

# REFLECTIVE ACTIVE MATRIX LIQUID CRYSTAL DISPLAYS WITH MIXED TWISTED NEMATIC AND BIREFRINGENT MODES

The invention relates to a reflective active matrix liquid crystal display mixed with mixed twisted nematic and birefringent modes.

## FIELD OF THE INVENTION

The present patent deals with reflective mode liquid crystal displays that combine the waveguiding effect and the birefringent effects of twisted nematic liquid crystals. By optimizing the various optical arrangements of the liquid crystal display such as the twist angle, the retardation and the polarizer angle, a series of mixed twisted nematic - birefringent (MTB) display modes has been invented.

There has previously been considerable activity in the study of reflective liquid crystal displays (RLCD). Broadly speaking RLCD can be divided into 2 categories: those

that do not rely on polarizers and those that do. Examples of the former are reflective cholesteric displays and absorptive guest-host displays. The latter categories are necessarily *nematic* liquid crystal displays. These are displays that are based on polarization manipulation, as in ordinary twisted nematic LCDs. However, unlike ordinary LCD, there is only one front polarizer and the rear polarizer is eliminated.

The main applications for such RLCDs are in direct view displays with no backlighting, and in projection displays using crystalline silicon backplane with integrated CMOS drivers, or in reflective liquid crystal light valves (LCLV) in general.

Reflective nematic LCD has been investigated. One of the successful inventions is the so-called TN-ECB mode. A variation of this has been reported recently by Wu et al. It has a 90° twist angle. There are many names given to display modes that operate on a combination of the waveguiding TN effect and the pure birefringent effect, e.g. the 45° hybrid-field-effect (HFE) mode, the 63° TN-ECB mode, the 90° mixed TN (MTN) mode, the self-compensated TN (SCTN) mode and the 52° RTN mode.

A generalized picture of reflective twisted nematic LCD is disclosed herein that encompasses all of these mixed mode displays, and provide a method of optimizing them all at the same time. Many new operating conditions can be found that have not been reported and are the subject of the present invention.

These reflective liquid crystal displays can be fabricated on passive matrix or active matrix backplanes. The active matrix backplane can be fabricated on glass or on silicon wafers.

## SUMMARY OF THE INVENTION

As shown in Fig. 1, the reflective nematic LCD consists of a polarizer, a twisted nematic liquid crystal cell, and a reflector, which can be part of a circuit in an active matrix device. The polarizer can either be a sheet type polarizer or a polarizing beam splitter as shown. In this invention, the PBS case is generally described as it is the most popular geometry for silicon microdisplays.

As discussed in the paper by H. S. Kwok, ["Parameter space representation of liquid crystal display operating modes," J. Appl. Phys., 80(7), 3687-3693 (1996)], all nematic RLCD modes can be represented in the parameter space diagram. The parameter space in the case of twisted nematic RLCD is particularly useful, as it shows the relationship between the TN-ECB, MTN, SCTN and ECB modes. The reflectance  $R$  of the RLCD is a function of 3 major parameters: twist angle  $\phi$ , polarizer angle  $\alpha$  between the polarizer and the input director of the LC cell, and the LC cell retardation  $d\Delta n$  where  $d$  is the cell thickness. The wavelength  $\lambda$  always appears together with the retardation as  $d\Delta n/\lambda$  in the Jones matrix. Therefore it can be treated as just a scaling of  $d\Delta n$ . Hence, if one of the 3 parameters ( $\alpha$ ,  $\phi$ ,  $d\Delta n$ ) is fixed,  $R$  can be plotted as a function of the other two parameters in a 2D parameter space using contour lines.

Figure 2 shows a series of parameter spaces for the RLCD, with  $\alpha$  varying from 0 to 45°. A wavelength of 550nm is assumed in the calculations. The contours indicate constant reflectance in steps of 0.1. The wells in Fig. 2 are the so-called TN-ECB minima. The center of the well corresponds to either maximum reflectance for crossed

polarizers or minimum reflectance for parallel polarizers. For example, with a polarizing beam splitter (PBS) in the display,  $(\alpha, \phi, d\Delta n) = (0, 63.5^\circ, 0.18\mu\text{m})$  will give  $R = 1$ . This corresponds to the first TN-ECB minimum. It is marked in Fig. 2. The SCTN mode and the MTN mode are also indicated in Fig. 2 for the appropriate  $\alpha$ .

Polarizer angles larger than  $45^\circ$  are not depicted in Fig. 2. It is because that beyond  $45^\circ$ , the parameter space repeats itself, except for a reflection of the x-axis, i.e. the parameter space for  $\alpha = 90^\circ - \alpha$  is the same as the one for  $\alpha$ , with  $\phi$  changed to  $-\phi$ . From Fig. 2, it can be seen that there are 2 sets of operating modes for reflective LCD. One set of modes are the "in-well" kind which correspond to the islands in the parameter space, such as the TN-ECB, MTN, SCTN modes. The other set of modes are the "out-well" modes which are located outside the TN-ECB wells, such as the RTN, RSTN and HFE modes.

The "in-well" modes are disclosed herein. It can be seen in Fig. 2 that the various TN-ECB minima move systematically in the parameter space as  $\alpha$  is changed. In particular, the first TN-ECB mode with  $+\phi$  is examined. It can be seen that this mode becomes the MTN mode at  $\phi = 90^\circ$ ,  $\alpha = 22^\circ$ , then it becomes the SCTN mode at  $\phi = 60^\circ$ ,  $\alpha = 30^\circ$ . Finally, this first TN-ECB minimum becomes the true ECB mode at  $\phi = 0^\circ$  and  $\alpha = 45^\circ$ .

The situation is clearly shown by a plot of the trajectory of the center of the first TN-ECB minimum for the  $+\phi$  case as shown in Fig. 3. In this plot,  $\alpha$  goes from 0 to  $45^\circ$  in steps of  $5^\circ$ . It can be seen the first TN-ECB minimum first moves out and then towards the y-axis. The retardation increases monotonically as  $\alpha$  increases. The maximum twist angle reaches  $70.2^\circ$  at a polarizer angle of  $15^\circ$ . Fig. 4 is a similar plot of the 0.9 reflectance contours for  $\alpha$  ranging from 0 to  $90^\circ$ , again in steps of  $5^\circ$ . This plot is different from Fig. 3 because we also include  $\alpha$  from  $45^\circ$  to  $90^\circ$ . As can be seen from Fig. 4, as  $\alpha$  goes from  $45^\circ$  to  $90^\circ$ , the originally  $-\phi$  TN-ECB minimum moves

into the positive  $\phi$  side, thus forming a complete loop in the parameter space. This is more easily seen in a parameter space showing both positive and negative twists (Fig. 5.) Notice that the parameter space for  $\alpha$  and  $\alpha \pm 90^\circ$  are identical so that a complete trajectory is formed in Fig. 5 as  $\alpha$  goes from 0 to  $90^\circ$ . Fig. 3 indicates that for twist angles from  $-70^\circ$  to  $+70^\circ$ , there always exists 2 first order TN-ECB minima at different polarizer angles, one with a smaller  $d\Delta n$  value and one with a higher  $d\Delta n$  value.

The operating points of the MTN mode, the TN-ECB mode and the SCTN mode are also indicated in Fig. 4. Thus Fig. 4 unifies the entire picture for the TN-ECB, the MTN and the SCTN modes. They all operate with a combination of polarization rotation (TN) and birefringence (ECB) effects. They differ by a rotation of the polarizer relative to the input director, or, in other words, by the proportion of TN to ECB effects. Therefore, it should be possible to perform an optimization of these modes in a general sense, allowing for variations of all 3 parameters simultaneously.

The nomenclature of these nematic reflective LCDs will now be defined. Since all of these modes operate with a combination of TN effect and ECB effect, they can be called a hybrid mode or a mixed mode. They have been called TN-ECB, MTN, SCTN or HFE in the literature. Instead of calling them the TN-ECB/MTN/HFE mode, such LCD operating modes are hereinafter referred to as the generalized mixed TN-birefringence mode, or MTB mode in short.

In the optimization of the MTB mode, it can be assumed that high reflectance is desirable. If the desired reflectance or light efficiency is set to be 0.9, then the solution will be bound by the 0.9 reflectance contours depicted in Fig. 3. This limits the parameter space tremendously. Alternately, if the desired reflectance is set to be 0.7, then the solution space opens up even larger, and includes twist angles up to  $100^\circ$ . The 0.7 reflectance contour is plotted in Figs. 4-21 for polarizer angles in increasing step of  $5^\circ$ . This represents all the possibilities for the MTB mode. It is noted that all the previously reported modes are represented in Fig. 4-21. For example, the  $90^\circ$  MTN mode of Wu et al is included in Fig. 8. The SCTN mode of Yang is included in Fig. 10.

Fig. 22 is a composite of all the  $R = 0.7$  contours in Figs. 4-21. It is seen that there are always 2 distinct MTB modes for  $\phi$  less than  $70^\circ$ . Usually the solution with smaller  $d\Delta n$  is less wavelength dispersive than the larger  $d\Delta n$  one. However, a large  $d\Delta n$  is desirable from a cell making point of view.

Table I shows the normal operating brightness of the RLCD under various polarizer geometries and using different "in-well" and "out-well" modes. It can be seen that normally white (NW) and normally black (NB) operations can be achieved in both cases, depending on the polarizer geometry. The choice of polarizers has a profound effect on the optimization of the RLCD. In order to have excellent contrast, the dark state should be made as dark as possible. This is conveniently satisfied by the homeotropic alignment of the LC under high voltage bias where  $d\Delta n = 0$  (the x-axis in Fig. 2). This homeotropic state is nondispersive and should be used as the dark state whenever possible. For the MTB modes, which correspond to the centre of the wells in Fig. 1, the homeotropic state can be used as the dark state if a PBS is used. The display will then be normally bright.

However, if a parallel polarizer geometry is used, the high voltage homeotropic state is the bright state and the MTB wells become the dark state. That is undesirable since the MTB wells are dispersive and cannot be made very dark. Hence the contrast will be poor. So for direct view using MTB operation, a quarterwave retardation film has to be used to reverse the bright and dark states. Another solution is to make use of the "out-well" modes such as the RTN and HFE modes as the bright state. In the case of the RTN, the dark state can be made reasonable dark by further optimization of the polarizer angle.

Table II summarizes some of the new MTB modes provided using the parameter space method. These modes have reasonably good reflectance and low dispersion. All of them have not been presented before.

## BRIEF DESCRIPTION OF THE DRAWINGS

- Fig. 1 Geometry of the reflective liquid crystal display.
- Fig. 2 Parameter spaces for the MTB mode at different polarizer angles.
- Fig. 3 Trajectory of the peak of the MTB mode as  $\alpha$  is changed from 0 to 45°. Each point represents an increase of 5° in  $\alpha$ .
- Fig. 4 Reflectance = 0.7 contour line of the MTB mode for a polarizer angle of 0° or 90°.
- Fig. 5 Reflectance = 0.7 contour line of the MTB mode for a polarizer angle of 5° or 95°.
- Fig. 6 Reflectance = 0.7 contour line of the MTB mode for a polarizer angle of 10° or 100°.
- Fig. 7 Reflectance = 0.7 contour line of the MTB mode for a polarizer angle of 15° or 105°.
- Fig. 8 Reflectance = 0.7 contour line of the MTB mode for a polarizer angle of 20° or 110°.
- Fig. 9 Reflectance = 0.7 contour line of the MTB mode for a polarizer angle of 25° or 115°.
- Fig. 10 Reflectance = 0.7 contour line of the MTB mode for a polarizer angle of 30° or 120°.
- Fig. 11 Reflectance = 0.7 contour line of the MTB mode for a polarizer angle of 35° or 125°.
- Fig. 12 Reflectance = 0.7 contour line of the MTB mode for a polarizer angle of 40° or 130°.

Fig. 13 Reflectance = 0.7 contour line of the MTB mode for a polarizer angle of  $45^\circ$  or  $135^\circ$ .

Fig. 14 Reflectance = 0.7 contour line of the MTB mode for a polarizer angle of  $50^\circ$  or  $140^\circ$ .

Fig. 15 Reflectance = 0.7 contour line of the MTB mode for a polarizer angle of  $55^\circ$  or  $145^\circ$ .

Fig. 16 Reflectance = 0.7 contour line of the MTB mode for a polarizer angle of  $60^\circ$  or  $150^\circ$ .

Fig. 17 Reflectance = 0.7 contour line of the MTB mode for a polarizer angle of  $65^\circ$  or  $155^\circ$ .

Fig. 18 Reflectance = 0.7 contour line of the MTB mode for a polarizer angle of  $70^\circ$  or  $160^\circ$ .

Fig. 19 Reflectance = 0.7 contour line of the MTB mode for a polarizer angle of  $75^\circ$  or  $165^\circ$ .

Fig. 20 Reflectance = 0.7 contour line of the MTB mode for a polarizer angle of  $80^\circ$  or  $170^\circ$ .

Fig. 21 Reflectance = 0.7 contour line of the MTB mode for a polarizer angle of  $85^\circ$  or  $175^\circ$ .

Fig. 22 Reflectance = 0.7 contours for polarizer angles ranging from  $0$  to  $90^\circ$ .

Fig. 23 Reflectance dispersion curves for a few MTB modes.

Fig. 24 Measured (normalized) reflectance vs wavelength for the  $(70^\circ, 30^\circ, 0.31\mu\text{m})$  display.

Fig. 25 Measured (normalized) reflectance vs voltage for the  $(70^\circ, 30^\circ, 0.31\mu\text{m})$  display.

## DETAILED DESCRIPTION

The operation of the reflective LCD is completely determined by the twist angle  $\phi$ , the retardation value  $d\Delta n$  of the LC cell and the angle between the polarizer axis and the input director of the LC cell  $\alpha$ . Figs. 4-21 represents the 0.7 reflectance contours of all the possible  $(\alpha, \phi, d\Delta n)$  combinations. These are defined as the MTB modes.

Here we describe details of the method to obtain the constant reflectance contour lines as depicted in Figs. 2-21. The reflectance  $R$  is calculated by the equation

$$R = \left| (-\sin \alpha \cos \alpha) \cdot H \cdot M(\phi) \cdot H^{-1} \cdot M(-\phi) \cdot \begin{pmatrix} \cos \alpha \\ \sin \alpha \end{pmatrix} \right|^2 \quad (1)$$

where  $H$  is the rotation matrix

$$H = \begin{bmatrix} \cos \phi & \sin \phi \\ -\sin \phi & \cos \phi \end{bmatrix} \quad (2)$$

with  $\phi$  as the twist angle of the liquid crystal cell and  $\alpha$  as the polarizer angle between the polarizer and the input director of the liquid crystal cell.  $M$  is the Jones matrix of the liquid crystal cell given by

$$M = \begin{pmatrix} A - iB & -C - iD \\ C - iD & A + iB \end{pmatrix} \quad (3)$$

$$\text{where} \quad A = \cos \phi \cos \beta d + \frac{q}{\beta} \sin \phi \sin \beta d \quad (4)$$

$$B = \frac{k_a}{\beta} \cos \phi \sin \beta \quad (5)$$

$$C = \sin \phi \cos \beta d - \frac{q}{\beta} \cos \phi \sin \beta d \quad (6)$$

$$D = \frac{k_a}{\beta} \sin \phi \sin \beta d \quad (7)$$

In eq. (4)-(7),  $q = 2\pi/p$ , where  $p$  is the pitch of the LC cell; and

$$\beta = [k_a^2 + q^2]^{1/2} \quad (8)$$

For a twisted nematic cell, the pitch is related to  $\phi$  by

$$qd = \phi \quad (9)$$

Also  $k_a = \pi\Delta n/\lambda \quad (10)$

where  $\Delta n = n_e - n_o \quad (11)$

is the birefringence of the liquid crystals.

The  $R=0.7$  contour lines in Figs. 4-21 are obtained by setting  $R=0.7$  in equation (1).

Table II shows the optical properties of some of the new MTB modes obtained from the above procedure. It can be seen from Table II that for each twist angle, many combinations of  $d\Delta n$  and  $\alpha$  are possible to get a good contrast ratio. Also, not quite evident from Table II is the effect of changing  $\alpha$  on the dispersion characteristics of the MTB cell. It is observed that for twist angles smaller than  $70^\circ$ , both the bright and the dark states become more dispersive, and also the colour coordinates of the display shifts as the voltage is varied. So they are not quite desirable.

It should be emphasized that Table II is by no means an exhaustive list of all the optimal MTB operating conditions. As a matter of fact, there are an infinite number of combinations of conditions as shown in Figs. 3-5 for the MTB mode. If one were to sacrifice the peak reflectance, the solution space for the MTB will open up even wider, leading to more possibilities.

Fig. 23 shows the wavelength dependent reflectance of both the on and off states for some of the MTB modes invented here. These modes are selected because they have either (1) low wavelength dispersion, or (2) high contrast upon application of a voltage, or (3) reasonably large cell gaps so that manufacturing is possible. The values of  $(\alpha, \phi, d\Delta n)$  for the curves are, from the top,  $(26^\circ, 43^\circ, 0.35\mu\text{m})$ ,  $(30^\circ, 50^\circ, 0.35\mu\text{m})$ ,  $(34^\circ, 54^\circ, 0.35\mu\text{m})$ ,  $(40^\circ, 63^\circ, 0.35\mu\text{m})$  respectively.

To verify the theoretical simulations, sample cells were made and tested. A sample cell was made with cell parameters of  $(30^\circ, 70^\circ, 0.31\mu\text{m})$ . Liquid crystal model number ZLI-1695 from E. Merck with a low  $\Delta n$  of 0.0625 was used in order to increase the cell gap. The experimental cell gap was  $5\mu\text{m}$ , giving a  $d\Delta n$  of  $0.3175\mu\text{m}$ , which is quite close to the targeted design value. Standard rubbed polyimide films were used to align the LC molecules to form the  $70^\circ$  twist cell. The accuracy of the twist angle is better than  $1^\circ$  due to the equipment used. The LC cell has indium-tin-oxide as the transparent electrodes on one side and aluminum coated glass as the reflective electrode on the other side.

Fig. 24 shows the experimental reflectance-voltage curve of this new MTB mode under *white light* illumination. From this figure, we can find that there is a good dark state at 3.6V. There is also a slight increase in the reflectance at 1.2V. The operation voltage for the dark state is only 2.5V which is well suitable for CMOS AMLCD applications<sup>3</sup>.

Fig. 25 shows the experimental reflectance vs wavelength of this MTB mode. The vertical scale is normalized to the peak value. It can be seen that at long wavelengths, the reflectance agrees with the theoretical simulation quite well. At short wavelengths, however, there is some deviation from the theory. This is because the PBS used in the experiment has poor optical characteristics in this wavelength range. Another reason is that the cell thickness was not exactly  $5\mu\text{m}$ . The actual cell thickness was measured to be about  $5.2\mu\text{m}$ . So its real  $d\Delta n$  was about  $0.325\mu\text{m}$ .

In addition to the low operating voltage, the 5  $\mu\text{m}$  cell gap is also a comfortable value for cell fabrication. In particular, it is suitable for crystalline silicon based CMOS LCD. The uniformity requirement should also be easy to satisfy for such large cell gaps. Further experiments will focus on the cell thickness of about 4.5  $\mu\text{m}$ . We believe that this smaller cell gap will further lower the cell color dispersion and operating voltage.

Table I. Normal states of various combinations

|                                                | //-// polarizers (sheet type) | //- $\perp$ polarizers (PBS) |
|------------------------------------------------|-------------------------------|------------------------------|
| In-well modes (TN-ECB, MTB, MTN, Figure 6SCTN) | Normally black                | Normally white               |
| Out-well modes (HFE, RTN, RSTN)                | Normally white                | Normally black               |

Table II. Reflectance for several MTB modes.

| Twist angle | Polarizer angle | $d\Delta n$ ( $\mu\text{m}$ ) | Reflectance |
|-------------|-----------------|-------------------------------|-------------|
| 50°         | 28°             | 0.35                          | 1.0         |
| 50°         | 35°             | 0.36                          | 1.0         |
| 50°         | 25°             | 0.35                          | 0.94        |
| 60°         | 25°             | 0.32                          | 1.0         |
| 60°         | 35°             | 0.35                          | 0.97        |
| 60°         | 30°             | 0.34                          | 1.0         |
| 70°         | 30°             | 0.31                          | 1.0         |
| 70°         | 25°             | 0.30                          | 1.0         |
| 70°         | 36°             | 0.34                          | 0.95        |
| 80°         | 30°             | 0.3                           | 0.9         |
| 80°         | 20°             | 0.26                          | 0.97        |
| 80°         | 21°             | 0.28                          | 1.0         |
| 90°         | 25°             | 0.26                          | 0.87        |
| 90°         | 30°             | 0.3                           | 0.83        |
| 90°         | 20°             | 0.24                          | 0.9         |



# CLAIMS



1. A single polariser reflective liquid crystal display device with an angle  $\alpha$  between the polariser and the input director of the liquid crystal device, twist angle  $\phi$ , retardation  $d\Delta n$ , and characterised in that the values for  $\alpha$ ,  $\phi$  and  $d\Delta n$  satisfy the following equation:

$$0.7 \leq \left| (-\sin \alpha \cos \alpha) \cdot H \cdot M(\phi) \cdot H^{-1} \cdot M(-\phi) \cdot \begin{pmatrix} \cos \alpha \\ \sin \alpha \end{pmatrix} \right|^2 \quad (1)$$

where H is the rotation matrix

$$H = \begin{bmatrix} \cos \phi & \sin \phi \\ -\sin \phi & \cos \phi \end{bmatrix} \quad (2)$$

where M is the Jones matrix of the liquid crystal cell given by

$$M = \begin{pmatrix} A - iB & -C - iD \\ C - iD & A + iB \end{pmatrix} \quad (3)$$

$$\text{where } A = \cos \phi \cos \beta d + \frac{q}{\beta} \sin \phi \sin \beta d \quad (4)$$

$$B = \frac{k_e}{\beta} \cos \phi \sin \beta \quad (5)$$

$$C = \sin \phi \cos \beta d - \frac{q}{\beta} \cos \phi \sin \beta d \quad (6)$$

$$D = \frac{k_e}{\beta} \sin \phi \sin \beta d \quad (7)$$

In eq. (4)-(7),  $q = 2\pi/p$ , where  $p$  is the pitch of the LC cell; and

$$\beta = [k_s^2 + q^2]^{1/2} \quad (8)$$

and the pitch is related to  $\phi$  by

$$qd = \phi \quad (9)$$

Also  $k_z = \pi \Delta n / \lambda$  (10)

where  $\Delta n = n_e - n_o$  (11)

2. A single polarizer liquid crystal display device according to Claim 1, characterised by an angle of  $0 \pm 2^\circ$  or  $90 \pm 2^\circ$  between the polarizer and the input director of the liquid crystal cell, and by a twist angle  $\phi$  and retardation  $d\Delta n$  given by values bounded by  $R=0.7$  contour lines.

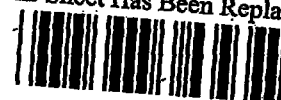
3. A single polarizer liquid crystal display according to Claim 1, characterised by an angle of  $5 \pm 2^\circ$  or  $95 \pm 2^\circ$  between the polarizer and the input director of the liquid crystal cell, and by a twist angle  $\phi$  and retardation  $d\Delta n$  given by values bounded by  $R=0.7$  contour lines.

4. A single polarizer liquid crystal display device according to Claim 1, characterised by an angle of  $10 \pm 2^\circ$  or  $100 \pm 2^\circ$  between the polarizer and the input director of the liquid crystal cell, and by a twist angle  $\phi$  and retardation  $d\Delta n$  given by values bounded by  $R=0.7$  contour lines.

5. A single polarizer liquid crystal display device according to Claim 1, characterised by an angle of  $15 \pm 2^\circ$  or  $105 \pm 2^\circ$  between the polarizer and the input director of the liquid crystal cell, and by a twist angle  $\phi$  and retardation  $d\Delta n$  given by values bounded by the  $R=0.7$  contour lines.



6. A single polarizer liquid crystal display device according to Claim 1, characterised by an angle of  $20 \pm 2^\circ$  or  $110 \pm 2^\circ$  between the polarizer and the input director of the liquid crystal cell, and by a twist angle  $\phi$  and retardation  $d\Delta n$  given by values bounded by  $R=0.7$  contour lines.
7. A single polarizer liquid crystal display device according to Claim 2, characterised by an angle of  $25 \pm 2^\circ$  or  $115 \pm 2^\circ$  between the polarizer and the input director of the liquid crystal cell, and by a twist angle  $\phi$  and retardation  $d\Delta n$  given by values bounded by  $R=0.7$  contour lines.
8. A single polarizer liquid crystal display device according to Claim 1, characterised by an angle of  $30 \pm 2^\circ$  or  $120 \pm 2^\circ$  between the polarizer and the input director of the liquid crystal cell, and by a twist angle  $\phi$  and retardation  $d\Delta n$  given by values bounded by  $R=0.7$  contour lines.
9. A single polarizer liquid crystal display device according to Claim 1, characterised by an angle of  $35 \pm 2^\circ$  or  $125 \pm 2^\circ$  between the polarizer and the input director of the liquid crystal cell, and by a twist angle  $\phi$  and retardation  $d\Delta n$  given by values bounded by  $R=0.7$  contour lines.
10. A single polarizer liquid crystal display device according to Claim 1, characterised by an angle of  $40 \pm 2^\circ$  or  $130 \pm 2^\circ$  between the polarizer and the input director of the liquid crystal cell, and by a twist angle  $\phi$  and retardation  $d\Delta n$  given by values bounded by  $R=0.7$  contour lines.
11. A single polarizer liquid crystal display device according to Claim 1, characterised by an angle of  $45 \pm 2^\circ$  or  $135 \pm 2^\circ$  between the polarizer and the input director of the liquid crystal cell, and by a twist angle  $\phi$  and retardation  $d\Delta n$  given by values bounded by  $R=0.7$  contour lines.





12. A single polarizer liquid crystal display device according to Claim 1, characterised by an angle of  $50 \pm 2^\circ$  or  $140 \pm 2^\circ$  between the polarizer and the input director of the liquid crystal cell, and by a twist angle  $\phi$  and retardation  $d\Delta n$  given by values bounded by  $R=0.7$  contour lines.

13. A single polarizer liquid crystal display device according to Claim 1, characterised by an angle of  $55 \pm 2^\circ$  or  $145 \pm 2^\circ$  between the polarizer and the input director of the liquid crystal cell, and by a twist angle  $\phi$  and retardation  $d\Delta n$  given by values bounded by  $R=0.7$  contour lines.

14. A single polarizer liquid crystal display device according to Claim 1, characterised by an angle of  $60 \pm 2^\circ$  or  $150 \pm 2^\circ$  between the polarizer and the input director of the liquid crystal cell, and by a twist angle  $\phi$  and retardation  $d\Delta n$  given by values bounded by  $R=0.7$  contour lines.

15. A single polarizer liquid crystal display device according to Claim 1, characterised by an angle of  $65 \pm 2^\circ$  or  $155 \pm 2^\circ$  between the polarizer and the input director of the liquid crystal cell, and by a twist angle  $\phi$  and retardation  $d\Delta n$  given by values bounded by  $R=0.7$  contour lines.

16. A single polarizer liquid crystal display device according to Claim 1, characterised by an angle of  $70 \pm 2^\circ$  or  $160 \pm 2^\circ$  between the polarizer and the input director of the liquid crystal cell, and by a twist angle  $\phi$  and retardation  $d\Delta n$  given by values bounded by  $R=0.7$  contour lines.

17. A single polarizer liquid crystal display device according to Claim 1, characterised by an angle of  $75 \pm 2^\circ$  or  $165 \pm 2^\circ$  between the polarizer and the input director of the liquid crystal cell, and by a twist angle  $\phi$  and retardation  $d\Delta n$  given by values bounded by  $R=0.7$  contour lines.





18. A single polarizer liquid crystal display device according to Claim 1, characterised by an angle of  $80 \pm 2^\circ$  or  $170 \pm 2^\circ$  between the polarizer and the input director of the liquid crystal cell, and by a twist angle  $\phi$  and retardation  $d\Delta n$  given by values bounded by  $R=0.7$  contour lines.

19. A single polarizer liquid crystal display device according to Claim 1, characterised by an angle of  $85 \pm 2^\circ$  or  $175 \pm 2^\circ$  between the polarizer and the input director of the liquid crystal cell, and by a twist angle  $\phi$  and retardation  $d\Delta n$  given by values bounded by  $R=0.7$  contour lines.

20. A single crystal polarizer liquid crystal display device, according to any preceding claim, characterised by indium-tin oxide as transparent electrode and aluminium coated glass as reflective electrode.

21. A single crystal polarizer liquid crystal display device according to Claim 20, characterised by comprising a  $70^\circ$  twist cell.

This Sheet Has Been Replaced

