other methods than the one to be described below are necessary to map successfully the director configuration in this last case.

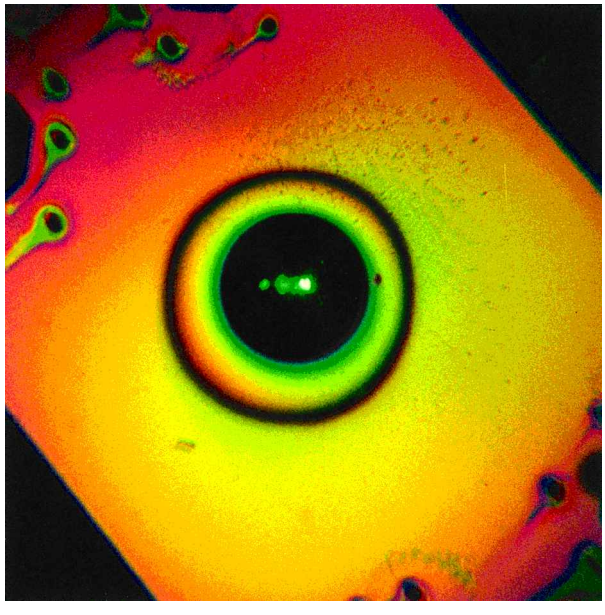

Figure 3. A cell with temperature dependent director orientation illuminated with a high power laser beam (green spots) and viewed between crossed polarizers. The laser power was 2·4 W and the beam radius approximately 0·1 mm.

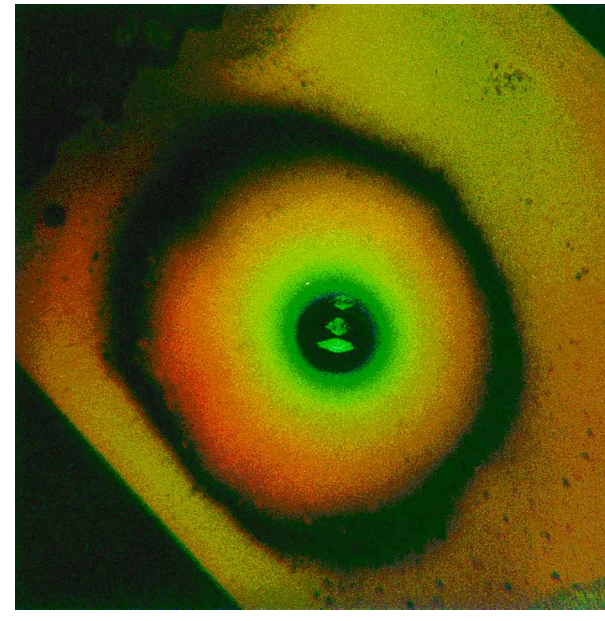

Figure 4. Similar to figure 3 but with the sample and sample holder heated to approximately 35°C. The power of the laser beam was less than in figure 3 (here $\sim$1 W).

By simultaneously rotating the two crossed polarizers, the director configurations in the cells were determined (alternatively, only the samples could be rotated). The black ring which represents the extinction direction (see figure 3) can then be seen to increase or decrease its radius. Doing this in steps of ten degrees gives a satisfactory map of the configuration, which is schematically shown in figure 5.

Combining the results from figure 2, where the azimuthal angle is given as a function of temperature, and the results from the plot of the azimuthal angle versus radial distance (figure 5), we obtain the temperature in different areas of the cell as a function of the radial distance from the high power laser beam, as shown in figure 6. In figure 6 we have included one measurement with the liquid crystal material ZLI-2806 (from Merck Ltd) which has a clearing point at around 100°C. This

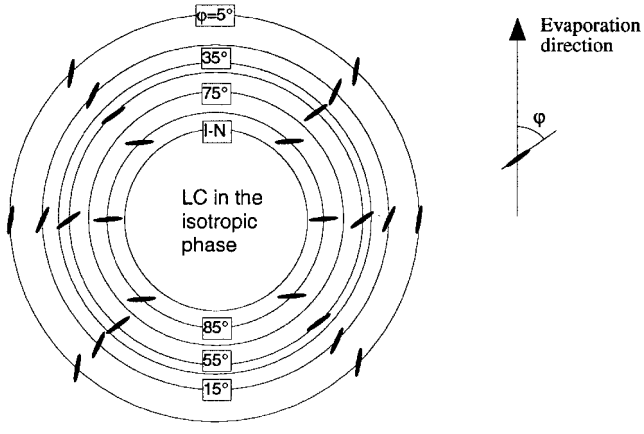

Figure 5. Schematic representation of the director configuration in cells as shown in figures 3 and 4. The number of degrees refers to the azimuthal angle, φ, of the director (zero is along the evaporation plane).

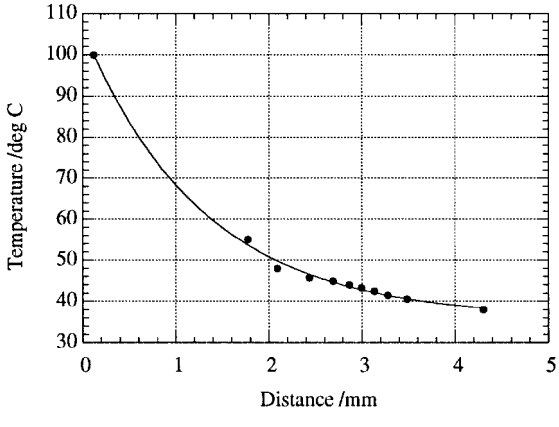

Figure 6. A plot of the temperature in the liquid crystal cell as a function of the radial distance from the laser beam. The line is a curve fit of equation (2) to the experimental data (dots). The laser power was 2·4 W and the beam radius ~0·1 mm.

was done in order to obtain the temperature close to the spot where the laser beam impinges onto the sample. Hence, this measurement point gives the possibility of mapping the temperature distribution over a longer distance. It should be noted here that the isotropic to nematic phase transition in ZLI-2806 occurs at a radial distance of about 0·15 mm from the centre of the laser beam, while the laser beam radius is approximately 0·1 mm (at 2·4 W power). Indeed, the isotropic area then barely exceeds the laser beam area. The sample used for the ZLI-2806 mixture had the same properties as the ones used for the investigation of E7, as described in § 2 above.

3. Discussion

The liquid crystal is heated in the centre where the laser beam impinges, due to absorption of some of the laser light in the ITO and SiO_x layers on the glass plate surfaces [6, 7]. The high temperature in the centre creates a cylindrically symmetric temperature gradient in the liquid crystal; heat diffuses outwards from the centre. A simple model describing the heat diffusion is given by a Debye relaxation equation, assuming a single relaxation time [8, 9]. In terms of the radial diffusion distance r from the point of impingement of the laser beam, we write this as

$$\frac{dT}{dr} + \frac{1}{r_D} T(r) = A \tag{1}$$

where r_D is a characteristic diffusion distance and A is an inverse diffusion constant. The solution of equation (1) is given by

$$T(r) = A r_D + B \exp(-r/r_D) \tag{2}$$

where B is related to the temperature $T_0 = T(0)$ at the spot of impingement of the laser beam as

$$B = T_0 - A r_D. \tag{3}$$

Equations (1)–(3) are seen to give a good description of the experimental data in figure 6, where a curve fit (solid line) given by equation (2) is shown. The following parameter values are obtained from the fit:

$$\begin{aligned} A r_D &= (35{\cdot}86 \pm 1{\cdot}02)^\circ\mathrm{C} \\ B &= (70{\cdot}34 \pm 1{\cdot}24)^\circ\mathrm{C} \\ r_D &= (1{\cdot}29 \pm 0{\cdot}07)\ \mathrm{mm} \\ \chi^2 &= 6{\cdot}417 \\ R &= 0{\cdot}99893 \end{aligned} \tag{4}$$

where χ^2 is the mean square error and R is the regression coefficient of the fit. The results in (4) give $A = (27{\cdot}8 \pm 2{\cdot}3)^\circ\mathrm{C\,mm^{-1}}$ and $T_0 = (106{\cdot}2 \pm 2{\cdot}3)^\circ\mathrm{C}$.

The temperature T_0 is related to the laser beam intensity, I, and assuming a single relaxation time, it can

be expressed as [6, 7, 10, 11]

$$T_0(I) = T_{\text{ambient}} + kI \tag{5}$$

where the coefficient k is given by [6, 7, 10, 11]

$$k = \frac{\tau_T \alpha}{C_P} \tag{6}$$

where τ_T is the thermal relaxation time, C_P is the heat capacity per unit volume and α is the absorption coefficient. The absorption coefficient is defined through the relation

$$Q = \alpha I \tag{7}$$

where Q is the production of heat per unit volume and time. With $T_0 = 106°C$, $T_{\text{ambient}} = 22°C$, $P \sim 2{\cdot}4$ W and a laser spot radius of about 0·1 mm, $k \sim 0{\cdot}01$ K cm^2 W^{-1} is obtained. This value is about one order of magnitude lower than that reported in a previous study of opto-thermal reorientation in chiral smectic liquid crystals [12]. Since the heat absorption takes place in the aligning layers of the glass substrates, the main reason for the difference could be the greater thickness of the aligning layers used in ref. [12] than in the present study.

The thermally induced in-plane reorientation of the liquid crystal molecules in nematics with two-fold degenerate alignment results in a large deviation of the preferred direction of alignment from the initial one. Our experiment shows that it is possible to exploit this effect to map the temperature distribution across the liquid crystal cell, as far as a calibration linking the azimuthal angle to temperature is available. The novelty of the method is that it allows a direct knowledge of the 'local' temperature of the sample. In our case a laser beam with a high c.w. power was used as point heat source. Of course the reported technique can be used to monitor how the temperature distribution is affected by laser spot size, intensity and duration of illumination, as well as by cell and liquid crystal material parameters. Such a study would certainly give new information about opto-thermal effects in liquid crystals.

As a matter of fact, the light excitation will also induce a strong thermal indexing, however this phenomenon does not affect the method presented. The mapping is performed just by checking the location of the dark ring, and is not dependent on changes in optical anisotropy which on the contrary will affect the intensity and distribution of the observed light pattern. In particular, when observing the sample between crossed polarizers using white light, a change of optical anisotropy will change the wavelength for which the half-wave condition of constructive interference between the ordinary and extraordinary rays is fulfilled. The result is a change of the colour of the texture. As may be noted in figure 3, there is in fact a gradual colour change when moving radially outwards from the I–N transition: green–yellow–orange–red. Then comes the black ring which originates from the molecular reorientation. The effects of reorientation and thermal indexing are thus separable.

A development of the present method might be the use of a pump–probe technique, i.e. scanning the illuminated sample by a single laser beam of low intensity to probe the local director alignment. In this situation, it may be of great interest to investigate the liquid crystal orientation inside the area illuminated by the exciting light spot. As an example, the use of a spatially modulated laser beam can allow us to investigate under what circumstances the temperature modulation is kept or washed out in the medium.

Of course the effect of opto-thermal reorientation demonstrated in this work can also be used to design new optically addressed devices. A simple scheme is an opto-optical switch realized using the same pump–probe geometry; in this case the transmittance of the probe beam can be controlled by the exciting beam. Another field of possible application might be spatial filtering as recently demonstrated using a different approach [13].

4. Conclusions

We have studied a light-induced in-plane reorientation in nematics with two-fold degenerate alignment due to the indirect heating of the liquid crystal layer caused by high power laser light absorption in the ITO and SiO_x layers. Since the azimuthal and polar angles of the preferred direction of alignment are coupled and temperature dependent, the distribution of the temperature in the illuminated cell can be easily visualized. In fact, the temperature-induced anchoring transition can be successfully utilized in different optical elements for the almost in-plane switching of the liquid crystal molecules.

D. Hanstorp and J. Enger (Atomic Physics Group at Chalmers University of Technology) are gratefully acknowledged for providing access to the high power laser set-up. This work was supported by the Swedish Research Council for Engineering Sciences.

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