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Reflective Bistable Twisted Nematic Liquid Crystal Display

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A reflective bistable twisted nematic (BTN) liquid crystal display has been developed. It combines the advantages of a truly reflective display without the rear polarizer, and the bistable nature of the zero voltage state. It was found experimentally that switching between the two bistable twist states could be achieved by adjusting the magnitude of the selection voltage pulse, just like the case in transmittive BTNs. In demonstrating the reflective BTN, we also show for the first time bistability between the $-36°$ and $324°$ twist states.

KEYWORDS: bistable TN displays, reflective liquid crystal displays

1. Introduction

Bistable twisted nematic (BTN) liquid crystal displays (LCD) that could be switched between two metastable twist states using specially shaped electrical pulses were discovered by Berreman and Heffner in 1981.(1) A 0 to 2π bistability was reported in that publication. Recently, Tanaka *et al.*(2) developed a method for passive-matrix addressing of such BTN displays. Due to the bistability, this passive matrix display can be driven like an active matrix display. This high-performance LCD rekindled much interest in BTN LCD.(3–8) We recently developed a BTN based on $(-\pi/2,\ 3\pi/2)$ bistability, as well as one that could be switched between the $(\pi/2,\ 5\pi/2)$ twist states.(4) On other fronts, Dozov *et al.*(5) proposed a new fast bistable twisted nematic display using monostable surface anchoring. Bryan-Brown *et al.*(6) proposed a grating aligned BTN LCD that can be switched by sub-millisecond pulses. The physics of the BTN switching dynamics was also theoretically studied recently.(7,8)

So far, all the BTN displays reported have been in the transmittive mode. A front and a rear polarizer are used to complete the display. There is also recent interest in reflective LCDs which do not require the rear polarizer or any polarizer at all.(9–15) Such truly reflective displays are desirable for portable, low-power applications. There are many advantages to eliminating one or all of the polarizers, including increased brightness and simpler manufacturing. The rear reflector can also be incorporated as part of the LC cell, thus eliminating any viewing parallax, which also means potentially higher resolution. Recently, Kobayashi *et al.* demonstrated a polarizer-free reflective guest-host display based on the bistable supertwisted nematic display.(15) In this paper, we shall propose and demonstrate a new reflective BTN (RBTN) display based on the polarization manipulation effect with a single front polarizer. This display combines the advantages of reflective displays and the bistable driving characteristics of normal BTN. In this RBTN, the structure consists simply of a front polarizer, the LC cell and a rear reflector. It is similar to the RTN and RSTN reported by us recently.(10–14)

There are two aspects to the study of reflective BTN: (1) optimization of the twist angle to produce the best optical performance and (2) optimization of the LC cell parameters in order to achieve bistability using the prescribed twist angles obtained in (1). These procedures will be described in the following sections.

2. Optics of Reflective BTN

The physics of the BTN is actually quite intuitive. If the surface rubbing condition of a LCD favors a ϕ twist, then that boundary condition can also be satisfied by an LC with a $\phi + 2\pi$ twist. If the natural twist of the LC, as controlled by a chiral dopant, is $\phi + \pi$, then ϕ and $\phi + 2\pi$ will have the same deformation energy and bistability will occur. Thus, using this simple intuitive picture, the thickness-to-pitch (d/p) ratio of the LC cell should be $0.5 + \phi/2\pi$. In actual practice however, the d/p ratio is always somewhat larger than the simple argument presented here.(4)

The optics of the transmittive BTN has been described before.(16) It was shown, using the parameter space(17) approach, that if the bistable twist states are ϕ and $\phi + 2\pi$, then ϕ should be $-\pi,\ -\pi/2,\ 0,\ \pi/2,\ \pi,\ \cdots$. In fabricating the BTN, ϕ should be the preferred twist angle of the LC, as defined by the boundary surfaces. The $(0, 2\pi)$, $(-\pi/2,\ 3\pi/2)$ and $(\pi/2,\ 5\pi/2)$ transmittive BTNs have been experimentally demonstrated.(4) For the case of reflective BTN without the rear polarizer, these angles are no longer the best choices. A reflective parameter space must be employed to obtain the best twist angles. Fortunately, for both the transmittive and the reflective BTN, the twist in the LC cell is uniform. Hence the simple Jones matrix can be applied to calculate the transmittance and reflectance. For a LC cell with uniform twist, zero tilt, and with the input director along the x-axis, the Jones matrix is given by(17)

$$M = \begin{pmatrix} A - iB & -C - iD \\ C - iD & A + iB \end{pmatrix}, \tag{1}$$

where

$$A = \cos\phi\cos\beta d + \frac{q}{\beta}\sin\phi\sin\beta d \tag{2}$$

$$B = \frac{k_\mathrm{a}}{\beta}\cos\phi\sin\beta \tag{3}$$

$$C = \sin\phi\cos\beta d - \frac{q}{\beta}\cos\phi\sin\beta d \tag{4}$$

$$D = \frac{k_\mathrm{a}}{\beta}\sin\phi\sin\beta d. \tag{5}$$

In eqs. (2)–(5), $q = 2\pi/p$, where p is the pitch of the LC cell

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and

$$\beta = [k_a^2 + q^2]^{1/2}. \tag{6}$$

For a twisted nematic cell, the pitch is related to ϕ by

$$qd = \phi. \tag{7}$$

Also,

$$k_a = \pi \Delta n / \lambda, \tag{8}$$

where

$$\Delta n = n_e(\theta) - n_o \tag{9}$$

is the birefringence of the tilted liquid crystals. Finally, $n_e(\theta)$ is the extraordinary index at an average director tilt angle of θ and is given by the usual expression

$$\frac{1}{n_e^2(\theta)} = \frac{\cos^2\theta}{n_e^2} + \frac{\sin^2\theta}{n_o^2}. \tag{10}$$

Note that even though there are 3 variables in the Jones matrix, only 2 parameters are needed to completely define M, since d and Δn always appear together as $d\Delta n$.

The geometry of the reflective BTN is very simple. The input director is defined as the x-axis. The polarizer makes an angle α with the x-axis. The twist angle ϕ is positive if it is a right-handed twist along the direction of the incident light. The Jones matrix of the LC cell upon reflection is related to M by a rotation of the coordinate system and a change in the twist direction of the LC cell. Hence the reflectance of the reflective nematic display is given by

$$R = \left| (-\sin\alpha \cos\alpha) \cdot H \cdot M(-\phi) \cdot H^{-1} \cdot M(\phi) \times \begin{pmatrix} \cos\alpha \\ \sin\alpha \end{pmatrix} \right|^2, \tag{11}$$

where H is the rotation matrix

$$H = \begin{bmatrix} \cos\phi & \sin\phi \\ -\sin\phi & \cos\phi \end{bmatrix}. \tag{12}$$

The reflectance $\boldsymbol{R}$ parameter space can be calculated using ϕ and $d\Delta n$ as the free parameters,[17] with α fixed. For each value of ϕ, we also calculate the reflectance of the $\phi + 2\pi$ twist state. Then the contrast ratio (CR) for this RBTN will be either $\boldsymbol{R}(\phi)/\boldsymbol{R}(\phi+2\pi)$ or $\boldsymbol{R}(\phi+2\pi)/\boldsymbol{R}(\phi)$, depending on which reflectance is smaller.

Figure 1 shows a contour map of CR as a function of $d\Delta n$ and ϕ for the case of $\alpha = 0$. The contour lines are shown in steps of 3. Figure 2 shows a similar case for $\alpha = 45°$. It can be seen that in all cases, there are many islands in the $d\Delta n$ and ϕ parameter space for a high-contrast display. However, unlike the case of transmittive displays, the high-contrast parameter spaces are quite narrow and sensitive to changes in $d\Delta n$. In particular, the contour lines become very dense near the top of the peaks. The reason is that in the CR case, one of the reflectivities approaches zero and thus the CR can change drastically.

Upon examining several parameter spaces for various values of α, it is determined that the peak at $d\Delta n = 0.94\,\mu$m and $\phi = -36°$ in Fig. 1 is a good candidate for the RBTN. The criteria for choosing a good operating point are (1) $\boldsymbol{R}$ and CR should not be sensitive to changes in $d\Delta n$, and (2) the value of $d\Delta n$ should be large so that the cell can be made easily. The peak at $\alpha = 0$, $d\Delta n = 0.94\,\mu$m and $\phi = -36°$ seems to satisfy these requirements. It has a reasonable cell thickness requirement, and the value of ϕ falls between those of the two demonstrated cases of bistability (−90° and 0°).[2,4] Figure 3 shows the individual reflectance of the 2 bistable twist states, $\boldsymbol{R}(-36°)$ and $\boldsymbol{R}(324°)$, together with the contrast CR as a function of $d\Delta n$. It can be seen that a high-contrast display should be possible for $d\Delta n = 0.94\,\mu$m, with a peak reflectance of almost 100%, assuming polarized input light, or 50% for unpolarized light.

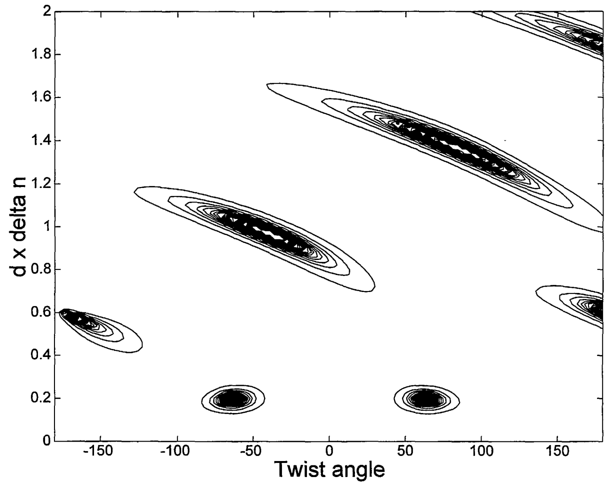

Fig. 1. Contrast ratio of the RBTN as a function of $d\Delta n$ and ϕ for $\alpha = 0$. Each contrast contour line represents an increase of 3.

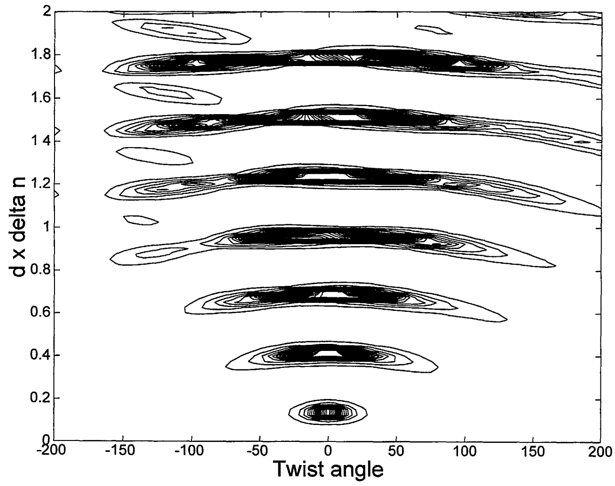

Fig. 2. Contrast ratio of the RBTN as a function of $d\Delta n$ and ϕ for $\alpha = 45°$. Each contrast contour line represents an increase of 3.

3. Experimental Results

Several cells with the parameters discussed above were fabricated. The LC cell was comprised of a pair of transparent electrodes and polyimide alignment layers separated by a gap d. The cell was assembled in such a way that the directors of the LC on opposite surfaces form a −36° (or equivalently 324°) twist. A commercial LC (MLC5700–5800 mixture) was used to produce the necessary Δn. It was doped with an appropriate amount of chiral additive (S-811) to produce

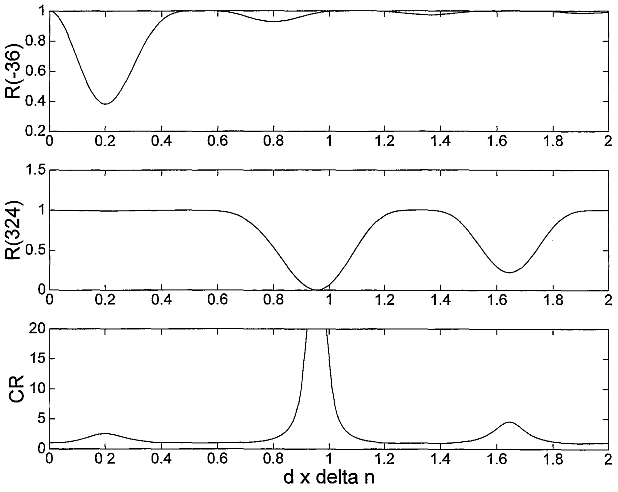

Fig. 3. Reflectance of the two bistable states (top) and the contrast ratio (bottom) as a function of $d\Delta n$ for $\phi = -36°$.

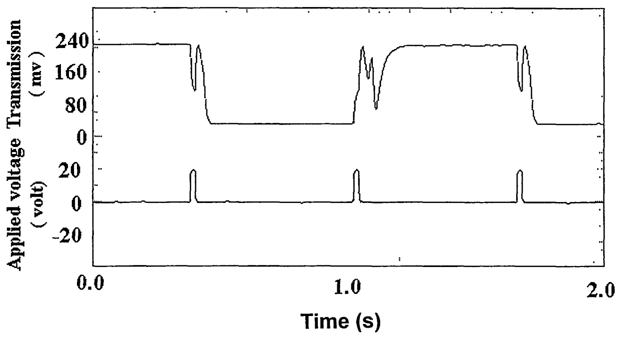

Fig. 4. Measured reflectance of the RBTN cell (upper) and the driving pulse (lower).

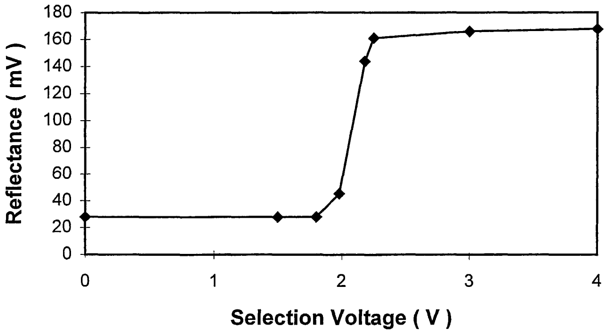

Fig. 5. Measured reflectance of the RBTN as a function of the selection pulse voltage.

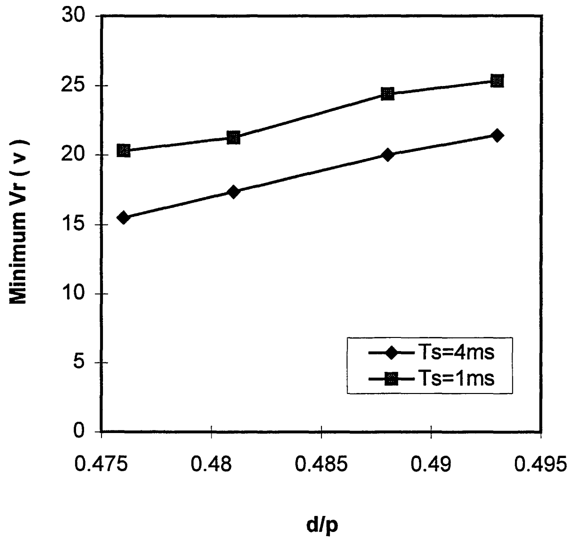

Fig. 6. Minimum reset voltage as a function of the d/p ratio.

the appropriate pitch. The LC cell was deliberately wedged so that the d/p values fell within the 0.476–0.493 range.

Figure 4 shows the time-dependent reflectance curve and the driving pulse for the RBTN cell. In this measurement, the LC cell was placed between an input polarizer and a rear mirror. For the present mode, the input director of the LC cell and the polarizer were parallel. The driving waveform consisted of a reset pulse followed by a selection pulse. It was essentially the same as that reported by Tanaka *et al.*2) The reset pulse voltage V_r and duration T_r were typically 20 V and 22.5 ms, respectively. The duration T_s of the selection pulse was 7.5 ms for this figure. The selection pulse amplitude was varied to select the 2 bistable states. In Fig. 4, the selection pulse voltage V_s alternates between 4 V and 0 V. It can be seen that bistability is clearly achieved. The 324° twist state corresponds to a low reflectance and is obtained using the 4 V select pulse. The $-36°$ state corresponds to a high reflectance and is obtained using the 0 V select pulse. It can be also seen that there is an "optical bounce" during the switching from one state to another. The same phenomenon was also observed with the $(0, 2\pi)$ and $(-\pi/2, 3\pi/2)$ BTNs.4,8)

Figure 5 shows the dependence of the reflectance on the selection pulse amplitude. High reflectance corresponds to the 324° state, and low reflectance corresponds to the $-36°$ state. The contrast ratio measured is about 6:1. This is much lower than that predicted using the results in Fig. 3. Possible explanations are the reflectivity of the uncoated glass, and inaccuracies in the $d\Delta n$ value. As shown in Fig. 3, CR is quite sensitive to $d\Delta n$. If $d\Delta n$ is 0.9 μm, CR drops to near 15. Nevertheless, the reflectance vs selection voltage curve has a very steep transition between the high and low reflectance states. Therefore high-performance passive-matrix addressing should be possible, similar to the case of the $(0, 2\pi)$ BTN.2)

The d/p dependence of the RBTN is shown in Fig. 6. In that graph, we plotted the required reset voltage as a function of d/p. The reset time T_r was 40 ms while the selection voltage was 4 V. It can be seen that between the range of 0.476 and 0.493, even for a selection time of 1 ms, switching is possible. According to the simple intuitive argument, the d/p ratio required for bistability should be $0.3\ (0.5 + \phi/2\pi)$. Therefore the present result is consistent with the observation that the experimentally determined d/p is always larger than the intuitive value of d/p in order to observe bistability. The selection time of 1 ms is consistent with transmittive BTNs and is governed by the LC backflow dynamics.8) A selection time of 1 ms per line implies a frame time of 0.2 s for a 200-line display, which is typical for personal data assistants and palmtop computers. Ideally, the frame rate should be 4 times faster for video applications.

In Fig. 7, the minimum selection voltage is plotted as a

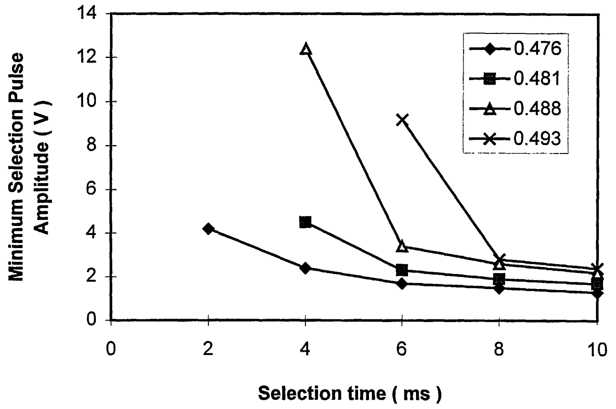

Fig. 7. Minimum selection voltage as a function of the selection time.

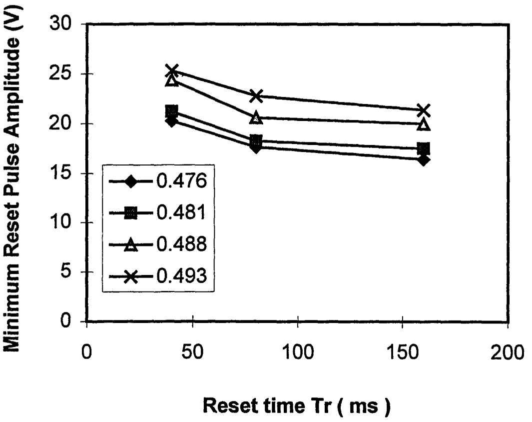

Fig. 8. Minimum reset pulse amplitude as a function of the reset time. The selection time is fixed at 1 ms.

function of the selection time for a few d/p ratios. The reset voltage was 15 V and the reset pulse duration was 80 ms. This study is important because the selection pulse duration basically determines how fast the lines in a RBTN display can be addressed. In general, a smaller selection time will require a larger selection voltage. If the selection voltage required is too large (near the reset voltage) then bistability cannot be achieved. Again, for the d/p range studied, except for large d/p near 0.49, bistability can be attained and the selection voltages are reasonable. For this particular measurement, because of the small reset voltage, a selection time of 1 ms is not possible. Hence there is no data point for 1 ms. In general, as shown in Fig. 6, a reset voltage of >20 V is needed for 1 ms selection.

Finally, we plot the reset voltage as a function of the reset time in Fig. 8. The selection time and voltage are fixed at 1 ms and 4 V, respectively. Again, if the reset pulse duration is short, the amplitude required will increase. Figure 8 shows that the reset pulse duration must be 40 ms in order for the voltage to be less than or equal to 20 V. These are convenient values and can be achieved in practice using conventional LCD drivers.

4. Conclusions

We have successfully developed a reflective BTN LCD that requires only one front polarizer. This RBTN, in theory, should have excellent contrast and brightness. It does not require a rear polarizer so that the reflector can, in principle, be placed inside the LC cell, thus eliminating viewing parallax. This RBTN should also be addressable by a passive-matrix method. Because of the bistability, such displays can be matrix driven without the usual crosstalk problems associated with multiplexing.

The switching response time for this RBTN is slower than that of transmittive BTN, even though the selection time can be as low as 1 ms. The optical bounce is on the order of 0.2 s. Therefore, this display is not suitable for fast frame rates. However, it has been observed that the optical bounce depends critically on the cell gap and the driving waveform.[4] For the case of the (0, 2π) BTN, fast switching of <10 ms is possible. At present, we are working on reducing the switching time by adopting other regions shown in Fig. 1 as the operating point, and also by varying the cell thickness and liquid crystal material parameters.

This RBTN is based on bistability between the $-36°$ and $324°$ twist states. It is the first time such a bistability has been demonstrated. Previously, only the $(0°, 360°)$ and $(-90°, 270°)$ cases have been reported for stable twisted nematic bistability. The case of $(90°, 450°)$ has also been observed recently by us.[4] Therefore the present case of $(-36°, 324°)$ adds to the expanding repertoire of possible BTNs. The contrast ratio of this RBTN was measured to be about 6:1. It is believed that better values could be obtainable with further optimization.

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