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Dual-Mode Liquid Crystal Devices with Switchable Memory and Dynamic Modes

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Abstract

A liquid crystal device with switchable dynamic and memory modes was investigated and developed. The proposed device reveals the splay, π-twist, and bend states via selective switching among them. In the dynamic mode, the device is operated in the bend state, which exhibits a wide viewing-angle and a fast-response-time due to its self-compensated bend structure and flow-accelerated fast response time, respectively. In the memory mode, the permanent memory characteristics in the splay and π-twist sates are obtained, respectively. The switching mechanisms of the tristate device are also proposed.

Keywords: dual mode, bistable, switchable, LCD, flow effect

1. Introduction

The existing liquid crystal devices can be classified into two categories: the monostable and bistable modes. Nowadays, the monostable device with a permissible stable state with an electric field is widely applied to mobile, monitor, and television LCDs due to its high optical performance [1]. On the other hand, the bistable device with two stable states without an electric field is widely applied to electronic books, electronic papers, and price tags because of its low power consumption [2-7].

Lee et al. proposed a tristate liquid crystal device that can be operated in both the monostable and bistable modes. Its switching can be realized by using both the horizontal and vertical electric fields generated from the three-terminal electrode structure. In this paper, a tristate device with a simple electrode structure is proposed. The switching of the proposed device is accomplished by an electrodynamics flow of a dual-frequency liquid crystal (DFLC) material. Through the optimization of the concentration of the chiral additive, this device reveals not only tristate characteristics but also switchable characteristics between the monostable and bistable modes. Unlike complex electrode structures, the single electrode on the top and bottom substrates, respectively, whose structure is the same as that of the conventional electrode in TN devices, was simply exploited. The dynamics and switching mechanisms of this tristate device were investigated in this work.

The tristate LCD can be fabricated by using a parallel rubbed cell filled with DFLC. The dielectric anisotropy △ε of DFLC varies with the frequency: The dielectric anisotropy is positive upon biasing at a low frequency and negative upon biasing at a high frequency. By doping a certain amount of left-handed chiral dopant into DFLC and applying the appropriate electric field and driving frequency to each texture, the texture transitions of the splay, left-handed π-twist (LHT), right-handed π-twist (RHT), and bend states can be obtained.

Fig. 1 shows the texture transitions of a dual-mode LCD. When the voltage is applied at a low f1, the initial

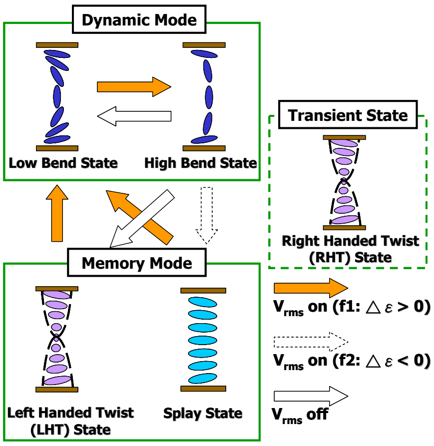

Fig. 1. Director configurations of the splay, bend, LHT, and RHT states, and the associated switching mechanisms of the dual-mode device.

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splay state will be switched to a high bend state via a low bend state. Once the voltage is removed, the bend state is relaxed to the LHT state. If the driving frequency is suddenly switched from a low f1 to a high f2, the high bend state goes back to the initial splay state via a transient RHT state.

2. Experiments

To investigate the texture transitions and operation principles of dual-mode devices, several test cells were fabricated. The indium-tin-oxide-(ITO)-coated glass substrates were coated with the alignment material of PIA-5570 (Chisso Co.), which produced a pretilt angle of 3° after the parallel rubbing processes. The thickness (d) of the fabricated cell was 4.5 um. A chiral additive material was doped into the DFLCs of MLC-2048 [$\triangle\varepsilon = +3.3$ at a low frequency of 1 kHz and $\triangle\varepsilon = -3.4$ at a high frequency of 100 kHz (Merck)] to achieve a thickness that would allow the (d/p) ratio of -0.2 to be pitched. The symbol "-" indicates the left-handed π-twist. Finally, the DFLC blended with chiral dopant was injected into the empty cells.

The transition textures of a tristate cell are shown in Fig. 2. Fig. 2(a) shows the initial splay state due to the lower-than-0.25 absolute d/p ratio value, in which the splay and LHT states possess the same Gibbs free energy density, as shown in Fig. 3 [8]. When the voltage is applied to the top and bottom electrodes, the splay state is switched to the bend state, as shown in Fig. 2(b). Due to the topological inequivalence between the splay and bend states, the transition is accomplished via the propagation of disclination lines. When the applied voltage is immediately removed, the bend state relaxes directly to the LHT state because it is topologically equivalent to the splay state, as shown in Fig 2(c). To switch back to the splay state, the LHT state is first switched back to the bend state by applying a voltage at a low f1. Then, the driving frequency is suddenly changed from f1 to a high f2 after the formation of the bend state. At the same time, the dielectric anisotropy of DFLC is changed from a positive to a negative $\triangle\varepsilon$. Therefore, the directors of liquid crystals tend to tilt downward. Finally, the transition from the bend to the splay state occurs via a transient state (i.e., the RHT state), that is, RHT state, as shown in Fig. 2(d). The RHT state with a high Gibbs-free-energy density is unstable and is gradually replaced by the splay state, which possesses a lower Gibbs-free-energy density than the LHT state.

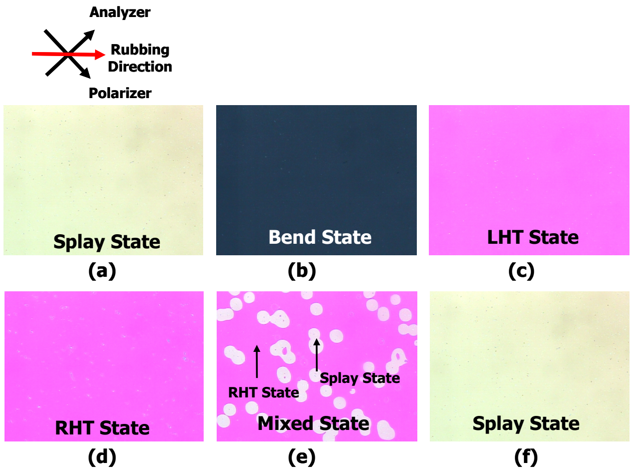

Fig. 2. Transition textures of a dual-mode cell observed under a polarizing optical microscope:(a) the splay state; (b) the bend state; (c) the left-handed π-twist state; (d) the right-handed π-twist state; (e) the mixed-splay and right-handed π-twist states; and (f) the splay state.

When an appropriate concentration of a chiral additive is doped to DFLC, this device will reveal bistable characteristics. Without the application of an electric field, the splay and LHT states will show an equal elastic-free-energy density at a d/p ratio of -0.25, as shown in Fig. 3. Due to the topological inequivalence between the splay and π-twist states, this device reveals permanent bistability. As previously reported, a π bistable twist nematic (BTN) with two topologically equivalent states shows a longer memory time compared to a 2π BTN device with two topologically inequivalent states [9]. Therefore, the splay and π-twist states are suitable for the memory states of a bistable device. Although true bistable states can be obtained with a d/p ratio of -0.25, -0.2 is proposed in this paper as the optimized d/p ratio value. An energy gap between the splay and LHT states is needed to come up with a switchable bistable device. The RHT state is a transient state with a higher elastic-free-energy density than the splay and LHT states. Transition from the RHT to the splay state accompanies the propagation of a disclination lines. The propagation velocity of disclination line is proportional to the energy difference between the splay and LHT states. The same free-energy density of the splay and LHT states at a d/p ratio of -0.25

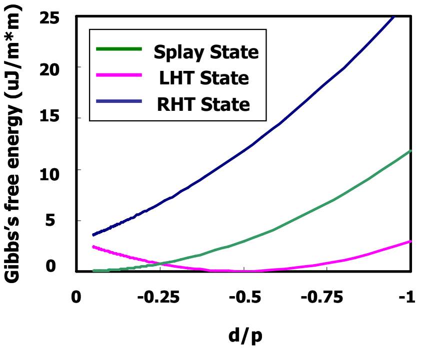

Fig. 3. The d/p-ratio-dependent free energy of the different configurations.

will hinder the motion of the disclinaton lines.

When a voltage is applied to the device in the LHT state, the LHT state is directly switched to the bend state due the topological equivalence between these two states. Once the applied voltage is removed, the bend state relaxes to the LHT state. The bend-LHT transition is continuous and reversible without the propagation of disclination lines. By applying an appropriate voltage, the device can be dynamically operated between the low and high bend states. As a consequence, a dual-mode device with both bistable and monostable characteristics is obtained, with a parallel rubbed cell filled with a DFLC with a d/p ratio of -0.2 [7].

3. Results and Discussion

3.1 Electro-optical characteristics

To measure the electro-optic characteristics of the proposed device, the test cell was placed between two crossed polarizers, in which the angle between the rubbing direction and the transmissive axis of the input polarizer was 45°. A 632.8-nm-wavelength He–Ne laser was used as the light source. The voltage waveforms that were applied to the test cell were generated using an arbitrary-function generator. The applied voltage waveform and the output of the photodetector were simultaneously monitored using a digital storage oscilloscope.

The electro-optical characteristics of memory mode switching are shown in Fig. 4 and 5. Fig. 4 shows the transient transmittance when switching from the splay to the LHT state by applying a pulse with a voltage amplitude of 20 V and a frequency of 1 kHz. As liquid crystals possess a positive dielectric anisotropy within the pulse duration, the molecules in the splay state are reoriented vertically. Finally, a bend state with a low transmittance is obtained. When the voltage is turned off, the LC molecules relax to the LHT state with a high transmittance. As shown in Fig. 5, the LHT can be switched back to the bend state via the application of a pulse with a voltage amplitude of 20 V and a frequency of 1 kHz. When the frequency is suddenly changed to 100 kHz, the LC molecules of the middle layer lie down in the opposite direction due to the reverse twist deformation caused by the backflow effect, and the RHT state is generated. The RHT state with high elastic free energy is unstable, however, and is gradually replaced by the splay state, which is the most stable state of this device.

Fig. 6 shows the voltage-transmittance curve of the dynamic-mode operation between the LHT and bend states. In the operation between the low and high bend states, this device reveals a monotonic decrease of the transmittance with an applied voltage larger than 4 V. Light leakage results from the residual phase retardation in the high bend state, which can be compensated via the use of compensation films.

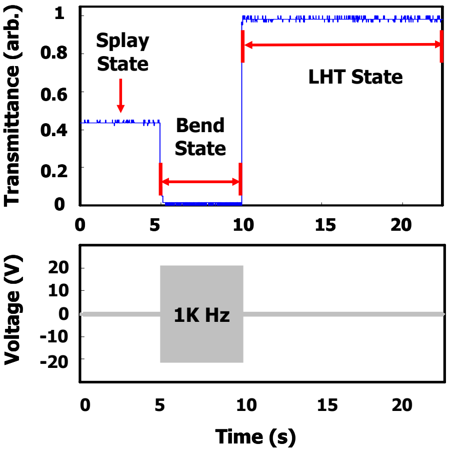

Fig. 4. The transient transmittance and the corresponding driving waveform of the dual-mode device switched from the splay to the LHT state in the memory mode. The amplitude of the driving pulse was 20 V, and the frequency was 1 kHz.

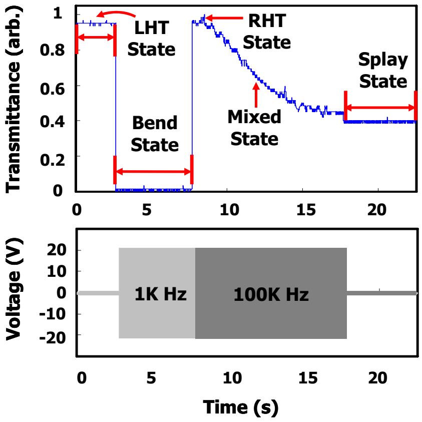

Fig. 5. The transient transmittance and the corresponding driving wave form of the dual-mode device switched from the LHT to the splay state. The amplitude of the driving pulse was 20 V. The frequency was switched from 1 to 100 kHz.

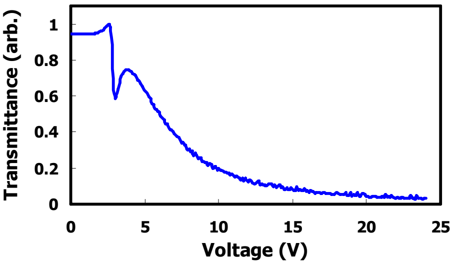

Fig. 6. Measured V-T curve of the dual-mode device operated between the LHT and bend states in the dynamic mode.

3.2 Dynamics

To understand the switching mechanisms, the dynamic behavior of the directors was simulated based on the Ericksen-Leslie-Parodi hydrodynamic theory. The simulator, which was originally developed at NCTU LC Laboratory, was modified at FCU LC Laboratory to determine the director behavior of DFLC [10, 11]. In the previous studies conducted by these researchers, the helical twist direction temporarily switched to the opposite direction due to the flow-induced tip-over effect during the relaxation from the high-tilt bend state to the π-twist state. [12] In this work, the calculation conditions were the same as those of the fabricated cells. The applied voltage was 20 V and the dielectric constants were 3.3 and -3.4 at low and high driving frequencies, respectively. Fig. 7 shows the behavior of the LC directors during the LHT-to-bend and bend-to-RHT transitions. From the bottom to the top substrate, it is considered that one end of the director (of unit length) was fixed at the origin, and that the other end traced a curve from (1, 0) to (-1, 0). When the voltage was applied to the LHT state at a low frequency, the LC directors switched to the bend state after 3 ms. At the time of 0 ms, the frequency changed from a low to a high one in the high-tilt bend state, and the dielectric anisotropy of DFLC became negative. The flow-induced viscous torque kicked the LC directors in the mid-layer back to the opposite side, and then the helical structure changed to the RHT configuration. Finally, the LC directors lay down due to the negative dielectric isotropy of DFLC, and the LHT state was formed after 1 ms. The flow effect can thus be said to be a key parameter to achieve the switching between the RHT and LHT states.

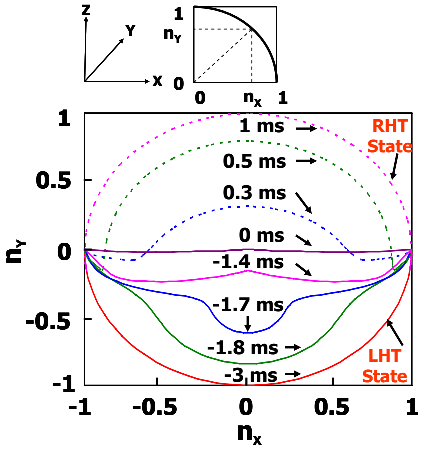

Fig. 7. Result of the of the calculation behavior of the LC directors during the LHT-to-bend and bend-to-RHT transitions by changing the frequency from a high to a low one.

4. Conclusions

A dual-mode device with a conventional electrode structure that can be operated in both the dynamic and memory modes is proposed herein. This device reveals tristate characteristics, including the splay, LHT, and bend states, which were demonstrated using a parallel rubbed cell filled with DFLC and with a d/p ratio of -0.2. In the memory mode, the splay and LHT states showed a permanent memory time because of the topologically inequivalent states. In the dynamic mode, a wide viewing angle and a fast response time can be obtained due to the bend-to-bend operation.

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