New bistable twisted nematic liquid crystal displays

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We have developed new bistable twisted nematic (BTN) displays that operate between the $-\pi/2$ and $3\pi/2$ twist states and between the $\pi/2$ and $5\pi/2$ twist states. Together with the $(0,2\pi)$ BTN, this forms a set of all possible transmittive BTNs. Experimentally, it was confirmed that several switching wave forms could be used to switch the BTN from one state to another. Voltages below 10 V are sufficient to reset and switch these BTNs. The effect of the d/P_0 ratio on the bistable switching characteristics is also investigated.
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I. INTRODUCTION

Bistable twisted nematic (BTN) liquid crystal displays (LCD) that could be switched between two quasistable twist states electrically were discovered by Berreman and Heffner in 1981.[1] Heuristically, this bistability is due to a mismatch in the nematic liquid crystal natural pitch P_0 and the LC cell alignment conditions for a given cell thickness d. For supertwisted nematic (STN) LCDs, this mismatch generally leads to a switching hysteresis and has to be avoided.[2] In a BTN however, this mismatch is deliberately increased to produce alignment bistability. It has been shown that bistability occurs for a particular range of d/P_0 ratios.[3] Recently, Tanaka *et al.*[4] successfully made use of this bistability to produce a BTN display with surprisingly good qualities.

The optical properties of BTN are better than ordinary passive matrix driven STN displays. The contrast ratios are generally much better than STN displays since there is no requirement for a steep transmission-voltage curve anymore. Because of this bistability, the BTN can also be passive matrix driven without cross talk problems. Another unexpected benefit is that the view angle of a BTN is better than a STN display because of the fact that both bistable states are twist states. In a STN display, the select state has a higher voltage and a near homeotropic alignment. Thus for the select state, the brightness is strongly viewing angle dependent. In a BTN, this does not occur. Both bistable twist states have in-plane alignment. Therefore, the viewing angle of a BTN is very wide.[5]

There have been quite a few studies recently on understanding and improving the BTN display. Kim *et al.*[6] and Qian *et al.*[3,7] successfully modeled the dynamical switching behavior between the bistable twist states. It is shown that this switching is based on the backflow dynamics of the LC director.[8] More recently, Hoke *et al.*[9] investigated the switching of this BTN LCD and reported submillisecond selection. They also found theoretically the conditions that both bistable twist states can become stable rather than quasistable.[10] Bryan-Brown *et al.*[11] proposed a grating aligned BTN LCD that can also be switched by submillisecond pulses, which has been recently modeled by Newton *et al.*[12] Finally Martinot-Lagarde *et al.*[13] developed a novel fast BTN LCD that was controlled by simple monostable anchoring and obtained very fast switching times.

In all previous reports, the BTN switches between the 0 and 2π twist states. Miyama *et al.*[14] reported a field-induced transition between the $-\pi/2$ and $3\pi/2$ twist states in a wedged cell but that study dealt mainly with the d/P_0 dependence of the stability of the two states in the presence of a field. Bistability of these states and the dynamics of switching between them were not examined. In our previous publication,[3] we reported the switching dynamics of the $(-\pi/2, 3\pi/2)$ BTN. In this paper, we wish to report a further detailed study of this $(-\pi/2, 3\pi/2)$ BTN. We shall show that for this $(-\pi/2, 3\pi/2)$ BTN, bistability can be obtained for a wide d/P_0 range, and that switching can be achieved with many different kinds of electrical pulse shapes. The optical properties of this $(-\pi/2, 3\pi/2)$ BTN is actually slightly better than the $(0,2\pi)$ BTN because of a slightly higher contrast and brightness.

We shall also report in this paper a novel $(\pi/2, 5\pi/2)$ BTN. This $(\pi/2, 5\pi/2)$ BTN has never been observed before. We shall show that the switching dynamics of this BTN is similar to the other cases. However, the d/P_0 range required is very narrow. Its practical use is therefore quite limited. This $(\pi/2, 5\pi/2)$ BTN, together with the $(0,2\pi)$ and $(-\pi/2, 3\pi/2)$ BTNs should exhaust all possibilities of transmittive BTN at present. All other combinations of twist angles are either not desirable optically, or too difficult to make in practice. The relative merits of the $(0,2\pi)$ and $(-\pi/2, 3\pi/2)$ BTNs will be compared in the last section.

II. OPTICS OF BTN

The LC twist of any LCD depends on the surface rubbing orientation, the tilt angles of the directors at the boundaries and the d/P_0 ratio. Suppose the alignment layers favor a twist angle of ϕ_0, then the elastic energy of the LC layer

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TABLE I. Theoretical and experimental values of d/P_0.

ϕ_0	Heuristic value	Experimental value	Dynamical modeling
$-\pi/2$	0.25	0.285–0.305	0.425
0	0.5	0.55–0.7	0.85
$\pi/2$	0.75	0.9	unstable

will have minima for twist angles of $\phi_0 \pm 2N\pi$ for integer values of N. In the absence of any pretilt, and if the natural twist of the LC director is $\phi_0+\pi$, then the minima at ϕ_0 and $\phi_0+2\pi$ will have equal deformation energies and bistability will occur. Therefore for any value of ϕ_0, the bistable states are $(\phi_0, \phi_0+2\pi)$ with $d/P_0=0.5+\phi_0/2\pi$. Hence for $\phi_0=0$, the bistable states are $(0,2\pi)$ and the d/P_0 value should be about 0.5. For $\phi_0=-\pi/2$, the bistable states are $(-\pi/2, 3\pi/2)$ and the d/P_0 ratio should be about 0.25. For $\phi_0=\pi/2$, the bistable states are $(\pi/2, 5\pi/2)$ and the d/P_0 ratio should be about 0.75. Table I lists these heuristic d/P_0 values together with the actual experimental and theoretical values. The theoretical values are based on dynamical calculations.[3]

It is also possible to analyze the BTN from the optical contrast point of view to determine the best values of ϕ_0 and the best polarizer arrangement.[15,16] A general parameter space approach has to be used.[17] The contrast ratio is defined as either $T(\phi_0)/T(\phi_0+2\pi)$ or $T(\phi_0+2\pi)/T(\phi_0)$, whichever is larger. T is the transmittance which can be calculated using the standard Jones matrix of the LC cell.[17] Figure 1 shows the constant contrast contour curves as a function of $d\Delta n$ and ϕ_0. The contrast ratio in this case is calculated assuming a cross polarizer geometry with the polarizers at 45° to the input director of the liquid crystal cell. Two interesting facts can be observed from Fig. 1. First, it is symmetrical about $\phi_0=-\pi$. The reason is quite simple. The $(\phi_0, \phi_0+2\pi)$ BTN is equivalent to the $(-\phi_0, -\phi_0-2\pi)$ BTN. For example, the (−270°, 90°), (−90°, 270°) BTNs are the same. Hence, the parameter space should be symmetrical about $\phi_0=-\pi$. Second, given this symmetry, it can be seen that BTNs with good contrasts are given by $\phi_0=-\pi/2$, 0, $\pi/2$, and π. Actually, there are BTNs with larger values of ϕ_0, but they are difficult, if not impossible to produce experimentally.

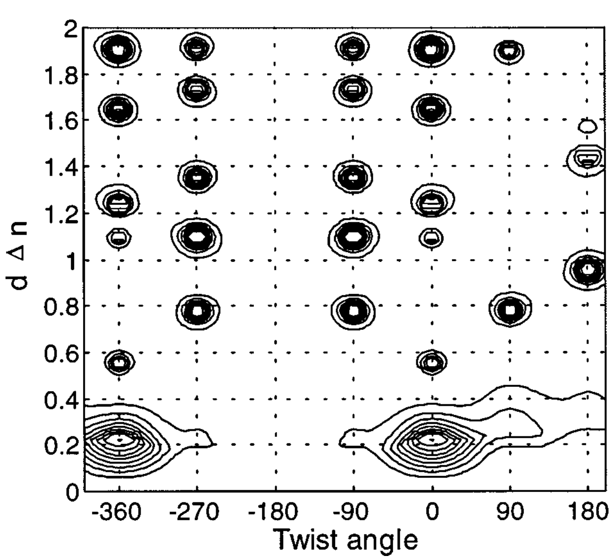

FIG. 1. Contrast parameter space for a BTN with twist angles ϕ_0 and $\phi_0+2\pi$. Each contour line represents an increase of 5 in contrast.

While Fig. 1 is calculated for perpendicular polarizers and a polarizer angle of 45°, similar parameter spaces can also be obtained with parallel–parallel polarizer geometry, and for a polarizer angle of 0°. These results also indicate that the best ϕ_0 values are $-\pi/2$, 0, $\pi/2$, and π. However, the $d\Delta n$ values are different and depend on the polarizer arrangements. Hence, theoretically, possible BTN can be made with bistable twist states of $(-\pi/2, 3\pi/2)$, $(0,2\pi)$, $(\pi/2, 5\pi/2)$, and $(\pi,3\pi)$. Of course good optical properties and the actual stability of the BTN are two separate issues. The latter depends on the d/P_0 ratio and other dynamical factors. Experimentally, we have achieved the first three types of BTN. The cases of $(-\pi/2, 3\pi/2)$ and $(\pi/2, 5\pi/2)$ will be presented in the following sections. So far, the case of $(\pi,3\pi)$ has not been possible.

The optical properties of the BTN can actually be understood without the complete parameter space. For the case of the $(-\pi/2, 3\pi/2)$ BTN, we chose the geometry of two crossed polarizers with the input polarizer at $\pi/4$ to the input director of the LC cell. In this situation, the transmittance of the system is given by the formula[14]

$$T=\cos^2(\phi\sqrt{1+u^2}) \tag{1}$$

where

$$u=\pi d\Delta n/\phi\lambda \tag{2}$$

for twist angles ϕ that are odd multiples of $\pi/2$. In Eq. (1), Δn is the optical birefringence, and λ is the wavelength of the incident light. Accordingly, the transmittance of the system shows the minimum value of 0 for $\phi=-\pi/2$ and $d\Delta n=\sqrt{2}\lambda$. The $3\pi/2$ twist state corresponds to the bright state with $T=0.96$ under the same conditions. This is in agreement with Fig. 1 and provides the design parameters for this $(-\pi/2, 3\pi/2)$ BTN.

For the $(\pi/2, 5\pi/2)$ BTN, we chose a geometry of parallel polarizers with the input director of the LC cell parallel to the polarizers. Under this situation, it can be shown that the transmittance of the LCD is given by

$$T=\frac{1}{1+u^2}\sin^2(\phi\sqrt{1+u^2}), \tag{3}$$

for ϕ that are odd multiples of $\pi/2$. Therefore, it is obvious that $T=0$ for $\phi=\pi/2$ if $d\Delta n/\lambda=\sqrt{3}/2$. The transmittance of the bright $5\pi/2$ twist state will be 0.72 under the same conditions. In principle, the contrast ratio of both BTNs will be infinite. However, in the above calculations, $T=0$ for one wavelength only. So if white light is used as the input, the contrast will degrade considerably. Even if a single wavelength light is used in the measurement, it is very difficult to adjust the $d\Delta n$ values to be exactly given by Eqs. (1) and (3) so the experimental contrasts are typically less than 100:1.

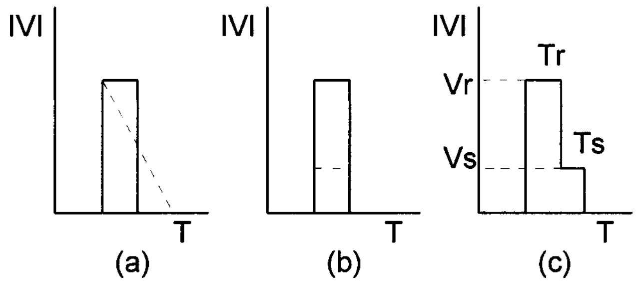

FIG. 2. Pulse wave forms used to switch the ($-\pi/2$, $3\pi/2$) BTN.

III. ($-\pi/2$, $3\pi/2$) BTN EXPERIMENTAL RESULTS

For investigating BTN with ϕ_0 of $-\pi/2$, we made several LC cells with d/P_0 values near 0.25. The chiral additive, S-811 was used to control the d/P_0 value of the cells. A commercial nematic liquid crystal (MLC 6218) was used. The cell gap was varied around 5 μm. The input polarizer was at 45° to the input director and perpendicular to the output polarizer. This is the same configuration as discussed above.

Several wave forms were used in switching the BTN. They are shown in Fig. 2. For wave form (a), the $3\pi/2$ state can be obtained by turning the voltage pulse off suddenly, while the $-\pi/2$ state can be obtained by switching the pulse slowly. For wave form (b), switching is accomplished by the different pulse amplitudes. Driving wave form (c) consists of a reset pulse to switch the LC to the near-homeotropic state, followed by a selection pulse to select one of the two metastable states. This is the same as the wave form used by Tanaka *et al.*[4,18] The advantage is that the selection pulse can be much shorter than the pulses in wave forms (a) and (b).

Figure 3 shows the time-dependent transmission curve and the voltage pulse for the BTN LC cell switched by wave form (a). A 10 V pulse is used. It can be seen that the $-\pi/2$ twist state which corresponds to low transmission can be obtained by turning the voltage pulse off slowly, and the $3\pi/2$ state which corresponds to high transmission can be obtained by turning the voltage pulse off suddenly. In both cases, an optical bounce effect can be observed.[3,8] The measured contrast ratio in the normal direction is 30:1. The $-\pi/2$ twist state displays a deep purple color while the $3\pi/2$ twist state shows a yellowish color. Both the $-\pi/2$ and the $3\pi/2$ states can stay for several seconds after the electric field is removed, after which time they will relax to the stable $\pi/2$ state. So indeed the bistable $-\pi/2$ and $3\pi/2$ states are metastable states.

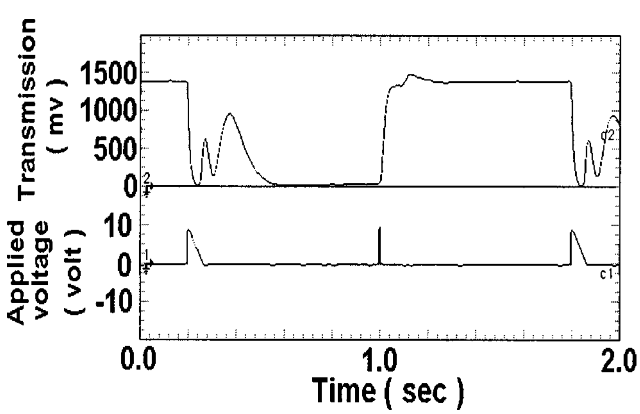

FIG. 3. Transmission of the LCD (upper) and the applied voltage pulses (lower) as a function of time. Wave form (a) in Fig. 2 is used. The $-\pi/2$ state has low transmission and the $3\pi/2$ state has high transmission.

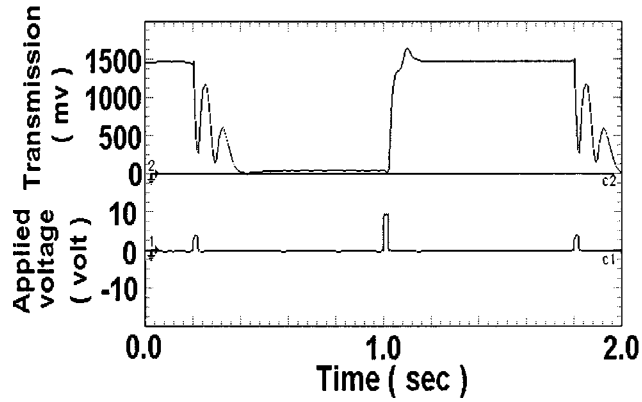

FIG. 4. Same as Fig. 3 with wave form (b) as the switching pulse.

Figure 4 shows the time-dependent transmission curve and the voltage pulses for the BTN LC cell driven by wave form (b). The pulse duration is 20 ms. It can be seen that the $-\pi/2$ twist state can be obtained by using a weaker (4 V) pulse, and the $3\pi/2$ state can be obtained by using the stronger (10 V) pulse. The contrast ratio measured is also 30:1, the same as in Fig. 3.

Figure 5 shows the time-dependent transmission curve and the voltage pulses for the BTN LC cell switched by wave form (c). For this measurement, the reset time is fixed at 20 ms with an amplitude fixed at 10 V. The selection time is fixed at 4 ms. It can be seen that the $-\pi/2$ twist state can be obtained by using a weaker selection pulse and the $3\pi/2$ state can be obtained by using a stronger selection pulse. Figure 6 shows the switching dependence of the BTN on the selection voltage amplitude. It can be seen clearly that there is a finite voltage range of between 1.7 and 5.5 V for the selection of the $-\pi/2$ state. Beyond this range, the $3\pi/2$ state is obtained. The transition between the two selection regions is very sharp. There is no intermediate state, which

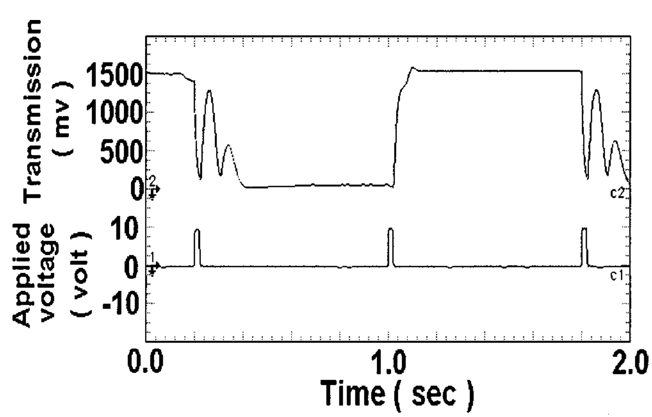

FIG. 5. Same as Fig. 3 with wave form (c) as the switching pulse.

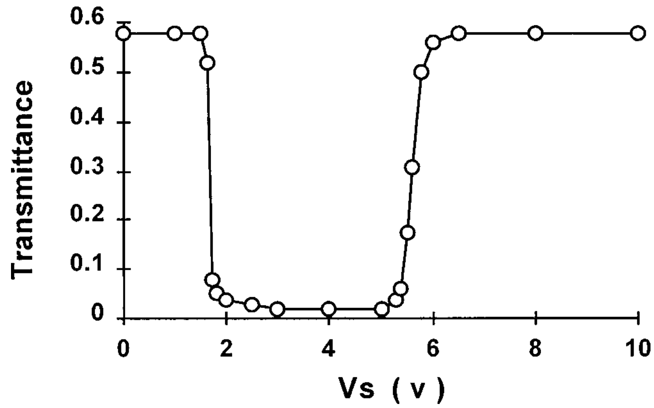

FIG. 6. Dependence of the final state of the $(-\pi/2, 3\pi/2)$ BTN on the selection pulse voltage.

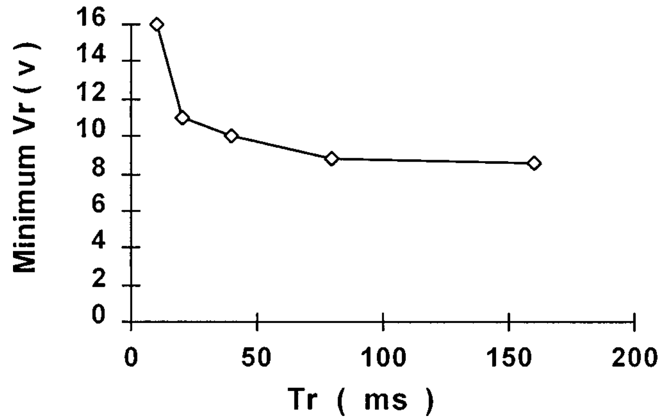

FIG. 8. Dependence of the minimum reset voltage as a function of the reset pulse duration for the $(-\pi/2, 3\pi/2)$ BTN.

can make greyscaling for the BTN rather tricky. The measured contrast ratio is also 30:1.

The effect of d/P_0 on the range of the selection for the $-\pi/2$ state is shown in Fig. 7. The upper and lower curves define the region of stability for the $-\pi/2$ state. For small d/P_0, no selection is possible and the display is always in the $-\pi/2$ state. For large d/P_0 values, the display will always be in the $3\pi/2$ state. The d/P_0 value should be within 0.285–0.305 for bistability to occur. This is a reasonable range for manufacturing tolerance.

Finally, Fig. 8 shows the relationship between the reset pulse duration and the reset pulse width. In this measurement, the selection pulse width and pulse amplitude are kept constant. It can be seen that for pulses shorter than 20 ms, a higher voltage is needed to reset the BTN. There seems to be little dependence for durations longer than 20 ms. This is probably due to the typical response time of nematic liquid crystals. It takes typically 10–20 ms for the liquid crystal to achieve a homeotropic (reset) alignment after the high voltage reset pulse is applied.

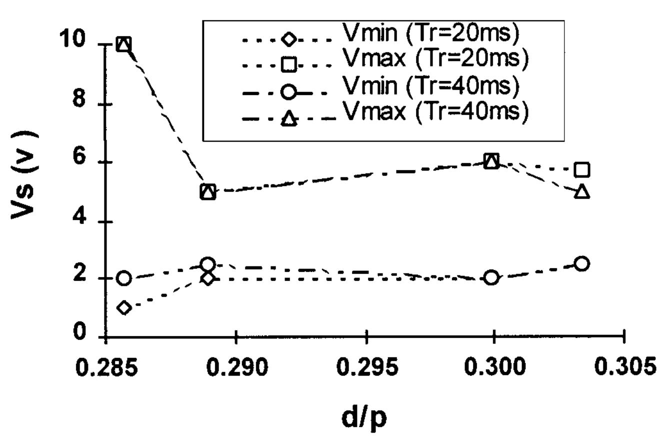

FIG. 7. Dependence of the selection voltage range on the d/P_0 value of the $(-\pi/2, 3\pi/2)$ BTN cell. The upper and lower curves correspond to the voltage limits in Fig. 6. $V_r = 10$ V and $T_s = 4$ ms.

IV. $(\pi/2, 5\pi/2)$ BTN EXPERIMENTAL RESULTS

A similar study was carried out with $\phi_0 = \pi/2$. A commercial liquid crystal (MLC 7500/000) was used. S-811 is again used to adjust the d/P_0 ratio. The cell gap was near 4.6 μm. For this measurement, a parallel polarizer geometry was used. The input director of the cell is also parallel to the polarizers. It has been shown by optical calculation that it is easier to observe bistability using this polarizer arrangement.[15] All other arrangements will have a sensitive dependence on $d\Delta n$. Wave form (c) was used since it is the most practical one for selecting the two bistable twist states. The reset pulse amplitude and duration were 20 V and 22.5 ms, respectively.

Figure 9 shows the time dependent transmission wave form of this BTN. In this measurement, the selection pulse alternates between 0 and 5 V. For 0 V, the high transmission $5\pi/2$ state is obtained. For 5 V, the low transmission $\pi/2$ state is obtained. As seen in Fig. 9, bistability is clearly achieved for this twist angle.

It can also be seen that there is an increase in transmission when the cell switches from $\pi/2$ to $5\pi/2$ twist. This is because at the intermediate twist condition, the transmission is higher. As seen from the calculation in Sec. II, the $5\pi/2$

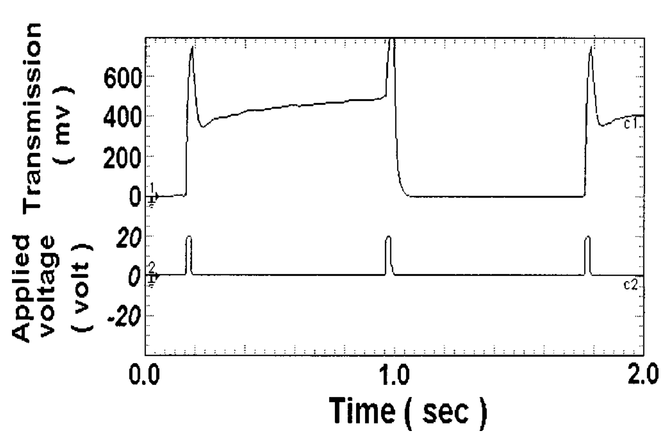

FIG. 9. Transmission of the $(\pi/2, 5\pi/2)$ BTN LCD (upper) and the applied voltage pulses (lower) as a function of time.

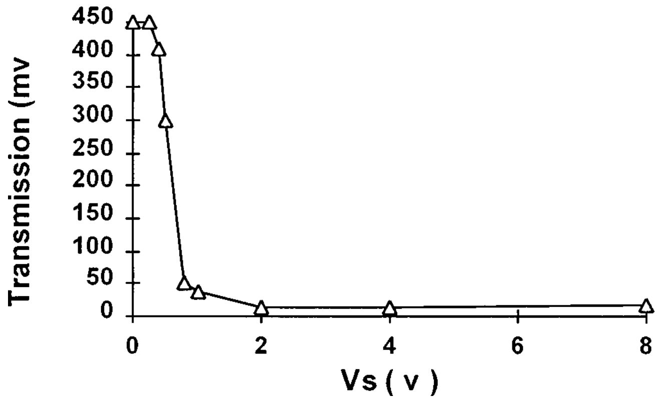

FIG. 10. Transmission of the ($\pi/2$, $5\pi/2$) BTN as a function of the selection pulse voltage.

high transmittance state only has a transmittance of 0.72. It also points to the fact that this BTN is very sensitive to the value of $d\Delta n$.

Figure 10 shows the dependence of the transmittance on the selection pulse amplitude. The duration of the reset and selection pulses were the same as that in Fig. 9. It can be seen that the high and low transmittance states are very sensitive to the selection pulse voltage. The selection pulse amplitude between the two bistable states is less than 1 V. Unlike Fig. 6, the high transmittance state cannot be selected again at high selection pulse voltage. It points to the fact that the $\pi/2$ twist state is more stable. The contrast of this display is measured to be about 36:1.

For this BTN, the d/P_0 value is very critical. So far we have only been successful in observing bistability in a sample with $d/P_0=0.9$. In view of this sensitivity to d/P_0, it is unlikely that this display can be made into a practical device.

V. DISCUSSIONS AND CONCLUSIONS

In summary, we have studied novel ($-\pi/2$, $3\pi/2$) and ($\pi/2$, $5\pi/2$) BTNs. Together with the ($0,2\pi$) BTN, these two cases exhaust all possibilities of transmittive BTNs. Even though ($\pi,3\pi$) etc. BTN may be possible theoretically, they should be very difficult to realize because of the stringent d/P_0 requirements. We have shown that in general, all BTNs can be driven by three kinds of switching wave forms to switch the cell from one bistable state to another. It was also shown that high contrast ratios can be achieved in all cases because of the bistability.

Even though there are three kinds of transmittive BTN, only the ($0,2\pi$) and ($-\pi/2$, $3\pi/2$) BTNs are easy to make and are practical. They have their own merits and drawbacks. In terms of contrast, both types can achieve a high contrast, as demonstrated in Figs. 3 and 9. The switching speed is also similar. It is observed, and it is predicted by optics calculations,[15] that the ($-\pi/2$, $3\pi/2$) BTN has more color dispersion than the ($0,2\pi$) BTN. The on-state is yellowish-green and the off-state is dark purple. Actually, the ($-\pi/2$, $3\pi/2$) BTN is quite similar to the yellow mode STN optically. While this coloration may be a drawback, however, it was also observed that the on-state of the ($-\pi/2$, $3\pi/2$) BTN is quite a bit brighter than the on-state of the ($0,2\pi$) BTN. As indicated in Sec. 2, the transmittance of the on-state of the ($-\pi/2$, $3\pi/2$) BTN is 0.96.

The ($-\pi/2$, $3\pi/2$) BTN also has another interesting advantage over the ($0,2\pi$) BTN. Since in any BTN, both bistable states are actually metastable, the twist state of the LC cell will actually relax to the $\phi_0+\pi$ state after a few seconds. For the ($-\pi/2$, $3\pi/2$) BTN, the stable state is the $\pi/2$ twist state, which is optically equivalent to the $-\pi/2$ twist state. Hence the relaxation of the $-\pi/2$ to the $\pi/2$ twist should be unnoticeable. For the ($0,2\pi$) BTN, the stable state is the π twist state which has a very different appearance from both the 0 and 2π twist states. Constant refreshing is therefore necessary. Since passive matrix driven ($0,2\pi$) BTN has already been demonstrated,[4] it should be interesting to show a passive matrix driven ($-\pi/2$, $3\pi/2$) BTN and compare their operating characteristics.

Finally, it is interesting to note that in all three cases of BTN reported here, the d/P_0 ratio of the practical cell is always larger than the heuristic theoretical values. Table I lists the various d/P_0 values. This effect has actually been predicted by our earlier dynamical modeling. For example, for the $-\pi/2$ case, the simplistic value should be 0.25. The practical value is 0.285–0.305, while the numerical simulation[3] gives a value of 0.425. It is noticed that dynamical modeling consistently overestimates the d/P_0 value, and that it fails to model the ($\pi/2$, $5\pi/2$) case. Obviously some improvement is necessary, even though that calculation can predict the temporal switching behavior very well.

In this paper, only transmittive BTNs are discussed. It is also possible to fabricate reflective BTN where there is only one front polarizer.[19] For such reflective displays, ϕ_0 will no longer be $-\pi/2$, 0, $\pi/2$, etc. as shown in Fig. 1. Other values are possible. In particular, we have shown that it is possible to fabricate a good quality reflective BTN with $\phi_0=-36°$.

APPENDIX

This research was supported by the Hong Kong Industry Department.

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