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 transmissive 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. © 1998 American Institute of Physics.

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.\textsuperscript{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 super-twisted nematic (STN) LCDs, this mismatch generally leads to a switching hysteresis and has to be avoided.\textsuperscript{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.\textsuperscript{3} Recently, Tanaka et al.\textsuperscript{4} 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.\textsuperscript{5} More recently, Hoke et al.\textsuperscript{6} investigated the switching of this BTN LCD and reported submillisecond se-

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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 $\phi_0$ and $\phi_0 + 2\pi$ will have equal deformation energies and bistability will occur. Therefore for any value of $\phi_0$, the bistable states are $(\phi_0, \phi_0 + 2\pi)$ with $d\Delta P_0 = 0.5 + \phi_0/2\pi$. Hence for $\phi_0 = 0$, the bistable states are $(0, 2\pi)$ and the $d\Delta P_0$ value should be about 0.5. For $\phi_0 = -\pi/2$, the bistable states are $(-\pi/2, 3\pi/2)$ and the $d\Delta P_0$ ratio should be about 0.25. For $\phi_0 = \pi/2$, the bistable states are $(\pi/2, 5\pi/2)$ and the $d\Delta P_0$ ratio should be about 0.75. Table I lists these heuristic $d\Delta P_0$ 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 $\phi_0$ 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 $\phi_0$. The contrast ratio in this case is calculated assuming a cross polarizer geometry with the polarizers at $45^\circ$ 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 $(-270^\circ, 90^\circ)$, $(-90^\circ, 270^\circ)$ 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 $\pi$. Actually, there are BTNs with larger values of $\phi_0$, but they are difficult, if not impossible, to produce experimentally.

While Fig. 1 is calculated for perpendicular polarizers and a polarizer angle of $45^\circ$, similar parameter spaces can also be obtained with parallel–parallel polarizer geometry, and for a polarizer angle of $0^\circ$. These results also indicate that the best $\phi_0$ values are $-\pi/2$, 0, $\pi/2$, and $\pi$. 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 $d\Delta P_0$ 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\(^{14}\)

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

(1)

where

$$u = \pi d\Delta n / \phi \lambda$$

(2)

for twist angles $\phi$ that are odd multiples of $\pi/2$. In Eq. (1), $\Delta n$ is the optical birefringence, and $\lambda$ 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

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

(3)

for $\phi$ 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.

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**TABLE I. Theoretical and experimental values of $d\Delta P_0$.**

<table>
<thead>
<tr>
<th>$\phi_0$</th>
<th>Heuristic value</th>
<th>Experimental value</th>
<th>Dynamical modeling</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-\pi/2$</td>
<td>0.25</td>
<td>0.285–0.305</td>
<td>0.425</td>
</tr>
<tr>
<td>0</td>
<td>0.5</td>
<td>0.55–0.7</td>
<td>0.85</td>
</tr>
<tr>
<td>$\pi/2$</td>
<td>0.75</td>
<td>0.9</td>
<td>unstable</td>
</tr>
</tbody>
</table>

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**FIG. 1. Contrast parameter space for a BTN with twist angles $\phi_0$ and $\phi_0 + 2\pi$. Each contour line represents an increase of 5 in contrast.**
III. ($-\pi/2, 3\pi/2$) BTN EXPERIMENTAL RESULTS

For investigating BTN with $\phi_0$ 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 $\mu$m. 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.\textsuperscript{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 suddenly, 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.\textsuperscript{3,8} The measured contrast ratio in the normal direction is 30:1.

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
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 $\pm \pi/2$ 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.

**IV. $\pm \pi/2$, $5\pi/2$ 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 $\mu$m. 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. 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 $5\pi/2$

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig6}
\caption{Dependence of the final state of the ($-\pi/2$, $3\pi/2$) BTN on the selection pulse voltage.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig7}
\caption{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.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig8}
\caption{Dependence of the minimum reset voltage as a function of the reset pulse duration for the ($-\pi/2$, $3\pi/2$) BTN.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig9}
\caption{Transmission of the ($\pi/2$, $5\pi/2$) BTN LCD (upper) and the applied voltage pulses (lower) as a function of time.}
\end{figure}
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 dln.

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 $(0,2\pi)/2$ BTN, these two cases exhaust all possibilities of transmissive 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 transmissive 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, 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 BTN 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 $\pi$ twist state which has a very different appearance from both the $0$ and $2\pi$ twist states. Constant refreshing is therefore necessary. Since passive matrix driven $(0,2\pi)$ BTN has already been demonstrated, 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 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 transmissive BTNs are discussed. It is also possible to fabricate reflective BTN where there is only one front polarizer. For such reflective displays, $\phi_0$ 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 $\phi_0=-36^\circ$.

APPENDIX

This research was supported by the Hong Kong Industry Department.


