Optimization of reflective bistable twisted nematic liquid crystal displays

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The contrast ratio of reflective bistable twisted nematic displays are optimized by means of a parameter space approach. By plotting the contrast ratio as a function of the twist angle and thickness-birefringence product of the display, the regions where the display shows the best contrast ratio are clearly shown. Both the absolute reflectance and wavelength dispersion of two bistable twisted states are investigated. It is confirmed that high contrast ratio of over 100 and reflectance of 100% with polarized light input are possible for such reflectance bistable displays. © *1999 American Institute of Physics.* [S0021-8979(99)04317-0]

I. INTRODUCTION

Bistable twisted nematic (BTN) liquid crystal display (LCD) that can be switched between two metastable twisted states was discovered by Berreman[1] and Heffner in 1981. Recently, Tanaka *et al.*[2] successfully made use of this bistability to develop a bistable LCD with black and white video graph array (VGA) image. This display can be passive matrix driven, and it has a wide viewing angle characteristic. Therefore, there have been many studies on improving this transmittive BTN LCD.[3–10] Very recently, a reflective BTN LCD where the field-off state can exhibit bistability has been developed.[11,12] The structure of the reflective BTN consists simply of a front polarizer, a LC cell and a rear reflector. Like the reflective twist nematic (TN) and super twist nematic (STN) reported recently,[13–16] the reflective BTN has many advantages, such as eliminating one of the polarizers, increasing brightness and simplifying manufacture. Because the rear reflector can also be incorporated as part of the LC cell, any viewing parallax can be eliminated for the reflective BTN to bring about a higher resolution.

Since no holding voltage is needed to display images, LC alignment of the reflective BTN can take on either of two twisted states at 0 V, due to a proper choice of the rubbing directions of the alignment layers and the d/p ratio. 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 $\phi+2\pi$ are equally stable (or metastable). Hence, for bistability to occur, the d/p ratio of the LC cell should be $\sim(0.5+\phi/2\pi)$, where d and p are the thickness and pitch of LC cell, respectively. In actual practice however, the d/p ratio is always somewhat larger than that by simple argument presented here.[4] Because of its bistable nature, the reflective BTN can be passive matrix driven without a multiplex level limit in principle.

Several studies have been devoted to such reflective BTN modes. Xie and Kwok[11] developed a reflective BTN LCD that can be switched between $-36°$ and 324° twisted states by adjusting the voltage magnitude of a selection pulse. The effects of the d/p, selection time and reset time on the voltage magnitude are investigated. Kim, Yu, and Lee[12] studied the electro-optic (EO) characteristics of a reflective BTN cell as a function of the reset, selection, and data signals in the driving scheme. So far the optical properties of reflective BTNs have not been thoroughly investigated.

It is the purpose of this article to examine the optics of reflective BTNs for general values of twist angle and polarizer angle. The contrast ratio of various configurations will be studied systematically for the entire parameter space[17] of such reflective BTNs. The peak reflectance and wavelength dispersion of the reflective BTN modes will be investigated. The optimal operation conditions will be reported for various types of reflective BTN.

II. PARAMETER SPACE FOR REFLECTIVE BTN

The starting point for our analysis of the reflective BTN is the Jones matrix of the LC cell. The basic idea is that since both bistable twisted states operate at $V=0$, the static parameter space is ideal in analyzing its optical properties. The reflectance of any twisted nematic display is a unique function of the polarizer angle α, the LC twist angle ϕ, and the thickness-birefringence product $d\Delta n$.[10] With any one parameter fixed, the reflectance of the LC cell can be plotted as a function of the remaining two parameters in two-dimensional (2D) contour map. When α is fixed, the contrast ratio for any value of ϕ and $d\Delta n$ can be obtained by calculating the ratio between the reflectance (R) of two twisted states. The contrast ratio (CR) is defined as $CR(\phi)=R(\phi)/R(\phi+2\pi)$ or $R(\phi+2\pi)/R(\phi)$ depending on whichever ratio is larger. In our calculation, the input light wavelength $\lambda=550$ nm and

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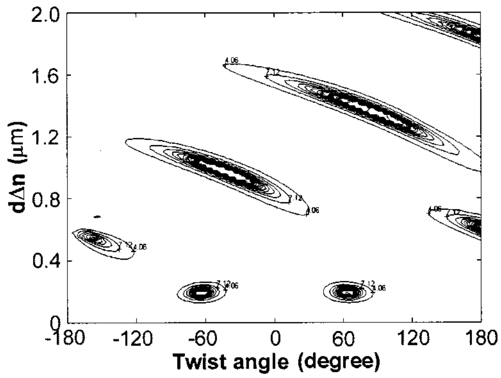

FIG. 1. Contrast ratio of the reflective BTN as a function of $d\Delta n$ and ϕ for α=0°. Each contrast contour line represents an increase in 3.

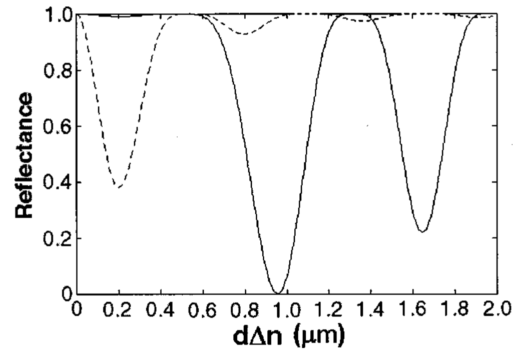

FIG. 3. Reflectance of the −36° twist state (dashed) and the 324° twist state (real line) as a function of $d\Delta n$ for α=0°.

the pretilt angle θ=0°. It was shown previously that a (ϕ, $d\Delta n$) parameter space for fixed α was very useful in analyzing transmittive BTN displays.[18]

Figure 1 shows a contour map of the contrast ratio as a function of $d\Delta n$ and ϕ for the case of α=0°. The contour lines are shown in steps of 3. Clearly, the high contrast ratio can be obtained in many island regions. Compared with transmittive BTN displays, the high contrast regions 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, because one of the reflectance approaches zero and thus the contrast ratio can change drastically. Several good candidates can be determined at the points of 63°, 0.18 μm, −63°, 0.18 μm, 36°, 0.94 μm, etc., in the (ϕ, $d\Delta n$) parameter space.

Figure 2 shows a similar situation for the case of α=45°. Obviously, the good contrast points locate at 0°, 0.14 μm, 0°, 0.40 μm, etc. The higher the $d\Delta n$ value, the wider in ϕ the good contrast region becomes. Every high contrast region is also sensitive to changes in $d\Delta n$. Comparing between Figs. 1 and 2, it is found that all peak tops will move into the line of ϕ=0° when the polarizer angle changes from 0° to 45°.

III. BRIGHTNESS/EFFICIENCY OF THE REFLECTIVE BTN MODES

The contrast ratio is only one of the criteria for a good reflective BTN display. The other measures of a good display are the peak reflectance of its bright state, and the color dispersion of its dark state and its bright state. To examine the details of the specific reflective modes, it is better to plot the reflectance of two bistable states together. These results are shown in Figs. 3–6. In calculating these curves, a simple solution of the complicated Jones matrix is possible. Figure 3 shows the results for the case used by us,[11] namely, α=45° with ϕ=−36° and ϕ=324°, respectively. Here, the reflectance $R(-36°)$ and $R(324°)$ are plotted as a function of $d\Delta n$. Notice that in Figs. 3–6 the input light is assumed to be polarized linearly along the input polarizer. Hence the maximum reflectance or light utilization efficiency is 1.0. If the input light is not polarized, the maximum reflectance should become 0.5. In Fig. 3, the 98% reflectance of the bright state and zero reflectance of the dark state appear at $d\Delta n = 0.94\,\mu$m, thus the high contrast ratio and high brightness of the reflective BTN can be obtained. However, the dark state has great color dispersion as will be shown in the next section.

Figure 4 shows the $\phi=-63°$ and $\phi=297°$ cases for $\alpha=0°$. Apparently, both points of $d\Delta n = 0.18\,\mu$m and $d\Delta n = 1.04\,\mu$m are good choices. The latter has higher light efficiency than the former in bright state, while the former is

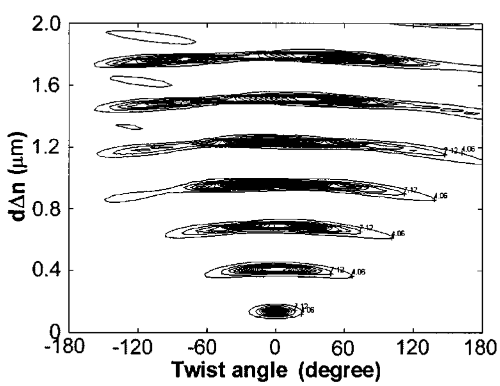

FIG. 2. Contrast ratio of the reflective BTN as a function of $d\Delta n$ and ϕ for α=45°. Each contrast contour line represents an increase in 3.

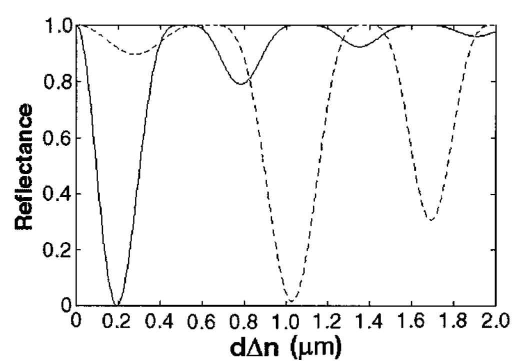

FIG. 4. Reflectance of the −63° twist state (real line) and the 297° twist state (dashed) as a function of $d\Delta n$ for α=0°.

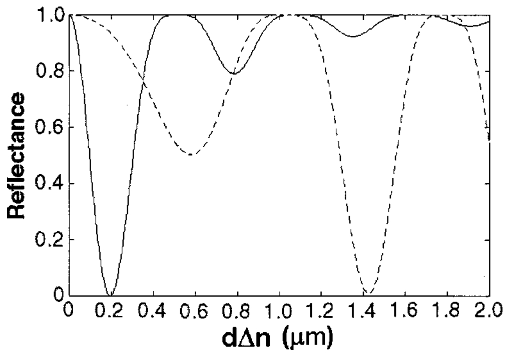

FIG. 5. Reflectance of the 63° twist state (real line) and the 423° twist state (dashed) as a function of $d\Delta n$ for $\alpha=0°$.

better in dark state and contrast ratio. Considering color dispersion, as will be shown in the next section, possibly the better choice is the point of $d\Delta n=0.18\ \mu$m.

Figure 5 shows the light efficiency of the $\phi=63°$ and $\phi=423°$ twisted states for $\alpha=0°$. It can be seen that the good points are $d\Delta n=0.18$ and 1.42 μm in terms of contrast ratio and brightness. Considering color dispersion, the point of $d\Delta n=0.18\ \mu$m is a better one.

Figure 6 shows the $\phi=0°$ and $\phi=360°$ cases for $\alpha=45°$. Evidently, high contrast can be obtained at $d\Delta n$ of 0.14, 0.40, 0.68, 0.96, 1.24, 1.52, and 1.80 μm because their dark states have zero reflectance. The corresponding reflectance of their bright states is about 1.0, 0.94, 0.82, 0.70, 0.98, 0.88, and 0.44. Thus for high contrast and high light efficiency, the BTN cell should have a $d\Delta n$ of 0.14, 0.40, and 1.24 μm. However, the state with large $d\Delta n$ is too dispersive as shall be seen in the next section. The best point would locate at $d\Delta n=0.14\ \mu$m, where the peak brightness is 100% and the contrast is over 100. In addition, the point with $d\Delta n=0.40\ \mu$m is also a good choice for reflective BTN display.

It should be mentioned that besides reflective BTN described above, other values of ϕ are possible by rotating the polarizer angle. Of course, having good optical properties does not guarantee that the reflective BTN can exist. Other considerations, such as the d/p ratio, have to be taken into account.

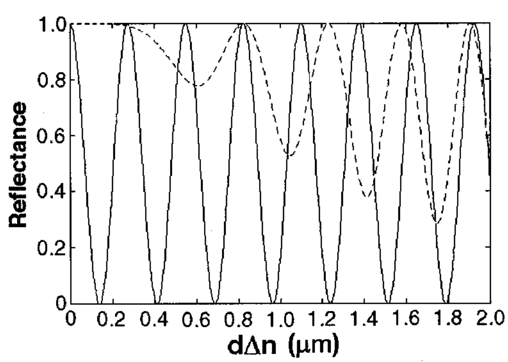

FIG. 6. Reflectance of the 0° twist state (real line) and the 360° twist state (dashed) as a function of $d\Delta n$ for $\alpha=45°$.

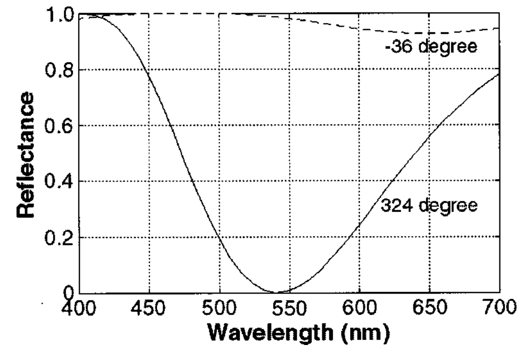

FIG. 7. Reflectance spectra of the $-36°$ twist state (top) and the 324° twist state (bottom) in the case of $d\Delta n=0.94\ \mu$m and $\alpha=0°$.

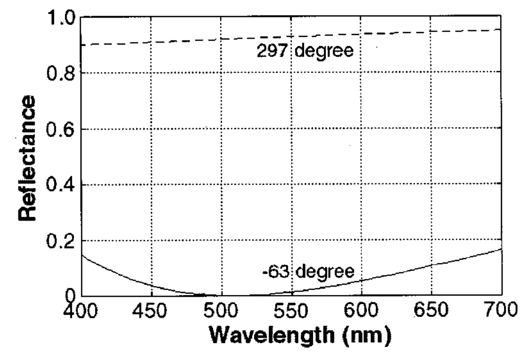

FIG. 8. Reflectance spectra of the $-63°$ twist state (bottom) and the 297° twist state (top) in the case of $d\Delta n=0.18\ \mu$m and $\alpha=0°$.

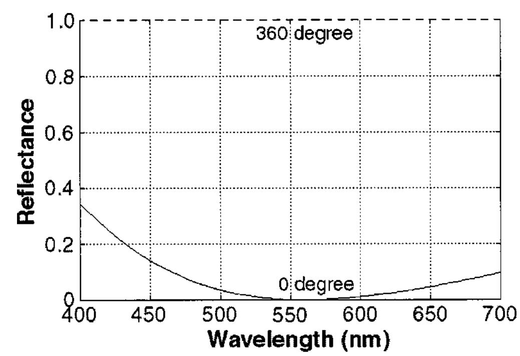

FIG. 9. Reflectance spectra of the 0° twist state (bottom) and the 360° twist state (top) in the case of $d\Delta n=0.14\ \mu$m and $\alpha=45°$. Note that the spectrum for the bright state overlaps with the 100% reflectance line.

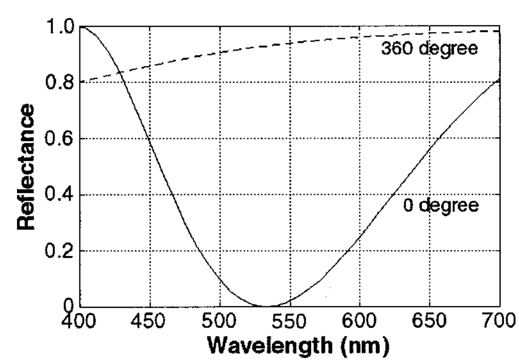

FIG. 10. Reflectance spectra of the 0° twist state (bottom) and the 360° twist state (top) in the case of $d\Delta n=0.40\ \mu$m and $\alpha=45°$.

IV. REFLECTANCE SPECTRA OF THE REFLECTIVE BTN MODES

Besides contrast ratios and brightness, another important criteria for a good reflective BTN display is the color dispersion of dark and bright states. Let us first examine the reflective BTNs for the case of $\alpha=0°$. Figure 7 shows the reflectance spectra of the $\phi=-36°$ and $\phi=324°$ states for $d\Delta n=0.94\,\mu$m. Clearly, a good contrast ratio can be obtained between the bright and the dark states. Low dispersion appears in the bright state, while high dispersion appears in the dark state because of its large $d\Delta n$ value. The bright and dark states show white and dark violet, respectively.

Also for the case of $\alpha=0°$, Figure 8 shows the reflectance spectra of $\phi=-63°$ and $\phi=297°$ for $d\Delta n=0.18\,\mu$m. Indeed, a very nice display with low dispersion and reasonably good contrast can be obtained in Fig. 8. Moreover, for another good point of 63°, 0.18 μm, the reflectance spectra of $\phi=63°$ and $\phi=423°$ twist states are the same as those of $\phi=-63°$ and $\phi=297°$ twist states. Being of low dispersion in two bistable states, the two reflective BTN modes will show black–white display. Their only drawback that $d\Delta n$ value is quite small will make this display difficult to manufacture with good yield.

Finally, we plot the dispersion curve of reflective BTN operated between $\phi=0°$ and $\phi=360°$ for $\alpha=45°$. Figure 9 shows the case of $d\Delta n=0.14\,\mu$m. Clearly, the 100% reflectance and non-dispersion appear in the bright state, and the dark state shows the low reflectance and little dispersion. So highest contrast and brightness as well as black–white display can be obtained in such reflective BTN mode.

Figure 10 shows the dispersion curve of reflective BTN operated between $\phi=0°$ and $\phi=360°$ for the case of $\alpha=45°$ and $d\Delta n=0.40\,\mu$m. Compared with that in Fig. 9, the dispersion of both states in Fig. 10 becomes larger since the $d\Delta n$ of this reflective BTN is increased and the light efficiency of bright state become worse. So the optimal operation condition for a reflective BTN should locate at the point of $\phi=0°$ and $d\Delta n=0.14\,\mu$m for $\alpha=45°$.

V. CONCLUSIONS

In summary, by using the parameter space approach, the optical properties of reflective bistable nematic liquid crystal displays could be visualized and optimized. All the adjustable variables that affect the optical properties of the reflective BTN can be taken into account, except for the tilt angle, which is only of secondary importance in determining the optical properties. However, the tilt angle is important in determining the stability and switching behavior of the two bistable states. It should be emphasized that in determining the stable optical properties, details of the switching from one state to another can be ignored, since both bistable states are field-off states.

The other relevant properties of the reflective BTN such as the peak light efficiency and the wavelength dispersion of two bistable states were also calculated. Optimal $d\Delta n$ values were derived for several reflective BTN modes. It is found that the literature value[11] is actually quite optimal. However, several other reflective BTN operating conditions that may have good performance were proposed as well. It is believed that the present results are useful for the further design and optimization of these reflective BTN displays.

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