

High Performance Transmissive Bistable Twisted Nematic Liquid Displays

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Several new transmissive bistable twisted nematic liquid display (BTN-LCD) modes are developed. Unlike previous versions, these BTN modes do not require cross polarizers. Experiments confirmed that these modes have high contrast ratio and reasonably high transmittance. The dispersion characteristics of some of these modes are comparable to ordinary waveguiding TN modes. That is, they afford true black/white operations without any need for further color compensation.

KEYWORDS: Liquid crystal displays, bistability, twisted nematic

1. Introduction

Bistable twisted nematic (BTN) liquid crystal display (LCD) that can be switched between two metastable twist states were first discovered by Berreman and Heffner in 1981.¹⁾ A 0 to 2π bistable twist configuration was reported. Heuristically, this bistability is due to a mismatch in nematic liquid crystal natural pitch p and the LC cell alignment conditions for a given cell thickness d . This mismatch is deliberately increased to produce alignment bistability. It has been shown theoretically that bistability occurs for a particular range of d/p ratio.^{2,3)} Recently, many studies have been devoted to this BTN-LCD, including reflective mode BTN (RBTN).⁴⁾ Tanaka *et al.*⁵⁾ developed a passive-matrix BTN display that can be driven like an active matrix display.

In most of the reported BTN studies, the display switches between the 0 and 2π twist states. Xie *et al.*⁶⁾ present the BTN device switch between the $-\pi/2$ and $3\pi/2$ twist states and between the $\pi/2$ and $5\pi/2$ twist states. They also found that $(-\pi/2, 3\pi/2)$, $(\pi/2, 5\pi/2)$ and $(0, 2\pi)$ twist states exhausted all possibilities of transmissive BTNs when cross polarizers were used. However, such cross or parallel polarizer geometry may not be necessary in general. Recently, Tang *et al.* made use of the 4×4 Mueller matrix to derive many general transmissive and reflective BTN modes.⁷⁾ While that approach is elegant and is able to search for good optical modes, we shall show in this paper, that it is possible to search for these modes where the input/output polarizers are not necessarily perpendicular or parallel to each other by using the 2×2 Jones matrix. The good optical properties of these new BTNs are experimentally confirmed. It will be shown that these BTNs can be made quite easily in the laboratory.

The BTNs discussed in this paper are the twisted nematic type. There are several other kinds of bistable nematic displays that are different from the normal BTN discussed here. Dozov *et al.*⁸⁾ proposed a new fast BTN display using monostable surface-anchoring. Bryan-Brown *et al.*⁹⁾ presented a grating aligned BTN LCD that can be switched by sub-millisecond pulses. These displays operate on a different principle from the BTN reported in refs. 1–7. For the bistable twist states, their physics based on a backflow mechanism have been theoretically studied.^{2,3)}

In the following sections, we shall first discuss the general BTN mode using the 2D parameter space diagram approach.¹⁰⁾ Their optimization will then be described, followed by a presentation of the experimental verification. It is be-

lieved that these new BTN modes are much better than the traditional $(0, 2\pi)$ mode and should find applications in practical devices.

2. Optics of the BTN Display

2.1 On the range of LC parameters

The major LC cell parameters, which determine the optical properties of the display, are the input polarizer angle α , the output polarizer angle γ , the twist angle ϕ , the LC cell thickness d and the LC birefringence Δn . The latter 2 parameters always appear together as $d\Delta n/\lambda$ and therefore can be regarded as just one parameter. In this section, we shall discuss the range of these parameters for practical BTN displays.

Let us first consider the twist angle ϕ . In our discussions, we shall denote the 2 bistable twist angles as ϕ_1 and $\phi_2 = \phi_1 + 2\pi$. The BTN mode is therefore denoted by $(\phi_1, \phi_1 + 2\pi)$. Experimentally, it was found that it was very difficult to obtain bistable states when the twist angle was higher than 2π . A dynamical modeling also failed to model the $(\pi/2, 5\pi/2)$ BTN, though the case was obtained in experiment with very critical d/p ratio.^{2–4)} So we shall restrict ourselves to ϕ_1 values smaller than $\pi/2$.

Another reason to restrict ϕ_1 to smaller than $\pi/2$ is that for high twist states, it has been pointed out that an unwanted striped texture often appears.¹¹⁾ This has been studied thoroughly for the case of supertwisted nematic (STN) cells with high twist angles and is related to domain formation due to the high twist.¹²⁾ These striped textures will undoubtedly degrade display performance. From the two reasons given above, we shall limit our choice of twist angle being no more than $5\pi/2$ in any state, i.e. the $(\pi/2, 5\pi/2)$ mode. Naturally, it is much better if one state has a left-handed twist angle and another has a right-handed twist angle, so that both bistable twist states are of small angles, such as the $(-\pi/2, 3\pi/2)$ BTN.⁴⁾

The next parameter that should have a natural limit is the retardation $d\Delta n$. It is found that if $d\Delta n$ is larger than $1.1 \mu\text{m}$, the dispersion is large. This large dispersion is especially bad for the dark state since it affects the contrast ratio of the BTN LCD. Hence large $d\Delta n$ is not desirable. Additionally, if $d\Delta n$ is smaller than $0.2 \mu\text{m}$, although the dispersion is small, the cell thickness is also small and cannot be easily put into practice. Therefore, we shall restrict $d\Delta n$ to values between 0.2 and $1.1 \mu\text{m}$.

2.2 Jones matrix analysis

The optics of the twisted nematic layer can be described by using the 2×2 Jones matrix method.¹⁰⁾ In a recent paper, Tang *et al.* used the 4×4 Mueller matrix to describe the optics of

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the BTN display.⁷⁾ Many display modes can be obtained using that elegant approach, especially for the BTN where both stable states are of uniform twists. In this paper, however, we shall use the Jones matrix approach. This method is quite intuitive and physical. Using the Jones matrix, it is very easy to describe the optics of the two metastable twist states as both have a uniform twist angle and a small tilt angle. For such cases, defining the x -axis to the direction of the input director, the Jones matrix is given by,¹⁰⁾

$$M = \begin{pmatrix} A - iB & -C - iD \\ C - iD & A + iB \end{pmatrix} \quad (1)$$

where

$$A = \cos \phi \cos \chi + \frac{\phi}{\chi} \sin \phi \sin \chi \quad (2)$$

$$B = \frac{\delta}{\chi} \cos \phi \sin \chi \quad (3)$$

$$C = \sin \phi \cos \chi - \frac{\phi}{\chi} \cos \phi \sin \chi \quad (4)$$

$$D = \frac{\delta}{\chi} \sin \phi \sin \chi \quad (5)$$

and

$$\chi = (\delta^2 + \phi^2)^{1/2} \quad (6)$$

$$\delta = \pi d \Delta n / \lambda \quad (7)$$

$$\Delta n = n_e(\theta) - n_o \quad (8)$$

In these equations, n_o is ordinary index, $n_e(\theta)$ is extraordinary index at an average director tilt angle of θ and given by the usual expression

$$\frac{1}{n_e^2(\theta)} = \frac{\cos^2 \theta}{n_e^2} + \frac{\sin^2 \theta}{n_o^2}. \quad (9)$$

We shall assume θ to be zero in this paper.

In a simple transmittive LCD, a liquid crystal cell is placed between two polarizers. The input and output polarizer axes are at an angle of α and γ to the input director of the liquid crystal cell, respectively. The transmittance of this optical arrangement is given by

$$T(\alpha, \gamma, \phi, \delta) = \left| (\cos \gamma \sin \gamma) \cdot M \cdot \begin{pmatrix} \cos \alpha \\ \sin \alpha \end{pmatrix} \right|^2. \quad (10)$$

It is straight-forward to show that eq. (10) gives

$$T(\alpha, \gamma, \phi, \delta) = \left[\cos \chi \cos(\phi + \alpha - \gamma) + \frac{\phi}{\chi} \sin \chi \sin(\phi + \alpha - \gamma) \right]^2 + \frac{\delta^2}{\chi^2} \sin^2 \chi \cos^2(\phi - \alpha - \gamma). \quad (11)$$

We can denote the 2 bistable twist angles to be ϕ_1 and ϕ_2 . In the first case, we shall assume that ϕ_1 is the dark state and ϕ_2 is the bright state with

$$\phi_2 = \phi_1 + 2\pi. \quad (12)$$

In order to obtain the best display optical performance, the conditions of $T(\alpha, \gamma, \phi_1, \delta) = 0$ and $T(\alpha, \gamma, \phi_2, \delta) = 1$ are required. This will guarantee a high contrast ratio and a high

transmittance in the bright state.

2.2.1 Case 1

It can easily be seen that $T(\alpha, \gamma, \phi_1, \delta) = 0$ if

$$\chi_1 = N\pi \quad N = 0, 1, 2, \dots \quad (13)$$

$$\phi_1 + \alpha - \gamma = \frac{\pi}{2} \pmod{\pi}. \quad (14)$$

Equation (13) is known as integral waveplate condition.¹³⁾ When the liquid crystal layer fits this condition, it can be treated as a polarization rotator with a rotation angle of ϕ_1 .

Using eqs. (12) and (14), the transmittance of the ϕ_2 state can be written as

$$T(\alpha, \gamma, \phi_2, \delta) = \sin^2 \chi_2 \left(1 - \frac{\delta^2}{\chi_2^2} \cos^2 2\alpha \right). \quad (15)$$

It can be shown that $T(\alpha, \gamma, \phi_2, \delta) = 1$ when the following two conditions are met

$$\chi_2 = N\pi + \frac{\pi}{2} \quad (16)$$

$$\alpha = N\pi \pm \frac{\pi}{4}. \quad (17)$$

From eq. (17), we can use the value $\alpha = \pi/4$. It can be verified that the $-\pi/4$ value of α does not yield additional new results. The values of $\alpha, \gamma, \phi_1, \phi_2, d\Delta n$ can then be obtained by solving eqs. (12), (13), (14) and (16). Table I shows five results of these BTN where $d\Delta n$ is smaller than $1.6 \mu\text{m}$ for $\lambda = 550 \text{ nm}$. They will be referred to as the Case 1 first mode, second mode etc. These results are essentially the same as reported by Tang *et al.* except that they were derived using the 2×2 matrix. This is to be expected since the 4×4 matrix is derived from the 2×2 matrix in the first place.

2.2.2 Case 2

For every solution given in Table I, there is a corresponding solution which can be obtained by reversing the dark and bright states, and rotating γ by $\pi/2$. Thus instead of eq. (14), we have the condition

$$\phi_1 + \alpha - \gamma = 0 \pmod{\pi}. \quad (18)$$

These solutions can be called Case 2 solutions. Hence the ϕ_1 state will correspond to the bright state. They are quite different from Case 1 solutions in that the dark and bright states are reversed and the dispersion properties are different. Fig. 1 illustrates the relationship between Case 1 and Case 2 solutions. In that Figure, we plot the transmission spectra of the bright and dark-states of the third mode in Table I. It can be seen that for the Case 1 solution, the bright-state is slightly dispersive while the dark-state is quite non-dispersive. The Case 2 solution is just the reverse of the Case 1 solution. The bright-state is non-dispersive and the dark-state is slightly dispersive.

Table I. Five conditions for good display performance for $\lambda = 550 \text{ nm}$ and $\alpha = \pi/4$. For such Case 1 solutions, ϕ_1 corresponds to the dark state.

No.	γ	ϕ_1	ϕ_2	$d\Delta n$
1	$\pi/16$	$-11\pi/16$	$21\pi/16$	0.3994
2	$\pi/16$	$5\pi/16$	$27\pi/16$	0.5225
3	$13\pi/16$	$-31\pi/16$	$\pi/16$	0.2728
4	$\pi/16$	$-23\pi/16$	$9\pi/16$	0.7648
5	$5\pi/16$	$-7\pi/16$	$25\pi/16$	1.0734

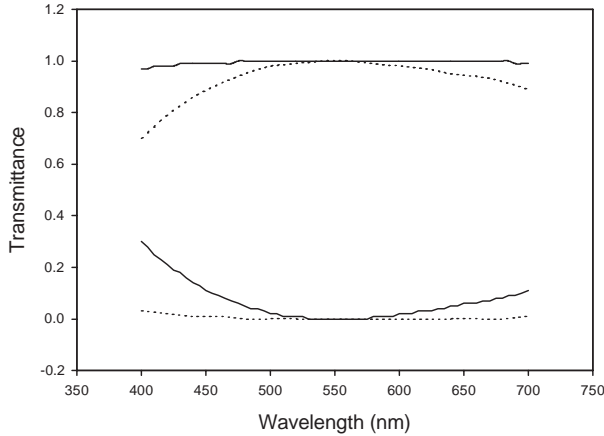


Fig. 1. Transmittance spectra of the Case 1 mode and the Case 2 mode. Values in the number 3 mode in Table I are used.

2.3 Comparison with previous BTN modes

In this section, we shall compare the optical properties of the new modes found in this paper and those published previously. First, it should be mentioned that the modes found in this paper are the same as those of Tang *et al.*,⁷⁾ which were obtained using the Mueller matrix approach. So the comparison will mainly be with earlier publications.

Reviewing the literature, most of the BTNs have bistable 0 and 2π twists. This $(0, 2\pi)$ mode was used in the original Berreman paper,¹⁾ as well as the Tanaka paper.⁵⁾ We shall refer to this as the Tanaka mode, with $(\alpha, \phi, \phi + 2\pi, d\Delta n) = (45^\circ, 0, 2\pi, 0.275 \mu\text{m})$. There is another $(0, 2\pi)$ mode obtained by Xie *et al.*⁶⁾ That mode was optimized in terms of maximizing the contrast using the 2D parameter space. Its $(\alpha, \phi, \phi + 2\pi, d\Delta n)$ values are $(0, 0, 2\pi, 0.78 \mu\text{m})$ respectively. This combination will be called the Xie mode. Examining Table I, it is seen that the closest mode that is nearest to this $(0, 2\pi)$ mode is the third mode of $(\pi/16, -31\pi/16)$. This mode can also be referred to as the $(-\pi/16, 31\pi/16)$ mode by inverting the signs of all angles. This way, it looks more like the $(0, 2\pi)$ mode. We shall refer to this as the Guo mode. So we shall compare this Guo mode with the Xie mode and the Tanaka mode since they all have similar bistable twist angles.

Figure 2 shows the transmission spectra of the bright and dark-states of the Tanaka mode, the Xie mode and the Guo mode respectively. The parameters for the calculation are summarized in Table II. It can be seen that the Xie mode is bad in the bright state transmittance, but excellent in the dark-state transmittance. As a matter of fact, the dark-state is identically zero, independent of wavelength. This can be useful in some applications where the contrast is important. The bright-state transmittance of the Tanaka mode and the Guo mode are very close to each other. However the dark-state transmittance of the Guo mode is significantly better than that of the Tanaka mode. All in all, it is seen that the Guo mode represents a considerable improvement in the optical properties of the BTN. Note that this $(-\pi/16, 31\pi/16)$ Guo mode is only one of many modes discovered using the new optimization scheme in this paper and that in Tang's paper.⁷⁾

Another BTN mode discussed in the literature is the $(-\pi/2, 3\pi/2)$ twist mode presented by Xie *et al.*⁶⁾ Again, that mode was optimized for maximum contrast, and the

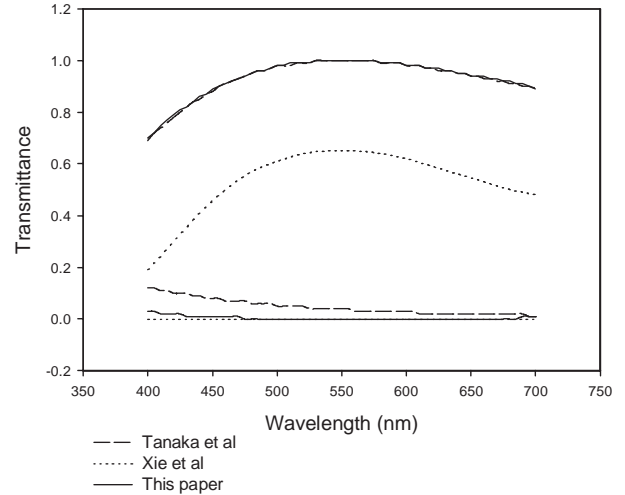


Fig. 2. Transmittance spectra of the Tanaka mode, the Xie mode and the Guo mode (this paper), with similar bistable twist angles. Note that the bright state transmittance of the Tanaka mode and the Guo mode are almost identical.

Table II. Parameters used in calculating the transmittance spectra in Fig. 2.

	α	γ	ϕ_1	ϕ_2	$d\Delta n$ (μm)
Tanaka <i>et al.</i>	45°	-45°	0	2π	0.275
Xie <i>et al.</i>	0	90°	0	2π	0.78
This paper	-45°	$11\pi/16$	$-\pi/16$	$31\pi/16$	0.2728

peak transmittance was not considered. Its optical properties, therefore, will not be as good as those obtained here. From Table I, it can be seen that the fourth $(-9\pi/2, 23\pi/16)$ mode and the fifth $(-7\pi/16, 25\pi/16)$ mode are very close in the values of the bistable twist angles, and can be treated as optimization of the $(-\pi/2, 3\pi/2)$ mode. To reiterate, a major difference between the optimization in Xie's paper and the present paper is that in Xie's case, the contrast is optimized. In here the overall transmittance of both the bright and dark states are used for optimization.

2.4 Simulation results for real devices

While Table I in the above section gives all the operating parameters for a perfect BTN with $T = 1$ for one twist state and $T = 0$ for the other twist state, it is only perfect for one wavelength. In this section, we shall perform simulation with white light illumination taken into account. Moreover, in order to make the simulation more realistic, we shall also apply the actual commercial LC and polarizer parameters. That is, the dispersion, the absorption properties of the LC as well as the polarizers are taken into account. Achem AG1-105NT type polarizers and Merck MLC5300-5400 LC are used here. A 4×4 matrix is used in this simulation calculations.¹⁴⁾

For each twist angle ϕ , we calculate the transmittance of the on and off-states, with γ given by either eq. (14) or (18). α is always 45° . And $d\Delta n$ is allowed to vary freely. The white light transmittance is given by

$$T = \int_{400}^{700} T(\alpha, \gamma, \phi, \delta) f(\lambda) d\lambda \quad (19)$$

where $f(\lambda)$ is the photopic response of the eye. The contrast ratio is then calculated as the ratio $T(\phi_2)/T(\phi_1)$ for Case 1

modes and $T(\phi_1)/T(\phi_2)$ for Case 2 modes.

For each set of values $(\phi_1, d\Delta n)$, the transmittance of the on state and the contrast is computed. Thus a 2D parameter space can be plotted with the contour lines drawn for constant transmittance and constant contrast. These results are shown in Figs. 3 and 4. Figure 3 is for the Case 1 mode solutions while Fig. 4 is for the Case 2 mode solutions. The difference is in the values of γ . These parameter spaces are similar to those in reference 4, with the main difference being that in all previous PS, α and γ are fixed. In here, α is fixed while γ changes as ϕ_1 changes. From Figs. 3 and 4, it can be seen that there are islands of good contrast, similar to the case in reference 6. The peak transmittance is only 33%, which is due to absorption of the polarizers and due to the photopic

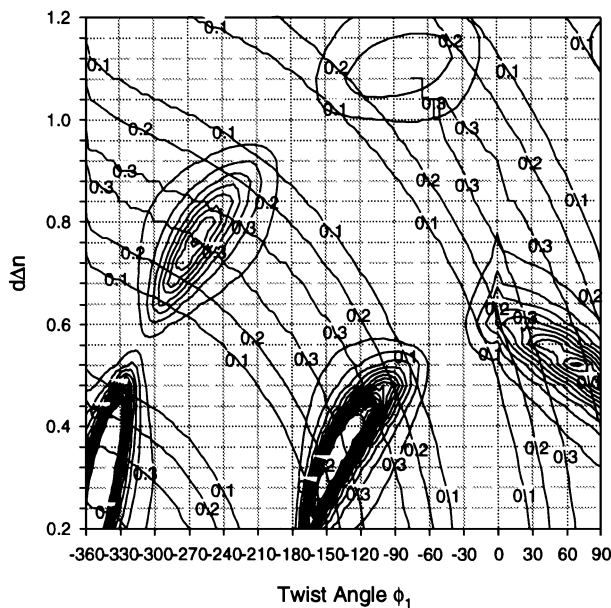


Fig. 3. Contrast and transmittance parameter space for BTN with ϕ_1 and $d\Delta n$ as the independent parameters. $\alpha = \pi/4$ and $\gamma = \phi_1 + \alpha - \pi/2$. Constant transmittance contours of the bright state are labeled. The other curves are contours of constant contrast ratio, with each contour line representing an increase of two in contrast.

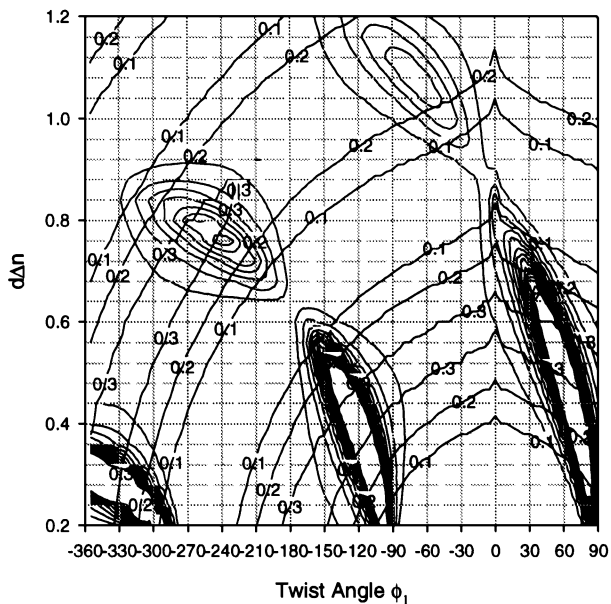


Fig. 4. Same as Fig. 1 but with $\gamma = \phi_1 + \alpha$.

response of the eye. It is comforting to see that the maximum contrast regions also corresponds to maximum brightness.

Besides the parameter space, it is also possible to compute the dependence of $d\Delta n$ and contrast ratio as functions of the twist angle ϕ_1 for the best BTN modes. In this calculation, we fix α to be $\pi/4$ as before, and let γ be given either by eq. (14) or (18) as a function of ϕ_1 . Again, they correspond to the Case 1 and Case 2 solutions. The value of $d\Delta n$ is then determined by letting $T = 0$ at $\lambda = 550$ nm. This can be obtained by solving eq. (13). These $(\alpha, \gamma, \phi_1, d\Delta n)$ values are then used to calculate the on and off state transmissions using wavelength averaging in eq. (19). These transmittances are then used to calculate the white light contrast. The resultant curves are shown in Figs. 5 and 6 respectively. In principle, the on-state transmittance can also be plotted together. But it will make the Figures too crowded. The curves in Figs. 5 and 6 are easier to visualize than the contour maps in Figs. 3 and 4 in identifying the best operating conditions. It can be

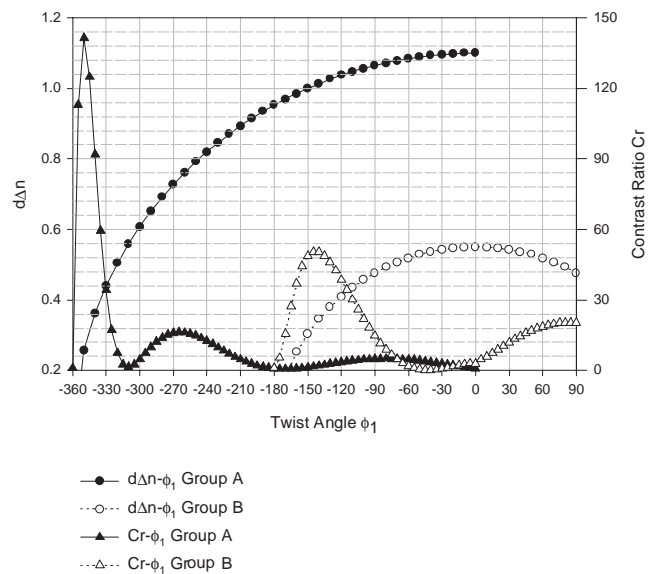


Fig. 5. Dependence of contrast and $d\Delta n$ on ϕ_1 for Case 1 modes.

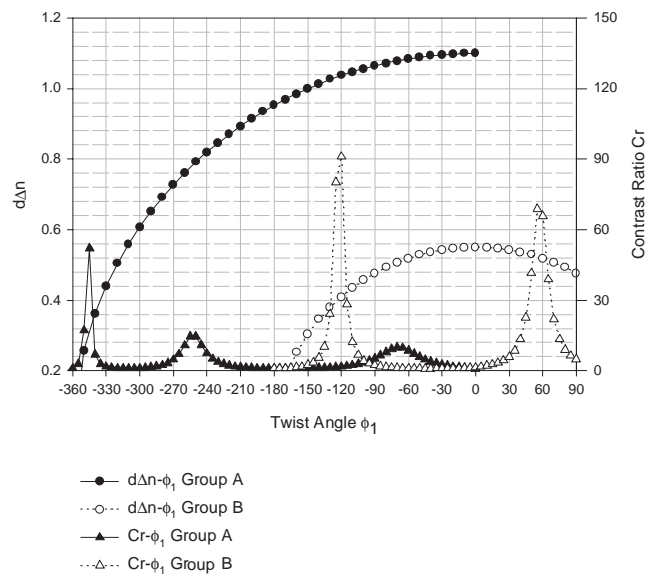


Fig. 6. Dependence of contrast and $d\Delta n$ on ϕ_1 for Case 2 modes.

seen that in Fig. 5, all points except the 5th one in Table I present a contrast ratio more than 15 : 1. In Fig. 6, the contrast ratios are generally larger than those in Fig. 5.

From the above results, it is concluded that high quality BTN-LCD with high contrast ratio and high transmittance should be possible. The contrast ratio can be larger than 50 : 1 with white light illumination. Even taking into account dispersion and polarizer absorption, the transmittance of the bright state can reach more than 0.33, which is very good, considering that the transmittance is 0.33 for two parallel polarizers (AG1-105NT). We did not pick a particularly good polarizer in our simulation.

The following observations can be made about the simulation results:

1. For normal use, the 4th mode is a good choice. Its twist angle ϕ_1 range is from -270° to -240° , $d\Delta n$ is about $0.8 \mu\text{m}$ and the contrast ratio is more than 12 : 1. It is also easily made.
2. For higher contrast ratios, the 1st and 3rd modes can be selected, though they have a slightly smaller $d\Delta n$.
3. The 1st and 4th modes have bistable twist angles that are nearest to $-\pi$ or π .
4. Due to small contrast ratio, the 5th mode is not fit for display.

From the Figures, we find that the operating conditions of the BTN are not very sensitive to the twist angle and $d\Delta n$. For example, if we want a transmittance of bright state bigger than 0.3 and a contrast ratio bigger than 30 : 1 in 1st point 2nd mode case, the twist angle can be permitted to change by $\sim 10^\circ$, and $d\Delta n$ can be permitted to change by $\sim 0.04 \mu\text{m}$.

It should be noted that the results in Figs. 3–6 also include the case of cross polarizers as discussed in ref. 6. In Figs. 3 and 5, (α, γ) will correspond to cross polarizers if $\phi_1 = -2\pi$, $-\pi$, or 0. In Figs. 4 and 6, cross polarizers cases are achieved for $\phi_1 = -3\pi/2$, $-\pi/2$, or $\pi/2$.

3. Experimental Results and Discussions

We made some BTN samples to confirm our simulated results. We made several LC cells according to the design parameters given in Table I. In particular, we fabricated cells with $\phi_1 = -260^\circ$, $d\Delta n = 0.76 \mu\text{m}$ (the 4th mode in Table I), $\phi_1 = -120^\circ$, $d\Delta n = 0.40 \mu\text{m}$ (the 1st mode) and $\phi_1 = 60^\circ$, $d\Delta n = 0.54 \mu\text{m}$ (the 2nd mode).

The LC cells were made using conventional procedure. Commercial LC (MLC5300-5400 mixture and ZLI-6295) were used to produce the necessary $d\Delta n$. They were doped with an appropriate amount of chiral additive (S-811) to produce the appropriate pitch. Bistable states were achieved by adjusting carefully the d/p ratio. Obviously, a lot of samples had to be made.

The driving waveform is similar to previous studies.⁶⁾ The pulse train 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. Figure 7 shows the timing diagram of a typical BTN LCD. In general, bistability can be obtained for all the three cells studied. We measured the transmittance spectral characteristics of these devices. The bistable driving conditions for each of them are presented in Table III. In that Table, V_r is the reset voltage pulse, V_s is select voltage pulse, T_r is the duration of the reset voltage and T_s is the duration of the select voltage applied to device. T

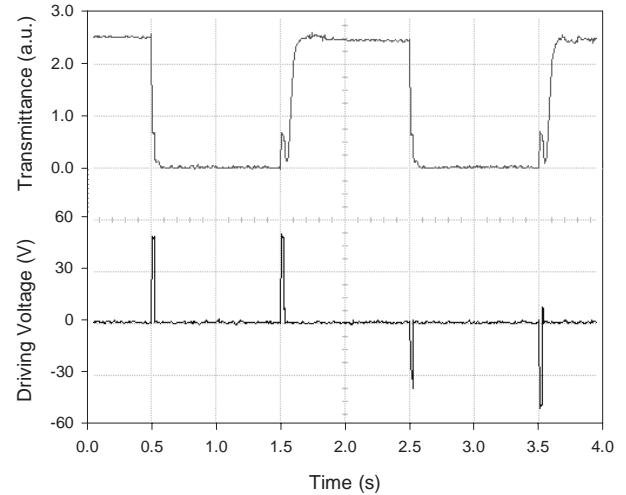


Fig. 7. The transmittance at 543.5 nm of the $\phi_1 = -120^\circ$ Case 2 mode BTN-LCD (upper curve) and the applied voltage pulses (lower curve) as a function of time.

Table III. Bistable driving conditions for some of the modes in Table I.

ϕ_1	V_r (V)	T_r (ms)	V_s (V)	T_s (ms)	T (s)
-260°	20	16	4	8	2.5
-120°	42	12	10.5	6	3.3
60°	22	20	5.5	10	2.0

Table IV. Summary of measured spectral characteristics for some of the new BTN modes.

ϕ_1	Case	T_r	C_r
-260°	1	17%	11 : 1
-260°	2	16%	4 : 1
-120°	1	22%	11 : 1
-120°	2	19%	57 : 1
60°	1	20%	7 : 1
60°	2	14%	13 : 1

is the display period from one dark (or bright) state to next dark (or bright) state. No attempt was made to minimize the selection pulse durations or the voltages, as the emphasis here is to examine the optical properties of these BTN modes.

The spectral characteristics of the three devices are shown in Table IV. The same LC cell can be operated either as Case 1 or Case 2 modes. Hence there are 6 possibilities in Table IV. All the results were measured with a tungsten halogen light source. T_r is the transmittance and C_r is the contrast ratio. It can be seen that reasonably good results can be obtained. In particular, the -120° mode (the first mode) shows the best transmittance and contrasts. It should be emphasized again that the maximum transmittance is 0.33 due to polarizer absorption. So the peak transmittance of 0.22 implies actually a transmittance of 66% for the LC alone.

As shown in Figs. 3–6, the contrast ratios of the $\phi_1 = -260^\circ$ Case 1 mode, the $\phi_1 = -120^\circ$ Case 2 mode and the $\phi_1 = 60^\circ$ Case 2 mode are larger than those of other modes. The contrast ratio of the $\phi_1 = -120^\circ$ mode can almost reach 60 : 1. This mode is examined in more details. Figure 7 shows the time-dependent transmittance curve and voltage pulse for the Case 2 $\phi_1 = -120^\circ$ BTN-LCD. The period

of the driving wave pulse is two seconds. The reset pulse is 42 V. The -120° state, corresponding to bright state, can be obtained by using a proper selection pulse and the 240° state, corresponding to dark state, can be obtained by turning the reset voltage abruptly to zero (zero select voltage). Figure 8 shows the measured spectral performance for this device in a normally white arrangement.

From the experimental result, we notice that the contrast ratio of the Case 1 mode is smaller than that of the Case 2 mode. Also the bright state transmittance of the Case 1 mode is larger than that of the Case 2 mode. These results are identical to that presented in Figs. 3–6. The contrast ratio of the Case 2 mode is approximately 60 : 1, which fits the simulation result very well. However, the bright state transmittance is only 20%, which is smaller than that given by the simulation (nearly 30%). We believe that one reason is that the polarizer used in the experiment has a high absorption. The transmittance of a pair of parallel polarizers is only 30%. Another reason is that the value of $d\Delta n$ may be slightly different from the desired value of $0.4 \mu\text{m}$.

We also compared the transmittance spectrum of this BTN with that of a normally white TN-LCD with the same kind of polarizers. It is well known that normal TN-LCD has high measured transmittance and low dispersion due to its waveguiding properties. The results are shown in Fig. 8 as well. It can be seen that the bright state transmittance of the Case 1 mode is almost the same as that of TN LCD. This proves that the BTN-LCD has high transmittive performance and the transmittance can be increase with high transmittive polarizers. It also means that this type of BTN-LCD has white-black display performance.

Figure 9 shows some photographs of the BTN-LCD as compared to the normally white TN-LCD. A piece of white paper written ‘TN’ and ‘BTN’ written on it was placed below the devices. A white light source was used as the illumination. The words could be seen clearly when the devices were in the high transmittance bright state, and they could not be seen in the dark state. The color of the bright state of the Case 1 mode is the same as the TN-LCD, and that of the Case 2 mode is also close to the TN display. The colors of BTN in

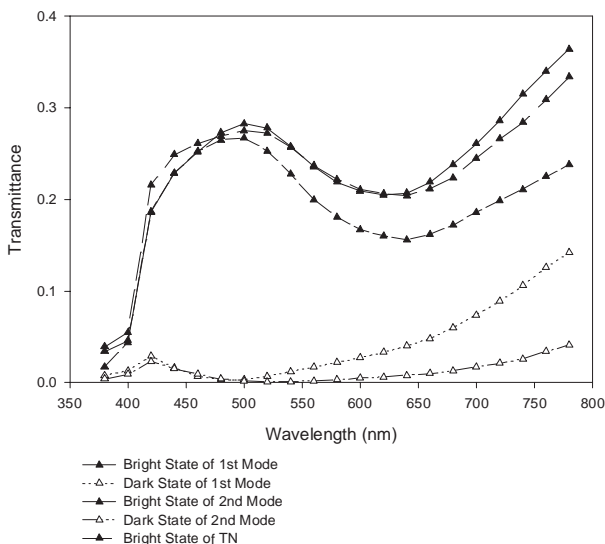
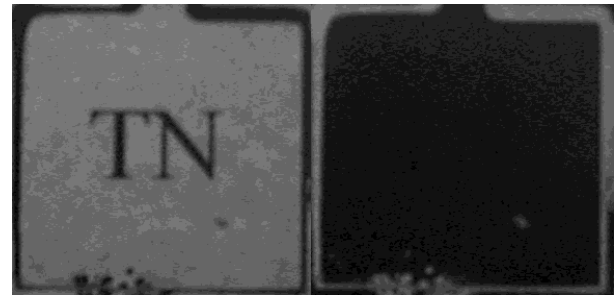
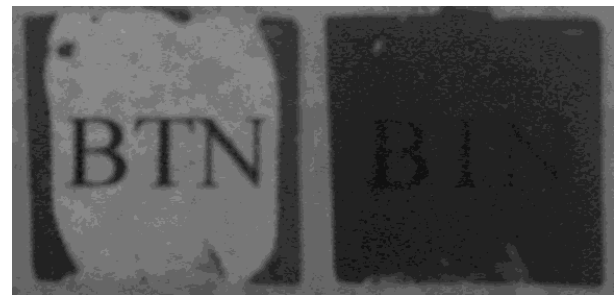


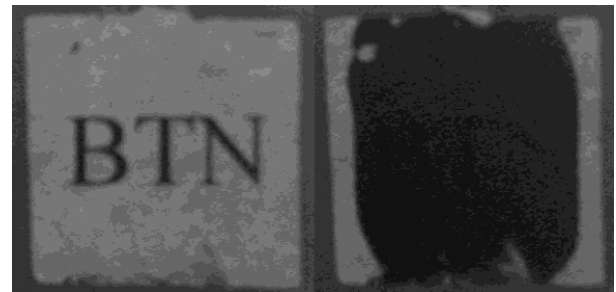
Fig. 8. Transmittance spectra of the $\phi_1 = -120^\circ$ BTN-LCD and a 90° TN-LCD.



(a)



(b)



(c)

Fig. 9. Images of the bright states (left) and dark states (right) for (a) conventional TN, (b) BTN with $\phi_1 = -120^\circ$ Case 1 mode, and (c) BTN with $\phi_1 = -120^\circ$ Case 2 mode.

dark states are also close to the TN display. The devices of $\phi_1 = -260^\circ$ and $\phi_1 = 60^\circ$ also show good performance. The case of $\phi_1 = -260^\circ$ can be made easily and its 11 : 1 contrast ratio is suitable for normal use. Its contrast ratio and transmittance can be increased if the polarizers and $d\Delta n$ are chosen carefully. The case of $\phi_1 = 60^\circ$ can be made to have similar performance as the $\phi_1 = -120^\circ$ case. From the point of stability, we would like to use $\phi_1 = -120^\circ$ instead of $\phi_1 = 60^\circ$. Also the 3rd mode in Table I should have very good performance, though it is not easy to make because of its small $d\Delta n$.

4. Conclusions

In this paper, we have presented several new BTN-LCD modes with non-crossed polarizers using the 2×2 matrix. The results are similar to those obtained using the more com-

plicated 4×4 matrix. Most of these BTN modes present high contrast ratio and high transmittance. Some of these displays actually have optical performances that are as good as the TN-LCD in terms of color non-dispersion. They can also be made easily with non-critical cell thickness.

We have experimentally demonstrated a few of these modes and found that they indeed performed as expected. A measured white light contrast of nearly 60 : 1 is possible in the best case. Most of the other cases have white light contrasts of over 10 : 1.

BTN can be driven in a passive matrix without cross talks. Additionally, they have very good viewing angles because of their in-plane switching properties. They are useful in many applications where grayscales are not needed.

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- 1) D. W. Berreman and W. R. Heffner: *J. Appl. Phys.* **52** (1981) 3032.
- 2) T. Z. Qian, Z. L. Xie, H. S. Kwok and P. Sheng: *Appl. Phys. Lett.* **71** (1997) 596.
- 3) J. C. Kim, G.-J. Choi, Y.-S. Kim, K. H. Kang, T.-H. Yoon and K. G. Nam: *Symp. Dig. SID* (1997) p. 33.
- 4) Z. L. Xie and H. S. Kwok: *Jpn. J. Appl. Phys.* **37** (1998) 2572.
- 5) T. Tanaka, Y. Sato, A. Inoue, Y. Momose, H. Noruma and S. Lino: *Proc. 15th IDRC (Asia Display'95) Hamamatsu, 1995*, p. 259.
- 6) Z. L. Xie and H. S. Kwok: *J. Appl. Phys.* **84** (1998) 77.
- 7) S. T. Tang, H. W. Chiu and H. S. Kwok: to be published in *J. Appl. Phys.*
- 8) I. Dozov, M. Nobili and G. Durand: *Appl. Phys. Lett.* **70** (1997) 1179.
- 9) G. P. Bryan-Brown, C. V. Brown and J. C. Jones: *Patent GB 9521106.6* (Oct 1995).
- 10) H. S. Kwok: *J. Appl. Phys.* **80** (1996) 3687.
- 11) P. J. Kedney and F. M. Leslie: *Liq. Cryst.* **24** (1998) 613.
- 12) V. G. Chigrinov, V. V. Belyaev, S. V. Belaev and M. F. Grebenkin: *Sov. Phys. JETP* **50** (1979) 994.
- 13) E. P. Raynes: *Mol. Cryst. Liq. Cryst. Lett.* **4** (1987) 69.
- 14) D. W. Berreman: *J. Opt. Soc. Am.* **63** (1973) 1374.