Optical Properties of Bistable Twisted Nematic LCD and Its Switching Mechanisms

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Abstract

The brightness and contrast ratio of bistable twisted nematic displays are studied using the parameter space approach. By plotting the contrast ratio as a function of the twist angle and birefringence of the display, regions where the bistable twisted nematic display shows the best contrast ratio are clearly shown. We also studied the switching mechanisms of such displays.

1. Introduction

Recently, a new class of twisted nematic (TN) liquid crystal displays (LCD) where the field-off state can exhibit bistability has been demonstrated[1-4]. Such bistable TN (BTN) displays has the advantage that, unlike ordinary LCD, no holding voltage is needed to display the images. At zero volts, the alignment of the BTN can take on either of two twist states, due to a proper choice of the rubbing directions of the alignment layers and the *d/p* ratio, where *d, p* are the thickness and pitch of the LC cell respectively. If the rubbing of the alignment layers favors a twist angle of ϕ, and if the natural twist of the nematic LC itself is $\phi + \pi$, then the twist states ϕ and $\phi + 2\pi$ are equally stable (or metastable). Hence, for bistability to occur, the *d/p* ratio of the LC cell should be ~ $(0.5 + \phi/2\pi)$. Because of its bistable nature, a BTN can be driven like an active matrix display. Hence high contrast and brightness can be possible using simple multiplex driving schemes.

While several studies have been devoted to the electrical switching properties of such BTNs and their electrical driving schemes, their optical properties have not been thoroughly investigated. We and others have recently showed that the switching of the BTN from one state to another is related to the backflow dynamics in the liquid crystal cell[5,6]. Interestingly, all reported BTNs[1-3] assume a ϕ value of 0^o, so the bistable twist angles are 0 and 2π. Moreover, a polarizer angle of 45^o is always used. We recently reported a BTN[4] with $\phi = -\pi/2$ so that the bistable states are $-\pi/2$ and $3\pi/2$.

We examined the optics of BTNs for general values of ϕ and polarizer angles. The contrast ratio as well as the optical efficiencies for various configurations will be studied systematically for the entire parameter space[7,8] of such BTNs. We shall show that for transmittive BTN, indeed a ϕ of 0^o and an α of 45^o is a good choice. However, we shall also show that there are other BTN operating modes that may have good optical properties as well. Using this method, we also obtained the best values of the birefringence $d\Delta n$ of the BTN. We also showed the effect of the polarizer angle on the peak transmittance and wavelength dispersion of the BTN modes. The optimal operating conditions for various types of BTN are reported.

2. Parameter space for transmittive BTN

The starting point for our analysis of the BTN is the Jones matrix of the LC cell[7,8]. The basic idea is that at V = 0, the transmittance of any twisted nematic display is a unique function of the polarizer angle α, the LC cell twist angle ϕ, and the thickness-birefringence product $d\Delta n$. By fixing any one parameter, the reflectance or transmittance of the LC cell can be plotted as a function of the remaining 2 parameters in a 2D contour map.

We showed previously that a $(\phi, d\Delta n)$ parameter space[7,8] for fixed α can be very useful in analyzing reflective as well as transmittive displays. For the case of a BTN, both bistable twist states operate at V = 0. So the static parameter space is ideal in analyzing its optical properties. We can calculate the contrast ratio of the BTN for any value of ϕ and $d\Delta n$ by calculating the transmittance of the 2 bistable twist states separately. The contrast ratio is defined as

$$CR = T(\phi)/T(\phi+2\pi) \quad \text{or} \quad T(\phi+2\pi)/T(\phi) \qquad (1)$$

depending whichever ratio is larger. The twist state with a lower transmittance is regarded as the dark state. Fig. 1 shows the dependence of CR on ϕ and $d\Delta n$ for a BTN with $\alpha = 45^o$ and a cross polarizer geometry. It is basically the same conditions as those in references 1-3. In this calculation, the wavelength was assumed to be 540 nm.

Each contour line in Fig. 1 represents an increase of 10 in the contrast ratio. ϕ is used as the independent parameter though it should be remembered that the bistable states are ϕ and $\phi+2\pi$. From Fig. 1, it can be seen that there are many regions where good contrast can be obtained. They are concentrated at $\phi = 0^o$ and $\pm 90^o$. The operating conditions of the BTN in Tanaka et al[1] corresponds to the large island at $\phi = 0^o$ and $d\Delta n = 0.2$ µm. Notice that the contrast is not as large in this island as compared to the others. But we shall show that it is nevertheless a good choice for the operation of the BTN.

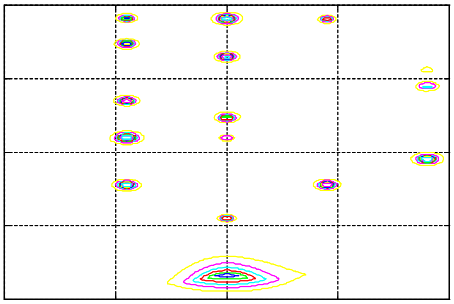

***Fig. 1* Parameter space showing contours of constant contrast ratios. *a* = 45^o.**

Fig. 2 shows the same BTN with $\alpha = 0^o$ and cross polarizers. The parameter space is now quite different. The region of good contrast is dominated by the large elongated islands at $\phi = 0^o$ and a smaller island at $\phi = 180^o$. Thus, Figs. 1-2 show clearly the values of ϕ and $d\Delta n$ in order for any BTN to produce a good contrast ratio. In particular, even if ϕ is correct, the BTN will show poor optical properties if $d\Delta n$ is not properly chosen.

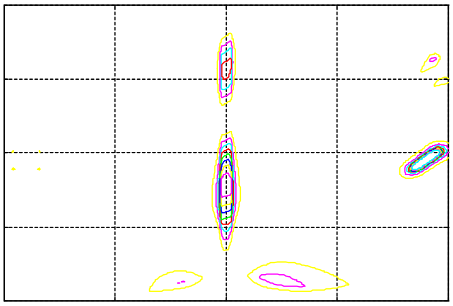

***Fig. 2* Constant contrast parameter space for *a* = 0^o with cross polarizers.**

3. Brightness/efficiency of the BTN modes

The contrast ratio is only one of the criteria for a good BTN display. The other measures of a good display are the peak transmittance of the bright state, and the color dispersion of the dark and bright states. In order to examine the details of the specific BTN modes, it is better to plot the transmittance of the two bistable states and the contrast ratio together. These results are shown in Figs. 3-4. In calculating these curves, a simple solution of the complicated Jones matrix is possible. It can be shown that for LC twist angles F that are ±odd multiples of $\pi/2$, the transmittance of the LC cell under crosspolarizers is given by

$$T(F) = \cos^2 [\pi^2 d^2 \Delta n^2/\lambda^2 + F^2]^{1/2} \qquad (2)$$

where λ is the wavelength of the incident light. A similarly simple expression exists for the case of parallel polarizers. Fig. 3 shows the results for the case used by Tanaka et al[1], namely, $\phi = 0^o$ and $\alpha = 45^o$ with cross polarizers. Here, we plot the transmittance $T(\phi)$, $T(\phi+2\pi)$ and CR as a function of dΔn. Notice that in Figs. 3-4 we assumed the input light to be polarized linearly along the input polarizer. Hence the maximum *T* or light utilization efficiency is 1.0. If the input is not polarized, the maximum *T* should become 0.5.

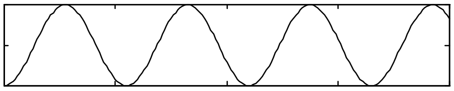

Fig. 3 Transmittance of the 0^o twist state (Top), of the 2p twist state (middle), and the contrast ratio (bottom).

It can be seen from Fig. 3 that high contrast can be obtained at dΔn of 0.15 μm, 0.55 μm, 1.17 μm, 1.2 μm, 1.62 μm and 1.86 μm. The corresponding transmittance of the bright state is about 0.6, 0.5, 0.33, 0.5, 0.86 and 1.0. Thus for high contrast and high throughput, the BTN cell should have a dΔn of 1.86 μm. However, that state is too dispersive as shall be seen in the next section. It is also possible to sacrifice the contrast and operate at dΔn = 0.25 μm where the peak transmittance is near 1.0 and the contrast is 20, which was actually the case in reference 1.

Fig. 4 shows the case for the -π/2 and 3π/2 bistable display. For this case, both parallel and cross polarizers are acceptable as well. Fig. 4 is calculated using $\phi = -90^o$, $\alpha = 45^o$ with cross polarizers. It can be seen that the best choice seems to be at dΔn of 0.75 μm where the contrast is high and the light efficiency is close to 100%. The dΔn value is also a convenient and similar to ordinary TN displays.

It should be mentioned here that besides BTN with $\phi = 0^o$ (0, 2π bistable), and $\phi = -90^o$ (-π/2, 3π/2 bistable), other values of φ are possible by rotating the polarizer angle. For example, at $\alpha = 25^o$, the parameter space for the BTN indicates good contrast can be obtained for $\phi = -142^o$ and 50^o. Of course, having good optical properties does not guarantee that the BTN can exist. Other considerations, such as the *d/p* ratio, have to be taken into account.

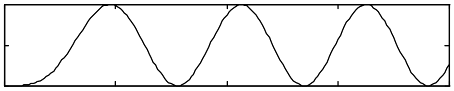

Fig. 4 Transmittance of the -90^o twist state (Top), of the 270^o twist state (middle), and the contrast ratio (bottom).

4. Switching Mechanisms

The switching mechanisms of the (0, 2π) and (-π/2, 3π/2) BTNs were studied by solving the dynamic equation for the LC director[5]. In this numerical approach, the Erickson-Leslie hydrodynamic equations were solved for φ between -π/2 and 0. It is verified that indeed, for specific values of *d/P*, bistability occurs.

Moreover, detailed numerical results show that switching between the bistable twist states can be accomplished with specially shaped electrical pulses. For the case of 0-2π bistability, a pulse that has sufficient amplitude to turn the LC homeotropic and falls “gently” to zero will favor the 0 twist state. If the pulse drops to zero abruptly, the 2π state will occur. This is due to a flow of the director at the mid-plane of the LC cell. The calculated transmittance of the BTN agrees well with the experimental results, which is shown in Fig. 5. In that figure, it can also be observed that the “optical bounce” phenomena is observed during

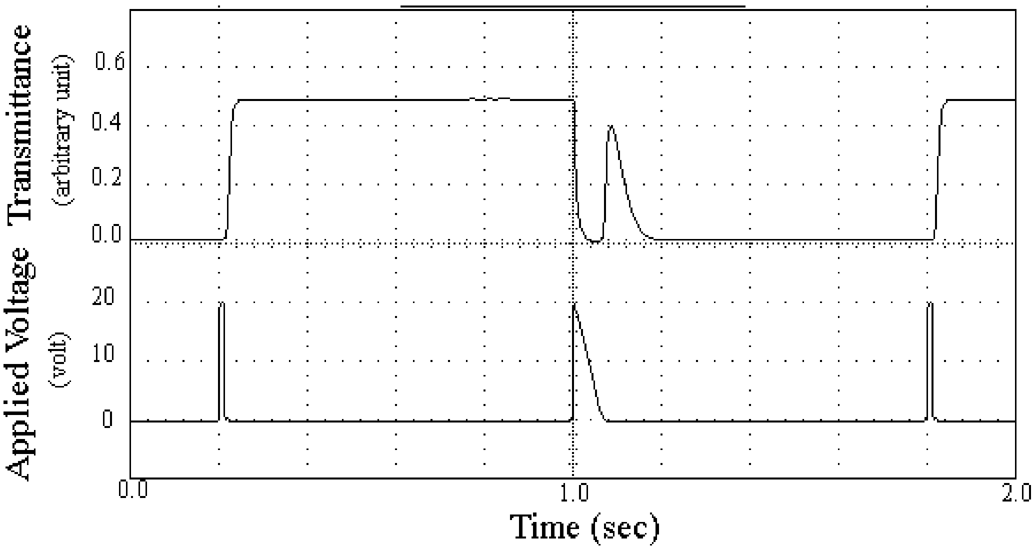

Fig. 5 Time dependence of the transmission of the BTN cell (upper curve) and the applied voltage pulse (lower curve).

the switching process. Such optical bounce is also predicted by the numerical calculation.

5. Conclusions

In summary, we showed that by using the parameter space approach, the optical properties of bistable nematic liquid crystal displays can be visualized and optimized. All the adjustable variables that affect the optical properties of the BTN can be taken into account.

We also calculated the other relevant properties of the BTN such as the peak light efficiency and the wavelength dispersion of the 2 bistable states. Optimal dΔn values were derived for several BTN modes.

The dynamics of the BTN was also modeled numerically. For the case of 0-2π BTN, the temporal behavior of the switching from one state ot the other can be satisfactorily predicted for triangular electrical pulses. It is shown that the bistability is due to backflow phenomena.

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