Design and fabrication of reflective nematic displays with only one polarizer

H. S. Kwok¹, F. H. Yu², S. T. Tang and J. Chen

Center for Display Research and Department of Electrical and Electronic Engineering
The Hong Kong University of Science & Technology, Clear Water Bay, Hong Kong

ABSTRACT

Reflective LCDs (RLCDs) have high brightness and are free from viewing parallax. They also cost less materials to construct and are compatible with existing manufacturing and driving practices. In this paper, a parameter space description of RLCD as a function of polarizer angle, liquid crystal twist angle and birefringence is discussed. It is shown that all published RLCD modes can be depicted in this parameter space, including the twisted-nematic-electrically controlled birefringence (TN-ECB) modes, the hybrid field effect (HFE) mode, the mixed-mode TN (MTN), and the self-compensated TN (SCTN) mode. Additionally we show several new RLCD modes, including the reflective TN (RTN) and the reflective STN (RSTN) which can be obtained from searching the parameter space systematically. All RLCD modes are related by a variation of the 3 LCD parameters. The RTN and RSTN modes have applications to both direct view and projection display systems. Sample RTN and RSTN displays were fabricated. Experimental results show good agreement with theoretical predictions.

Key Words Parameter space, reflective liquid crystal displays, TN-ECB, HFE, MTN, SCTN, RTN, RSTN

Fig.1 The configuration of RLCD for the projection with polarization beam splitter (PBS)

Fig. 2 Structure of RLCD with single polarizer and no retardation film

¹ H. S. Kwok: Email: eekwok@usthk.ust.hk.

² F. H. Yu: Permanent address: State Key Laboratory, Department of Optical Engineering, Zhejiang University, Hangzhou, P. R. China

INTRODUCTION

The simplest reflective liquid crystal display (RLCD) consists of just an input polarizer (a sheet or a prism beam splitter), an LC cell and a rear reflector which can be placed inside or outside the LC cell (Fig. 1 and Fig. 2). These RLCDs have many advantages, such as increased brightness, less material consumption and elimination of parallax. Many different RTN modes have been published in the literature. Examples include:

- (1) The 45° and 90° hybrid field effect (HFE) mode which was widely used in LCLV projection systems.^[1,2] The output is elliptically polarized.
- (2) The twist nematic-electrically controlled birefringence (TN-ECB) mode with twist angles given by $f = \pm (2N - 1)\pi / 2\sqrt{2}$ where N is an integer^[3-7]. The twist angles of the TN-ECB mode are therefore $\pm 63^\circ$, $\pm 200^\circ$ and $\pm 310^\circ$ etc. The TN-ECB modes are improvements over the HFE modes in that the output light is linearly polarized and therefore have 100% efficiency. However, for white light input, this TN-ECB mode is quite color dispersive. The first TN-ECB minimum at 63° has the best performance in terms of contrast and color dispersion. However, it requires a very small $d\Delta n$ value ($0.19\mu\text{m}$) which makes the LC cell difficult to fabricate.
- (3) The recently discovered mixed-TN (MTN) mode^[8-9] with $\phi = 90^\circ$ and $d\Delta n = 0.25\mu\text{m}$ has excellent color dispersion properties and high contrast. However, it has to operate in the normally dark mode and a quarter wave retardation film (or a PBS) is needed to make it normally white. The light efficiency is relatively low and its $d\Delta n$ value is also rather small for cell fabrication.
- (4) The self-compensated TN (SCTN) mode^[10] has a twist angle of near 60° and a moderate $d\Delta n$ value. Its advantage is a lower operating voltage, at the expense of rather large color dispersions.
- (5) It is possible to compensate for the strong color dispersion of TN-ECB modes by placing a retardation film either between the liquid crystal cell and the rear reflector^[11], or between the polarizer and the LC cell^[12,13]. These designs can be called film-compensated RLCDs. In the former design, highly nondispersive reflective displays can be made. But it does not allow the reflector to be placed inside the liquid crystal cell and thus a big advantage of reflective displays is lost. The second design allows the LC cell and the rear reflector to be integrated, but full compensation is difficult to achieve. Recently Fukuda et al have successfully analyzed and demonstrated such displays^[12,13].

In this paper, we shall introduce our recently developed parameter space representation^[14] to obtain more RLCD modes. It will be seen that 2 different normally white modes are found. The low twist case will be called the RTN mode, while the high twist case will be called the RSTN mode. The RTN mode has excellent optical properties in terms of brightness and color dispersion. This RTN mode has a low twist of 52° . It also has a mild reflectance-voltage behavior and is suitable for active matrix LCD. Moreover, its optical efficiency is higher than that of the HFE mode. A major application can be in reflective active matrix displays that do not require any backlighting. The RSTN modes have high twist angles of near 200° and 240° . They have sharp reflectance-voltage characteristics and are suitable for high multiplex displays. They are ideal replacements of ordinary STN displays for passive matrix direct view applications.

In this paper, an optimization of the MTN mode is also presented. The optimized MTN modes have higher light efficiency. We also present a modified SCTN mode that operates at lower voltages at the dark state and has a larger and thus more practical cell gap ($5\mu\text{m}$ when $\Delta n = 0.065$). This new mode also has low color

dispersion. It is a variation of the TN-ECB mode and is quite suitable for CMOS driven LCD where the second polarizer cannot be attached.

Fig. 3 The ϕ - $d\Delta n$ parameter space for RLCDs. The contour lines of constant reflectance are in steps of 0.01 and varies from 0° to 45°

PARAMETER SPACE

Optical modeling of liquid crystal displays ^[14, 15-28] is very important both from a fundamental point of view and for practical applications. In a previous work, we proposed a new systematic method called parameter space representation ^[14] to depict LCD operating conditions. Since the optical properties of a LCD depends mainly on the

birefringence $d\Delta n$, the twist angle ϕ of the LC cell, and the angle α between the input polarizer and the input director, it is therefore possible to plot the reflectance (or transmittance) of a display in a $(\alpha, \phi, d\Delta n)$ parameter space. Using the simple Jones matrix, the parameter space can be calculated depicting the dependence of the reflectance on the various cell parameters systematically. As we have demonstrated, all types of LCDs which are based on light polarization manipulation can be analyzed in this manner. It serves as a very fast analytical tool for the design and optimization of LCDs. At the same time it can provide a clear physical understanding of various display modes.

In reflective LCDs, the back polarizer is eliminated and a rear mirror is used as reflector either inside or outside the LC cell. The geometry for this case is very simple and the reflectance Jones matrix can be calculated in a straight-forward manner. As mentioned above, the RLCD has 3 major variables: ϕ , α and $d\Delta n$. Any 2 of these variables can be used to generate a parameter space of the reflectance in a contour plot or a 3D plot. The most revealing parameter space is obtained by fixing α and plotting the reflectance of the RLCD as a function of ϕ and $d\Delta n$. The different operating modes can be visualized in the static ($V = 0$) condition in such parameter spaces.

Fig. 3 shows the ϕ - $d\Delta n$ parameter space diagram of RLCDs for $\alpha = 0^\circ, 15^\circ, 30^\circ$, and 45° respectively. The contour lines are lines of constant reflectance. For a single sheet polarizer, zero reflectance occurs near the center of the various “wells”. These minima are called the TN-ECB modes ^[3-7]. For example, for $\alpha = 0$, the wells of minimum reflectance are symmetrically placed about $\phi = 0$. It can be seen that when α is increased, the TN-ECB modes move towards the center of the parameter space diagram as shown, with the positive and negative modes interleaving each other. The parameter space becomes asymmetrical. At $\alpha = 45^\circ$, the interleaving is complete and the TN-ECB minima are all along $\phi = 0$. They are now exactly the normal ECB modes! Though not shown in Fig. 3, as α increases further, the TN-ECB modes begin to slide in the same direction. The $\alpha = 60^\circ$ parameter space is exactly the same as the $\alpha = 30^\circ$ diagram, except that it is inverted about $\alpha = 0^\circ$. Likewise the $\alpha = 90^\circ$ parameter space is exactly the same as the $\phi = 0^\circ$ parameter space. All possible display modes can be identified on these parameter space diagrams. They are indicated in Fig. 3. The MTN and SCTN modes are located in the center of the TN-ECB wells, while the others such as the HFE, RTN and RSTN modes are located in the unity reflectance regions outside the wells. Hence the MTN and SCTN modes are normally black (NB) while the others are normally white (NW). Recently we have developed a chromatic parameter space approach which shows that the high order TN-ECB modes have much larger color dispersion ^[29]. Therefore only the first order TN-ECB modes are good choices for B/W operation.

In Fig. 3, the new RTN and RSTN modes are shown. They are reflective modes that have not been discovered before. In particular, the RSTN mode shows great promise as a practical high information content display mode for passive matrix LCD. These new RLCD modes will be described below.

In the RLCD, the input and output polarizers can either be in a $//$ - $//$ geometry or in a $//$ - $\perp$ geometry. For direct view applications, the input and output polarizers are the same, so the polarizers will have to be a $//$ - $//$ geometry. In both cases, the display can also be operated in the normally white (NW) or normally black (NB) modes. These 4 combinations of $//$ - $//$, $//$ - $\perp$ polarizer geometry and NB/NW conditions are related to each other by a quarterwave retardation plate, or by a proper rotation of the polarizer.

RTN MODE

We performed a systematic search for the optimal operating conditions of the 3 LCD parameters by generating a 2D parameter space diagram in $d\Delta n$ and α for each value of twist angle ϕ . There are many combinations of $d\Delta n$ and α that will give a reflectance of 0%. The optimal condition is then further refined by finding a $(d\Delta n, \alpha)$ combination that will produce a broad $R = 0\%$ region for different wavelengths when a voltage

is not applied and that will produce a high reflectance when a voltage is applied. Also the dispersion characteristics of the voltage-on state should be as nondispersive as possible.

Fig. 4 Simulated RVC of the 45° HFE and RTN LCD.

Fig. 5 Calculated reflectance spectra of the RTN and 45° HFE LCD.

Fig. 6 Experimental RVCs of 45° and RTN sample cells.

Fig. 7 Experimental reflectance spectra of the RTN and 45° HFE cells.

In order to obtain the reflectance-voltage curve (RVC), we followed the standard procedure for LC modeling: first the 1D Euler-Lagrange equations for the director deformation were solved to give the director angles $\phi(z)$ and $\theta(z)$ for all values of z inside the cell. Then the reflectance was calculated by dividing the cell into many layers and treating each layer as a birefringent plate, and multiplying together all the Jones matrices.

Fig. 4 shows one example of such a calculation using $\phi = 45^\circ$ (HFE) and 52° (RTN), and $d\Delta n = 0.54\mu\text{m}$. The values of the elastic constants used for this calculation are those of a typical liquid crystal with a pretilt angle of 1° . It can be seen that a threshold voltage of 1.5V is obtained, followed by a increase in reflectance. When the voltage is 2.6V, the maximum reflectance for both the 52° and 45° cells is obtained. From Fig. 4, we find that the

reflectance of the optimal cell is 10% greater than that of the 45° cell. A wavelength of 550 nm is assumed in this calculation.

The complete reflectance vs. wavelength curves are shown in Fig. 5 for both the field-off state (0V) and the field-on state (2.6V). From Fig. 5, we find at the field-off state, the reflectance vs. wavelength of both curves are identical. But at the field-on state, the reflectance of the RTN cell is 10% greater than that of the cell.

Fig. 8 The maximum reflectance of MTN with different twist angle f

To verify our theoretical simulation, two groups of sample cells were fabricated, one with 52° twist and the other with 45° twist. Their measured RVCs for 514nm wavelength are shown in Fig. 6. Also their reflectance vs. wavelength curves are shown in Fig. 7. The agreement between theory and experiment is good. The slight deviation in the threshold voltage is because of the refractive index uncertainty.

OPTIMIZED MTN MODE

The MTN mode is normally black as shown in Fig. 3. There are also 3 parameters ($f, a, d\Delta n$) for the MTN cell. For a given twist angle f , we used a 2-D search within a proper range of ($a, d\Delta n$) for finding the best operating points of the MTN display. Fig. 8 shows the 1st order maximum reflectance of the MTN display as a function of the twist angles f . From Fig. 8, it can be seen that the efficiency of the

MTN mode decreases gradually when the twist angle is larger

than 70° . Moreover, it is found that for low twist angles, the $d\Delta n$ required becomes quite small. This will lead inevitably to difficult cell fabrication as well as a poor dark state. So we shall concentrate on the range of $f = 60^\circ \sim 90^\circ$ for optimizing the MTN mode. For the ideal case of no light loss, $f = 90^\circ$ yields a reflectance of 89%, while for the $f = 80^\circ$ MTN cell, 97% reflectance is obtained.

Fig. 9 shows the $\alpha-d\Delta n$ parameter space for the MTN mode. The contour lines of constant reflectance are in steps of 0.1. The values of ϕ are 60° , 70° , 80° , and 90° respectively. A, B, C and D are the possible static operating points of the 60° , 70° , 80° , and 90° MTN cells. Through the further refinement, we select some best operating points for different twist angles. Their ($f, a, \Delta n$) values are $(60^\circ, -5^\circ, 0.19)$, $(70^\circ, 7^\circ, 0.22)$, $(80^\circ, 15^\circ, 0.24)$ and $(90^\circ, 20^\circ, 0.25)$. The optimization wavelength is 550nm. The Δn values are given in μm .

Fig.10 shows the reflectance vs. wavelength characteristic of these cells. From Fig.10 we find that at the voltage-off state the RVCs for the cells of 60° , 70° , 80° , are about 10% higher than that of the 90° cell. Moreover, it can be seen that in all cases, the dark states are very nondispersive, which is a major characteristic and advantage of the MTN mode^[9].

We plot the RVCs of the $(80^\circ, 15^\circ, 0.24)$ MTN cell in Fig. 11. R, G and B represent red, green and blue lights at 650nm, 550nm and 450nm respectively. Compared with the RVCs of the 90° MTN cell, we find that the reflectance of 80° MTN in Fig.11 is higher while the dispersion is similar. Thus, the light efficiency of the 80° MTN cell (40% for G light) is higher than that of the 90° MTN cell (35% for G light). The RVCs of the 60° and 70° MTN cells have also been simulated. Their reflectance is also higher than that of 90° MTN cell, but their voltage-on states are not very dark and also their $d\Delta n$ values are too small to fabricate. After considering these constraints, we believe that $(80^\circ, 15^\circ, 0.24)$ represents the optimal MTN cell.

Fig. 9 α - $d\Delta n$ parameter space for RLCDs. The contour lines of constant reflectance are in steps of 0.1. The values of ϕ are fixed at 60° , 70° , 80° , and 90° respectively.

To verify the theoretical simulation, sample cells for the optimal 80° and the 90° MTN cells were made. We used a mixture of MLC 5300 and MLC 5400 to get the exact Δn . The cell gap was controlled by $2.2\mu\text{m}$ spacers. Fig.12 shows the spectral responses of these sample cells. In Fig.13, the RVCs for white light are also given. From Fig.12 and Fig.13, we found that the optimal 80° MTN cell has 10% higher light efficiency than that of 90° MTN cells.

For the MTN mode, the largest $d\Delta n$ is about $0.24\mu\text{m}$ for the 90° MTN cell. The smallest $d\Delta n$ is about $0.18\mu\text{m}$ for the 60° MTN cell. When the cell twist angle becomes smaller, the operating voltage becomes higher and higher. For the 60° , 70° , 80° and 90° MTN cells, through numerical simulations, we found that when the

Fig.10 Reflectance vs. wavelength relation at the voltage-off and voltage-on states

Fig. 11 Reflectance vs. voltage relation of (80°, 15°, 0.24) cell

Fig.12 The experimental RVCs of optimal and 90° MTN cells at voltage-on and off states.

Fig.13. The experimental RVCs of the optimal and 90° MTN cells for white light

dark state operating voltage is 4V, their white light contrast ratio will be 15, 21, 32 and 65 respectively. If we increase the operating voltage to 6 V, their white light contrast ratio will be 37, 53, 78 and 116 respectively. Such thin cell gap (normally about 2-3 μ m) cannot usually operate at such voltages due to cell shorting. Special techniques

Voltage Cell parameters	4V	5V	6V
70°, 0.28, 22°	36	68	74
70°, 0.31, 30°	74	96	106
70° MTN	20	37	52
90° MTN	65	103	115
60° SCTN	76	100	111

Table 1 Contrast ratios of different cells under operating voltages of 4V, 5 V, and 6 V.

have to be adopted to eliminate the electrical shorting problem. The thin cell gap also makes the cell difficult to manufacture. The high dark state operating voltage also makes the cost of the LCD driver higher. Thus, new RLCD with thicker cell gaps and lower operating voltages should be developed.

Recently, Yang proposed a new SCTN mode ^[10]. In this SCTN mode, the dark state can be obtained at a low operating voltage. However, the color dispersion for this SCTN cell is quite serious. Actually, the SCTN mode is the same as the MTN mode except that a different TN-ECB maximum is used as the static operating point as indicated in Fig. 3. Fig. 9 shows the static working point (point A') of the SCTN mode. As seen in Fig. 9, the positive and negative TN-ECB modes (A' and A) merge into one region. Any point in this A-A' region and likewise the B-B' region can serve as the static operating point for the SCTN mode. The RVCs of the cells with the parameters (70°, 30°, 0.31) and (60°, 30°, 0.33) are plotted in Fig. 14 and Fig. 15 respectively. Fig. 15 actually corresponds to the SCTN mode of Yang, while Fig. 14 corresponds to a new “hybrid” TN-ECB mode.

Fig.14 Reflectance vs. voltage relation of different parameters combinations(70°, 30°, 0.31)

Fig.15 Reflectance vs. voltage relation of different parameters combinations(60°, 30°, 0.33)

Comparing the RVCs in Fig. 14 and 15, we find that the color dispersion of the new TN-ECB is much better than that of the SCTN. As a comparison, we list the contrast ratios of the MTN, SCTN and TN-ECB cells under different operating voltages in Table 1. One can select different parameter combinations to satisfy various needs of either low operating voltage or high contrasts. When $d\Delta n = 0.31\mu\text{m}$, for $\Delta n = 0.065$, the cell gap will be $5\mu\text{m}$, which is easily manufacturable. The dark operating voltage will be 4 V for a 74 contrast ratio.

RSTN MODE

By varying α , ϕ and $d\Delta n$ near the second TN-ECB minimum, it is possible to obtain a NW reflective mode with 100% light efficiency and low dispersion. In searching the parameter space, we concentrate on ϕ near 200-240° since this corresponds nearly to the common STN mode. The same optimization procedure as the RTN was used in optimizing the RSTN. Fig. 16 shows the calculated and experimental RVC for such an optimized RSTN. The experimental cell was fabricated in the usual manner with a 4-bottle LC system in order to adjust the $d\Delta n$ value. It can be seen that the RVC of the RSTN is rather sharp. A steepness coefficient of 1.2 can be obtained implying a

multiplexing capability of 30 lines. The threshold voltage is also reasonable. This RSTN therefore should be useful for pagers and PDA applications.

Figure 17 shows the dispersion curve for this RSTN. The dotted line is the experimental result while the solid line is the theoretical simulation. It can be seen that the agreement between them is rather good. More importantly, it can be noted that the RSTN is much more wavelength independent than a comparable STN display without film compensation. Typically the yellow mode of a STN has a 50% variation in reflectance in the visible. The RSTN on the other hand has only a 20% variation. Hence the RSTN can be used to make a good B/W display.

Fig.16 Comparison of experimental and theoretical RVC for the RSTN display.

Fig.17 Comparison of experimental and theoretical reflectance spectra for the RSTN display.

Fig.18 The reflectance vs voltage curve using the conditions of point A in Fig.2

Fig.19 The complete RWCs for the voltage of 2.25 V, 2.30 V, 2.40 V, 2.50 V and 2.55 V using the conditions of point A in Fig.2

For higher mux numbers, the 200° cell does not provide a steep enough RVC. Fig.18 shows the case of a 240° twist cell with $d\Delta n = 0.85\mu\text{m}$ and $\alpha = 6^\circ$. It can be seen that a threshold voltage of 2.25V is obtained, followed by a sharp drop in reflectance. The steepness of this RVC is good enough for multiplex applications similar to transmissive STN. The V_{ns} is about 2.25 V and $V_s = 2.55$ V. Thus $V_s/V_{\text{ns}} \leq 1.13$, implying that a 100 lines multiplexing panel can be obtained. Another important observation about Fig. 18 is that R reaches to nearly 0% over a wide voltage range. Green light at 550 nm was assumed in this calculation. The complete reflectance spectra are shown in Fig. 19 for of 2.25 V, 2.30 V, 2.40 V, 2.50 V and 2.55 V respectively. It shows much lower dispersion as compared to conventional STN displays.

The significance of the results presented in Fig. 16-19 is that (1) A good contrast can be obtained with this new RSTN display. (2) The dispersion of the reflectance is excellent. It is better than transmissive STN LCD without film compensation. (3) High multiplexing of 100 lines can be obtained. We believe that after further optimization, higher multiplexing can be possible. This RSTN can replace conventional STN in many applications.

CONCLUSIONS

In this paper, we showed that by introducing the recently developed parameter space diagrams ^[14], many reflective twisted nematic modes that have excellent optical properties could be found. These new modes are related to the literature RLCD modes through a systematic variation of the LCD parameters. For the low twist case, it is called the RTN mode. This RTN has a mild reflectance-voltage behavior and is suitable for active matrix LCD. It is also ideally suitable for reflective projection displays.

The higher twist angle RSTN modes have twist angles near 200° and 240° . They are highly multiplexable and are suitable for passive matrix direct view LCD. Unlike the MTN mode, they do not require any quarterwave retardation plates for NW operation. Hence single polarizer sheet can be used in making a reflective display without backlighting. This display mode is suitable for PDA and pager applications.

We also showed an optimization of the MTN mode in this paper. The optimized MTN cell have high light throughput efficiency. In order to lower the operating voltage of the dark state and increase the cell gap, we also presented a modified SCTN mode which is just another TN-ECB mode. This new TN-ECB has large cell gap, low color dispersion and low operating voltage. It is quite suitable for crystal silicon CMOS driven active matrix LCD where the second polarizer cannot be applied.

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