Optimization of reflective bistable twisted nematic displays with retardation compensation

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The contrast ratios of reflective bistable twisted nematic liquid crystal displays with a rear quarter-wave film 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 ($d\Delta n$) of the display, the regions where the displays show the best contrast ratio are clearly shown. Both the absolute reflectance and the wavelength dispersion of two bistable twisted states are investigated. It is confirmed that superhigh contrast ratio (infinite in principle), reflectance about 95% with polarized-light input, a large $d\Delta n$ value (0.63 μm), and low dispersion are possible for such reflective bistable liquid crystal display.
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I. INTRODUCTION

A bistable twisted nematic (BTN) liquid crystal display (LCD) that can be switched between two metastable 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 bistable LCD with a black–white 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]

Since no holding voltage is needed to display images, the LC alignment of the BTN can take on either of two twisted states at 0 V. 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 ϕ and $\phi+2\pi$ twist states 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 is the gap of the LC cell and p is the pitch of LC. In actual practice however, the d/p ratio is always somewhat larger than the simple argument presented here.[4] Because of its bistable nature, the reflective BTN can be passive-matrix driven without a multiplex limit in principle.

More recently, a new kind of reflective BTN LCD without retardation compensation has been developed.[11–13] This reflective BTN consists simply of a front polarizer, a LC cell, and a rear reflector. It has many advantages, such as eliminating one of the polarizers, increasing brightness, and simplifying manufacture. Because its rear reflector can also be placed inside the LC cell, any viewing parallax can be eliminated to bring about a higher resolution. Several studies have been devoted to such reflective BTN LCD. 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. Kim *et al.*[12] studied the electro-optic characteristics of a reflective BTN cell as a function of the reset-data and selection-data signals in the driving scheme. Xie *et al.*[13] optimized the contrast ratios of reflective bistable twisted nematic displays and confirmed that a high contrast ratio of over 100 and a reflectance of almost 100% with polarized light is possible for such reflectance bistable displays.

So far a reflective BTN with retardation compensation has not been investigated, though the reflective TN or STN LCDs with retardation compensation have been demonstrated.[14,15] It is the purpose of this article to examine the optics of the reflective BTNs with rear retardation compensation for general values of twist angle and polarizer angle. The contrast ratios of various configurations will be studied systematically for the entire parameter space[16] of such reflective BTNs. The peak reflectance and wavelength dispersion of such reflective BTN modes will be investigated. The optimal operation conditions will be reported for various types of reflective BTNs with rear retardation compensation.

II. PARAMETER SPACE FOR REFLECTIVE BTN WITH RETARDATION COMPENSATION

The starting point for our analysis of such reflective BTNs is the Jones matrix of a LC cell. The basic idea is that since both bistable twisted states operate at $V=0$, the static parameter space is ideal in analyzing the optical properties of such reflective BTN. The geometry for this reflective BTN LCD; as shown in Fig. 1, consists of a polarizer, a liquid crystal cell, a rear retardation film, and a reflector. The polarizer and the retardation film axes are an angle of α and χ

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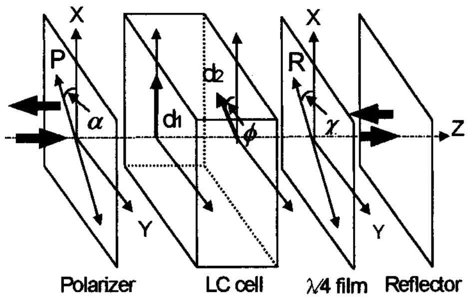

FIG. 1. Schematic diagram of a reflective display. A retardation film is inserted between the liquid crystal cell and the back reflector.

to the input director of the liquid crystal cell, respectively. The reflection of this optical arrangement is given by[15]

$$R=\left|(\cos\alpha\ \ \sin\alpha)\cdot HMH^{-1}FM\cdot\begin{pmatrix}\cos\alpha\\ \sin\alpha\end{pmatrix}\right|^2, \tag{1}$$

where

$$H=\begin{pmatrix}\cos\phi & \sin\phi\\ \sin\phi & -\cos\phi\end{pmatrix}, \tag{2}$$

$$M=\begin{pmatrix}A+iB & -C-iD\\ C-iD & A-iB\end{pmatrix}, \tag{3}$$

and

$$F=R_\chi^{-1}\begin{pmatrix}e^{-i\delta} & 0\\ 0 & e^{i\delta}\end{pmatrix}R_\chi. \tag{4}$$

In Eqs. (1)–(4), HMH^{-1} represents the Jones matrix of the nematic cell with light traveling in the opposite direction, F is the square of the Jones matrix of the retardation film, and R_χ is the rotation matrix for transforming F the proper coordinate system.[15]

The reflectance of such a display is a unique function of the fast axis angle χ, the polarizer angle α, the LC twist angle ϕ, and the thickness–birefringence product $d\Delta n$.[15] By fixing any two parameters, the reflectance of the LC cell can be plotted as a function of the remaining two parameters in the two-dimensional (2D) contour map. When α and χ are fixed, the contrast ratio for any value of ϕ and $d\Delta n$ can be obtained by calculating the reflectance R of two twisted states. The contrast ratio (CR) is defined as CR $(\phi)=R(\phi)/R(\phi+2\pi)$ or $R(\phi+2\pi)/R(\phi)$. The formula used depends on whichever ratio is larger. In our calculation, the input-light wavelength λ is 550 nm and the pretilt angle θ is 0°. It was shown previously that a $(\phi,d\Delta n)$ parameter space for fixed α was very useful in analyzing reflective BTN displays without retardation film.[13]

Figure 2 shows a contour map of the contrast ratio as a function of $d\Delta n$ and ϕ for the case of $\alpha=45°$ and $\chi=0°$. Each contour line in Fig. 2 represents an increase by steps of 9 in the contrast ratio. ϕ is used as the independent parameter although it should be remembered that the bistable states are ϕ and $\phi+2\pi$. It can been seen that the x axis corresponds to $d\Delta n=0$ or no liquid crystal cell. Hence CR=1. The y axis corresponds to the CR between the $-180°$ twist state and 180° twist state, hence the CR=1 as well. Clearly, the high contrast ratio can be obtained in the centers of many island regions. Similar to the transmittive BTN displays,[17] the high contrast regions are concentrated at the vertical lines of $\phi=0°$, $\pm90°$, and 180°. In particular, the contour lines become very dense near the center of the island, because one of the reflectance of two twist states approaches zero and thus the contrast ratio between two twist states can change drastically. It can be seen that from Fig. 2, that the best operating condition of such reflective BTN corresponds at the point of $(\phi,d\Delta n)=(0°,0.13\,\mu\text{m})$ in this parameter space, because the region near the operating point has a high contrast and the high contrast is not very sensitive to the change in $d\Delta n$ *and* ϕ.

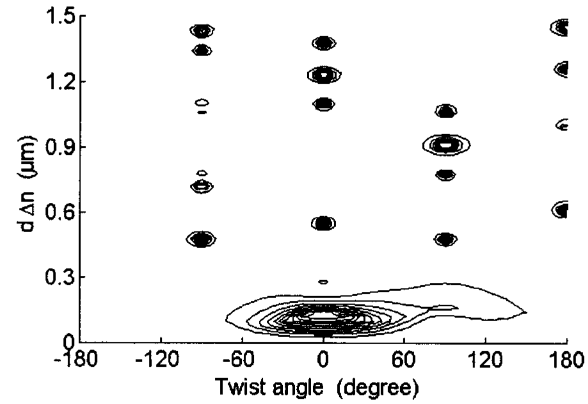

FIG. 2. Contrast ratio of the reflective BTN as a function of $d\Delta n$ and ϕ for $\alpha=45°$ and $\chi=0°$. Each contrast contour line represents an increase of 9.

Figure 3 shows the same reflective BTN with a rear quarter-wave film for the case of $\alpha=0°$ and $\chi=45°$. The parameter space is now quite different. Obviously, the regions of good contrast are dominated by a large elongated island at the vertical lines of $\phi=0°$, and several middle islands at the vertical lines of $\phi=\pm90°$ and $\phi=180°$. Indeed, the points locating at $\phi=0°$ and $d\Delta n\approx0.8\,\mu$m is a very good choice for the operation of such reflective BTN with a retardation film. The high contrast region near the point is also large and not sensitive to the change in $d\Delta n$.

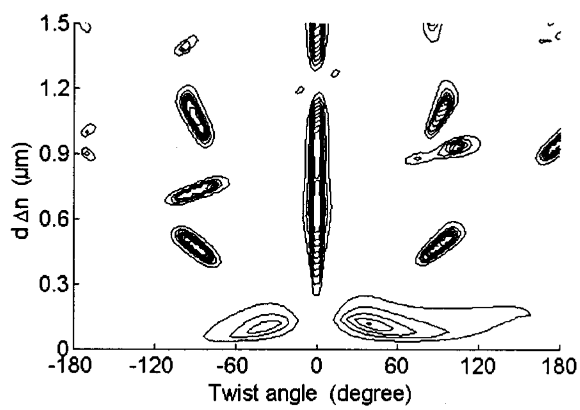

FIG. 3. Contrast ratio of the reflective BTN as a function of $d\Delta n$ and ϕ for $\alpha=0°$ and $\chi=45°$. Each contrast contour line represents an increase of 9.

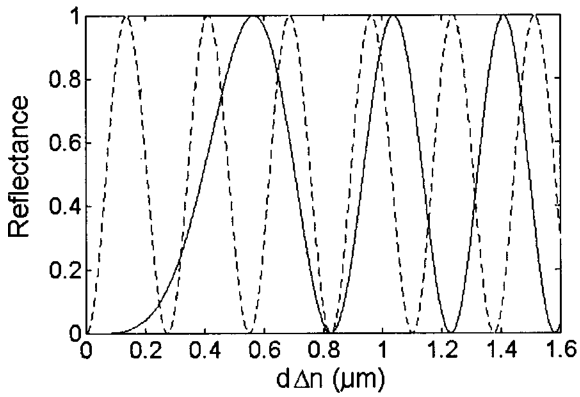

FIG. 4. Reflectance of the 0° twist state (dashed line) and 360° twist state (solid line) as a function of $d\Delta n$ for the case of $\alpha=45°$ and $\chi=0°$.

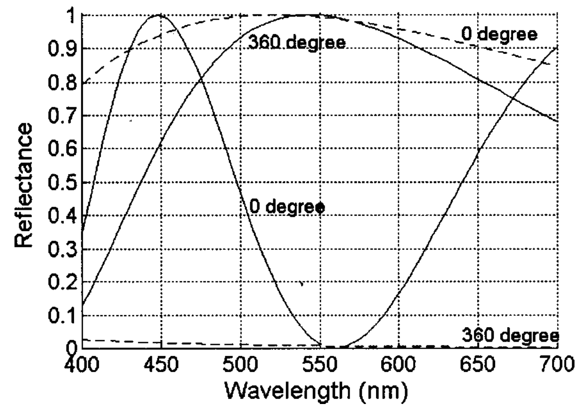

FIG. 6. Reflectance spectra of the 0° twist state 360° twist states with $d\Delta n=0.13\ \mu$m (dashed lines) or with $d\Delta n=0.55\ \mu$m (solid lines) for the case of $\alpha=45°$ and $\chi=0°$.

Moreover, Fig. 3 shows several regions of high contrast, clustered at $\phi=\pm90°$ and 180°. Nevertheless those high contrast regions are in the middle and more sensitive to the change in $d\Delta n$. Thus for the case of $\alpha=0°$ and $\chi=45°$, the point (0°, ~0.8 μm) is the best choice for such reflective BTN LCD. Clearly, we can intuitively choose the optimal values of ϕ and $d\Delta n$ from Figs. 2 and 3 in order for any reflective BTN with a rear quarter-wave retardation film to produce a good contrast ratio.

III. BRIGHTNESS/EFFICIENCY OF THE REFLECTIVE BTN MODES WITH REAR RETARDATION COMPENSATION

The contrast ratio is only one of the criteria for a good reflective BTN display with retardation compensation. Another measure of a good display is the peak reflectance of 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. 4 and 5. In calculating these curves, a simple solution of the complicated Jones matrix is possible. Notice that in Figs. 4 and 5 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.

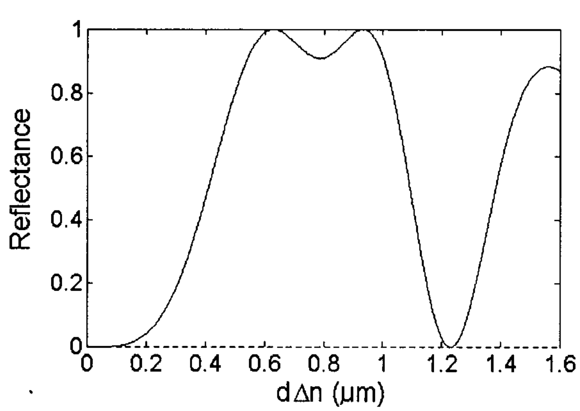

FIG. 5. Reflectance of the 0° twist state (dashed) and the 360° twist state (solid line) as a function of $d\Delta n$ for $\alpha=0°$ and $\chi=45°$.

To begin with the case of $\alpha=45°$ and $\chi=0°$. Figure 4 shows the reflectance of the $\phi=0°$ (dashed line) and $\phi=360°$ (solid line) twisted states as a function of $d\Delta n$. Clearly, high contrast can be obtained at $d\Delta n$ of 0.12, 0.28, 0.55, 1.10, 1.24, 1.37, and 1.58 μm due to their dark states having almost zero reflectance. The reflectance of the corresponding bright states is about 0.98, 0.15, 0.99, 0.77, 1.0, 0.88, and 0.51, respectively. Thus for high contrast, and especially for high efficiency, the BTN cell should has one of the $d\Delta n$ values of 0.12, 0.55, and 1.24 μm. However, the state with large $d\Delta n$ is too dispersive as shall be seen in Sec. IV. The best point locates at $d\Delta n=0.12\ \mu$m, where the peak brightness is 98% and the contrast is over 100. In addition, the point with $d\Delta n=0.55\ \mu$m is also a good choice for this reflective display mode. Considering color dispersion as shown in Sec. IV, possibly the better choice is the point of $d\Delta n=0.12\ \mu$m.

For the case of $\alpha=0°$ and $\chi=45°$, Fig. 5 shows the reflectance of the $\phi=0°$ (dashed line) and $\phi=360°$ (solid line) twisted states as a function of $d\Delta n$. Apparently, $\phi=0°$ twisted state shows the zero reflectance for any $d\Delta n$ value, hence high contrast ratio between two twisted states can be obtained within a wide $d\Delta n$ range (Fig. 5). Having 100% light efficiency and over 100 contrast ratio, both points of $d\Delta n=0.63\ \mu$m and $d\Delta n=0.93\ \mu$m are excellent choices for the display mode. Considering color dispersion as shown in Sec. IV, possibly the better choice is the point of $d\Delta n=0.63\ \mu$m.

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

IV. REFLECTANCE SPECTRA OF THE REFLECTIVE BTN MODES WITH REAR RETARDATION COMPENSATION

Besides contrast ratio and brightness, another important criteria for a good reflective BTN display is the color dispersion of its dark and bright states. Let us first examine the

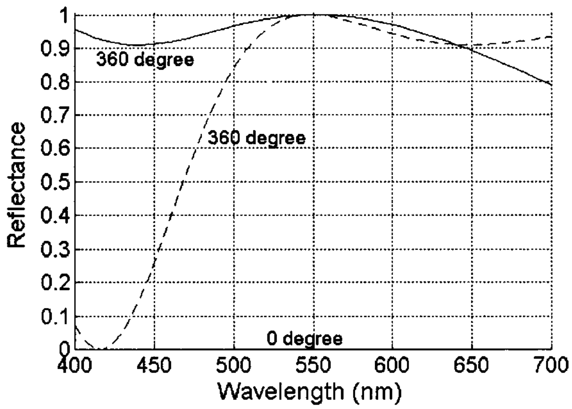

FIG. 7. Reflectance spectra of the 0° twist state 360° twist states with $d\Delta n = 0.63\ \mu$m (solid lines) and with $d\Delta n = 0.93\ \mu$m (dashed lines) for the case of $\alpha = 0°$ and $\chi = 45°$. Note that the spectrum for the dark state overlaps the zero reflectance line for both $d\Delta n$ values.

bistable reflective BTN for the case of $\alpha = 45°$ and $\chi = 0°$. In this case, Fig. 6 shows the reflectance spectra of the $\phi = 0°$ and $\phi = 360°$ states for the two conditions of $d\Delta n = 0.12\ \mu$m (dashed line) and $d\Delta n = 0.55\ \mu$m (solid line). For the condition of $d\Delta n = 0.12\ \mu$m, indeed a very nice display with low dispersion and reasonably good contrast can be obtained in Fig. 6. Being of the low dispersion in two bistable states, this reflective BTN mode will show a black–white display. Its only drawback is that a quite small $d\Delta n$ value will make it difficult to manufacture with good yield. When $d\Delta n = 0.55\ \mu$m, clearly, a good contrast ratio can also be obtained between the bight and dark states, but large dispersion appears in both of its bright and dark states. The two states will show green and violet, respectively. This means that a larger $d\Delta n$ value will produce a larger dispersion.

Moreover, for another case of $\alpha = 0°$ and $\chi = 45°$, Fig. 7 shows the reflectance spectra of the $\phi = 0$ and 360° states for $d\Delta n = 0.63\ \mu$m (solid line) and $d\Delta n = 0.93\ \mu$m (dashed line). Obviously, for $d\Delta n = 0.63\ \mu$m the zero reflectance and nondispersion appear in the dark state, and the bright state shows a high reflectance over 95% and little dispersion. So superhigh contrast, high brightness, and true black–white display can be obtained in such a reflective BTN mode. When the $d\Delta n$ value changes from 0.63 to 0.93 μm, the zero reflectance and nondispersion also appear in the dark state where the superhigh contrast can also be obtained in such a reflective BTN mode. Since the $d\Delta n$ of this reflective BTN increases, the dispersion of the bright state become larger. As a result the bright state shows the high reflectance from 500 to 700 nm and shows the low reflectance below 500 nm. Thus the two states will show bright yellow and true black, respectively. So the optimal operation condition for such reflective BTN mode should be $\phi = 0°$, $d\Delta n = 0.63\ \mu$m, $\alpha = 45°$, and $\chi = 0°$.

V. CONCLUSIONS

In summary, by using the parameter space approach, the optical properties of reflective bistable nematic liquid crystal displays with a rear retardation film 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 behaviors of the 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 have also been calculated. Optimal $d\Delta n$ values have been derived for several reflective BTN modes. However, several reflective BTN operating conditions that may have good performance have been proposed. It is believe that the present results are useful for the further design and optimization of the reflective BTN displays with rear retardation compensation.

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