Liquid Crystals
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713926090

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Online publication date: 06 August 2010

To cite this Article Wang, X. J. and Su, K. C.(1998) 'Sub-twisted nematic liquid crystal display', Liquid Crystals, 24: 3, 435 — 440
To link to this Article: DOI: 10.1080/026782998207262
URL: http://dx.doi.org/10.1080/026782998207262

Sub-twisted nematic liquid crystal display

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(*Received 18 July 1997; accepted 8 September 1997*)

A new reflective liquid crystal display, the sub-twisted nematic LCD (SBTN), is presented. The SBTN, specifically designed for its twist angle, the product of cell thickness and birefringence, the direction of its only polarizer, etc. exhibits good electro-optic performance. Brightness, contrast, colour dispersion and multiplexing ability, etc. were theoretically and experimentally examined. The prototype showed high brightness, little dispersion, good mutliplexing ability, good viewing angle and response behaviour. It also offers good manufacturing tolerance and low production cost.

1. Introduction

A new reflective type of liquid crystal display—the sub-twisted nematic display (SBTN)—has been proposed and extensively examined by Wang and co-workers [1, 2]. Compared with conventional twisted nematic (TN) and super-twisted nematic (STN) liquid crystal displays, such displays showed significant improvements in electro-optic performance.

The TN display was invented in 1971 [3] and has since been widely applied in applications such as wrist watches, calculators, games controllers, etc. Most TNs work as reflective displays and in the positive mode. Effort has since been made to improve the TN's performance, including the SBTN work presented in this article.

The basic structure of the SBTN is depicted in figure 1. The liquid crystal is homogeneously aligned on both front and back substrates and is sandwiched between two plates coated with ITO, which forms the transparent electrodes. It is twisted by an angle Φ, less than 90°, to form a helical structure. The high twist case has been discussed already [4]. Incident natural light becomes polarized after passing through the front polarizer and is then reflected by a reflector so that light passes through the helical liquid crystal layer twice and finally exits after passing through the polarizer again. By applying an electric voltage to the liquid crystal layer sandwiched by the electrodes, and thus causing the deformation of the liquid crystal orientations, the cell can be switched between a bright and a dark appearance. SBTN is not simply a device with smaller twist angle than TN; it works on a different principle.

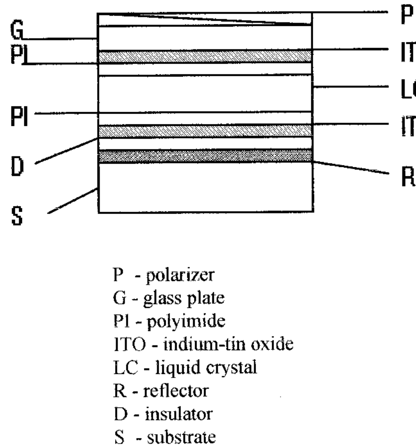

Figure 1. Configuration of the SBTN cell.

2. The optics of the SBTN

We assume a cell of thickness d, and the birefringence of the nematic liquid crystal $\Delta n = n_e - n_o$, where n_e and n_o are the refractive indices of the extraordinary and ordinary light, respectively. If the polarizer is oriented along the molecular orientation on the front plate the reflectance can be derived as

$$R = 1 - \left\{ \frac{2\alpha}{1+\alpha^2} \sin^2[\Phi(1-\alpha^2)^{1/2}] \right\} \qquad (1)$$

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where

$$\alpha = \frac{\pi}{\Phi}\frac{\Delta nd}{\lambda}$$

and λ is the wavelength of the incident beam. The equation is also valid when the polarization of the polarizer is perpendicular to the liquid crystal orientation on the front substrate.

The dependence of the reflectance on the product of liquid crystal birefringence and cell thickness, Δnd, is plotted in figure 2 for various twist angles $\Phi = 45°$, 60°, 90°, 180°. When $\Delta nd = ((m\pi/\Phi)^2 - 1)^{1/2}$ $(m = 1, 2, \ldots)$ the reflectance is equal to unity, the good transmission field-off state. However, at $\Delta nd = 0{\cdot}194\,\mu m$ for $\Phi = 63{\cdot}6°$ and at $\Delta nd = 0{\cdot}583\,\mu m$ for $\Phi = 190{\cdot}9°$, the reflectance approaches zero.

By appropriately assembling a liquid crystal cell according to the above arguments, either a positive or a negative LCD can be realized. It is indicated that by using a cell of 63·6° twist ($\Delta nd = 0{\cdot}194\,\mu m$) a good negative mode display (bright image on dark background) may be obtained [5]. In the field-off state, the cell acts as a half-wavelength plate which turns the incident linear polarized light from along (e.g.) the x axis to the y axis. Unfortunately, it is extremely difficult to process cells whose thickness is less than 2 μm. Grinberg *et al.* used a 45° twist cell working in a negative mode as an optical processing device [6]; they installed two crossed polarizers instead. The brightness of the device was not good. Actually, by appropriately combining twist angle, the product of cell thickness and liquid crystal birefringence, and the polarization direction of the polarizer, a similar negative model reflective SBTN can be achieved [2]. We will discuss such negative mode reflective displays in detail separately.

We quote in this article a liquid crystal cell of 55° twist biased at $\Delta nd = 0{\cdot}524\,\mu m$ as the example of a SBTN that will be applied in all that follows. The twist angle of 55° is not a unique value; any value less than 90° could be used so long as a satisfactory bright field-off state is achieved. In fact, the brightness of the field-off state of SBTN is not very sensitive toward fairly small variation in the twist angle. The SBTN is a reflective display and works in the positive mode (dark image on bright background). The SBTN acts as an optical rotator in the field-off state; it does not change the incident linearly polarized light, and needs only one polarizer. This cell shows a good electro-optic performance.

The quadratic form of the sine function in equation (1) assigns to SBTN specific characteristics: for example, the flat curve of the reflectance versus optical wavelength and thus the good black on white appearance, the large fabrication tolerance in cell thickness, the liquid crystal birefringence, the polarizer direction, etc.

The dependence of reflectance on wavelength for normal incidence for both the field-on and field-off states of SBTN cells is shown in figure 3. In this calculation, we assumed that the elastic constants of the liquid crystal K_{11}, K_{22}, K_{33} take the values 1×10^{-11}, $0{\cdot}5 \times 10^{-11}$, $1{\cdot}4 \times 10^{-11}$ N, and the dielectric constants $\varepsilon_{\parallel}$, $\varepsilon_{\perp}$ are 15 and 5, respectively. For simplicity, the dependence of birefringence dispersion on wavelength and polarizer efficiency are not taken into account. For the 55° SBTN, the field-off state reflectance at $\Delta nd = 0{\cdot}524\,\mu m$ is a transparent state (solid line). When an electric voltage is applied, the SBTN enters an opaque state (dashed curve).

A plot of reflectance versus applied voltage (figure 4) shows that SBTN has a similar flat curve to TN. As we know that TN provides a good black on white display, SBTN is also a good black on white display. Therefore, SBTN can easily be used in full colour displays by applying mosaic RGB colour filters without adopting film compensation. On the contrary, STN must be compensated first, by installing a violet colour filter

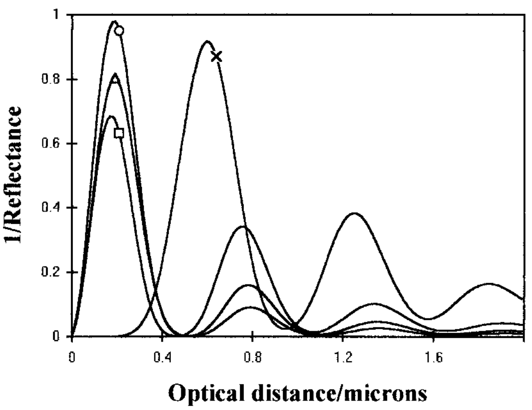


Figure 2. Dependence of the reflectance R on Δnd for various twist angles $\Phi = 45°$ (□), 60° (○), 90° (Δ) and 180° (×).

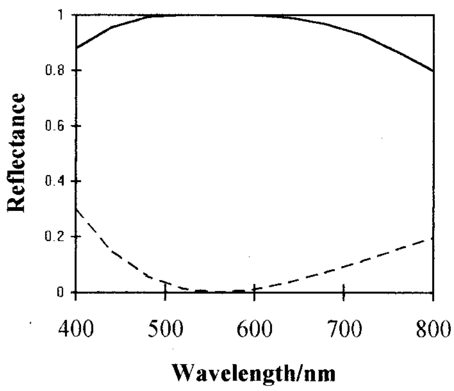


Figure 3. Reflectance versus wavelength for a 55° SBTN: field-on state (dashed line) and field-off state (solid line).

(the grey mode), a double-cell configuration (DSTN), or retardation film(s) (FSTN), in order to obtain a full colour display.

For a qualitative analysis, we let $\beta = \Phi(1+\alpha^2)^{1/2}$ and assume that the variation of β due to variation of wavelength around the central visible wavelength (~ 550 nm) is not great; the variation of the field-off reflectance of SBTN can then be written approximately as

$$\Delta R = -0{\cdot}3(\Delta\beta)^4. \qquad (2)$$

For the reflective TN operating at positive mode the reflectance variation is

$$\Delta R = -0{\cdot}4(\Delta\beta)^2 \qquad (3)$$

while for reflective STN the variation is

$$\Delta R = -2(\Delta\beta)^2. \qquad (4)$$

In addition, the equations can be used to compare qualitatively the tolerance margins of the three devices for cell thickness, liquid crystal birefringence and twist angle, as well as wavelength dispersion. Apparently, the quartic function leads to significant advantages for SBTN over the other two cell forms.

As an example, the second derivative of the reflectance with respect to cell thickness may give a reasonable estimate of the variation of reflectance with cell thickness fluctuation. For TN and STN, the second derivatives take finite values, approximately -12 and $-200\,\mathrm{nm}^{-2}$, respectively, with a cell thickness of 5 μm; for SBTN, the second derivative is zero. This implies that STN is the most sensitive to fluctuation of cell thickness (so that stringent cell gap control and uniformity are required in STN manufacturing), while SBTN is less dependent on cell thickness fluctuation.

As is well known, TN is basically independent of cell thickness so long as its Δnd is greater than a certain value, e.g. 1. The SBTN does not change its reflectance and electro-optic performance significantly so long as the deviation of cell thickness is controlled within, e.g. 15%, see figure 4. Thus, the SBTN has a wide margin for error in the cell thickness. On the contrary, the cell thickness of the STN has to be carefully maintained within $\pm 0{\cdot}1$ μm.

The SBTN does not need a back polarizer, unlike TN or STN; production cost can thus be reduced. With fewer polarizers the brightness of the display is expected to increase. Moreover, the SBTN has a twist angle of less than 90° so that it is unnecessary to dope with chiral materials. Chiral dopants usually play an essential role in order either to maintain the helical structure in STN or to avoid the counter-twist configuration in TN; this is an expensive element in cell manufacture.

Variation of the direction of the polarizer with respect to the liquid crystal orientation on the front plate of the

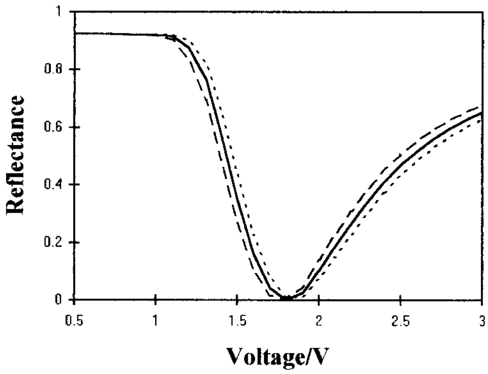


Figure 4. Reflectance versus applied voltage for SBTN (solid line), in comparison with cell thickness variations of ±10% (dashed and dotted lines).

SBTN cell does not change the field-off state reflectance, but it does change the field-on state reflectance and hence the contrast. By rotating the polarization direction of the polarizer, the SBTN remains in a bright state, but its appearance may become yellowish or bluish, depending on the angle and sense of the polarizer rotation. On rotating by 90°, the brightness of the display returns to that at zero off-set polarizer angle. In contrast, the TN appearance varies from transparent to opaque if one of its polarizers rotates by 90°, while the STN shifts from yellow mode to blue mode.

Let us assume two principal transmissions of the polarizers e.g. typically 0·85 and 0·01. For a reflective TN or STN the incident light has to go through polarizers four times, and the maximum reflectance is actually less than 26%. However, the SBTN has only one polarizer and the incident light goes through it only twice; maximum transmission is about 36%. It can be demonstrated that the brightness of a SBTN in the field-off state can increase to about 40%.

As is well known, the contrast ratio of an LCD depends not only on the density of the polarizer but also on the LC layer and its response to an applied electric field. In addition to the electro-optic effect of the LC layer, polarizers with a lower density may be utilized in a SBTN display to achieve a better contrast ratio. Moreover, the back glass plate may be replaced by a reflector, with a reduction in interface scattering. The reflectance of the SBTN can accordingly be further improved.

In addition, the reflector film can be mounted on the inside surface of the back plate so that ghost imaging can be significantly diminished. Because there is essentially nothing behind the reflector, such as a plastic polarizer, there is ample space for items such as the circuitry, dielectric mirror, thermostat, etc.

3. Electro-optic performance

Figure 5 shows the dependence of the transmission of a SBTN cell on the applied voltage in terms of a Berremann 4×4 matrix; the input data are assumed the same as those mentioned before. In this figure we plot R versus V for various elastic constants $K_{33}/K_{11} = 2$, 1·4 and 1.

The deformation profile against applied voltage of the SBTN is expected to be less severe than that of a 90° twist TN cell. However, the SBTN shows a steeper electro-optic curve. The dynamic and static electro-optic curves are plotted, respectively, in figures 6 (*a*) and 6 (*b*). In figure 6 (*a*) the abscissa of the plot is applied voltage. The average birefringence of the LC layer in the cell decreases as the voltage increases and thus the horizontal axis in the plot of the static curve, figure 6 (*b*), scales the reciprocal of the product of the cell thickness and the LC birefringence. Both plots indicate that the SBTN has a steeper electro-optic performance and hence is more multiplexable than the TN. Actually, a 16×102 matrix display has been satisfactorily made without optimization. A higher level multiplexing SBTN cell is expected soon to be available.

For a SBTN, the Fréedericksz electric threshold at which the LC directors at the middle plane of the cell start to deform is given by

$$V_{\text{th}} = \pi \left[\frac{K_{11} + (K_{33} - 2K_{22})^{*}(\Phi/\pi)}{\varepsilon_0 \Delta\varepsilon} \right]^{1/2} \tag{5}$$

where ε_0 is the dielectric permittivity of a vacuum and $\Delta\varepsilon$ is the dielectric anisotropy of the liquid crystal; K_{11}, K_{22} and K_{33} are the splay, twist and bend elastic constants of the liquid crystal, respectively. This equation is a direct derivation from LC continuum theory in the case of zero surface bias angle. The well-known TN result [3] is a special example of this equation.

The optical threshold given in the plot of optical reflectance against applied voltage is slightly greater than the Fréedericksz value by a few tenths of a volt.

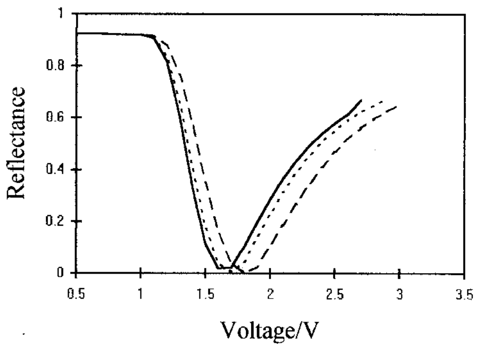
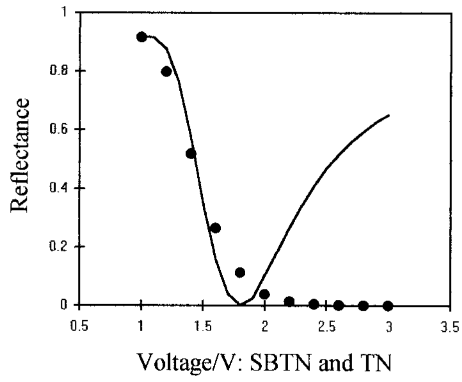
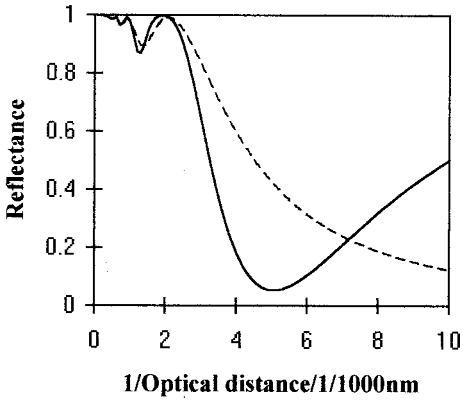


Figure 5. Reflectance versus applied voltage for SBTN where $K_{33}/K_{11} = 1{\cdot}1$ (dashed line), 1·4 (dotted line) and 2 (solid line).



(*a*)



(*b*)

Figure 6. Reflectance R versus (*a*) applied voltage (dynamic curve) and (*b*) $1/\Delta nd$ (static curve); for SBTN (solid line) and TN (dots or dashed line).

The saturation voltage depends on molecular parameters such as the elastic constants and dielectric permittivities. It is a weak function of the optical refractive indices and the cell thickness. The steepness of the electro-optic curve depends on the ratio of elastic constants, K_{33}/K_{11}. The lower the ratio, the steeper the curve, as shown in figure 6.

4. The off-axis polarizer arrangement

The SBTN does not always reach a good dark state as a voltage is applied. In order to achieve as dark as possible a field-on state, we may construct a SBTN cell by making the polarizer off-set (defined as the angle ξ_m), meanwhile requiring that the off-set arrangement does not essentially change the SBTN's black on white appearance.

ξ_m is a complex function of twist angle and other device parameters. In the first instance, it may be evaluated approximately according to the following equation

$$\tan 2\xi_m = -1/\Phi\alpha_m^2,$$
$$\tan \beta_m = \Phi\alpha_m^2(1+\alpha_m^2)^{1/2}. \quad (6)$$

For a 55° twist SBTN, $\xi_m = -11{\cdot}3°$.

Figure 7 shows that the relation of the reflectance to the optical distance for the SBTN where the polarizer is aligned to be along the orientation of the liquid crystal on the front plate and to be off-set by an angle $\pm 11{\cdot}3$ degrees.

It can be seen that the reflectance in figure 7 is never zero except when the field-on state is very dark. The difference is understandable because we are dealing with a LC layer with a birefringence corresponding to a bright state rather than a dark state. When an electric field is applied the reflectance of the SBTN does not completely follow the curve shown in figure 7.

4.1. *Field-off state appearance*

The field-off state dispersion of the reflectance is shown in figure 8 for polarizer off-set angles $\xi = \pm 11{\cdot}3°$. The figure is plotted for a SBTN with the same parameters as mentioned previously.

It is seen that when $\xi = -11{\cdot}3°$, the cell is of bright bluish colour, and when $\xi = 11{\cdot}3°$ its colour is bright yellowish. Experimental observations have confirmed such an effect. We have achieved both good contrast and good black on white appearance by adjusting the cell construction and the material parameters.

4.2. *Brightness*

The experimental data have shown that the field-off state reflectance of a SBTN is much greater than those of the conventional TN, and STN displays. An experimental increase by a factor of 20/12 has been achieved.

4.3. *Contrast*

Reflectance versus applied voltage for the SBTN is plotted in figure 10 where ξ is 11·3°, 0°, or $-11{\cdot}3°$. The

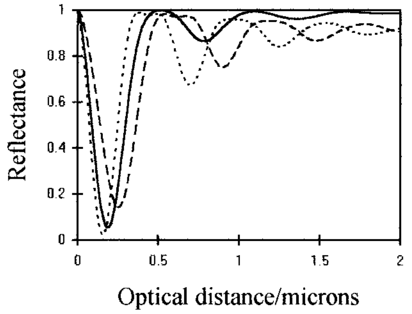


Figure 7. Reflectance R versus Δnd for SBTN with off-set angle 0° (solid line), 11·3° (dashed line) and $-11{\cdot}3°$ (dotted line).

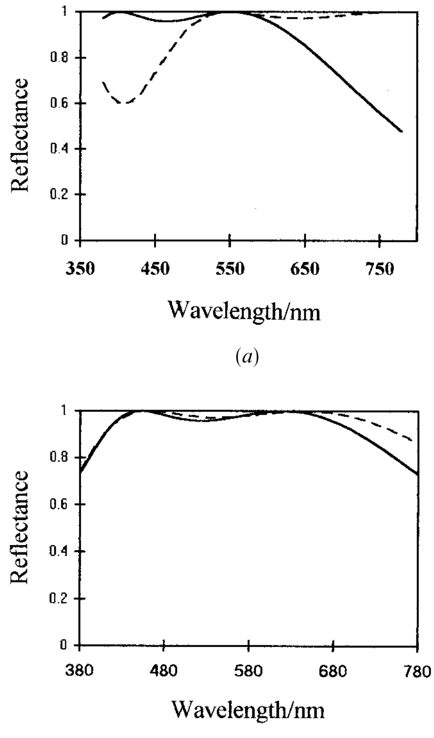


Figure 8. Field-off dispersion of reflectance for SBTN with off-set angle 11·3° (solid line) and $-11{\cdot}3$ (dashed line): (*a*) before varying birefringence of LC mixture; (*b*) after varying birefringence.

curves in figure 9 suggest that a SBTN cell with an off-set polarizer angle of $-11{\cdot}3°$ shows very good contrast. By adopting a small off-set angle polarizer, the reflectance of the SBTN in the field-on state can be further reduced, and accordingly the contrast can be increased significantly. Experiments on SBTN have demonstrated that the contrast of zero off-set SBTN is about 15. By adopting a $-11°$–$15°$ off-set arrangement of the polarizer, the contrast of the SBTN is increased

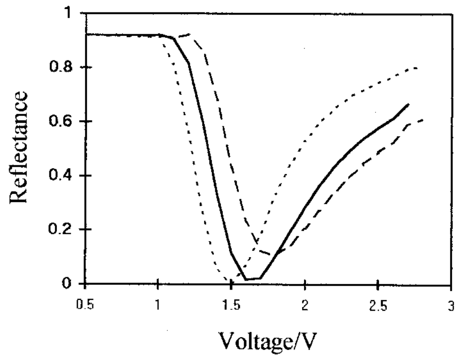


Figure 9. Reflectance versus applied voltage for SBTN where the off-set angle ξ is 0° (solid line), 11·3 (dashed line) and $-11{\cdot}3$ (dotted line).

Table. Relation of the electro-optic performance of the SBTN[a] to the off-set polarizer angle.

Off-set angle/°	Threshold voltage/V	Slope	Contrast
−79	2·0	1·50	8·9
−28	1·7	1·41	9·5
−15	1·93	1·43	26
−11	1·94	1·45	25
0	2·0	1·47	14
11	2·17	1·46	6·4

[a] The LC mixture was from E. Merck. It has slope 1·54–1·60 and is specified for 1st minimum TN displays.

to 26. The table lists experimental data on the contrast of a SBTN cell when varying the off-set angle of the polarizer. Maximum contrast occurs at angles between −11°–15° which is in agreement with the estimate of −11·3°.

In addition, the SBTN device displayed experimentally improvements on viewing angle and response time over a TN.

5. Summary

The twist of 55° for a SBTN cell is an example. The twist for a SBTN can be in a range between, e.g. 45° to 90°, depending on the parameters of the cell design, the LC material, and the polarizer orientation. Optimization has been carried out and the performance of the SBTN has been further improved.

The SBTN is a new kind of LCD which shows good optical and electro-optic performance: high field-off brightness, steep electro-optic curve, good contrast, good white on black appearance. It also has a large fabrication tolerance for cell thickness, liquid crystal birefringence, twist angle and polarizer direction, and a lower production cost. These conclusions suggest that the SBTN provides a very competitive form of liquid crystal display.

I would like to thank Dr X. J. Zhang for assistance in fabricating the cells; also Mr X. Y. Gong, and Mr Y. G. Ma for their assistance in the measurements; also Mr S. S. Chen (STD), Professors L. W. Fu (Tsinghua University), Q. F. Zhou (Peking University) and M. Warner (Cambridge University) for fruitful discussions.

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