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Bistable chiral tilted-homeotropic nematic liquid crystal cells

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A bistable chiral tilted-homeotropic nematic cell which uses dual-frequency liquid crystal is demonstrated. This cell can be switched between the tilted homeotropic state and the twisted state. The switching mechanisms are achieved by the backflow effect together with the anisotropic properties of the dual-frequency liquid crystal material. The experimental results of this bistable cell are described explicitly. © *2004 American Institute of Physics*. [DOI: 10.1063/1.1830681]

Bistable liquid crystal (LC) displays have received considerable attention recently because the power consumption can be reduced by their two (or more) stable states. Among them, the bistable twisted nematic (BTN) LC cell (2π-BTN[1,2]) can be switched between the $(\phi-\pi)$ and $(\phi+\pi)$ twisted states by controlling the flow effect. However, the lifetimes of these states are not very long because a more stable intermediate ϕ state exists. Although Wang and Bos[3] have achieved a long-term bistability by using multidimensional alignment structure to prevent the nucleation, the application is still limited. To make the states truly stable, several bistable modes have been demonstrated. For switching between the twisted states which differ by π, Bistable Nematic device (BiNem[4]) and comb-on-plate BTN (COP-BTN[5]) are comprised of asymmetric substrates with different anchoring energy to achieve anchoring energy breaking, and bistable chiral-splay nematic LC device (SCBN-LC[6]) and COP-BTN are constructed with three-terminal electrode structure to produce horizontal and vertical fields. Moreover, the substrates of the Zenithal Bistable Display[7] are made of the microstructure relief grating with short pitch and deep profile, and those of the micro-patterned surface alignment device[8] are patterned by using the atomic force microscope nano-rubbing technique. Due to the sophisticated substrates used in these modes, the manufacturing processes do not match the standard procedure in a typical LC display factory. On the other hand, our group has proposed the bistable chiral quasihomeotropic[9,10] device in which the conventional rubbing technique is employed to align the liquid crystal molecules. However, its two stable states exist only under an electric field. This drawback hinders the desired achievement in saving energy.

This letter demonstrates a scheme of a bistable LC cell, called the bistable chiral tilted-homeotropic nematic LC (BCTHN) device. This device can be switched easily between the tiltedly homeotropic state (TH state) and the twisted state (T state) because of the use of dual-frequency LC material. In comparison with the above-mentioned complex treatments of substrates, we simply exploit the conventional rubbing technique, which is part of a very popular manufacturing procedure performed in LC display factories, for the treatment of substrates. In addition, the two bistable states exist without electric field. In our experiment, the external voltage we applied to switch between the two stable states was 5 V_{rms}, which is much lower than most of the bistable devices reported in the literature. Furthermore, the simulation suggests that the contrast ratios of the transmissive or reflective cells under the crossed-polarizer condition are very high, comparable to those of chiral homeotropic liquid crystal cells.[11,12]

Consider a cell with a thickness-to-pitch ratio (d/p) around one. We obtain two stable states with the pretilt angle, measured from the substrates, in a suitable range which is determined by the LC parameters and the anchoring energy of the substrates. Figure 1 illustrates the textures of these two states and the transition processes of the proposed bistable cell consisting of a dual-frequency liquid crystal. When the cell is in the T state, an electric field with frequency f_1 applied in the vertical direction will pull the LC molecules vertically since the liquid crystals possess a positive dielectric anisotropy $(\Delta\varepsilon)$ at the very frequency. When the molecules reach balance, the cell exhibits the biased homeotropic (BH) state. The LC molecules in BH state are balanced by the elastic deformation torque and the electric torque. The middle-layer directors are vertical and the directors near the boundaries are slightly tilted in the rubbing

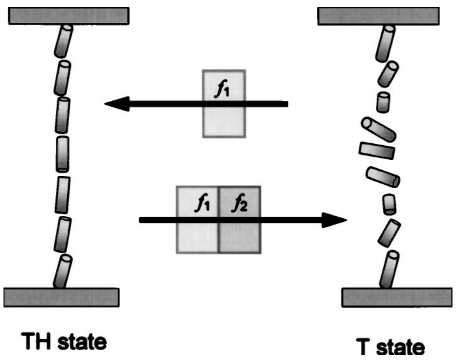

FIG. 1. Bistable textures and transition processes of the BCTHN device.

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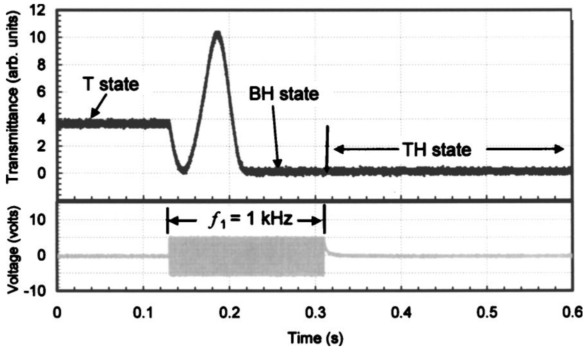

FIG. 2. The transient transmittance and the corresponding driving wave form of the BCTHN device switched from the T state to the TH state. The amplitude of the driving pulse is 5 V and the frequency is 1 kHz.

direction. Once the voltage is off, the molecules relax to the tiltedly homeotropic (TH) state. The molecules in TH state are aligned nearly homogeneous with a very high tilt angle.

To switch the TH state to T state, one can apply a pulse with frequency f_1, followed immediately by another pulse with a higher frequency of f_2. Upon the application of the first pulse, the cell is first switched to the BH state. When the frequency of the electric field is changed from f_1 to f_2, the dielectric anisotropy of the dual-frequency liquid crystal is changed to negative and the electric torque tends to align the molecules horizontally. This torque makes the directors near the substrates rotate faster than the mid-layer directors do and produces a flow velocity due to the coupling via viscous interaction. The spatial variation of the velocity gives rise to the tilt angle of the middle-layer directors being larger than $\pi/2$. This phenomenon is usually called the backflow effect. As a result, the directors of the cell rotate nearly 2π in the azimuthal angle. Finally the mid-layer directors become parallel to the substrates and the biased twisted (BT) state is generated. The directors relax to the T state with a slight tilt in the midle layer when the voltage is off.

To demonstrate the BCTHN device, we used indium-tin-oxide glasses as the substrates and coated them with RN-1338 (Nissan Chemicals Co.) to form the tiltedly homeotropic alignment layers. The rubbing directions of the top and the bottom alignment layers were antiparallel. The dual-frequency LC material we used was MLC-2048 (Merck Co.) with $\Delta\varepsilon=3.22$ at 1 kHz and $\Delta\varepsilon=-3.4$ at 100 kHz. Pairs of the substrates were combined by using 9.9 μm spacers mixed in the adhesive to form empty cells, which were then filled with MLC-2048 with a pitch of -10 μm. The TH state and T state coexisted when the cell was first assembled. And a dark state appeared after we applied a 1 kHz pulse under the crossed-polarizer condition. It is quite easy to have either one of the bistable states by using the switching mechanism proposed in Fig. 1.

The optical properties were measured under the crossed-polarizer condition with the transmission axis of the linear polarizer and the rubbing directions parallel to the x axis. The light source was a He–Ne laser with a wavelength of 632.8 nm. If the cell is in the TH state or BH state, the light goes through the cell with little phase-retardation so that the appearance of the cell is dark and the transmittance low. In contrast, if the cell is in the T state or BT state, the light leaks through the second polarizer so the transmittance is higher.

Figure 2 shows the transient transmittance of the BCTHN cell from T state to TH state by applying a pulse (voltage $=5$ V$_{\mathrm{rms}}$, frequency $=1$ kHz). The liquid crystal possesses a positive dielectric anisotropic within the pulse duration. The oscillation of the transmittance is due to the change in phase-retardation when the twisted molecules (in T state) are pulled to the vertical direction. As most of the LC molecules become vertical (BH state), the cell appears dark. When the voltage is turned off, the LC molecules relax to the TH state of which the transmittance is also very low.

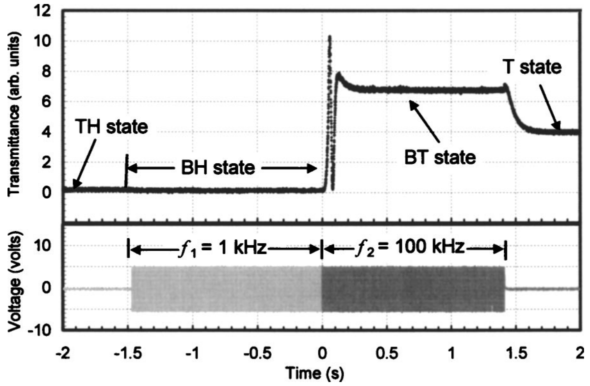

FIG. 3. The transient transmittance and the corresponding driving wave form of the BCTHN device switched from the TH state to the T state. The amplitude of the driving pulse is 5 V. The frequency is switched from 1 to 100 kHz.

Figure 3 shows the transmittance from TH state to T state as well as the corresponding driving wave form. When a voltage of 5 V$_{\mathrm{rms}}$ with a frequency of 1 kHz is applied to the cell, the LC molecules are switched to the BH state, keeping the transmittance almost unchanged. Then the frequency is changed to 100 kHz suddenly, the LC molecules of the middle layer tilt down in the opposite direction due to the backflow effect. Finally they lie in the $-x$ direction and the cell is in the BT state. Note that the oscillation of the transmittance following the onset of the frequency change is attributed to the phase-retardation change as the directors spread into the BT state. When the voltage is off, the LC molecules relax to the T state, which is the bright state.

Figure 4 shows the microscopic photographs of TH state, BH state, T state, and BT state in the crossed-polarizer condition with rubbing directions parallel to the polarizer. The TH state is not as dark as the BH state, because most directors in the BH state are vertical while the directors in the TH state are tilted. If some misalignment of the substrates exists, the directors in the TH state form a helical structure with a small conic angle, and the transmittance of the cell increases. Since the BT state is reddish while the T state is greenish, the transmittance of the BT state is higher when using a He–Ne laser as the light source, as shown in Fig. 2 and 3, and lower

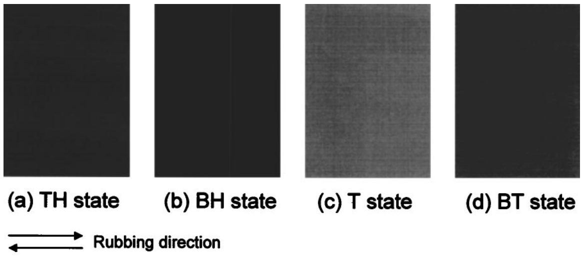

FIG. 4. Transmission micrographs of the BCTHN device under the crossed-polarizer condition. (a) The tiltedly homeotropic state; (b) the biased homeotropic state; (c) the twisted state; (d) the biased twisted state.

when taking black-and-white pictures under the microscope with a white light source. In BTCHN, the optimized value of $d\Delta n/\lambda$ for maximum light efficiency is related to the pretilt angle and LC parameters. In our simulations, the contrast ratio of 1000 is easily achieved at $\lambda = 550$ nm.

Experimentally, we find that the pretilt angle is crucial to the BCTHN device. As the pretilt angle is close to 90°, the cell prefers TH state and the focal conic tuxture.[13] However, small pretilt angle makes the T state more stable. The d/p ratio is another factor to affect the bistability. A larger d/p makes the TH state absent while smaller d/p makes T state vanish. These results have been confirmed by simulation. To make this bistable device applicable, the elastic constants of the liquid crystals, which influence the free energies of the two stable states, should be optimized. Dust particles and defects on the substrates also affect the bistable states. For example, after the cell is switched to the dark state (TH state) and the whole cell appears dark for about a few minutes, some bright spots may appear slowly and extend gradually to their peripheral areas. It needs about an hour to complete this process and the final status of the cell is half TH state and half T state.

In summary, a bistable chiral tilted-homeotropic cell using dual-frequency liquid crystal has been demonstrated. The switching mechanisms of our BCTHN cell are achieved by the flow effect of directors, together with the anisotropic properties of the LC material. By optimization of the LC parameters, it is expected to obtain the equal-free-energy states with high barrier so that the two states can be more stable.

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