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Electrically controlled director slippage over a photosensitive aligning surface; in-plane sliding mode

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We have studied the electro-optical characteristics of a homogeneously aligned nematic liquid crystal (LC) with weak planar anchoring of the director at the bounding substrates. By using the in-plane switching (IPS) of the LC which is achieved by an in-plane electric field, the driving voltage was confirmed to be far less than that of the conventional IPS mode in which both substrates possess strong anchoring characteristics. Moreover, because of the absence of strong subsurface director deformations, the cell could operate optically in the Mauguin regime. Using these features we propose a new type of LC switching mode—in-plane sliding (IPSL) mode. We have realized this mode in a LC cell comprising one reference substrate with strong director anchoring and one substrate covered with photoaligning material with weak anchoring. In order to clarify the switching process, we derived a simplified expression for the threshold voltage on the assumption of uniformity of the in-plane electric field. For the dynamical response of the LC to the in-plane electric field, the switching on and off relaxation times of the IPSL mode were found to be longer than for the traditional IPS mode. However, we have proposed an optimized cell geometry for the IPSL mode with a response time comparable to that of the IPS mode.

1. Introduction

The electro-optical characteristics of liquid crystals (LCs) have made them one of the most promising materials for practical applications in displays. A variety of principles of LC displays have been proposed. They differ in the type of reorientation modes and design of the LC cell. Twisted nematic (TN) [1] and super-twisted nematic (STN) [2] cells have been much used in practice, but the viewing angle characteristics have been recognized as a major weakness of the TN and STN based devices.

An increasing number of approaches have been tried to overcome this drawback. The most promising involve compensation of the optical phase retardation [3] and the multi-domain technique [4, 5]. Averaging the transmission of each domain, one can improve the viewing angle characteristics, but a decrease in the contrast ratio for oblique viewing could not be prevented and is due to the increased transmission in the dark state. The multi-domain mode devices also require a complicated process in the manufacturing stage. For the phase compensated devices it is difficult to maintain stable control using a bias voltage.

One feasible method to solve these problems has been proposed quite recently [6–12]. The idea was to use the in-plane switching (IPS) mode. In this mode the nematic LC is aligned homogeneously between the aligning substrates. Both substrates were covered with polymer material that provides strong anchoring of the LC. Interdigital comb shaped electrodes are placed onto one of the substrates. The director at the initial stage (without the electric field) coincides with the polarization axis of the polarizer. The polarizer and analyser are set at right angles to each other, so the configuration forms the black state when no electric field is applied.

By applying the in-plane electric field, the director gradually deviates from the polarization axis while

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remaining in the plane of the substrates. In a low electric field, polarization of the incident light follows the smooth director deformation over the cell (so-called Mauguin regime). Increase in the field leads to an increase of the subsurface director deformation and breaking of the Mauguin regime. The light transmission then gradually increases because of the phase retardation between the ordinary and extraordinary rays.

The variation of birefringence with the viewing angle direction in the IPS mode is much smaller than in the TN and STN modes. This results in excellent viewing angle characteristics for this mode. At the same time, the IPS mode has several drawbacks regarding its application in mass production. The main problems are the low brightness of the IPS LCD with typical driving voltages due to the large area of non-transparent interdigital electrodes, and the white colour shift into the blue and yellow for large viewing angles.

Attempts to improve the characteristics of the IPS mode have been made during recent years. The white colour shift can be suppressed by using a multi-domain structure with a chevron-like electrode structure [13, 14]. To improve the low brightness of the IPS LCD, Kelly *et al.* [15] proposed a new mode which combines the concepts of the IPS and vertical aligning modes. However, the driving voltage is very high (more than 20 V) and prevents the successful application of the IPS mode in the manufacture of LCDs.

In order to increase the brightness of the IPS LCD, we need to decrease the driving voltage, which enables an increase in the distance between interdigital electrodes, so resulting in an increase of aperture ratio [16]. There are three principal ways to decrease the value of the driving voltage. First, one can optimize the LC parameters, e.g. increase the value of the dielectric anisotropy, $\Delta\varepsilon$. Second, we can optimize the cell geometry—distance between electrodes, angle between the director on the substrates, cell thickness, etc. Finally, it is possible to use aligning surfaces with weak anchoring energy W, which allows surface director rotation even with a small electric field [17–19].

The last option became available recently with the development of photoaligning materials, the anchoring properties of which can be effectively controlled by exposure to polarized UV light [20, 21]. One of the promising photoaligning materials is poly(vinylcinnamate) (PVCN). Chigrinov *et al.* [19] and Andrienko *et al.* [22] demonstrated that the surface anchoring energy of a PVCN-treated substrate can be tuned in the range (10^{-4}–10^{-2}) erg cm^{-2}. However, most of the PVCN materials have a strong alignment memory effect, i.e. anisotropic adsorption of the LC molecules on the aligning surface. This effect results in an increase in the initially weak anchoring and causes strong anchoring of the LC. The alignment memory effect depends on the chemical structure of the photosensitive cinnamoyl fragment of the photoaligning material [23]. Thus, we have observed a strong memory effect on a surface of *ortho*-fluoro-PVCN and a negligibly small memory effect with the corresponding *para*-PVCN-F surface. Thus, the *para*-material can be used for assembling an IPS mode cell with weak surface anchoring.

In the present paper we report this novel concept for in-plane director reorientation. It allows a significant decrease in the driving voltage compared with the standard IPS mode, but naturally encapsulates the main advantage of the IPS mode—its superior viewing angle characteristics. We shall refer to this phenomenon as the in-plane sliding mode (IPSL). Basically, we studied the electro-optic characteristics of a cell that comprises one strongly anchoring substrate and one substrate with controllable anchoring strength. The weak anchoring lets the director slide over the aligning surface in the in-plane electric field. The director sliding decreases the driving voltage, while at the same time increasing the response time. However, the increase in the response time can be compensated by a proposed optimization of the LC cell design.

2. Director reorientation in the IPS cell with weak anchoring

An exact treatment of the electro-optics of the IPS cell is clearly beyond the scope of this paper. Indeed, three separate problems should be solved in order to obtain a complete description of the IPS mode [24]. First, it is necessary to obtain a reasonable electrostatic potential resulting from the striped electrodes. Second, we need to calculate the director distribution that results from this potential. A large anisotropy of the LC dielectric susceptibility makes the situation even more complicated, since the Maxwell equations and the equations for the director should be solved together. Finally, we must calculate the scattered light intensity due to the predicted director distribution. However, a simplified treatment can give an adequate physical picture of the director reorientation in the cell. Indeed, many investigations of the IPS effect use the model that the LC director rotates, driven by a uniform in-plane electric field [7, 10, 13]. With this assumption, the electric field E in the cell is homogeneous, parallel to the substrates, and relates to the applied voltage U as

$$U = \mathrm{E}d$$

where d is the distance between electrodes.

We also restrict our consideration to the threshold geometry. This means that the initial director distribution is parallel to the substrates and the applied electric field is perpendicular to the easy axis (figure 1).

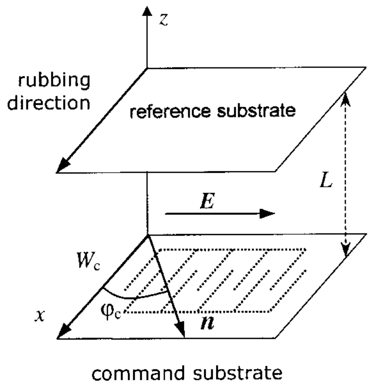

Figure 1. A schematic LC cell structure for IPS and IPSL modes.

The boundary conditions reflect the experimentally required situation. The reference substrate possesses strong anchoring and provides initial planar alignment of LC in the cell. The anchoring energy of the control substrate, W_c, can be tuned.

For the given geometry the free energy of the twist director deformation can be expressed as

$$F_b = S\int_0^L \left[\frac{1}{2}K_2\left(\frac{\partial\varphi}{\partial z}\right)^2 - \frac{\varepsilon_a}{8\pi}E^2\sin^2\varphi\right]dz - \frac{1}{2}W_c\cos^2\varphi_c \qquad (1)$$

where φ is the angle between the x axis and the director. Easy orientation axes are along the x axis, W_c is the anchoring energy of the control surface, K_2 is the twist elastic constant, S is the area of the substrates.

Minimizing the total free energy of the cell (1), one can obtain the equations for the director and the boundary conditions

$$L^2\frac{\partial^2\varphi}{\partial z^2} + \frac{\xi_E^2}{2}\sin 2\varphi = 0 \qquad (2)$$

$$\left[L\frac{\partial\varphi}{\partial z} - \frac{\xi_c}{2}\sin 2\varphi\right]_{z=0} = 0 \qquad (3)$$

$$\varphi|_{z=L} = 0$$

where $\xi_E = U(L/d)(\varepsilon_a/4\pi K_2)^{1/2}$ is the dimensionless electric field, and $\xi_c = W_c L/K_2$ is the anchoring parameter on the control surface.

Analysing the stability of the initial director distribution, $\varphi = 0$, we obtain the implicit equation for the threshold voltage U_{th}

$$\xi_c = -\frac{\xi_E^{th}}{\tan\xi_E^{th}}. \qquad (4)$$

Equation (4) gives the threshold voltage U_{th} as a function of the anchoring strength of the LC with the control surface, the cell thickness, and the distance between the interdigital electrodes. With this dependence we can describe the effect of the decrease of the threshold voltage for weak anchoring.

The dependence of the threshold voltage on the anchoring strength on the control surface given by equation (4) is plotted in the inset of figure 2. It is seen that a decrease of the anchoring energy results in a considerable decrease of the threshold voltage; it can be half that of the threshold voltage of the IPS mode. Indeed, in the case of infinite anchoring on both substrates ($\xi_c = \infty$), equation (4) can be solved explicitly and gives the solution $\xi_E^{th} = \pi$, or the threshold voltage for the standard IPS mode

$$U_0 = \pi\frac{d}{L}\left(\frac{4\pi K_2}{\varepsilon_a}\right)^{1/2} \qquad (5)$$

which agrees with the formula obtained in [10]. At the same time, for $\xi_c = 0$ (no anchoring) the solution is $\xi_E = \pi/2$, i.e. the driving voltage is half U_0.

However, the finite anchoring on one of the surfaces not only results in a decrease of the threshold voltage; it is also clear that the electric field turns the director at the control surface. To examine the equilibrium director distribution we solved the system of equations (2) and (3) numerically. The corresponding dependences for IPS and IPSL cells are presented in figures 3 (*a*) and 3 (*b*). It is seen that the deviation of the director on the command surface with weak anchoring can be rather big. As a result, the light transmission is no longer only a function of the phase retardation between the ordinary and extraordinary light waves. It also depends on the director deviation on the surface. This allows us to propose a new type of IPS mode—the in-plane sliding (IPSL) mode.

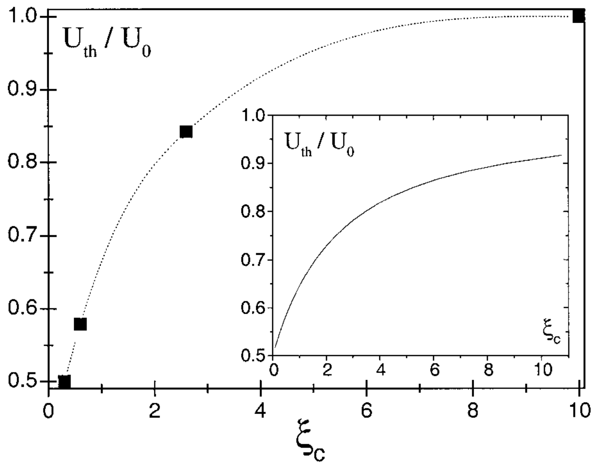

Figure 2. Dependence of the threshold voltage on the anchoring parameter. Inset: theoretical prediction for this dependence.

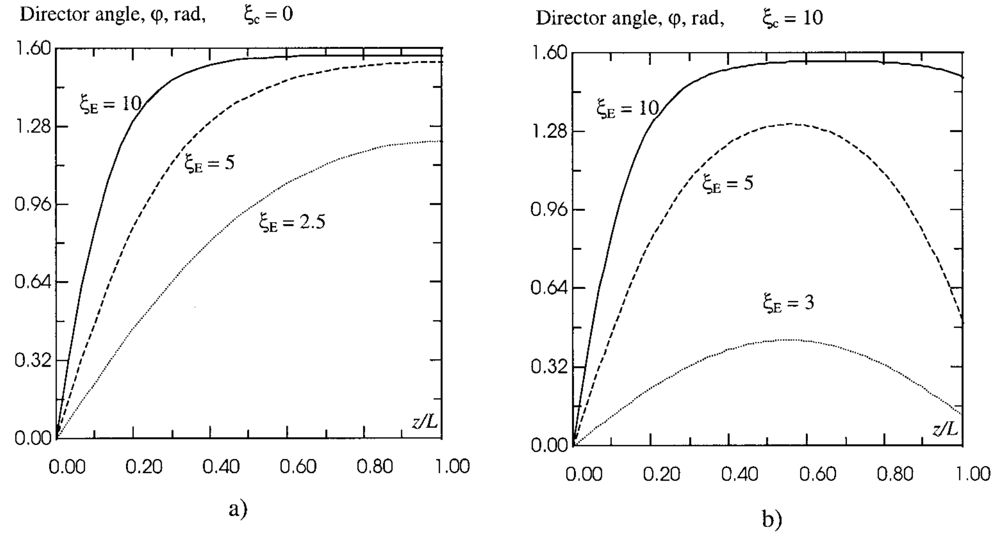

Figure 3. Director distribution in the cell with (*a*) a small anchoring parameter on the control surface, IPSL mode; (*b*) strong anchoring on the control surface, traditional IPS mode.

In the IPSL mode, the polarization of the light beam is parallel to the easy axis on the reference surface, and crossed polarizers provide an initial black state of the cell. The electric field reorients the director in the LC bulk and on the command surface. The polarization of the test beam follows the director rotation over the cell. As a result of the phase retardation between ordinary and extraordinary light waves and tracing of the surface director rotation by the polarization on the command surface, the light transmission increases.

The proposed IPSL mode, in addition to giving small threshold and driving voltages, should also encapsulate the superior viewing angle characteristics of the classical IPS mode.

3. Experimental

The experiments were carried out in combined IPSL cells consisting of two glass substrates with the nematic LC in between. The cell thickness was determined by cylindrical spacers with diameter 5 μm. The reference substrate was covered by a rubbed polyimide layer, which provided strong and slightly tilted alignment of the LC along the rubbing direction (pretilt angle $\theta_{PI} = 1.5°$). The command substrate was covered with the interdigital electrode pattern. The width of the electrodes was 5 μm and inter-electrode distance was 10 μm.

The electrode pattern was spin-coated with a layer of *para*-PVCN-F*. This layer was irradiated with polarized UV light from a Hg-lamp to produce an easy orientational axis perpendicular to the direction of the interdigital electrodes. The intensity of the UV light was about 5 mW cm^{-2} in the plane of the substrate. The exposure time, t_{exp}, was 0, 5, 10, 30 and 300 s which corresponds to a change in the azimuthal anchoring energy for the LC 5CB in the range 2×10^{-4}–10^{-2} erg cm^{-2} (see figure 4 where the results from [22] are reproduced).

The tilt angle, φ_0, of the LC 5CB on *para*-PVCN-F* layer also depended on the exposure time. The dependence $\varphi_0(t_{exp})$, measured using the rotation technique [25], is presented in figure 5.

The IPSL cells were filled with 5CB in the nematic state. The cells were set between crossed polarizer and analyser. The LC director was parallel to the polarizer, i.e. the black state corresponded to the off-state. Because of the weak planar anchoring on the command surface and the strong anchoring on the reference substrate, the tilt angle on the command surface, φ_{com}, was 1°–2° for short exposures ($t_{exp} = 0, 5, 10$ s). Longer exposures provided zero tilt angle. The electric field (100 Hz, 0–10 V)

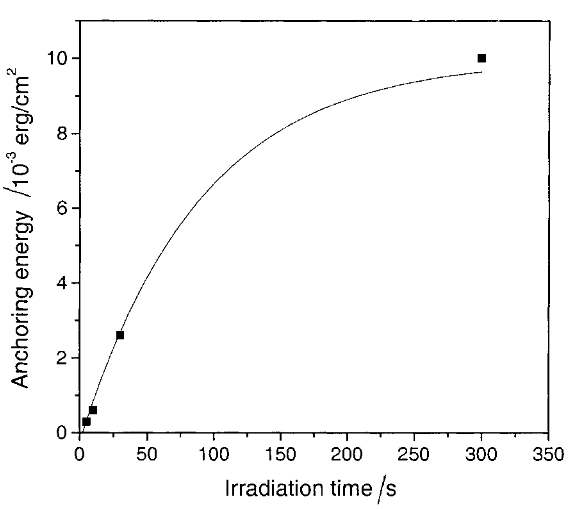

Figure 4. Anchoring energy of *para*-PVCN-F*–5CB as a function of the UV exposure.

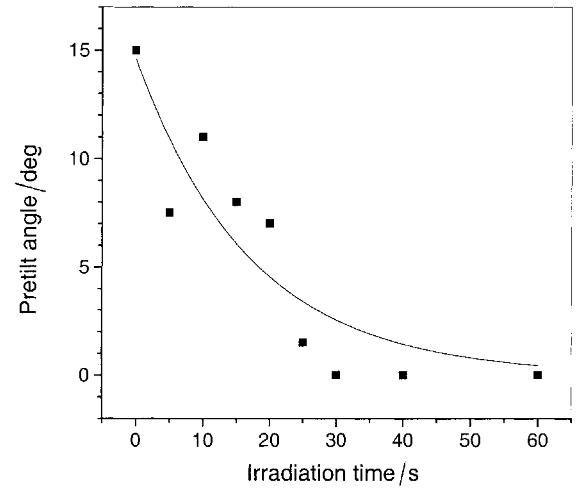

Figure 5. Dependence of the tilt angle on the UV exposure.

was applied to the interdigital electrodes and the light signal behind the analyser was detected by the photodiode attached to a computer. In addition, the electro-optical characteristics of the cells were measured.

The measurements of the transmittance–voltage characteristics obtained for different UV exposure times are presented in figure 6. It is seen that both threshold and driving voltages decrease with decrease in the UV exposure, i.e. with the decrease in anchoring energy. In figure 2 the dependence of the threshold voltage on the anchoring parameter is presented. One can see that this dependence qualitatively agrees with theoretical estimations (inset of figure 2), and extremely small threshold and driving voltages can be achieved ($U_{\rm th} = 0.95$ V, $U_{\rm dr} = 1.5$ V in comparison with $U_{\rm th} = 1.9$ V, $U_{\rm dr} = 5$ V in the case of strong anchoring).

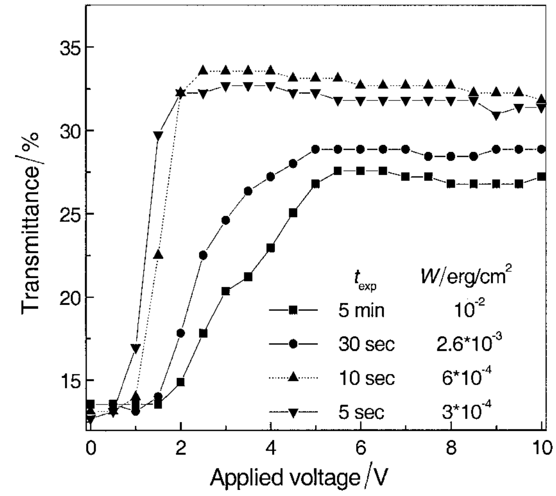

Figure 6. Typical transmittance–voltage characteristic of the IPSL mode. The driving voltage decreases significantly with decrease in the anchoring energy.

We found that for the cell with weak anchoring ($t_{\rm exp}$ = 5 and 10 s), rotation of the analyser allowed us to achieve the dark state over all the range of an applied electric field. This means that the test light beam remained linearly polarized after propagating through the cell. Therefore, one can conclude that the IPSL cell operates in the Mauguin regime.

We measured the viewing angle characteristics of the IPSL samples and found that they do not depend essentially on the exposure time and are analogous to the viewing angle characteristics of the traditional IPS mode. Therefore, the IPSL mode does encapsulate the excellent optical characteristics of the IPS mode, while at the same time providing lower driving voltages.

The essential drawback of the IPSL mode is its slow dynamics. The time of director reorientation back to the initial off-state increases considerably for cells with weak surface anchoring. Indeed, for the traditional IPS mode, the characteristic decay time, $t_{\rm off}$, is determined by the LC constants and is proportional to the square of the cell thickness, L^2. Because of weak anchoring, the effective cell thickness is effectively larger than L. In particular, it is equal to $2L$ for zero anchoring on the command surface. We obtained the value $t_{\rm off} = 120$ ms for the smallest exposure time ($t_{\rm exp} = 5$ s) which is twice that achieved for the traditional IPS cell.

However, the IPSL cell geometry used in our experiments was not optimized. Our attempts to match an appropriate LC material and the geometry of the IPSL cell have allowed us to achieve both low driving voltage characteristics and a relatively fast response. We have made the first attempts to optimize the characteristics of the IPSL mode in a cell with the LC MLC-9704 (Merck, $\Delta n = 0.08$, $\Delta\varepsilon = 8.5$) and a photosensitive aligning material poly(vinylsiloxane-cinnamate) (PVSN). We have optimized the transmittance–voltage and response time characteristics by changing the anchoring energy on the command surface and varying the angle between the easy axis on the test surface and the direction of the electric field (pretwist angle). The results of this optimization are presented in figure 7. One can see that the cell is characterized by rather low threshold and driving voltages, $V_{\rm th} = 1.5$ V, $V_{\rm dr} = 3.3$ V, and reasonably fast total response time ($t_{\rm on}$ = 23 ms, $t_{\rm off}$ = 41 ms).

4. Conclusions

In conclusion, we have studied the electro-optical effects and switching principles of a nematic liquid crystal subjected to an in-plane electric field in a cell with weak surface anchoring. As a result, we have proposed a novel concept for the in-plane switching mode in which the director can slide over the command surface—the in-plane sliding (IPSL) mode. The most outstanding features of the IPSL mode are a significant decrease in the driving

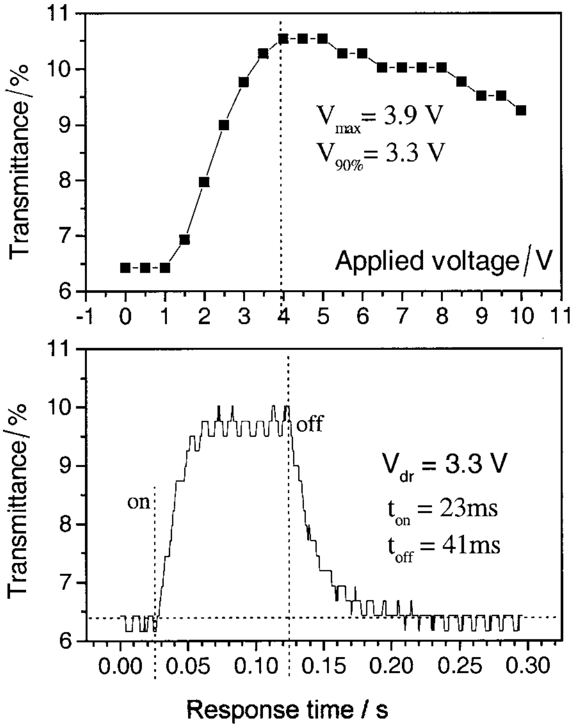

Figure 7. Transmittance–voltage and response time characteristics of the IPSL cell with optimized response time.

voltage and even better optical characteristics in comparison with the traditional in-plane switching mode. The IPSL mode has been realized in a combined LC cell with one control substrate covered with a special type of photoaligning material with weak anchoring and no surface memory effect.

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