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Homeotropic liquid-crystal device with two metastable states

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We report a homeotropic liquid-crystal device which has two metastable states when an electric field is applied. The behaviors of these two metastable states are similar to the bistable twist nematic device. We control this device electrically in the rising period to switch it from the homeotropic state toward either the twist or homogeneous state. It not only behaves as a conventional homeotropic cell but also provides another twist structure for further applications. The back-flow effect in the rising period plays an important role in the switching mechanism. The experimental results are described in this letter. © *1999 American Institute of Physics.* [S0003-6951(99)01525-9]

Many electro-optical effects of liquid crystal (LC) have been used and LC devices have become important in modern electronic displays. The conventional homeotropic LC cell[1] can offer a good dark state when it is under the crossed-polarizer condition. It has been used in both transmissive-type direct-view and reflective-type projection displays. In the direct-view type, the oblique light leakage can be compensated by using suitable compensation films. Thus, a good viewing angle characteristic can be achieved.[2] Another derivation of the homeotropic cell is the chiral-homeotropic LC cell,[3,4] in which the LC directors have a twist structure in the field-on situation. It reduces the wavelength dependence of the transmittance in the field-on state, which occurs in the conventional homeotropic cell and still maintains a good dark state.

In this letter, we demonstrate a homeotropic LC device which operates on the homeotropic to either twist or homogeneous state transitions. It uses the LC material with negative dielectric anisotropy and can be controlled electrically to switch into the twist state or the homogeneous state in the rising period. It has two metastable states when we apply voltage to it. The behaviors of these two metastable states are analogous to the two stable states of the bistable twist nematic (BTN) liquid-crystal device,[5,6] which uses the LC material with positive dielectric anisotropy. The driving consideration is also similar to the BTN device which can be switched by different wave forms or pulses in the decay period.[7–9] This device not only can be used as a conventional homeotropic LC device, but also provides another twist state for further potential applications. For example, we can add some dyes into the LC material, then this cell may behave as a guest–host device. In the following, we describe the basic principle of this device and the properties of its transient transmittance.

Since the back-flow effect is usually obvious in the homeotropic-to-planar-state transition, the field-induced back flow in a homeotropic cell[10] is also able to lead a certain part of the directors to be ‘‘opposite tilt,’’ that is, the back flow causes the tilt angle of the directors to be over 90° from the substrate. Owing to the field-induced ‘‘opposite tilt,’’ if the LC material has a suitable helix pitch length and negative dielectric anisotropy, it is possible to use the back-flow effect to make a tristate LC device, which is homeotropic alignment in the absence of external field and has two metastable states in the field-on situation. We can suddenly apply a strong electric field to this homeotropic cell. Then, the fast rotation of the directors induces a strong back flow and this back flow will drive the directors become the ‘‘opposite tilt.’’ This ‘‘opposite tilt’’ could lead the cell to a twist state. On the other hand, when the applied voltage rises more gently, the gradually rising field makes the LC directors rotate more slowly. Thus, the induced back flow is relatively weak. This reduces or prevents production of the ‘‘opposite tilt’’ of the directors. In this situation, the cell will go toward the homogeneous state. Hence, we can switch the state at the rising period by controlling the rising rate of the applied voltage and a tristate LC device can be achieved.

To demonstrate this tristate LC device, we made several sample cells. We used indium–tin–oxide glass as the substrates and coated them with JALS 204 polyimides (from the Japan Synthetic Rubber Co.) to form vertical alignment layers. The alignment layers were parallel rubbed to obtain a uniform tilt direction at the field-off homeotropic state. The cell gap d is 5.25 μm. The liquid crystal is ZLI-2806 (from Merck), which has negative dielectric anisotropy. Some important physical properties of this LC material are: $n_e = 1.5183$, $\Delta n = 0.0437$ (at $\lambda = 589$ nm, 20 °C), $\epsilon_\perp = 8.1$, and $\Delta\epsilon = -4.8$. We added some ZLI-811 (from Merck) as the chiral dopant to obtain a suitable helix pitch length. To measure the optical properties of both the twist state and the homogeneous state, we put the cell between two crossed polarizers. The angle between the front polarizer and the rubbing axes was 45°. We used a He–Ne laser with a wavelength of 632.8 nm as the light source and a PIN diode as the photodetector. In the absence of the field, the homeotropic state contributes no phase retardation, so that a dark state appears. If the cell enters the homogeneous state, it will behave like a phase retarder and the light will leak from the second polarizer. On the other hand, if the cell enters the twist state, smaller light leakage will be obtained. It can be

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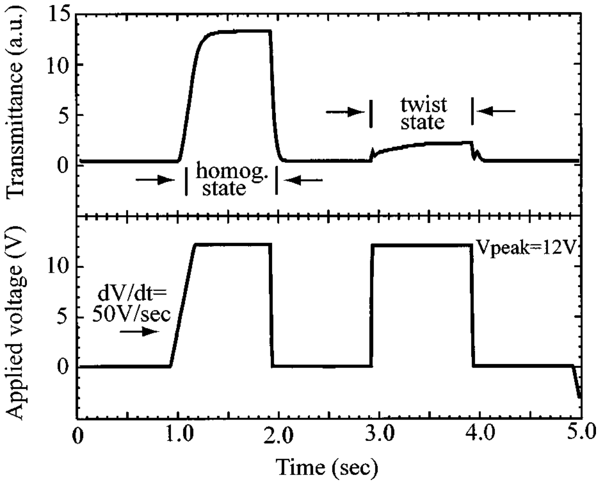


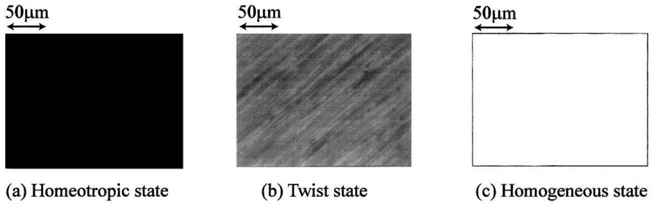
FIG. 1. Transient transmittance (upper trace) of the tristate device under the crossed-polarizer condition. The lower trace is the applied wave forms, $V_{\text{peak}}=12$ V. The rising rate of the first wave form is $dV/dt=50$ V/s. The the second wave form is a square wave.

estimated that the transmittance of the twist state is smaller than that in the homogeneous state because the product of the wavelength and the twist angle is comparable to the $d\Delta n$. That is, the cell operates in the region out of the Mauguin limit and this twist state just offers only a small phase retardation.

To switch between these three states, we designed two kinds of electric wave forms. One has a gradually rising rate ($dV/dt=50$ V/s) and the other has a rapidly rising voltage (it is an electric pulse in our experiment). The gradually rising wave form was used to drive the cell from the homeotropic state to the homogeneous state. The other rapidly rising voltage was used to induce strong back flow. Then, this back flow makes the director become the ''opposite tilt'' and guides the cell toward the twist state.

Figure 1 shows the transient transmittance of the tristate LC cell. We applied two different wave forms to the same amplitude on the cell and then the three states can be distinguished very clearly. In the first pulse, the applied voltage rose gradually and kept at a high value. Thus, this cell entered the homogeneous state and a higher transmittance was obtained. In the second pulse, the fast rising electric field drove this cell to the twist state and then the smaller phase retardation caused less light leakage. Figure 2 shows transmission micrographs of the same cell between the crossed polarizers. The applied wave forms in Fig. 2 are identical with those we used in Fig. 1. The existence of the three states was also confirmed by these pictures.

In our experiment, when the peak voltage of the pulses was low, the twist state did not appear after the rising period. Figure 3 shows that when the peak value of the applied voltage was not large enough; usually being less than 2.5 times of the optical threshold voltage in our experiment (V peak$=4.2$ V in Fig. 3), the cell behaved like a conventional homeotropic cell. The optical transmittances corresponding to these two different wave forms were almost the same. It may be that the back-flow effect was not strong enough to lead the cell to the twist state, and under this field strength, the energy barrier between the twist state and the homogeneous state was low. Thus, in the rising period the directors easily went toward the homogeneous state, which has a relatively lower energy.



(a) Homeotropic state (b) Twist state (c) Homogeneous state

FIG. 2. Transmission micrographs of the tristate device between two crossed polarizers. (a) The homeotropic state, (b) the twist state, and (c) the homogeneous state.

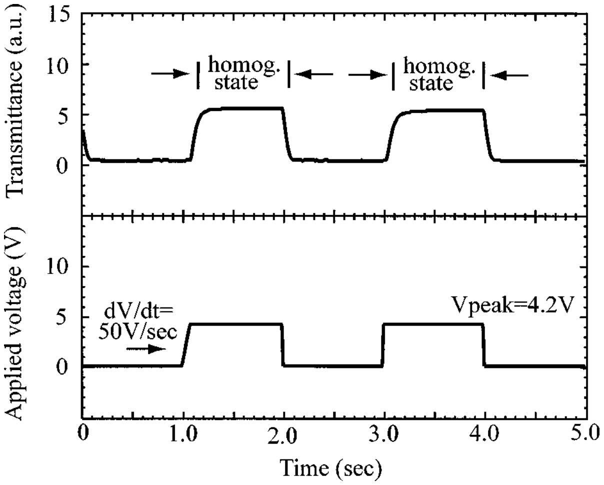


FIG. 3. Transient transmittance (upper trace) of the tristate device. The amplitude of the two pulses is $V_{\text{peak}}=4.2$ V. The transmittances of these two wave forms are almost the same. The rising rate of the first wave form is 50 V/s. The second wave form is a square wave.

Figure 4 shows the results that the peak voltage of the applied wave forms was in the middle range, that is, from 5 to 8 V in our experiment (the peak voltage in Fig. 4 is 6.5 V). The cell also behaved like a pure homeotropic cell when the applied wave form was gradually rising. However, when we applied a rapidly rising wave form, the twist state coexisted

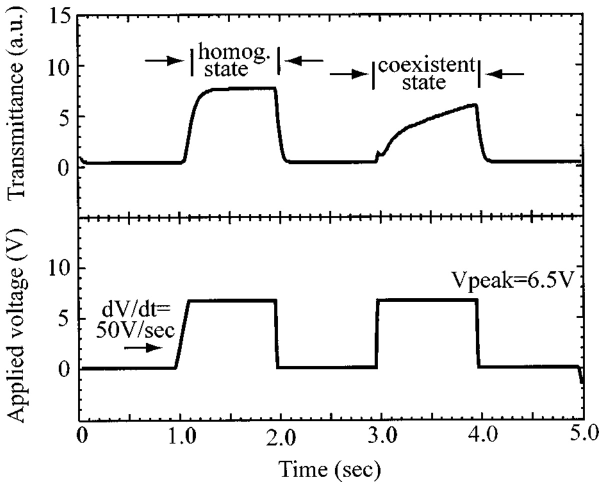


FIG. 4. Transmittance of the tristate device (upper trace). The applied voltage is in the middle range ($V_{\text{peak}}=6.5$ V). In the second pulse, the combination of the twist and the homogeneous states results in the variation of transmittance. The rising rate of the first wave form is 50 V/s. The second wave form is a square wave.

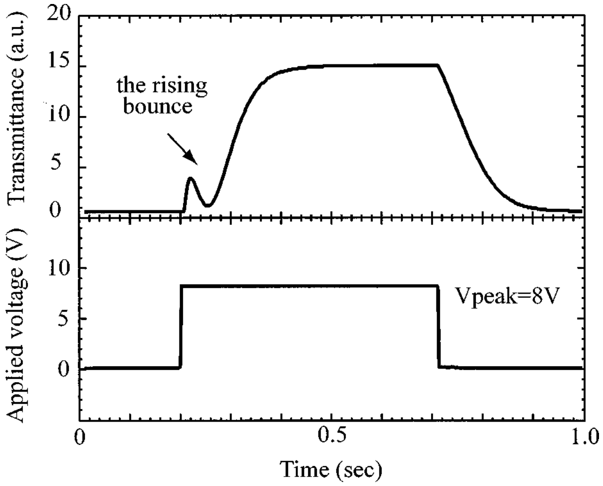


FIG. 5. An optical bounce of a conventional homeotropic cell. The upper trace is the transient transmittance under the crossed-polarizer condition. The angle between the rubbing axes and the front polarizer is 45 °. The cell gap is 6.25 μm. The liquid crystal is ZLI-2806. The wavelength is $\lambda = 632.8$ nm and the amplitude of the applied voltage is 8 V. Note an optical bounce appears in the rising period.

with the homogeneous state. These two coexistent states formed domains and then the combination of the domains resulted in a slow variation of the transmittance. This coexistent voltage region may be reduced by a careful surface treatment in the manufacturing process.

In addition to the tristate device, we also examined the back-flow effect in a pure homeotropic cell. We found that an optical bounce, which is originally found in the twist nematic (TN) cell, also appeared in the rising period of a homeotropic cell. In the TN case, when a large electric field applied to a TN cell is suddenly turned off, the strong elastic distortion torque causes a fast rotation of the directors near the substrates and induces a strong back flow. This back flow drives the directors in the midplane to the ''opposite tilt'' and then the relaxation process of this ''opposite tilt'' exhibits an optical bounce during the decay period.[11,12] Similarly, when we suddenly applied a strong electric field on the homeotropic cell, the electric-field-induced back flow drove the directors to the ''opposite tilt'' and then an optical bounce appeared during the rising period (See Fig. 5). On the other hand, if the applied voltage rose gradually, no bounce appeared (not shown). This rising bounce phenomenon not only confirms the ''opposite tilt'' of the homeotropic cell, but also supports our explanation of the switching mechanism for the tristate device. Although the mechanisms of the decay bounce in the TN cell and the rising bounce in the homeotropic cell seem to be similar, it should be noted that the rising bounce of a homeotropic cell is induced by the external electric (or magnetic) field, not the elastic force.

The 180° twist state has a lower twist energy than the other twist and homogeneous states in our tristate device, but a stable 180° twist state never occurred. Since the boundaries cause higher splay and bend energy in the 180° twist state, it is difficult to form the 180° twist configuration. The response time of this tristate device was about 100 ms, but it can be improved by using a thinner cell gap and choosing a LC material with low viscosity. For specific applications, we can change the rubbing angle between the top and bottom substrates. Thus, a different tristate structure is possible to accomplish. Instead of sloping wave forms, the electric driving scheme for switching between these states can be achieved by using pulses which have different amplitudes and widths. The driving voltage can be also reduced by using a LC material which has larger negative dielectric anisotropy.

In summary, we demonstrated a tristate liquid-crystal device which not only performs as a conventional homeotropic cell and has the same good dark state, but provides another twist state for further potential applications. The back-flow effect plays an important role on the state switching. The experimental results also show that in a homeotropic cell the back-flow effect should be considered. Further studies on this liquid-crystal device are under progress.

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