Dynamic flow and switching bistability in twisted nematic liquid crystal cells

Tie-Zheng Qian
Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong

Zhi-Liang Xie and Hoi-Sing Kwok
Centre for Display Research, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong

Ping Sheng[a)]
Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong

(Received 2 April 1997; accepted for publication 20 May 1997)

We investigate the switching bistability based on the interaction between dynamic flow and director rotation in twisted nematic liquid crystal cells. Numerical calculation shows that there exists a general type of bistable twisted director configuration. Two specific cases are verified experimentally. © *1997 American Institute of Physics.* [S0003-6951(97)02129-3]

Twisted nematic (TN) and super-twisted nematic liquid crystal displays (LCD) are used widely in many information display systems. Recently, a bistable TN(BTN)LCD has been demonstrated.[1,2] This BTN is based on a gross mismatch of the natural twist of the liquid crystal director and the rubbing boundary conditions of the two LC cell surfaces. If the LC cell alignment favors a Φ twist, then for some value of natural helical pitch, P, the LC cell can exist either in the Φ-twist state or the $(\Phi+2\pi)$-twist state. Roughly speaking, in the absence of pretilt of the director, the natural twist of the LC cell should be about $\Phi+\pi$. Hence the d/P ratio, where d is the LC cell thickness, should be about $0.5+\Phi/2\pi$ for the bistability to occur.

While practical displays have been made using this principle, the switching behavior of such BTN is not well known. It is evidently related to the hydrodynamics of director motion. The interaction between dynamic flow and director rotation was shown to be responsible in a theoretical explanation of the ''bounce'' phenomenon observed in the light transmission of twisted nematic liquid crystal cell (TNLCC).[3–5] More generally, a comparison between the results obtained by including and neglecting the fluid motion showed that under certain circumstances, dynamic flow can play a critical role in governing director rotation.

In this letter, the switching bistability that can originate from the flow effect on director rotation in TNLCC is investigated. The physical mechanism underlying the seemingly ''abnormal'' behavior of director motion is used as a guide to seek the switching bistability that can be realized in properly prepared TNLCCs. The bistable configurations consist of two twist states of twist angles Φ and $\Phi+2\pi$, respectively, with Φ specified by the relative arrangement of the two substrates with homogeneous alignment conditions. From the numerical solutions of the Ericksen–Leslie equations, we find that the switching bistability can be realized for $-\pi/2\leqslant\Phi\leqslant 0$ in cells with surface alignment pretilt angle $\sim 10°$ as measured from the substrate. The predicted switching bistability is confirmed by experiments. However, the observed range of d/P, within which the switching bistability can occur, shows a systematic deviation from the predicted values. Such deviation is observed to increase as the cell thickness decreases, and can be appreciable for $d\leqslant 7\ \mu$m. Apart from the d/P ratio, quantitative agreement between theory and experiment was obtained in the time profile of light transmission. It should be pointed out that the $\Phi=-\pi/2$ case has been reported recently, but the observation was for wedge-shaped cells only and the driving wave form is different from ours,[6] while the $\Phi=0$ case, reported long ago, was observed in cells with large pretilt angle $(>35°)$.[7] The results of our study show that the $\Phi=-\pi/2$ and $\Phi=0$ cases have the same dynamical symmetry and similar flow effect, and can thus be regarded as two specific examples of a general kind of switching bistability phenomenon.

The following dynamical symmetries were found numerically and proved to be rigorous analytically from the hydrodynamic equations of Ericksen and Leslie. With the directors at the lower and upper substrates denoted by $\mathbf{n}^L$ and $\mathbf{n}^U$, if $n_x^L=n_x^U$, $n_y^L=-n_y^U$, $n_z^L=n_z^U$, where the z axis is normal to the substrates, then the time-varying directors and velocities obey the relations $n_x(z)=n_x(d-z)$, $n_y(z)=-n_y(d-z)$, $n_z(z)=n_z(d-z)$, together with $v_x(z)=-v_x(d-z)$, $v_y(z)=v_y(d-z)$, provided the initial state has such symmetries. In this letter, the $\Phi=-\pi/2$ case corresponds to $n_x^L\sim\sqrt{2}/2$, $n_y^L\sim\sqrt{2}/2$, $n_z^L>0$, and the $\Phi=0$ case corresponds to $n_x^L\sim 1$, $n_y^L\sim 0$, $n_z^L>0$. The physical picture of switching dynamics may be described as follows. When a strong electric potential is applied across the cell, the field-induced correlation length can be much smaller than the cell thickness. As a consequence, the directors near the substrates can exhibit large elastic distortions, leaving the directors throughout the central part of the cell (nearly) uniformly vertical. When the large voltage is switched off, the large local elastic distortion energy density near the substrates, and consequently the large molecular field $\mathbf{h}$, can give rise to fast rotation of the directors. The near-substrate rotation of the

[a)]Electronic mail: phsheng@usthk.ust.hk

 0003-6951/97/71(5)/596/3/$10.00

directors would inevitably induce a flow velocity field due to the coupling between $\mathbf{n}$ and $\mathbf{v}$ through viscous interaction. In the law of friction, the forces are proportional to the fluxes, one of which is just the conventional $\partial_i v_j + \partial_j v_i$ term and the other one is the torque $\mathbf{N} = \dot{\mathbf{n}} - \boldsymbol{\omega} \times \mathbf{n}$ with $\boldsymbol{\omega} = \nabla \times \mathbf{v}/2$. The latter determines the rotational field $\boldsymbol{\omega}$ near the substrates. In all the cases we have studied, it is found that the near-substrate $\dot{\mathbf{n}}$ always induces a local $\boldsymbol{\omega} \times \mathbf{n}$ in the same direction, which means $\boldsymbol{\omega}$ is parallel to $\mathbf{n} \times \dot{\mathbf{n}}$. The knowledge of the near substrate $\boldsymbol{\omega} = (-\partial_z v_y, \partial_z v_x, 0)$, plus the boundary conditions and the dynamical symmetry relations, are sufficient to qualitatively determine the whole velocity field in the cell. The spatial variation of the velocity field near the midplane is therefore completely determined. As the directors throughout the central part of the cell are nearly homogeneous and hence the elastic distortion molecular field is weak, their motion is dominated by the gradient of the flow field. From angular momentum conservation, the initial flow at the midplane has to be opposite to those near the substrates. This is the origin of the so-called ''backflow'' phenomenon.

We consider cells in which the surface treatment imposes $\mathbf{n}(0) = \mathbf{n}^L$ at the lower substrate and $\mathbf{n}(d) = \pm \mathbf{n}^U$ at the upper substrate. Note $\mathbf{n}^L$ and $\mathbf{n}^U$ satisfy the director symmetry relation given above. We focus on the case of small pretilt angle, i.e., $n_z^L = n_z^U = \sin \psi_p$ with $\psi_p \sim 10°$, which is typical for rubbed polyimide-coated substrates. We numerically find that for $\Phi = -\pi/2$, if $d/P \sim 0.4$, there exists a switching bistability which may be explained from the mechanism of backflow, while for $\Phi = 0$, if $d/P \sim 0.8$, there is a similar switching bistability resulting from the backflow effect. The two twist states involved in the switching bistability are the Φ- and the $(\Phi + 2\pi)$-twist states. The Φ-twist state can be switched to the $(\Phi + 2\pi)$-twist state by applying the driving waveform $V_A(t)$ (for $\Phi = -\pi/2$) or $V_A'(t)$ (for $\Phi = 0$), and the reverse switching process can be realized by applying the driving wave form $V_B(t)$ (for $\Phi = -\pi/2$) or $V_B'(t)$ (for $\Phi = 0$). V_A' and V_B' are similar to V_A and V_B, respectively, implying a similar underlying mechanism in the two cases. Both $V_A(t)[V_A'(t)]$ and $V_B(t)[V_B'(t)]$ first jump from zero to a holding voltage V_H that is higher than a threshold value and lasts a certain duration. V_H is switched off suddenly in $V_A(t)[V_A'(t)]$, but gradually in $V_B(t)[V_B'(t)]$. In essence, right after the holding voltage V_H is switched off, the fast rotation of the directors near the substrates induces the flow velocity pattern which drives the midplane director towards a state with a larger twist angle ($3\pi/2$ and 2π, respectively), in a direction opposite to what the elastic distortion would enforce. Whether the final state can be of larger or smaller twist angle depends on the strength of the viscous molecular field $\mathbf{h}'$ in the initial stage of the relaxation process. This is controlled by the manner in which V_H is switched off, i.e., suddenly or gradually. It is clear that the more abruptly V_H is switched off, the larger would be the strength of $\mathbf{h}'$.

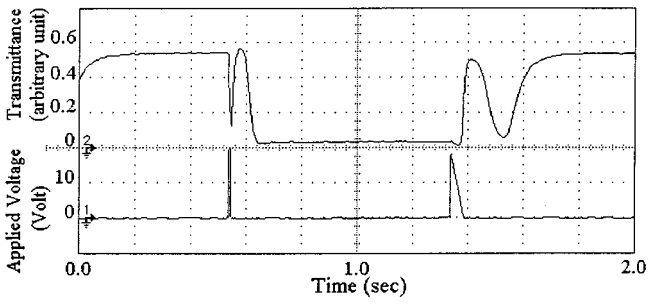

FIG. 1. Electro-optical response measured for the $\Phi = -\pi/2$ cell sandwiched between crossed linear polarizers. The lower curve shows the time profile of the applied voltage.

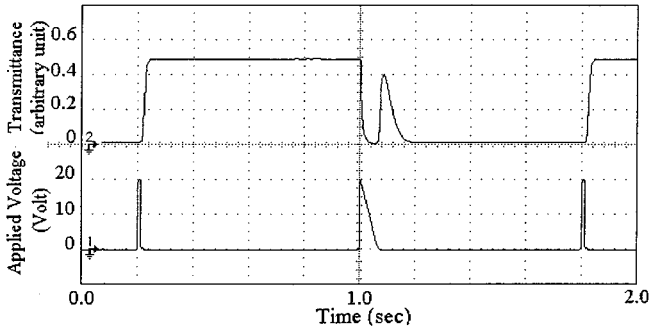

FIG. 2. Electro-optical response measured for the $\Phi = 0$ cell sandwiched between crossed linear polarizers. The lower curve shows the time profile of the applied voltage.

We made many LC cells sandwiched between rubbed polyimide-coated substrates, with surface pretilt angle $\psi_p \simeq 8°$ and rubbing conditions favoring 0 or $-\pi/2$ twist. The d/P ratio was varied systematically in order to establish the bistability conditions. It was found experimentally that for the 0-twist case, d/P should be about 0.6. For the $-\pi/2$ case, d/P should be 0.3. The LC and the chiral additive used are MLC-6218 or MLC-7500-000, and S-811 of Merck. The concentration of S-811 was varied to adjust d/P. The two cases discussed above were prepared and measured for $d = 2.5$, 5.0, and 7.0 μm. The electro-optical response, depicted in Figs. 1 and 2 with $V_H = 20$ V, was measured by placing the cells between crossed linear polarizers and making the optical axis of the incident light aligned by $\pi/4$ (for $\Phi = -\pi/2$) or parallel (for $\Phi = 0$), respectively, to the rubbing direction of the lower substrate. The cells with different twist angles are of different colors, determined by their respective dispersion properties. The uniformity of the optical response is perfect within the central area $\sim 1\ \mathrm{cm}^2$, ensured by the uniformity of the cell thickness.

The experimental data were modeled by calculating the director time dependence under the various voltage pulses. Using the Jones matrix method, the time-varying light transmittance is calculated from the director configurations. The involved material and optical constants are listed in Tables I and II. Here α_i/α_4 are taken from Ref. 5, suitable for MBBA, since very few measured viscosity coefficients are available. Using α_i/α_4 for PAA or 5CB only leads to a

TABLE I. The dimensionless viscosity coefficients and elastic constants used in the numerical calculation of hydrodynamics.

α_1/α_4	0.07808	α_2/α_4	-0.9315
α_3/α_4	-0.01435	α_5/α_4	0.5565
α_6/α_4	$(\alpha_2+\alpha_3+\alpha_5)/\alpha_4$		
K_2/K_1	0.5429	K_3/K_1	1.52

TABLE II. The optical parameters used in the calculation of light transmission. Note that n_e and n_0 are, respectively, the extraordinary and ordinary refraction indices of the LC; $\epsilon_\parallel$ and $\epsilon_\perp$ are the parallel and vertical components of the dielectric tensor of the LC; and λ is the laser wavelength used in measuring the transmittance.

Φ	$-\pi/2$	0
Material	MLC-6218	MLC-7500-000
n_e	1.6564	1.5869
n_0	1.4976	1.4830
$\epsilon_\parallel$	15.6	14.8
$\epsilon_\perp$	4.6	4.6
λ	0.543 μm	0.514 μm
d	7.0 μm	5.0 μm

slight change in numerical results. The dimensionless numerical solutions are obtained by choosing $d/P=0.425$ for $\Phi=-\pi/2$ and $d/P=0.85$ for $\Phi=0$. The time unit is given by $\tau=d^2\alpha_4/K_1$, where α_4 is the fourth Leslie coefficient and K_1 is the splay elastic constant. Comparing the time-varying light transmittance calculated from the numerical solution with the measured electro-optical response yields $\alpha_4/K_1=1.56\times10^6$ cm^{-2} s for MLC-6218 and $\alpha_4/K_1=2.30\times10^6$ cm^{-2} s for MLC-7500-000. The calculated light transmittance of the cell sandwiched between crossed polarizers is depicted in Fig. 3 for the $\Phi=-\pi/2$ case, and in Fig. 4 for the $\Phi=0$ case. For the case of $\Phi=-\pi/2$, it is interesting to compare Figs. 1 and 3. Experimentally as well as theoretically, an ''optical bounce'' [3] is observed in both switching directions. The shape of the transmittance curves, and the rise and fall times are quite well predicted. For the case of $\Phi=0$, (Figs. 2 and 4), the agreement is also excellent. While there is a bounce in 2π to 0 switching, the opposite switching direction is fast and clean. Both the experimental and theoretical risetime is about 20 ms. Thus the agreement between theory and experiment is remarkable. It should be noted that the calculated results are sensitive to the ordinary and the extraordinary refraction indices, the cell thickness, and the light wavelength, and may exhibit nonmonotonic behavior. Thus the quantitative agreement between the calculated and the observed results show that the kinematic behavior of the directors is correctly obtained, in spite of the fact that the experimental d/P value systematically deviates from that predicted theoretically. More recent experimental data show that deviations tend to vanish for thicker cells, implying that the dynamics in thin cells may involve novel physics beyond the conventional theory.

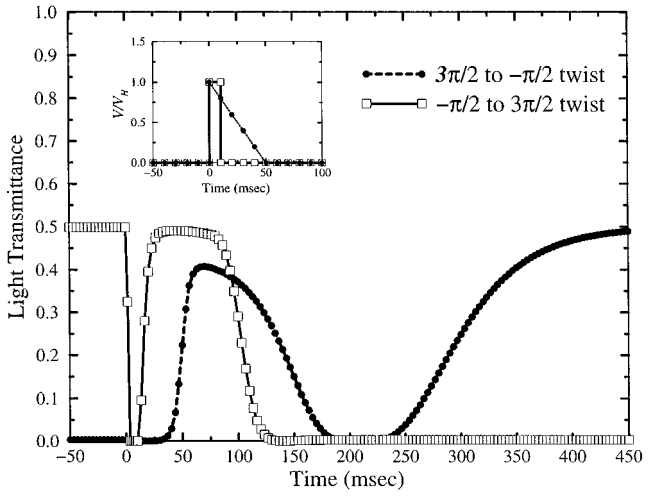

FIG. 3. Calculated electro-optical response of the switching bistability for $\Phi=-\pi/2$. The inset shows the time profile of the applied voltage.

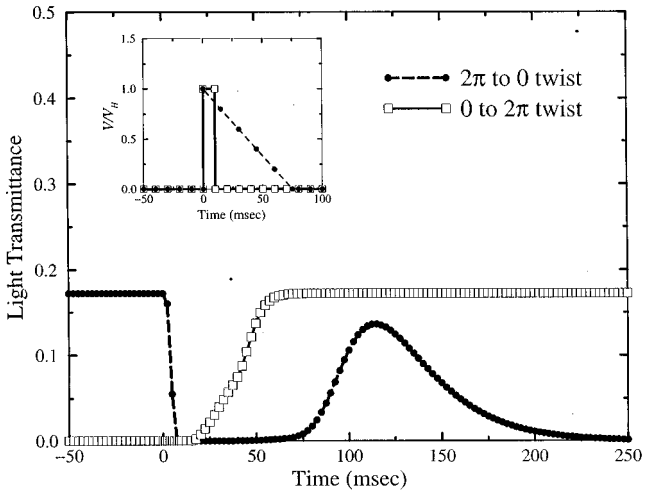

FIG. 4. Calculated electro-optical response of the switching bistability for $\Phi=0$. The inset shows the time profile of the applied voltage.

In summary, we have presented a theoretical picture of the switching behavior between the Φ and $\Phi+2\pi$ states of the BTN. This switching is based on the effect of backflow on the LC director under special conditions of driving voltages. Our theory agrees well with experimental data obtained with sample BTN cells for both the $\Phi=-\pi/2$ and $\Phi=0$ cases. Further refinement of this theory should allow us to optimize the driving voltage necessary for such switching bistability.

T.Z.Q. and Z.L.X. are supported by the Hong Kong Industry Department ITDC Grant No. AF/155/94.

[1] T. Tanaka, Y. Sato, A. Inoue, Y. Momose, H. Nomura, and S. Iino, Asia Display **95**, 259 (1995).
[2] Y. J. Kim, S. M. Park, I. Lee, S. W. Suh, and S. D. Lee, Eurodisplay **96**, 337 (1996).
[3] C. J. Gerritsma, C. Z. van Doorn, and P. van Zanten, Phys. Lett. A **48**, 263 (1974).
[4] C. Z. van Doorn, J. Appl. Phys. **46**, 3738 (1975).
[5] D. W. Berreman, J. Appl. Phys. **46**, 3746 (1975).
[6] Y. Miyama and S. Saito, Asia Display **95**, 571 (1995).
[7] D. W. Berreman and W. R. Heffner, J. Appl. Phys. **52**, 3032 (1981).