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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 or OCB-cell 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. Therefore, in practice, a few minutes of warm-up time period is required for the device using these cells.

Optical bounce in the TN, homogeneous and CHLC 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.

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, 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 φ = 0° at z = 0 to φ = −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 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).

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, there usually exists a strong coupling between the fluid flow and the director reorientation. Therefore, we used the Erickson–Leslie–Parodi theory to investigate the flow effect on the transient behavior of the twisted pi-cell during its switching process. As usual, 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 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.

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.
It is appropriate to analyze the transient director behavior by considering rotation viscosity only without flow. The corresponding director distributions 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.

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 \( \mathbf{G} \) 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 \( \mathbf{G}' \). The unbalanced elastic deformation torque due to the change of the applied voltage or the electric field is \( \mathbf{n} \times (\mathbf{G}' - \mathbf{G}) = \tau_1 \hat{i} + \tau_2 \hat{j} = \frac{\varepsilon_0}{2} \varepsilon(E_z^2 - E_z^2) \sin 2\phi \left( \sin \phi \hat{\mathbf{i}} - \cos \phi \hat{\mathbf{j}} \right) \), where \( \tau_1 \) and \( \tau_2 \) 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, \( \alpha \) is the tilt angle (= 90°—polar angle, \( -90^\circ \leq \alpha \leq 90^\circ \)) and \( \phi \) is the azimuthal angle of the director. As shown in Fig. 3(a), this unbalanced torque rotates the director \( \mathbf{n} \) (changing its tilt angle \( \alpha \)) 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 \( \dot{\mathbf{n}} \mathbf{v} = -\partial \tau_2 / \partial z \) and \( \dot{\mathbf{n}} = \partial \tau_1 / \partial z \). From the initial configuration depicted in Fig. 2, we can find the extreme positions of \( \tau_1 \) and \( \tau_2 \), 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 \( \mathbf{n} \times \mathbf{g}' = \tau_3 \hat{i} + \tau_4 \hat{j} + \tau_5 \hat{k} \) on the director, where

\[
\tau_3 = (\alpha_2 - \alpha_3) (n_\mathbf{y} n_\mathbf{z} - n_\mathbf{z} n_\mathbf{y}) - \alpha_3 n_\mathbf{y} n_\mathbf{y} \frac{\partial \mathbf{v}_x}{\partial z},
\]

\[
\tau_4 = (\alpha_2 - \alpha_3) (n_\mathbf{z} n_\mathbf{z} - n_\mathbf{y} n_\mathbf{y}) + \alpha_3 n_\mathbf{z} n_\mathbf{z} \frac{\partial \mathbf{v}_x}{\partial z},
\]

\[
\tau_5 = (\alpha_2 - \alpha_3) (n_\mathbf{y} n_\mathbf{y} - n_\mathbf{z} n_\mathbf{y}) - \alpha_3 n_\mathbf{y} n_\mathbf{y} \frac{\partial \mathbf{v}_x}{\partial z}.
\]

### Table I

<table>
<thead>
<tr>
<th>Twist angle</th>
<th>Cell gap</th>
<th>5.8 µm</th>
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</thead>
<tbody>
<tr>
<td>( \alpha_0 )</td>
<td>4.1</td>
<td>14.1</td>
</tr>
<tr>
<td>( n_\mathbf{z} )</td>
<td>1.4990</td>
<td>1.6312</td>
</tr>
<tr>
<td>( K_{11} )</td>
<td>12.5 pN</td>
<td>K_{22} 7.3 pN</td>
</tr>
<tr>
<td>( K_{33} )</td>
<td>17.9 pN</td>
<td>Pitch  -14.5 µm</td>
</tr>
<tr>
<td>( \alpha_1 )</td>
<td>-21.5 mPa</td>
<td>( \alpha_2 ) -153.4 mPa</td>
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<tr>
<td>( \alpha_3 )</td>
<td>-0.773 mPa</td>
<td>( \alpha_4 ) 109.5 mPa</td>
</tr>
<tr>
<td>( \alpha_5 )</td>
<td>107.1 mPa</td>
<td>( \alpha_6 ) -47.0 mPa</td>
</tr>
</tbody>
</table>

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 \( \alpha (=90^\circ) \)—polar angle \( \theta \), \( -90^\circ \leq \alpha \leq 90^\circ \)—and azimuthal angle \( \phi \) 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.
The reverse twist of the directors observed in Fig. 2(b) is induced by \( \tau_1 \), 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 \( \tau_2 \) at the midlayer is negative (since \( \partial \nu_x/\partial z = 0 \) and \( \partial \nu_z/\partial z > 0 \)) and that kicks the director of the midlayer to the other side \((+y, \phi = +90^\circ)\) 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 \( 180^\circ \) twist changes into a similarly sharp right-handed \( 180^\circ \) 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 \( 90^\circ \) 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 surfaces causes the optical phase retardation increases quickly. At the same time, the twist profile swings back parallel with \( x \) axes that further increase the effectively optical retardation. As a result, it reduces the optical phase retardation further and decreases the transmission 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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