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Dynamics of twisted nematic liquid crystal pi-cells

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A twisted nematic liquid crystal pi-cell with fast optical response time of 2.2 ms was prepared. We investigated the dynamics of this cell and observed the back-flow-induced optical overshoot phenomena both in homeotropic-to-planar state transition and planar-to-homeotropic state transition. We analyzed the behavior of the director and found that there is a tip-over phenomenon when the field is removed from relatively high voltage (>6 V). More important, the fluid flow effect results in the reverse twist both in the rising process and the decay process. Consequently, the reverse twist increases and decreases the effective phase retardation on the optical rising and decay process, respectively, and thus speeds up the optical response in both stages. © *2002 American Institute of Physics.* [DOI: 10.1063/1.1480880]

Twisted-nematic (TN) liquid crystal cell has been widely used in the active matrix liquid-crystal display technology. Unfortunately, a serious problem with slow response exists in the TN configuration. To overcome the drawback, recently pi-cell[1] or OCB-cell[2] has drawn considerable attention. However, a common problem in pi-cell and OCB-cell is that the bend configuration at low driving field is unstable.[3] Therefore, in practice, a few minutes of warm-up time period is required for the device using these cells.

Optical bounce in the TN,[4,5] homogeneous[1] and CHLC[6] cells had been observed in the homeotropic-to-planar state transition. These studies indicate that there is a strong coupling between the fluid flow and the director orientation in the homeotropic-to-planar state transition and the back-flow-induced optical bounce slows down the response. In the pi-cell, however, there is no optical bounce observed in the transient transmittance and the torque induced by the flow accelerates the relaxation.[7]

In this letter, we prepared a twisted pi-cell with fast response as pi-cell and OCB-cell but without the unstable problem. We studied its dynamic mechanism by Erickson–Leslie theory and calculated the transient director behavior with a numerical method. We found that although the response of the nematic liquid-crystal (LC) molecules is slow commonly, the flow-induced director configuration together with the optical component arrangement results in its fast optical response.

Samples of twisted pi-cell were assembled with two indium tin oxide (ITO)-coated glass plates. The substrates were coated with a 700–800 Å thick SE-3310 (Nissan Co.) alignment layer, which produces a pretilt angle of 3° for LC molecules after the rubbing process. The S-811 chiral molecules were doped in the liquid crystal of ZLI-2293 (Merck Co.) to achieve a left-handed 180°-twist pi-cell (twist from $\phi=0°$ at $z=0$ to $\phi=-180°$ at $z=d$) of 6 μm cell gap. To measure the transmittance of this cell, we inserted the LC cell between two crossed polarizers with the rubbing direction x of the front substrate rotated 45° from the transmission axis of the incident polarizer. The transient transmittance curves were measured by using a LC display panel evaluation device (LCD-5100) from Otsuka Electronics Co. with light propagates in the normal direction z of the substrate plate. A square wave form ac electric field was applied with a frequency of 100 Hz. We operated the twisted pi-cell between 10 and 2.6 V since the transmittance–voltage curve of the twisted pi-cell monotonically decay above 2.6 V. The measured results are shown in Fig. 1(a). It is obvious that there are optical overshooting phenomena both in the rising period (a peak) and in decay period (a valley). The enlarged valley is shown in the inset of Fig. 1(a). The response time $[t_{on}(100\%-10\%)+t_{off}(0\%-90\%)]$ is only 2.2 ms.

It is interesting to analyze the dynamic mechanism of the fast optical response since the characteristic response time of the nematic molecules is much slower. According to the previous studies[1,4–6] there usually exists a strong coupling between the fluid flow and the director reorientation. Therefore, we used the Ericksen–Leslie–Parodi theory to investigate the flow effect on the transient behavior of the twisted pi-cell during its switching process. As usual,[6,8] in our calculation, the fluid flow terms were included but the inertial terms of the directors were neglected. We used our one dimension simulator to calculate the transient director (n_x, n_y, n_z) and velocity (v_x, v_y) distributions. Then, the optical transmit-

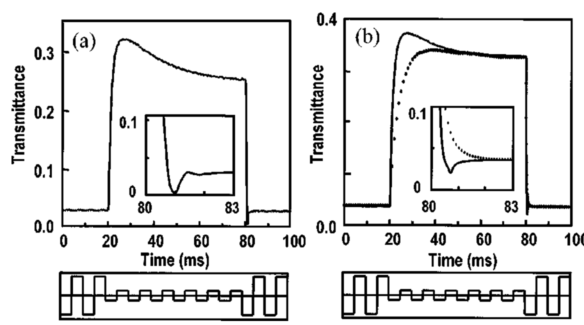

FIG. 1. (a) Measured and (b) calculated transient transmittance of the twisted pi-cell under crossed polarizers. The lower diagrams are the applied wave form which was switched from 10 to 2.6 V at 20 ms and persisted to 80 ms, then switched to 10 V at 80 ms. The insets are the enlarged optical valley.

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TABLE I. The parameters used in the simulation. K_{11}, K_{22}, and K_{33} are splay, twist, and bend elastic constant, respectively. The six Leslie coefficients are taken from MBBA.

Twist angle	−180°	Cell gap	5.8 μm
ε_0	4.1	ε_e	14.1
n_0	1.4990	n_e	1.6312
K_{11}	12.5 pN	K_{22}	7.3 pN
K_{33}	17.9 pN	Pitch	−14.5 μm
α_1	−21.5 mPa	α_2	−153.4 mPa
α_3	−0.773 mPa	α_4	109.5 mPa
α_5	107.1 mPa	α_6	−47.0 mPa

tance was obtained by using Jones matrix method with a wavelength of 589 nm. Table I shows the parameters used in the simulation. Due to lack of the Leslie coefficients of ZLI-2293, these coefficients were taken from the values of MBBA.[9] We had evaluated some Leslie coefficients of ZLI-2293 from its incomplete shear viscosity coefficients[10] that are close to and in the same sign with the values of MBBA. It is appropriate to analyze the transient director behavior by using the complete Leslie coefficients of MBBA. The calculated transmittance is shown in Fig. 1(b). The solid curve is the calculated results with the flow, while the dashed line is the calculated results by considering rotation viscosity only without flow. The corresponding director distributions (n_x, n_y, n_z) were transformed to tilt angle α($\equiv$ 90°—polar angle θ) and azimuthal angle ϕ and shown in Figs. 2 and 4. The typical velocity profiles are shown in Figs. 3(b) and 5(b) for rising process and decay process, respectively. It is obvious, as shown in Fig. 1, that the behavior of the calculated transient transmittance curve that includes the flow effect agrees with the experimental results qualitatively. The simulated optical valley is not as deep as the experimental one. This may be caused by the Leslie coefficients of MBBA being different from the values of ZLI-2293. The flow effect leads the acceleration both in rising and decay optical response of the twisted pi-cell. In the following, we describe how the change of external field induces the flow and the coupling of the flow to the director orientation and finally the optical signals.

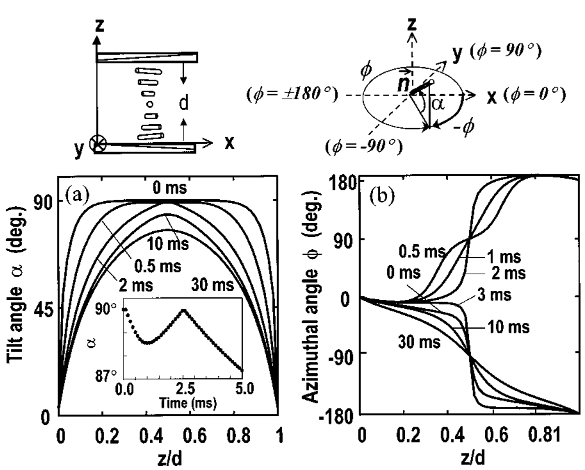

FIG. 2. Calculated transient (a) tilt angle and (b) twist angle distribution after switching to 2.6 V from 10 V at $t=0$. z is the axis perpendicular to the substrates and d is cell gap. Configuration of the twisted pi-cell (without applied field) and the definition of tilt angle α ($\equiv$90°—polar angle θ, $-90° \leqslant \alpha \leqslant 90°$) and azimuthal angle ϕ of the director orientation are shown above (a) and (b).

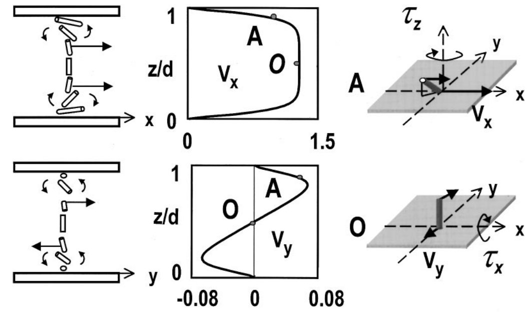

FIG. 3. (a) Director profile at high voltage (10 V). (b) Calculated flow velocity (mm/s) at $t=0.1$ ms after switching to 2.6 V from 10 V at $t=0$. (c) Schematic diagram showing the viscous torques induced by velocity gradient.

In the rising process of transmittance, the cell has been applied with the high voltage (10 V) for a long time, the directors in its initial static state has a profile as shown in Fig. 2. The external director body force[11] **G** is balanced with the elastic deformation force. The equilibrium is broken as the voltage switched to 2.6 V so the external director body force changed to **G**$'$. The unbalanced elastic deformation torque due to the change of the applied voltage or the electric field is $\mathbf{n}\times(\mathbf{G}'-\mathbf{G})=\tau_1\hat{i}+\tau_2\hat{j}=\frac{1}{2}\varepsilon_a(E_z'^2-E_z^2)\sin 2\alpha[\sin\phi\hat{i}-\cos\phi\hat{j}]$, where τ_1 and τ_2 are the induced torques in $\hat{i}$ and $\hat{j}$, respectively, E_z and E_z' are the electric fields in $\hat{k}$ for 10 V and 2.6 V, respectively, α is the tilt angle (=90°–polar angle, $-90° \leqslant \alpha \leqslant 90°$), and ϕ is the azimuthal angle of the director. As shown in Fig. 3(a), this unbalanced torque rotates the director **n** (changing its tilt angle α) and the rotation acts at its nearby fluid element a stress force via viscous interaction. The fluid element is accelerated with the resultant viscous force acting on it. It can be shown that the acceleration is proportional to the gradient of the torque namely $\dot{v}_x \propto -\partial\tau_2/\partial z$ and $\dot{v}_y \propto \partial\tau_1/\partial z$. From the initial configuration depicted in Fig. 2, we can find the extreme positions of τ_1 and τ_2, then from the sign of the torque gradient, we can obtain the profile of the velocity and confirm the behavior of the typical simulated curve shown in Fig. 3(b). Meanwhile, the gradient of the flow velocity induces a viscous intrinsic director body force $\mathbf{g}'$ that imposes a viscous torque $\mathbf{n}\times\mathbf{g}'=\tau_x\hat{i}+\tau_y\hat{j}+\tau_z\hat{k}$ on the director, where

$$\tau_x=(\alpha_2-\alpha_3)(n_y\dot{n}_z-n_z\dot{n}_y)-\alpha_3 n_x n_y\frac{\partial v_x}{\partial z}$$

$$-(\alpha_3 n_y^2-\alpha_2 n_z^2)\frac{\partial v_y}{\partial z},$$

$$\tau_y=(\alpha_2-\alpha_3)(n_z\dot{n}_x-n_x\dot{n}_z)+\alpha_3 n_x n_y\frac{\partial v_y}{\partial z}$$

$$-(\alpha_2 n_z^2-\alpha_3 n_x^2)\frac{\partial v_x}{\partial z},$$

$$\tau_z=(\alpha_2-\alpha_3)(n_x\dot{n}_y-n_y\dot{n}_x)$$

$$+\alpha_2 n_z\left(n_y\frac{\partial v_x}{\partial z}-n_x\frac{\partial v_y}{\partial z}\right)$$

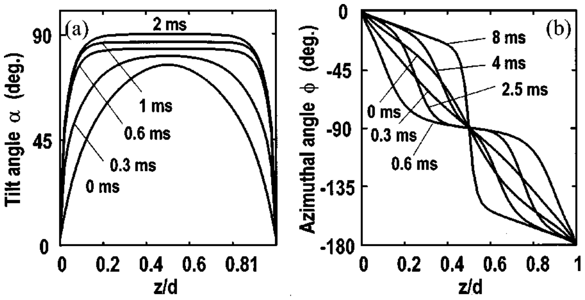

FIG. 4. Calculated transient (a) tilt angle and (b) twist angle distribution after switching to 10 V from 2.6 V at $t=0$.

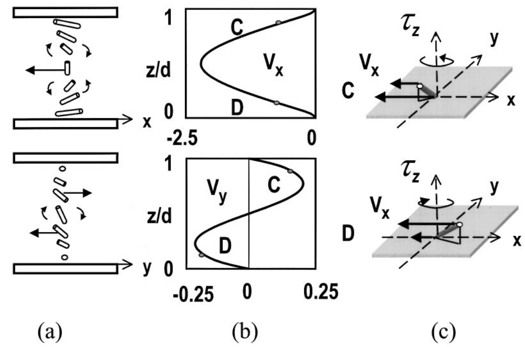

FIG. 5. (a) Director profile at low voltage (2.6 V). (b) Calculated flow velocity (mm/s) at $t=0.1$ ms after switching to 10 V from 2.6 V at $t=0$. (c) Schematic diagram showing the viscous torques induced by velocity gradient.

The reverse twist of the directors observed in Fig. 2(b) is induced by τ_z which is negative (positive) above (below) the midlayer at the beginning after the voltage has been switched. A schematic diagram is shown in Fig. 3(c) for point A. Besides, the viscous torque τ_x at the midlayer is negative (since $\partial v_x/\partial z=0$ and $\partial v_y/\partial z>0$) and that kicks the director of the midlayer to the other side ($+$y, $\phi=+90°$) as shown in Fig. 3(c). As a result, the tilt angle decreased [as in the inset of Fig. 2(a)] and the originally left-handed 180° twist changes into a similarly sharp right-handed 180° twist [as in Fig. 2(b)] (tip-over phenomenon). After some time has elapsed, the torque induced by the flow effect is decreased and is overcome by the elastic torque, the directors start to relax back (after 1 ms). In the relaxation process, the tilt angle in the midplane meets the 90° again at 2.5 ms, meanwhile, the twist profile restores to left-handed. At last, the tilt angle and the twist angle arrive at their stable state at about 30 ms. The rapid relaxing of the director tilt angle in the two intermediates near the surface causes the optical phase retardation increases quickly. At the same time, the induced reverse twist keeps these directors almost parallel with x axes that further increase the effectively optical phase retardation. As a result, it speeds up the increasing of the transmittance even over the saturation value and forms an optical peak as shown in Fig. 1. In other words, by switching down the applied voltage, the flow induces a reverse twist in the homeotropic-to-planar state transition that speeds up the optical rising response.

In the decay process of transmittance, similarly, the equilibrium is broken when the voltage switched to 10 V from 2.6 V. As depicted in Fig. 4, The LC molecules stand up (rotate) quickly owing to a much larger electric torque encountered throughout the cell. The extremes of the electric torque τ_2 are at two intermediates near the substrates where the tilt angle α is about 45°, while the minimum of τ_1 occurs at the midlayer. The fluid flow caused by the director rotation thus can be realized and indicated in Fig. 5(b). The flow induced torque τ_z of the director is positive (negative) above (below) the midlayer as indicated in Fig. 5(c). Consequently, as shown in Fig. 4(b), the twist orientation first swings to a direction away from its final equilibrium position and that persists up to 0.6 ms. After 0.6 ms, the rotating speed of the director slows down, the flow effect is weak and is overcome by the elastic torque due to the large deformation caused by the reverse twist, then the director twist profile swings back with a high tilt angle (Fig. 4) and finally the stable twist profile is reached at 8 ms. In the aspect of the optical signal, as the voltage increased, the rapid standing up of the director causes the transmittance decay quickly. In addition, the induced reverse twist pushes the directors away from the rubbing direction x in both areas near the substrates where the tilt angle has large deviation from 90° and contributes mainly to the transmittance. As a result, it reduces the effectively optical phase retardation further and decreases the transmittance even lower than the saturation value to form an optical valley as shown in Fig. 1. In conclusion, the flow induces an optical valley and speeds up the optical decay response when the applied voltage is switched up.

In summary, we report a twisted nematic LC pi-cell with fast optical response. It can be applied in light valves and LCDs with true video rate. The field-induced dynamic mechanism of the twisted pi-cell has been studied. A backflow-induced reverse twist in the homeotropic-to-planar state transition and the planar-to-homeotropic state transition is confirmed to have significant influences on the optical properties. As a result, the flow effect is shown to play a positive role for accelerating the optical response of the twisted pi-cell.

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