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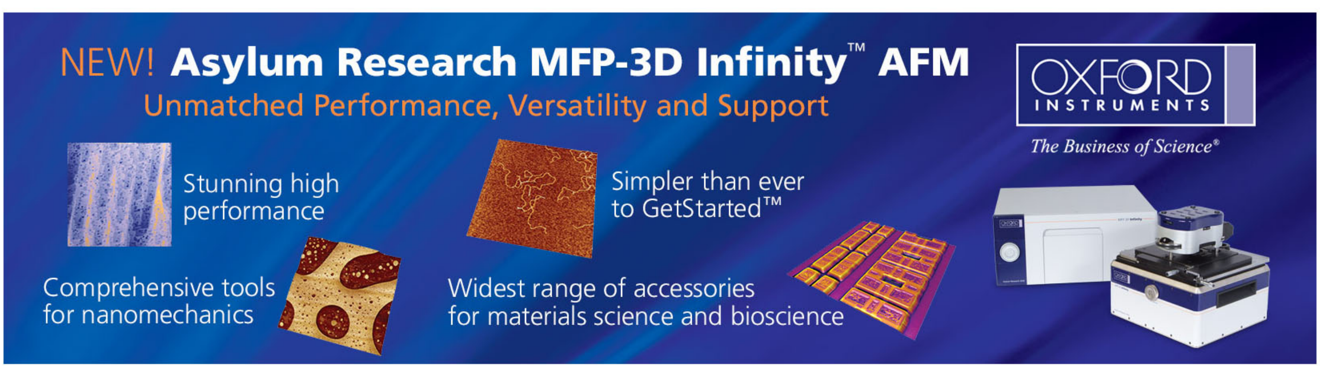

Dynamic behaviors of dual frequency liquid crystals in bistable chiral tilted-homeotropic nematic liquid crystal cell

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The switching behaviors of dual frequency liquid crystals (DFLC) in a bistable chiral tilted-homeotropic nematic (BHN) LC cell are simulated and compared with the observed results. This cell can be switched between tilted-homeotropic state and twisted state under the applied voltage as low as 5 V. The reason for the low switching voltage is attributed to the dielectric anisotropy character of DFLC. The analysis also shows that the switching wave form accelerates the switching behaviors of the directors which results in faster response in BHN LC cell. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2335392]

Bistable liquid crystal displays (LCDs) have a bright future because the power consumption can be reduced by using their two (or more) stable states to display information. Owing to this character they are suitable to be applied to e-books and other display devices which do not have to change the content constantly. Several bistable display technologies have been developed, such as bistable cholesteric display,[1] bistable twisted nematic display[2–5] which includes several variants with a π or 2π twist angle difference between the two stable states, zenithal bistable display,[6] ferroelectric LCD (Ref. 7) and bistable bend-splay LCD,[8,9] etc. However, each design has its own merits and difficulties.

Among some of bistable LCDs, the flow effect of liquid crystal (LC) material plays a very important role in the switching mechanism, including the bistable twisted nematic [BTN (Ref. 2)] LCD, bistable nematic [BiNem (Refs. 3)] display, comb-on-plate BTN [COP-BTN (Ref. 4)], bistable chiral-splay nematic [SCBN (Ref. 5)] LC device, etc. These bistable LCDs use conventional LC materials, thus the flow effects are mainly induced by the restoring forces caused by elastic deformation.[10] In addition to the flow effect, BiNem is composed of one weak anchoring alignment substrate in order to achieve anchoring energy breaking; SCBN and COP-BTN LCD adopt three-terminal electrodes to produce both vertical and horizontal electric fields to accomplish the switching mechanism.

Recently, our group proposed a bistable chiral tilted-homeotropic nematic (BHN) LC device,[11] which can be switched between the tiltedly homeotropic state (TH state) and the twisted state (T state) by using dual frequency liquid crystals (DFLC). The substrates are prepared by using conventional technique which is well established compared with the three-terminal electrodes or the weak anchoring energy alignment substrate. The use of DFLC in the LCDs is mostly concerned by its temperature dependence of the dielectric anisotropy, so-called dielectric heating effects.[12,13] Fortunately there is no problem in using DFLC material in the bistable LC devices because the external field is only applied when the displayed information is needed to change and the durations of the pulses are very short compared with the ordinary hold-type LCDs. Low operating voltage and faster response time are observed in dual frequency hybrid aligned nematic LC cell;[12,14] however, the application of DFLC in the bistable LCDs is rare[8] and has never been explicitly studied before.

In this letter, we analyze the dynamic behaviors of the directors when the applied electric field is switched from low to high frequency in BHN LCD. The simulated directors and flow velocity profiles reveal that the flow effect is induced when we change the frequency of the field and it is a crucial effect on the switching mechanism. The explanation of low applied field and fast switching time is also disclosed.

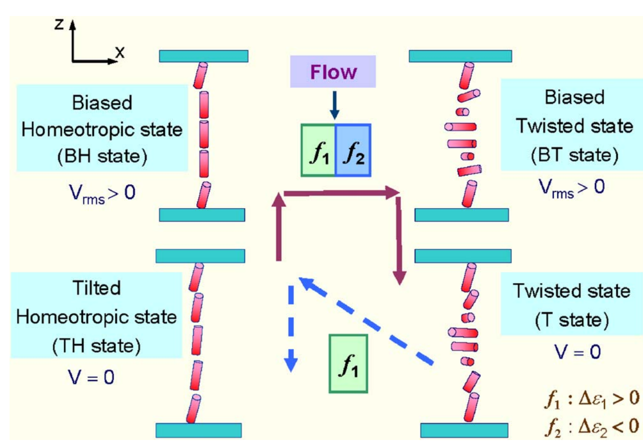

FIG. 1. Director configurations of the BH, BT, TH, and T states and their transition processes of the BHN LC device.

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TABLE I. Cell and liquid crystal material parameters used in the simulation. The six Leslie coefficients are taken from MBBA.

Pitch	−10 μm	Wavelength	632.8 nm
K_{11}	17.3 pN	Pretilt angle	75°
K_{22}	12.7 pN	Cell gap	9.6 μm
K_{33}	30.3 pN	n_e	1.6864
γ_1	153 mPa s	Δn	0.2254
α_1	−21.2 mPa s	Applied frequency	f_1=1 kHz
α_2	−153 mPa s	$\varepsilon_{\parallel}$	11.02
α_3	−0.773 mPa s	$\Delta\varepsilon_1$	3.22
α_4	109.5 mPa s	Applied frequency	f_2=100 kHz
α_5	107.1 mPa s	$\varepsilon_{\parallel}$	4
α_6	−46.0 mPa s	$\Delta\varepsilon_2$	−3.4

Figure 1 sketches the textures of two stable states in the lower row, two biased states in the upper row, and the transition processes of BHN LC cell. The dash lines illustrate the process from the twisted state (T state) to the tiltedly homeotropic state (TH state). That is when the cell is in the T state, which is depict at the lower right corner of Fig. 1, a vertical electric field pulse with a low frequency f_1 pulls the LC molecules vertically since the liquid crystals possess a positive dielectric anisotropy $\Delta\varepsilon_1$ at this frequency. The cell is switched to the biased homeotropic state (BH state). Once the voltage is off, the directors relax to TH state. To switch back to T state, which are drawn by the solid lines in Fig. 1, we first apply a pulse with frequency f_1 and the cell is back to BH state. Then, followed immediately by another pulse with a high frequency of f_2, in which the liquid crystals possess a negative dielectric anisotropy $\Delta\varepsilon_2$ at the very frequency, the cell is switched to the biased twisted state (BT state). When the voltage is off, the directors relax to T state. In the following, we use the Ericksen-Leslie-Parodi theory[15] to analyze the dynamic behaviors of the directors of DFLC in the BHN LCD from TH state to T state.

When we switch the BHN LC cell from TH state to T state, we first applied a field of $\mathbf{E}_1=(0,0,E_{1z})$ with frequency f_1 for a period of time until the external director body force,[17] $\mathbf{G}=\varepsilon_0\Delta\varepsilon_1(\hat{n}\cdot\mathbf{E}_1)\mathbf{E}_1$, is balanced with the elastic restoring force f_{elas}, that is,

$$G_i+(f_{\text{elas}})_i=0=\varepsilon_0\Delta\varepsilon_1(\hat{n}\cdot\mathbf{E}_1)E_{1i}+\lambda n_i-\frac{\partial F_{\text{def}}}{\partial n_i}+\frac{\partial}{\partial z}\frac{\partial F_{\text{def}}}{\partial n_{i,z}}, \qquad (1)$$

where $F_{\text{def}}=0.5\times[k_{11}(\nabla\cdot\hat{n})^2+k_{22}(\hat{n}\cdot\nabla\times\hat{n}+q_0)^2+k_{33}(\hat{n}\times\nabla\times\hat{n})^2]$, $\hat{n}$ is the LC director which is function of z, and λ is a Lagrange multiplier that ensures $|\hat{n}|=1$. k_{11}, k_{22}, and k_{33} are the splay, twist, and bend elastic constants, respectively. q_0 is $2\pi/p$, where p is the pitch of the helix.

This equilibrium is broken when the applied field is changed to E_2 and the frequency jumped to a higher frequency f_2. At this very moment, the forces acting on the directors are the new external director body force $\mathbf{G}'=\varepsilon_0\Delta\varepsilon_2(\hat{n}\cdot\mathbf{E}_2)\mathbf{E}_2$ and the elastic restoring force.[16] Since the movement of the directors is slow comparing to the switching of the frequency, the elastic restoring force is the same as that before changing the applied frequency. Therefore, the torque acting on the director, $\hat{n}=(\cos\alpha\cos\phi,\cos\alpha\sin\phi,\sin\alpha)$, is the external torque, $\boldsymbol{\tau}_{\text{ext}}=\mathbf{n}\times\mathbf{G}'$, and the elastic restoring torque, $\boldsymbol{\tau}_{\text{elas}}=\hat{n}\times\mathbf{f}_{\text{elas}}=-\hat{n}\times\mathbf{G}$, from the force balance equation [Eq. (1)]. That is,

$$\boldsymbol{\tau}_{\text{ext}}+\boldsymbol{\tau}_{\text{elas}}=\mathbf{n}\times(\mathbf{G}'-\mathbf{G})=-0.5\times\sin 2\alpha[|\Delta\varepsilon_2|E_{2z}^2+\Delta\varepsilon_1E_{1z}^2]\varepsilon_0(\hat{x}\sin\phi-\hat{y}\cos\phi), \qquad (2)$$

where E_{iz} is the electric fields in z axis of the first and second pulses and α and ϕ are the tilt and azimuthal angles of the director, respectively. These two torques are the sources to induced flow in the BHN LCD. Compared with conventional bistable LCD, the source to induce flow can only be one of them.

To analyze the movement of directors, we extend the simulator developed in our laboratory[16] to calculate the detailed dynamic behaviors of the director of DFLC in the BHN LCD. In the Ericksen-Leslie-Parodi theory, the hydrodynamic equations couple the director reorientation with the flow of the liquid crystals. We solved these equations by using relaxation method and neglect the inertial term of directors. The boundary directors are rigidly anchored in the x axis with a pretilt angle. The flow is restricted to the plane of the cell ($v_z=0$) with no-slip boundary conditions ($v_x=v_y=0$ at $z=0$ and d). The transient directors (n_x, n_y, n_z) and their velocities (v_x, v_y, 0) are function of z only. The optical transmittance is obtained by using Jones matrix calculus under a cross-polarizer condition with one of the transmission axis in the x axis. Table I shows the parameters used in the simulation. Due to lack of the Leslie coefficients of MLC-2048, these coefficients are taken from the values of MBBA. The time step of the simulation is 10^{-5} s, the dielectric anisotropy is changed from $\Delta\varepsilon_1$ to $\Delta\varepsilon_2$ at $t=0$, and we assumed that all the parameters but the dielectric constants of DFLC are the same when the applied frequencies are f_1 and f_2. The dynamic physical pictures of the directors and corresponding induced flow velocity profile at 1 ms after changing the ap-

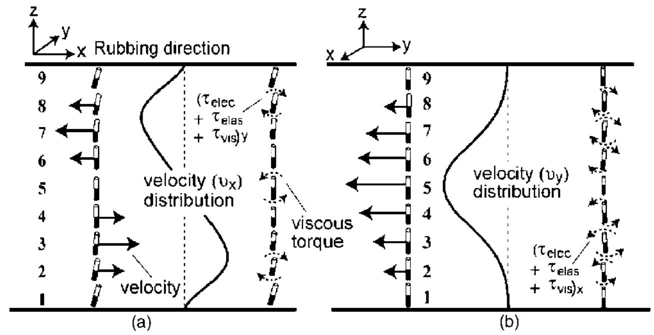

FIG. 2. Dynamic physical pictures of the directors and the induced velocity distribution in the (a) x-z plane and (b) y-z plane at 1 ms after the applied frequency changed from 1 to 100 kHz.

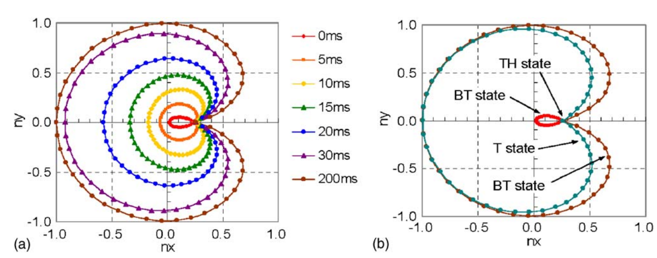

FIG. 3. (a) Transient director configurations projected on the x-y plane after the applied frequency is changed from 1 to 100 kHz. (b) The director configurations of the TH, BH, T, and BT states projected on the x-y plane.

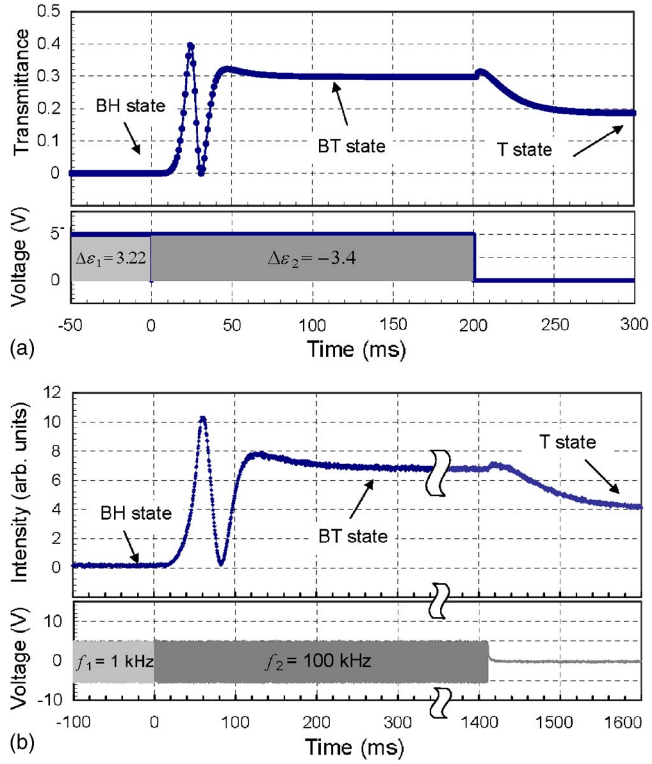

FIG. 4. (a) Calculated and (b) measured transmittance curves of the switching process. The cell is switched from BH state to T state by using the switching pulses of 5 V with the frequency changed from 1 to 100 kHz.

plied frequency are plotted in Fig. 2. Figure 3(a) illustrates the dynamic director configurations of the BHN LC cell projected in the x-y plane after changing the applied frequency and Fig. 3(b) depicts the director configurations of TH, BH, T, and BT states.

While the cell is under the field of E_1, the directors are vertical in the center part of the cell and exhibit largest elastic distortion near the substrates. As the applied frequency suddenly changed to f_2, the directions of $\boldsymbol{\tau}_{ext}+\boldsymbol{\tau}_{elas}$ are in the $+y$ direction near both substrates according to Eq. (2) and the tilt angle of the directors. Through the viscous interaction[17,18] of liquid crystals, the direction of the induced translational motion in the upper half of the cell is opposite to the lower half of the cell. The gradient of the induced flow velocity imposes a viscous torque $\boldsymbol{\tau}_{vis}$ to the directors. Since the directors on the central part of the cell are vertical, the electric and restoring torques are zero and the viscous torque rotates the directors in the $-x$ direction. These directors and the flow configurations are sketched in Fig. 2(a). Once the tilt angle of the director is larger than $\pi/2$, the electric torque pull it toward the negative x axis as shown in Fig. 3(a). At the same time in the y-z plane, $\boldsymbol{\tau}_{ext}+\boldsymbol{\tau}_{elas}$ have opposite direction near both substrates due to the twist of the directors in BH state as shown in Fig. 3(b). The induced translational motion is in the $-y$ direction, depicted in Fig. 2(b). Therefore the viscous torques are in opposite direction near two boundaries and are zero in the center. This viscous torque splays the directors and the electric torque accelerates them to the x-y plane. In brief, the combination of the viscous and electric torques promotes the directors to be switched to BT state. Figure 4(a) illustrates the calculated optical transient transmittance curve which behaves similarly to the experimental results shown in Fig. 4(b).

In our study, we use two connecting pulses to switch BHN LC cell from TH state to T state. The intention of the first pulse is to pull the directors vertical. Without the second pulse, it is a simple switching wave form for BTN LCDs from the homogeneous state to twisted state.[10] The elastic restoring torque is the only source to induce flow at the end of the pulse in its switching mechanism. In the BHN LC cell, when we add the second pulse of high frequency to DFLC, the flow effect is enhanced by both the elastic restoring and electric torques. Therefore, a smaller applied field can achieve the switching from TH state to T state. Moreover, the field of the second pulse continues adding a force to accelerate the directors moving to T state therefore the switching time is shorter.

On the other hand, without the first pulse, all the tilt angles of the directors equal to the pretilt angle before the high frequency pulse is applied. The required viscous torque must be strong enough to kick the midlayer director through $\pi/2$ to the opposite direction.[18] This is the switching mechanism of BCQH LC cell and is happened only when the pretilt angle is close to $\pi/2$. In the BHN LC cell, due to the first low frequency pulse the tilt angle of the middle directors is vertical when the second high frequency pulse is applied. Therefore the minimum viscous torque and the applied field can be reduced.

In summary, due to the dielectric anisotropy of DFLC, the sudden change of the applied frequency from f_1 to f_2 is confirmed to have positive impact on producing the flow effect when the cell is switched from BH state to BT state. By using the two frequency wave form and applying to DFLC, the switching voltage can be lower than that used in most bistable LCD and the switching time is decreased.

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