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$\pi/2$ and $5\pi/2$ twisted bistable nematic liquid crystal display

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A $\pi/2$ and $5\pi/2$ twist bistable nematic liquid crystal cell is optimized in optics by a parameter space approach. The cell possesses good contrast ratio, a preferable $d\Delta n$ value, a wide viewing angle, and black–white display. Three switching wave forms can be used to switch the cell between $\pi/2$ and $5\pi/2$ twist states. Controlling the selection voltage amplitude can provide gray scales for the cell. © *2000 American Institute of Physics.* [S0021-8979(00)06005-9]

I. INTRODUCTION

A bistable twisted nematic (BTN) liquid crystal (LC) cell, electrically switched between two quasistable twisted states, was discovered by Berreman and Heffner[1] in 1981. Recently, Tanaka *et al.*[2] successfully made use of this bistability to develop a LC display (LCD). This LCD can be passive matrix driven to show a black–white video graph array (VGA) image. Since both of its states have in-plane alignment, the LCD has a very good viewing-angle characteristic. Therefore, there have been many studies on improving the BTN LCD.[3–6]

A serious drawback of the BTN is its small $d\Delta n$ value ($\approx\lambda/2$), which requires its cell gap be about 2 μm. This thin of a gap can produce an intercell short circuit very easily when operating voltage (normally above 20 V) is applied to the cell. Hence a special technique should be adopted to prevent the short circuit from occurring. In addition, many waste products can occur in industrial fabrication since it is very difficult to keep a uniform gap in the cell.

To overcome this drawback, it is necessary to develop a new BTN LCD with a large $d\Delta n$. In our previous articles,[7,8] we reported a ($-\pi/2$, $3\pi/2$) BTN, a ($\pi/2$, $5\pi/2$) BTN, and a reflective BTN. The $d\Delta n$ values of those BTNs were 0.76, 0.48, and 0.94 μm, while their cell gap values were 5, 4.6, and 7 μm, respectively. Generally accepted in TN and STN (super twist nematic) industrial fabrication, these gap values seem to be suitable for the industrialization of BTN LCDs. But an optical bounce effect in both the ($-\pi/2$, $3\pi/2$) BTN and the reflective BTN was observed in our experiments. This effect will bring about a response time above 0.2 s and will cause a flicker when a frame time of 0.2 s is adopted with refreshing matrix addressing. Moreover, because of their having great color dispersion, both BTNs are unable to perform a black–white display. Therefore, both BTNs are unacceptable as new BTNs with a black–white VGA display.

Fortunately, the fact that no optical bounce effect was found in the ($\pi/2$, $5\pi/2$) BTN makes it possible to develop a new BTN LCD with a large $d\Delta n$. In our previous study, we only dealt with discovery of the bistability between $\pi/2$ and $5\pi/2$ twist states as well as a partial electrooptic curve of the ($\pi/2$, $5\pi/2$) BTN.[7] In this article, we wish to report further detailed study on its optical properties and its electrooptic behaviors.

II. OPTICAL PROPERTIES FOR A TRANSMISSIVE ($\pi/2$,$5\pi/2$) BTN

For a transmissive BTN, both bistable twist states are field-off states, therefore no dynamic calculation of director deformation is necessary to optimize the BTN. So a static parameter space is ideal for analyzing its optical properties. It was previously demonstrated that a (ϕ, $d\Delta n$) parameter space for a fixed α can be used to calculate the contrast ratio of transmissive BTN for any value of ϕ and $d\Delta n$ by calculating the transmittances of ϕ and $\phi+2\pi$ twist states, separately.[9] Here, ϕ is a twist angle, d is a cell gap, Δn is an optical birefringence, and α is the angle between the input polarization direction and the input LC director. Similarly, a (α, $d\Delta n$) parameter space for fixed ϕ can be used to calculate the contrast ratio of a ($\pi/2$, $5\pi/2$) BTN for any value of α and the $d\Delta n$ value. A contrast ratio (CR) between $\pi/2$ and $5\pi/2$ twist states is defined as

$$\mathrm{CR}=T(\pi/2)/T(5\pi/2)$$

or

$$T(5\pi/2)/T(\pi/2). \tag{1}$$

The formula used depends on which ratio is larger. T is the transmittance that can be calculated using the standard Jones matrix of the LC cell.[10] In our calculation, the input-light wavelength λ is 550 nm and the pretilt angle θ is 0°.

Figure 1 shows the dependence of the contrast ratio on α and $d\Delta n$ for an equilibrium ($\pi/2$, $5\pi/2$) BTN LC cell with parallel-polarizer geometry (the input and output polarizer directors are parallel). Each contour line in Fig. 1 represents an increase of 10 in contrast ratio. Clearly, good contrasts can be obtained for any value of α in a zone around $d\Delta n$ $=0.46$ μm. In this zone, the $d\Delta n$ ranges with good contrast

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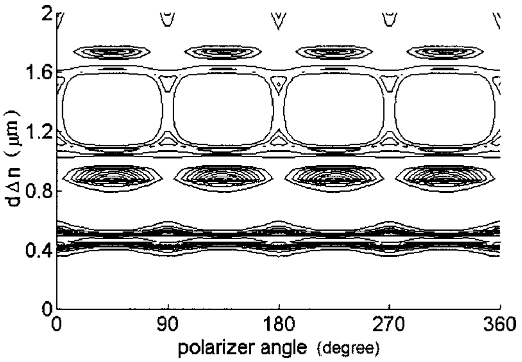

FIG. 1. Isocontrast parameter space for a ($\pi/2$, $5\pi/2$) BTN with parallel-polarizer geometry. Each contour line represents an increase of 10 in contrast.

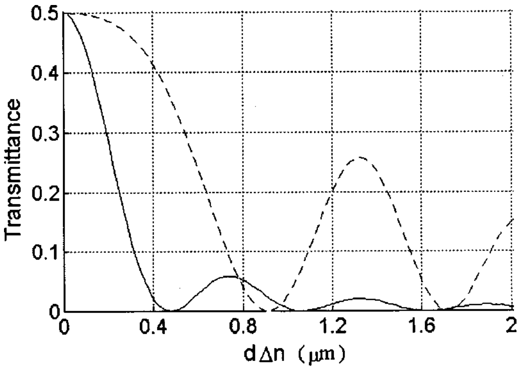

FIG. 3. Relationship between the transmittance of a ($\pi/2$, $5\pi/2$) BTN and $d\Delta n$ for the $\alpha=0°$ with parallel polarizers. A solid line represents a result for the $\pi/2$ twist state, and a dashed line that for the $5\pi/2$ twist state.

are slightly wider at $\alpha=0°$, 90°, 180°, and 270°. For a BTN, the wider its $d\Delta n$ range with good contrast, the smaller its color dispersion is, as well as the easier its manufacture will be. Therefore, the optimized points of the ($\pi/2$, $5\pi/2$) BTN cell should be located at 0°, 0.46 μm, 90°, 0.46 μm, 180°, 0.46 μm, and 270°, 0.46 μm in the (α,$d\Delta n$) parameter space with parallel-polarizer geometry.

Figure 2 shows the calculation results of the same ($\pi/2$, $5\pi/2$) BTN cell with cross-polarizer geometry instead of parallel-polarizer geometry. The good contrast regions look like four islands and are located around points of 45°, 0.78 μm, 135°, 0.78 μm, 225°, 0.78 μm, and 315°, 0.78 μm, respectively. Compared with Fig. 1, these regions are much smaller and more sensitive to changes in $d\Delta n$ and α. So the optimal operating point should be selected at 0°, 0.46 μm for a ($\pi/2$, $5\pi/2$) BTN LC cell with parallel-polarizer geometry. Its $d\Delta n$ value of 0.46 μm is twice that of Tanaka's operating point.

Besides contrast ratios, other important criteria for a good BTN display are brightness, color dispersion, and viewing angle. Figure 3 shows the relationship between the transmittance of the ($\pi/2$, $5\pi/2$) BTN and its $d\Delta n$ value for $\alpha=0°$ with parallel polarizers. A solid line represents a result for the $\pi/2$ twist state, and a dashed line that for the $5\pi/2$ twist state. When $d\Delta n=0.46$ μm, the $\pi/2$ state reveals near zero transmittance, and the $5\pi/2$ state shows about 0.38 transmittance. So a good dark state and a reasonably good bright state can be obtained in the ($\pi/2$, $5\pi/2$) BTN.

Figure 4 shows transmittance spectra of $\pi/2$ and $5\pi/2$ twist states for the case of $d\Delta n=0.46$ μm and $\alpha=0°$ with parallel polarizers. It is found that the color dispersion of both states was small and similar to that of the (0, 2π) BTN. The brightness and contrast ratio are slightly worse than those of the (0, 2π) BTN. Indeed, a black–white display with reasonably good contrast can be obtained for the ($\pi/2$, $5\pi/2$) BTN.

Figure 5 shows the isocontrast dependence of viewing angles for the ($\pi/2$, $5\pi/2$) BTN LC cell operated at its optimal point. In Fig. 5 each contrast ratio is labeled near each contour line. Evidently, a contrast ratio larger than 65:1 can be obtained within 20° in any direction, and still better than 10:1 contrast within 40° in any direction. Alternatively, a 45° rotated configuration may be used with a contrast larger than 20:1 from all reasonable horizontal or vertical viewing directions. This viewing characteristic is very similar to that of a TN cell compensated for by dual domain alignment. Therefore this BTN has a wide viewing-angle characteristic.

III. EXPERIMENT

Of course, good optical properties and the actual electrooptic behavior of the BTN are separate issues. For investigating the latter, we made a cell with a 7° pretilt angle and 90° planar alignment. The cell is filled with a commercial

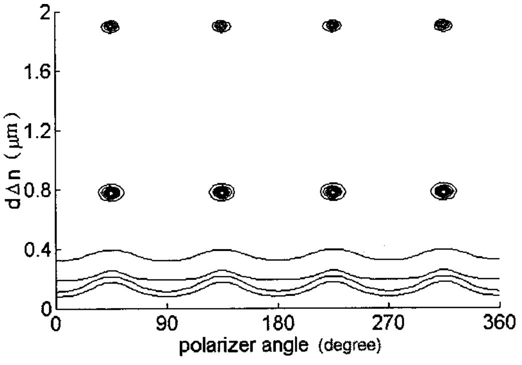

FIG. 2. Isocontrast parameter space for a ($\pi/2$, $5\pi/2$) BTN with cross-polarizer geometry. Each contour line represents an increase of 10 in contrast.

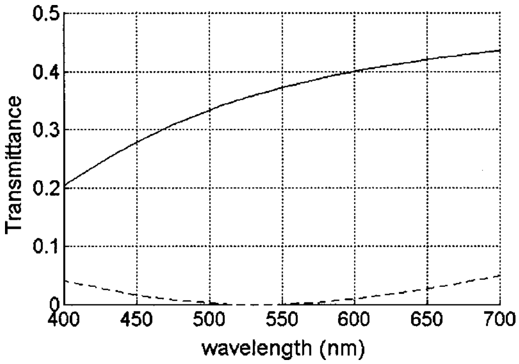

FIG. 4. Transmittance spectra of $\pi/2$ and $5\pi/2$ twist states. $d\Delta n=0.46$ μm, $\alpha=0°$, and parallel polarizers.

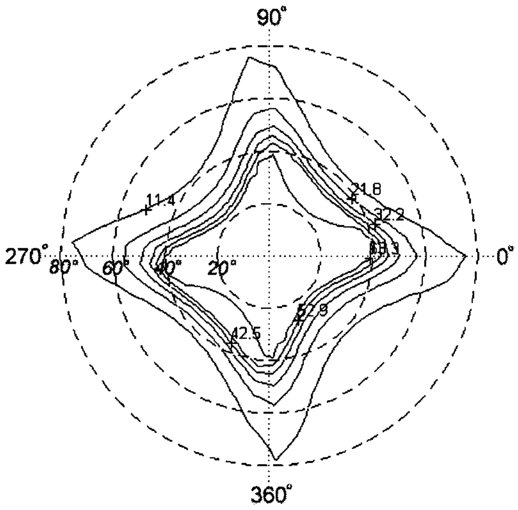

FIG. 5. Isocontrast dependence of the viewing angle for a ($\pi/2$, $5\pi/2$) BTN. $d\Delta n = 0.46$ μm, $\alpha = 0°$, and parallel polarizers.

liquid crystal (MLC 7500/000) and a chiral additive CB15, and its d/P_0 value is controlled near 0.9 (d is the cell thickness and P_0 is the LC inherent pitch). The cell gap is 4.6 μm. The input polarizer is parallel to the input director as is the output polarizer. This is the optimized configuration, as discussed above.

Figure 6 shows three pulse wave forms used to switch the ($\pi/2$, $5\pi/2$) BTN. For the wave form in Fig. 6(a), the $\pi/2$ state can be obtained by turning a voltage pulls off slowly, and the $5\pi/2$ states can be obtained by turning it off suddenly. For the Fig. 6(b) wave form, the different pulse amplitude accomplishes the switching between $\pi/2$ and $5\pi/2$ twist states. The wave form in Fig. 6(c) consists of a reset pulse to switch LC molecules to a near-homoetropic state, followed by a selection pulse to select one of two metastable states. This is the same as the wave form used by Tanaka *et al.*[2] The selection time in the wave forms in Fig. 6(c) is much shorter than that in the wave forms in Figs. 6(a) and 6(b).

IV. RESULTS AND DISCUSSIONS

Figure 7 shows the time dependence of a transmission and applied voltage pulse for the BTN LC cell switched by the wave form in Fig. 6(a). Obviously, the $\pi/2$ twist state which corresponds to low transmission can be obtained by turning a voltage pulse off slowly, and the $5\pi/2$ state corresponding to high transmission can be obtained by turning it off suddenly. In both cases, no optical bounce effect has been observed, and the response times are 30 and 10 ms, respectively. The contrast ratio measured in the normal direction is about 20:1. Seemingly, the $\pi/2$ twist state appears black, and the $5\pi/2$ twist state appears white. Both the $\pi/2$ state and the $5\pi/2$ state can last for several seconds after the electric field is removed. After this time they tend to relax to a stable $3\pi/2$ state. Indeed, the $\pi/2$ and $5\pi/2$ states are metastable states.

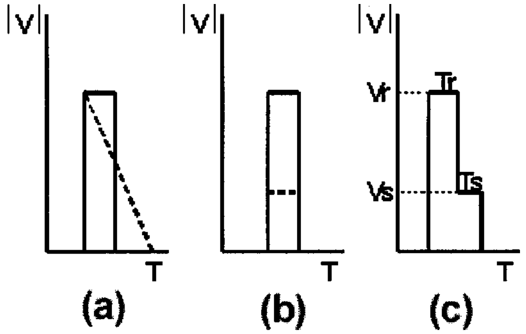

FIG. 6. Three pulses wave forms used to switch the ($\pi/2$, $5\pi/2$) BTN.

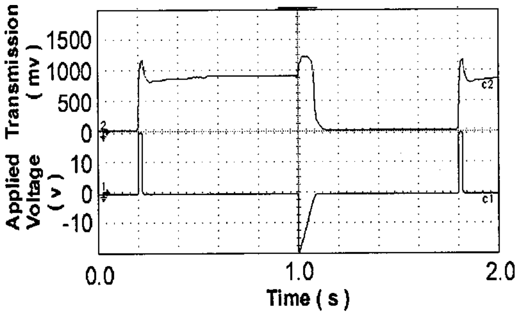

FIG. 7. Transmission of the LCD (upper panel) and applied voltage pulse (lower panel) as a function of time. The wave form in Fig. 6(a) is used. The $\pi/2$ state has low transmission and the $5\pi/2$ state has high transmission.

Figure 8 shows the time dependence of a transmission and applied voltage pulse for the BTN LC cell driven by the wave form in Fig. 6(b). The pulse duration is 20 ms. Apparently, the $\pi/2$ state can be obtained by a weaker pulse (8 V) and the $5\pi/2$ state by a stronger pulse (20 V). We can adjust the amplitude of the voltage pulse to select one of two metastable states. This wave form is the simplest and would be of great significance if it would work well. Unfortunately, during passive matrix addressing, the weaker pulse cannot switch the cell from the initial $3\pi/2$ state to the $\pi/2$ state, it can only switch the cell from the $5\pi/2$ state to the $\pi/2$ state. Therefore this wave form is not suitable for practical driving.

Figure 9 shows the time-dependent transmission curve and the voltage pulse for the BTN LC cell switched by the wave form in Fig. 6(c). For this measurement, the rest time is fixed at 22.5 ms with amplitude fixed at 20 V. The selection time is fixed at 7.5 ms and the selection voltage amplitude alternates between 0 and 8 V. The $\pi/2$ state is clearly obtained for 0 V and the $5\pi/2$ twist state for 8 V. Being somewhat complex, the driving wave form in Fig. 6(c) is the most

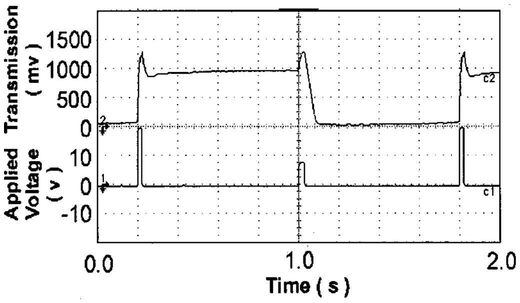

FIG. 8. Same as in Fig. 7 but with the wave form of Fig. 6(b) as the switching pulse. The pulse duration is 20 ms. The weaker pulse amplitude is 8 V and the stronger pulse amplitude is 20 V.

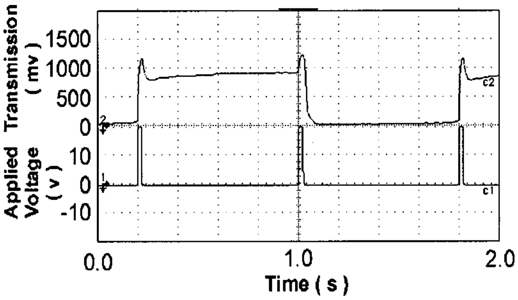

FIG. 9. Same as in Fig. 7 but with the wave form of Fig. 6(c) as the switching pulse. $Vr=20$ V, $Tr=22.5$ ms, and $Ts=7.5$ ms.

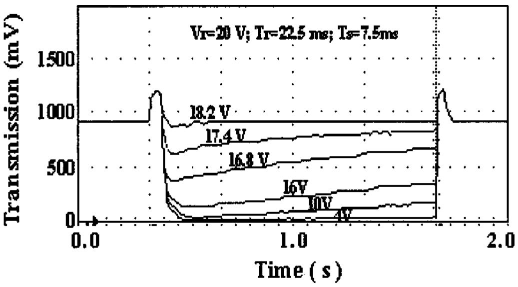

FIG. 11. Optical responses of six gray scale levels produced by a selection voltage variation between 4 and 18.2 V.

suitable and most practical for switching the BTN cell because it can be easily divided into a common scanning signal and segment data signal to facilitate passive-matrix addressing. Actually this wave form has been successfully applied to 0 and 2π twist BTN LCDs by Tanaka *et al.* We believe that the wave form in Fig. 6(c) is also suitable for $\pi/2$ and $5\pi/2$ switching.

Figure 10 shows the dependence of transmission of the BTN on the selection voltage amplitude. The reset pulse and duration of the selection pulse are the same as those in Fig. 9. There exists a finite amplitude range between 1 and 11 V for selection of the $\pi/2$ state. Beyond this range, the $5\pi/2$ state is obtained in range of below 1 or above 18.5 V. Interestingly, a slow transition between 11 and 18.5 V has been observed to make a better gray scale.

Figure 11 shows the optical response of six gray scale levels produced by a selection voltage variation between 4 and 18.2 V. None of the gray levels can stay at a fixed level. After the electric field is removed, each gray level will change gradually and disappear. So gray levels in ($\pi/2$, $5\pi/2$) BTN are metastable. The refresh time can be lengthened to 2 s since the disappearance of every gray scale needs about 2 s (Fig. 11). Although Bock[6] reported an analogue gray scale effect in a (0, 2π) BTN very recently, it is thought to be the first time that a gray scale effect in a ($\pi/2$, $5\pi/2$) BTN has been found. The crosstalk immunity and multiplexability of the ($\pi/2$, $5\pi/2$) BTN LCD will be investigated in the future.

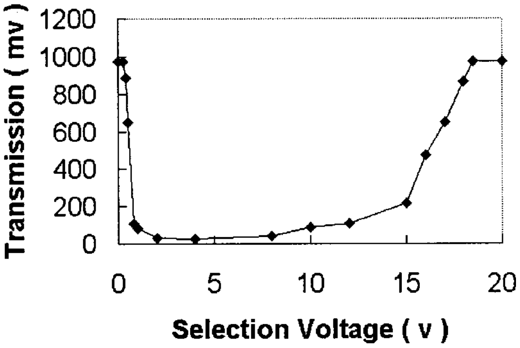

FIG. 10. Dependence of transmission of the ($\pi/2$, $5\pi/2$) BTN on the selection voltage amplitude. $Vr=20$ V, $Tr=22.5$ ms, and $Ts=7.5$ ms.

So far we have been successful in observing bistability of the ($\pi/2$, $5\pi/2$) BTN in samples within $d/P_0=0.90-0.94$. Although this d/P_0 range is narrower than that of the (0, 2π) BTN, when $d/P_0=0.92$ and $d=4.6$ μm, the ($\pi/2$, $5\pi/2$) BTN could be made into a practical device if its cell thickness uniformity can be controlled to within $\Delta d=\pm 0.1$ μm.

V. CONCLUSIONS

In summary, we have developed a $\pi/2$ and $5\pi/2$ twist BTN LCD that possesses a high contrast ratio, wide viewing angle, and black–white display. Passive-matrix addressing can be used to drive the ($\pi/2$, $5\pi/2$) BTN cell and to perform a gray scale which was found in ($\pi/2$, $5\pi/2$) BTN LCDs. Since it has a large cell gap, the ($\pi/2$, $5\pi/2$) BTN LCD could be put into industrial fabrication more easily.

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