Three-terminal bistable twisted nematic liquid crystal displays

Jian-Xin Guo, Zhi-Guo Meng, Man Wong, and Hoi-Sing Kwok[a]
Center for Display Research, Hong Kong University of Science and Technology, Clear Water Bay, Hong Kong

(Received 31 May 2000; accepted for publication 27 September 2000)

A three-terminal bistable twisted nematic liquid crystal display has been demonstrated. This display makes use of a combination of strong in-plane electric fields and vertical electric field for switching between the ϕ and the $\phi+\pi$ twist states. The lifetimes of the two bistable twist states are infinite, which is a significant improvement over conventional bistable twisted nematic displays. © *2000 American Institute of Physics.* [S0003-6951(00)00248-5]

There are many types of bistable liquid crystal displays (LCD). Among them, the bistable twisted nematic (BTN) LCD has one of the best optical properties with good contrast and brightness.[1–3] This display relies on adjusting judiciously the cell thickness to liquid crystal pitch (d/p) ratio to produce the metastable ϕ and $\phi+2\pi$ twist states. In this BTN, ϕ can be optimized to produce excellent optical properties.[3] However, the major problem of this BTN is that the ϕ and $\phi+2\pi$ twist states are metastable with short lifetimes. Indeed, the intermediate $\phi+\pi$ twist state is more stable and both the ϕ and $\phi+2\pi$ states will decay to it in a matter of seconds.

There have been several attempts to make the BTN truly bistable. Hoke *et al.* attempted to stabilize the 0 and 2π twist states by using polymer walls.[4] The success is quite limited, however. Bryan–Brown *et al.*[5] demonstrated a grating aligned bistable nematic display that can be switched by submillisecond pulses and has infinite time memory. This so-called zenithal bistability is greatly affected by the surface profile of the LC cell and is difficult to achieve. Dozov *et al.*[6] investigated a surface-controlled bistable nematic (SCBN) display using simple planar monostable anchoring. In this SCBN, the two bistable twist states are, respectively, the quasiuniform 0°-twist U state and the 180° twist T state. Short electric pulses break the surface anchoring condition and allow transition between the U and T state. Hydrodynamically coupled breaking of both anchoring conditions produces the T state. The U state is obtained by breaking only one anchoring condition. A high pretilt angle and a small cell gap are necessary to produce the bistability and switching between the 0 and π twist states.

In this letter, we will present a new bistable nematic display that is similar to this SCBN in that the bistable twist states differ by 180° in twist angle. However, switching between the bistable states is achieved using a special three-terminal structure. The bistable twist states have twist angles of ϕ and $\phi+\pi$, while doping of the LC is such that the $\phi+\pi/2$ twist is favored. Thus, similar to the case of ϕ and $\phi+2\pi$ twist BTN, bistability can be achieved. The most important difference is that in the present case, the rubbing condition favors the ϕ twist state. So the natural twist of $\phi+\pi/2$ is unstable against this boundary condition. Hence the ϕ and the $\phi+\pi$ state are permanently stable.

In the present BTN, switching between the two bistable twist states involves breaking of surface anchoring. This is accomplished through the use of a three-terminal electrode structure. This structure has been demonstrated recently in producing a wide viewing angle LCD.[7] The basic structure is shown in Fig. 1. It consists of a comb-on-plane (COP) structure on one side of the LCD. The new display is hence called COP-BTN. Electrical pulses can be applied to both the COP electrode or across the cell.

The COP electrode is characterized by a strong horizontal (in-plane) fringing field when a voltage is applied. Away from the COP electrodes, the electric field decays exponentially.[7] This field is effective in breaking the surface anchoring condition to produce switching between the two stable twist states of ϕ and $\phi+\pi$. Thus in the COP-BTN, two different electrical signals can be applied to the cell. The vertical field can affect the bulk liquid crystal molecules, while the horizontal field can affect molecules on the surface of the COP electrode. The synchronization condition required for SCBN can therefore be met easily even for thick samples.

The two bistable twist states in the COP-BTN (ϕ, $\phi+\pi$) differ by an angle of π. Similar to the conventional (ϕ, $\phi+2\pi$) BTN with a 2π difference in twist angles, the exact value of ϕ can be optimized to give perfect optical properties.[3] We have performed this optimization calculation. Table I shows the optimization results. In that table, the two twist angles, together with the LC cell retardation, the input and output polarizer angles α and γ, are listed. Notice that the bright and dark states can be reversed by simply rotating either α or γ by 90°. Also, all the angles can be reversed in sign and nothing will change. Details of this optical optimization will be given in another paper. In this let-

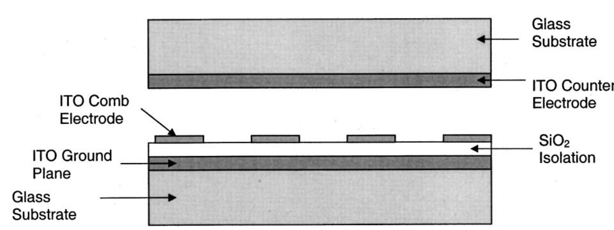

FIG. 1. Schematic diagram of the COP-BTN LC cell. COP electrodes are 2 μm wide with 2 μm gap.

[a]Electronic mail: eekwok@ust.hk

TABLE I. Optically optimized COP-BTN cell parameters. α and γ are such that $T(\phi_1)=1$. Bright and dark states can be reversed by rotating α or γ by 90°.

Mode No.	ϕ_1 (deg)	ϕ_2 (deg)	$d\Delta n$ (μm)	α (deg)	γ (deg)
1	−22.5	157.5	0.266	45	−67.5
2	22.5	202.5	0.546	45	67.5
3	67.5	247.5	0.799	45	22.5
4	112.5	292.5	1.045	45	−22.5
5	157.5	337.5	1.288	45	−67.5

ter, we shall choose the No. 1 mode to test the idea of this three-terminal BTN. Thus the bistable twist angles are $-22.5°$ and $157.5°$. The polarizers are arranged such that ϕ_1 $(-22.5°)$ corresponds to the bright state.

Several liquid crystal cells were fabricated and tested. The top substrate of the cell was ordinary ITO glass. The bottom substrate was the COP structure. The spacing and width of the comb electrodes were both 2 μm, thus the periodicity was 4 μm. The SiO_2 insulation layer was about 300 nm thick. The rubbing on COP substrates was along the comb direction. The rubbing direction on the top substrate was such that the smaller twist angle was favored. Thus for mode No. 1 used here, the top electrode was rubbed at $-22.5°$. The rubbing directions are shown in Fig. 2. Chiral additive, S811 was used to control the d/p ratio of the cells.

The driving method of the COP-BTN is quite flexible because of the three-terminal structure. Two independent signals can be employed to drive the device. In our experiment, the plane electrode (ITO ground plane in Fig. 1) was set to ground. The comb electrode signal V_c and top electrode (ITO counterelectrode in Fig. 1) signal V_t have different amplitudes, but the same pulse duration.

Figure 3 shows the driving pulses used to switch COP-BTN. V_{c1} and V_{t1} are used to obtain the ϕ_1 twist state, V_{c2} and V_{t2} are used to obtain the ϕ_2 $(=\phi_1+\pi)$ twist state. Figure 4 shows the transmittance of the COP-BTN as a function of time. The driving pulse duration was 10 ms. In Fig. 4, the various voltages are $V_{c1}=32.5$ V, $V_{t1}=24$ V, $V_{c2}=4$ V, and $V_{t2}=27$ V. It can be seen that indeed, switching from ϕ to $\phi+\pi$ and vice versa can be achieved readily with the particular combination of driving pulses. We have attempted to map out the parameter space for switching between the ϕ_1 and ϕ_2 states. It is rather complicated as the two voltages necessarily interfere with each other. Generally, the ϕ_1 state is obtained at higher comb voltages, and the ϕ_2 state is more stable at higher top voltages.

The rise and fall times measured are not very fast and certainly not as fast as reported for the Dozov SCBN device. This may be understandable since the cell gap in our device (3 μm) is much larger than the Dozov device (1.5 μm). The pretilt angles in our device $(1°-2°)$ are also much smaller. Thus hydrodynamic flow effect also plays a role in the switching mechanism. On the other hand, the tilt angle is much larger in the case of the true SCBN (75° SiO evaporation), and bulk effect does not play a major role.

Figure 5 shows the switching time of the COP-BTN as a function of the pulsewidth of the driving pulses. The solid circles correspond to the rise time $(\phi_1-\phi_2)$ while the open circles correspond to the fall time $(\phi_1-\phi_2)$. It can be seen that the rise and fall times have opposite trends. If the driving pulses are short, the rise time is correspondingly short, while the fall time increases. We do not have a good explanation of this phenomenon at this time. It most certainly has to do with the hydrodynamics of the LC director. Detailed modeling is necessary to understand this effect. To obtain faster response in our COP-BTN, smaller cell gaps and larger pretilt angles may be necessary.

Dozov *et al.* proposed an asymmetrical anchoring cell geometry to enhance the efficiency of the hydrodynamic coupling between the two substrates.[5] The main characteristic is that a tilt strong anchoring surface replaces one of the

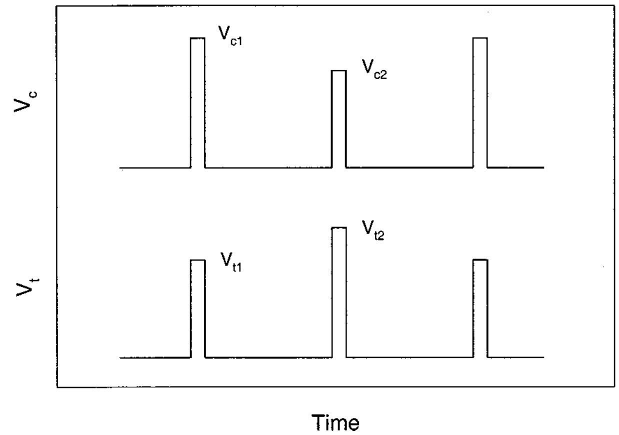

FIG. 3. Pulse waveforms used to switch the COP-BTN.

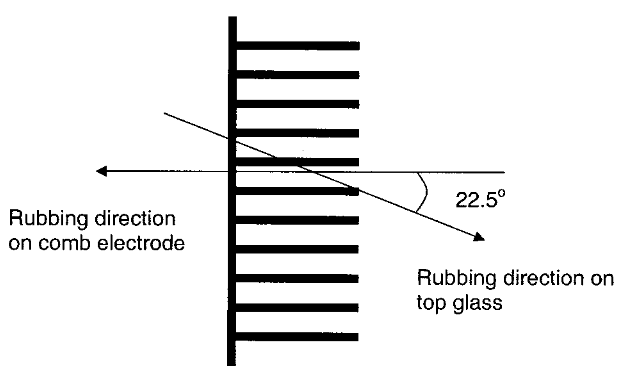

FIG. 2. Rubbing directions on the LC cell.

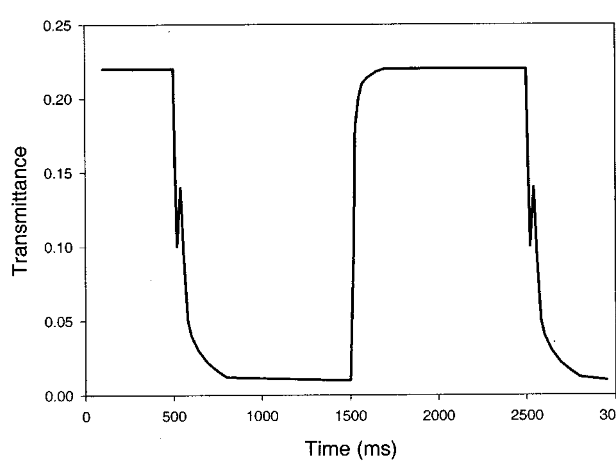

FIG. 4. Transmittance of the COP-BTN as a function of time.

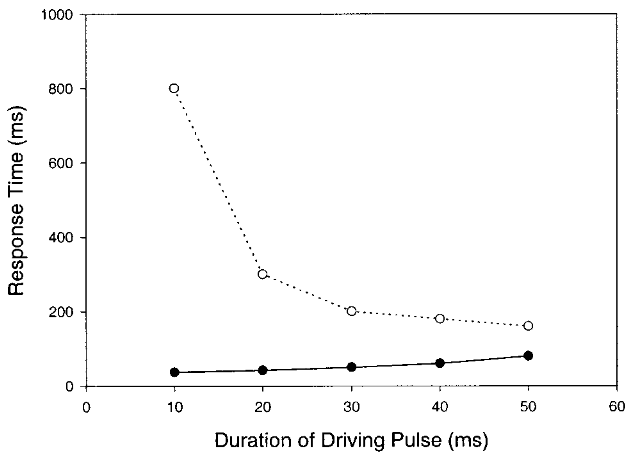

FIG. 5. Optical response time as a function of the duration of the driving pulse. ●: rise time; ○: fall time.

weak planar anchoring surfaces. The weak planar anchoring is broken by a short electric field pulse. The strong tilt anchoring is distorted by the applied field, but not completely broken. When the field is reduced, the strong oblique anchoring relaxes quickly back to its initial position, inducing a strong and well-defined shear flow in the cell. The shear surface torque forces the planar anchoring to tilt back in a direction opposite to the initial one, inducing the twisted state. We also tried this asymmetrical anchoring effect by using two different PI for the two surfaces. Weak planar anchoring surface is obtained by the low pretilt $(1°)$ PI, while strong anchoring is obtained by a high pretilt $(12°)$ PI. The critical voltage of the asymmetrical anchoring device is decreased by 2V compared to that of the device with symmetrical anchoring using two identical PI layers.

In summary, we have successfully obtained $(\phi, \phi+\pi)$ bistability in a three-terminal device. The switching mechanism is similar to the breaking of surface anchoring in the surface controlled twisted nematic display, except that in-plane fields are used to break the anchoring condition. Very long lifetimes of the display, of more than several weeks, have been obtained. This is a significant improvement over the conventional BTN, where the bistable ϕ and $\phi+2\pi$ states have lifetimes of seconds. Similar to the conventional BTN, this COP-BTN could also be multiplex driven in a passive matrix geometry to achieve high information content with low (no) crosstalk. With the three-terminal geometry, there should be much parameter space to optimize this display to produce the desired optical as well as electrical properties.

This research was supported by the Hong Kong Innovation and Technology Fund.

[1] D. W. Berreman and W. R. Heffner, J. Appl. Phys. **52**, 3032 (1981).
[2] T. Tanaka, Y. Sato, A. Inoue, Y. Momose, H. Noruma, and S. Iino, Proceedings of International Display Research Conference, Hamamatsu, Japan, 1995, p. 259.
[3] S. T. Tang, H. W. Chiu, and H. S. Kwok, J. Appl. Phys. **87**, 632 (2000).
[4] C. D. Hoke and P. J. Bos, 29th Soc. Info. Disp. Symp. Digest, 854 (1998).
[5] G. P. Bryan-Brown, C. V. Brown, and J. C. Jones, Patent No. GB 9521106.6 (1995).
[6] I. Dozov, M. Nobili, and G. Durand, Appl. Phys. Lett. **70**, 1179 (1997).
[7] Z. G. Meng, H. S. Kwok, and M. Wong, Proceedings of International Display Works, Sendai, Japan, 1999, p. 125.