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Bistability of splay and π twist states in a chiral-doped dual frequency liquid crystal cell

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A bistable liquid crystal cell with splay and π twist stable states is obtained by doping a chiral additive in a splay cell filled with dual frequency liquid crystals. The switching between the two states is achieved by using a sequential waveform of low and high frequencies. The switching mechanisms are proposed by using the backflow effect together with the anisotropic properties of dual frequency liquid crystals. As a result, the two stable states have the superior memory characteristics due to the topological inequivalence. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3078233]

Bistable liquid crystal (LC) devices have attracted lots of attentions in recent years owing to their ability to support memory access without the application of a voltage, subsequently reducing the power consumption. Currently, the switching mechanisms of bistable devices can be approximately classified into the two following types: volume switching type and surface switching type.[1] In the case of volume switching type, 2π-bistable twisted nematic[2] has topologically equivalent two stable states of $(\varphi-\pi)$ twist and $(\varphi+\pi)$ twist. However, the retention time of two states are short because a more stable intermediate φ twist state exists. Even though a long-time bistability can be achieved by using multidimensional alignment method, the application is still limited.[1] For the surface switching type, bistable nematic[3] has topologically equivalent two stable states of 0- and π twist. They show superior memory characteristics by using an adequate ratio of chiral additive for equalizing the elastic free energies of the two states. Its switching can be conducted through the shear flow effect and the polar anchoring breaking at an alignment layer. However, the sophisticated process for the alignment layer is troublesome compared to that of the conventional LC cells. Lee *et al.*[1] proposed a bistable chiral-splay nematic (BCSN) cell, which overcomes the disadvantages of the volume and surface switching bistable devices. The BCSN device fabricated by a conventional rubbing alignment process has topologically inequivalent two stable states of splay and π twist states that enables the excellent memory characteristics. Its switching can be realized by using both the horizontal and vertical electric fields, which is generated from the three-terminal electrode structure.

In this paper, we proposed another approach to a BCSN device. The switching of our proposed device is accomplished by an electrodynamics flow of a dual frequency LC (DFLC)[4,5] material. By optimizing the concentration of the chiral additive, this device reveals not only the superior memory time in both splay and π twist stable states but also the switchable characteristics between these two states. In comparison with the complex electrode structures, the conventional simple electrode structure with the single electrode on top and bottom substrates, respectively, is used. Moreover, the dynamic switching behavior dependent on an applied waveform and memory characteristic related to the elastic free energy of two states are analyzed.

The bistable device can be fabricated by using a parallel rubbed cell filled with DFLC. The dielectric anisotropy $\Delta\varepsilon$ 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 some amount of left-handed chiral dopant into DFLC, we can obtain the texture transitions of splay, left-handed π twist (LHT), right-handed π twist (RHT), and bend states by applying the appropriate electric field and driving frequency to each texture. Figure 1 shows the texture transitions of a BCSN device. When the voltage is applied at a low driving frequency f1, the initial splay state will be switched to a bend state. Once

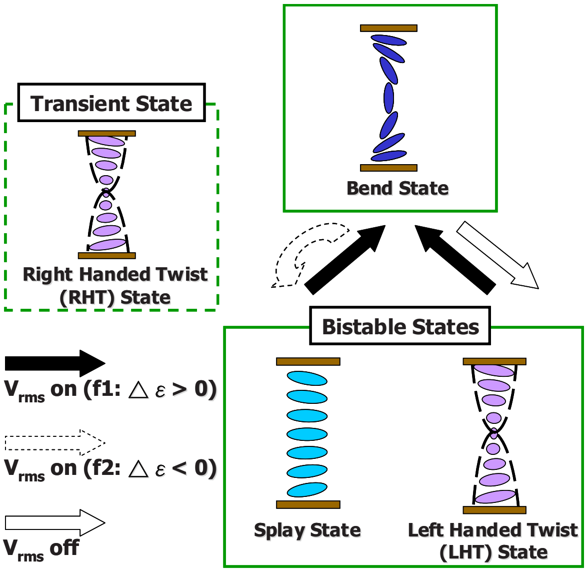

FIG. 1. (Color online) Director configurations of splay, bend, LHT and RHT states, and associated switching mechanisms of a bistable device.

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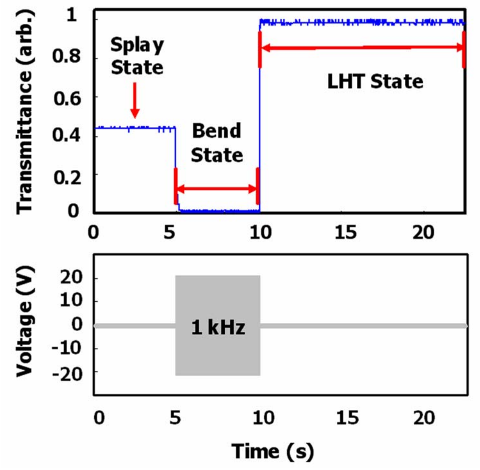

FIG. 2. (Color online) The transient transmittance and the corresponding driving waveform of the BCSN device switched from the splay state to the LHT state. The amplitude of the driving pulse is 20 V and the frequency is 1 kHz.

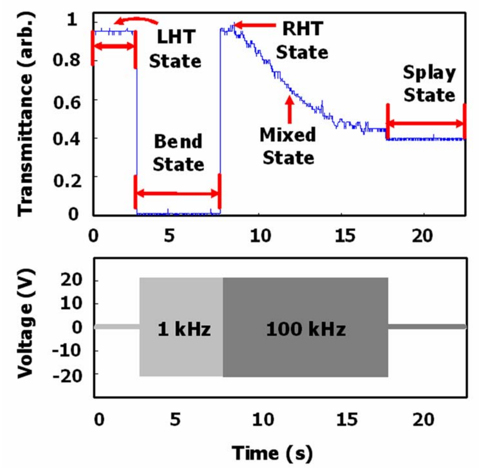

FIG. 3. (Color online) The transient transmittance and the corresponding driving waveform of the BCSN device switched from the LHT state to the splay state. The amplitude of the driving pulse is 20 V. The frequency is switched from 1 to 100 kHz.

the voltage is removed, the bend state is relaxed back to a LHT state. If the driving frequency is switched from a low frequency f1 to a high frequency f2 suddenly in the high tilt bend state, it returns back to the initial splay state via a transient RHT state.

To investigate the texture transitions and operation principles of BCSN 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.) that produced a pretilt angle of 3° after the parallel rubbing processes. The thickness (d) of the fabricated cell was 4.5 μm. A chiral additive material was doped into the DFLC of MLC-2048 [$\Delta\varepsilon=+3.3$ at a low frequency of 1 kHz and $\Delta\varepsilon=-3.4$ at a high frequency of 100 kHz (Merck)] to achieve a thickness to pitch (d/p) ratio of -0.2. The symbol "$-$" indicates the sense of left-handed twist. Finally, the DFLC blended with chiral dopant was then injected into the empty cells. To measure the electro-optical characteristics, the test cell is placed between two crossed polarizers, in which the angle between the rubbing direction and the transmissive axis of the input polarizer was 45°. A He–Ne laser of 632.8 nm wavelength is used as the light source. The vertical voltage waveforms applied to the test cell are generated using an arbitrary function generator. Both the applied voltage waveform and output of the photodetector are simultaneously monitored using a digital storage oscilloscope. The electro-optical characteristics of a BCSN device are illustrated in Figs. 2 and 3. Figure 2 shows the transient transmittance when switching from a splay state to a LHT state by applying a pulse with a voltage amplitude of 20 V and a frequency of 1 kHz. The LCs possess a positive dielectric anisotropy within the pulse duration, so the molecules in splay state are reoriented vertically. Finally, the 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 after 3 ms. As shown in Fig. 3, the LHT state can be switched back to bend state after 0.6 ms with an application of a pulse with a voltage amplitude of 20 V and a frequency of 1 kHz. When the frequency is changed to 100 kHz suddenly, the LC molecules of the middle layer lie down in the opposite direction due to reverse twist deformation caused by the backflow effect and the RHT state is generated. However, the RHT state with high elastic free energy is unstable and is gradually replaced by the splay state, which is the most stable state of this device.

To understand switching mechanisms, the dynamic behavior of the directors is simulated based on the Ericksen–Leslie–Parodi hydrodynamic theory. The simulator, originally developed at the NCTU LC laboratory, is modified to determine the director behavior of DFLC.[6,7] In our previous studies,[8] helical twist direction changes in the opposite direction temporarily by the flow-induced tip-over effect during the relaxation from the highly tilted bend state to the π twist state. In this letter, the calculating conditions are same as those of the fabricated cells. Figure 4 shows the behavior of LC directors during the LHT-to-bend and bend-to-RHT transitions. From the bottom substrate to the top substrate, it is considered that one end of the director (of unit length) is fixed at the origin and the other end traces out a curve from (1, 0) to (-1, 0). When the voltage is applied to the LHT

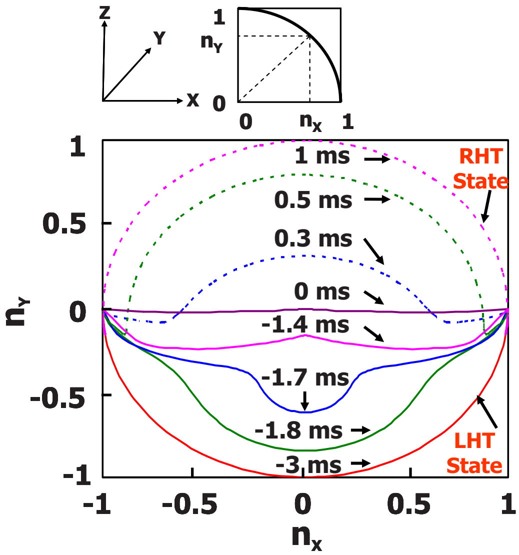

FIG. 4. (Color online) Calculated result of the behavior of LC directors during the LHT-to-bend and bend-to-RHT transitions by changing the frequency from a high frequency to a low one.

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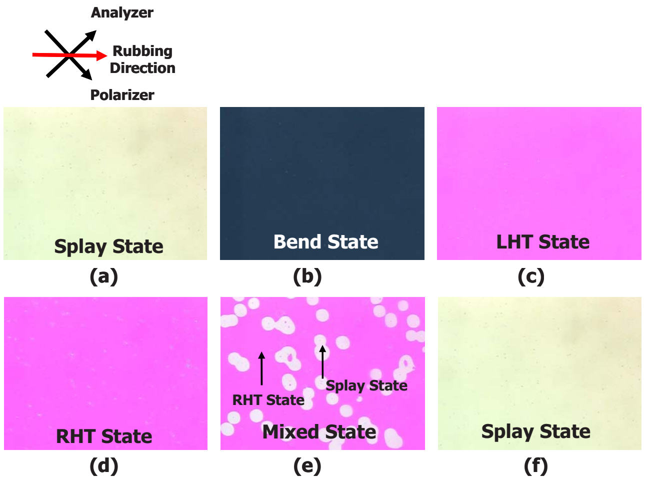

FIG. 5. (Color online) Transition textures of a BCSN cell observed under a polarizing optical microscope: (a) the splay state, (b) the bend state, (c) the left-handed π-twist state, (d) the right-handed π-twist state, (e) the mixed splay and right-handed π-twist states, and (f) the splay state.

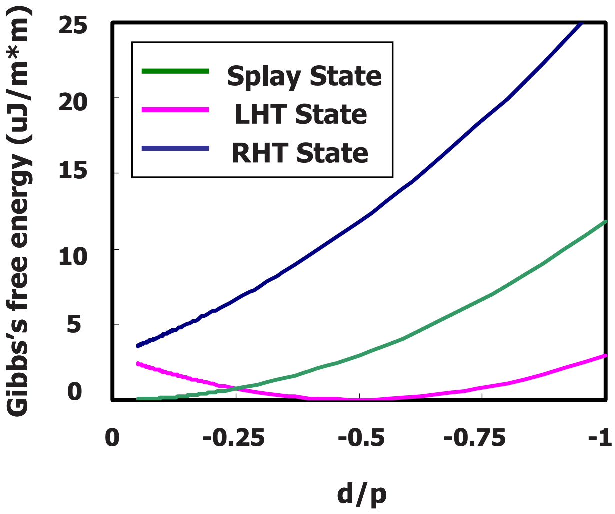

FIG. 6. (Color online) The d/p ratio dependent free energy of different configurations.

state at a low frequency, the LC directors are switched to the bend state after 3 ms. At the time of 0 ms, the frequency is changed from a low frequency to a high one in the high tilt bend state and the dielectric anisotropy of DFLC becomes negative. The flow-induced viscous torque kicks the LC directors in the midlayer back to the opposite side and then the helical structure changes to the RHT configuration. Finally, the LC directors lie down due to the negative dielectric isotropy of DFLC and a RHT state is formed after 1 ms. As a result, the flow effect is a key parameter to achieve the switching between RHT and LHT states.

The transition textures of a BCSN cell are illustrated in Fig. 5. Figure 5(a) shows the initial splay state due to the absolute value of d/p ratio is lower than 0.25, in which the splay and LHT states possess the equal Gibbs free energy density, as show in Fig. 6. By applying the voltage to the top and bottom electrodes, the splay state is switched to the bend state, as shown in Fig. 5(b). Once the applied voltage is removed immediately, the bend state relaxes directly to the LHT state because it is topologically equivalent to splay state, as shown in Fig. 5(c). To switch back to the splay state, the LHT state is first switched back to the bend state by applying a voltage at 1 kHz. Then, the driving frequency is changed from 1 to 100 kHz suddenly, after the formation of bend state is accomplished. Finally, the transition from bend state to the splay state occurs via a transient state, that is, RHT state, as shown in Fig. 5(d). The RHT state with the high Gibbs free energy density is unstable and is gradually replaced by the splay state, as shown in Figs. 5(e) and 5(f). Although true bistable states can be obtained with a d/p ratio of -0.25, the optimized d/p value in this letter is proposed to be -0.2. The energy gap between splay and LHT states is needed for a switchable bistable device. The RHT state is a transient state with the highest Gibbs elastic free energy density than those of splay and LHT states, as shown in Fig. 6. Transition from a RHT state to a splay state accompanies with the propagation of disclination lines. The propagation velocity of disclination line is proportional to the energy difference between splay and LHT states. The same free energy density of splay and LHT states at a d/p ratio of -0.25 hinders the motion of disclinaton lines.

In summary, a BSCN device is demonstrated by using a parallel rubbed cell filled with a DFLC material. The switching mechanisms of BCSN device are proposed by using the backflow effect together with the anisotropic properties of a DFLC material. The topologically inequivalent splay and π twist states have permanent memory characteristics.

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