Design and fabrication of reflective nematic displays with only one polarizer

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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

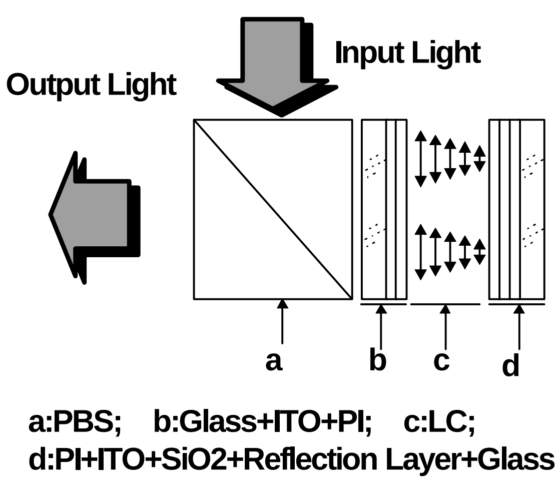

Fig.1 The configuration of RLCD for the projection with polarization beam spilitter (PBS)

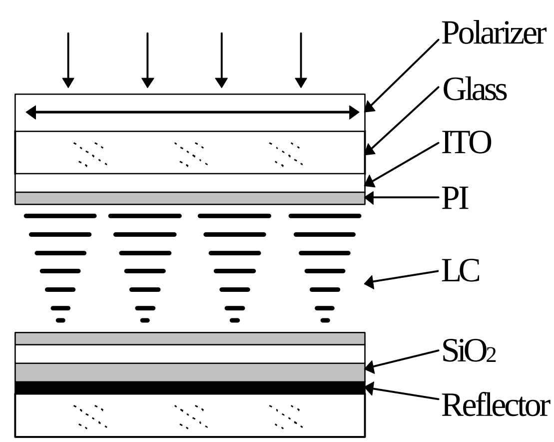

Fig. 2 Structure of RLCD with single polarizer and no retardation film

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INTRODUCTION

The simplest reflective liquid crystal display (RLCD) consists of just an i nput 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^o and 90^o 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 $f = \pm (2N-1)p / 2\sqrt{2}$ where N is an integer [3-7]. The twist angles of the TN-ECB mode are therefore $\pm 63°$, $\pm 200°$ and $\pm 310°$ 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 μm) which makes the LC cell difficult to fabricate.

(3) The recently discovered mixed-TN (MTN) mode [8-9] with ϕ = 90^o and $d\Delta n$ = 0.25 μm 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^o 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^o. It also has a mild reflectance-voltage behavior and is suitable for active matrix LCD. Moreover, its optical efficiency is higher that 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^o and 240^o. 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 se 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 μm 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.

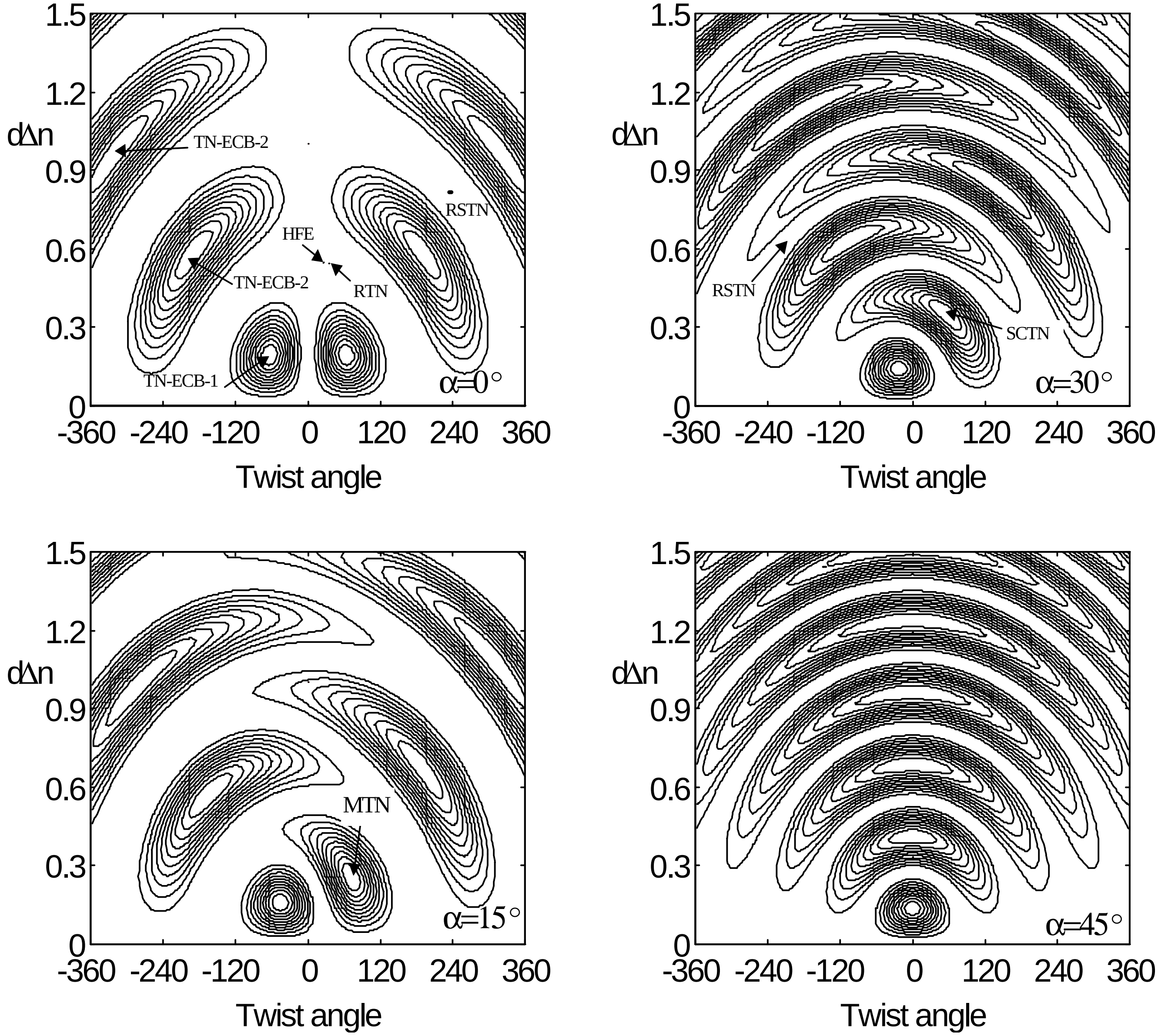

Fig. 3 The ϕ-dΔn parameter space for RLCDs. The contour lines of constant reflectance are in steps of 0.1. α varies from 0° to 45°

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 dΔn, 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 (α, φ, dΔn) 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 dΔn. The different operating modes can be visualized in the static (V = 0) condition in such parameter spaces.

Fig. 3 shows the φ-dΔn parameter space diagram of RLCDs for α = 0°, 15°, 30°, 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 α = 0, the wells of minimum reflectance are symmetrically placed about φ = 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 α = 45°, the interleaving is complete and the TN-ECB minima are all along φ = 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 α = 60° parameter space is exactly the same as the α = 30° diagram, except that it is inverted about α = 0°. Likewise the α = 90° parameter space is exactly the same as the φ = 0° 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 an output polarizers can either be in a //-// geometry or in a //-⊥ 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 //-//, //-⊥ 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 ($d\Delta n$, α) 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.

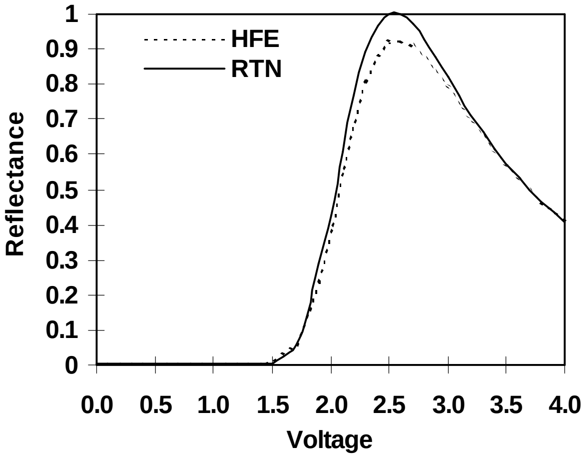

Fig. 4 Simulated RVC of the 45° HFE and RTN LCD.

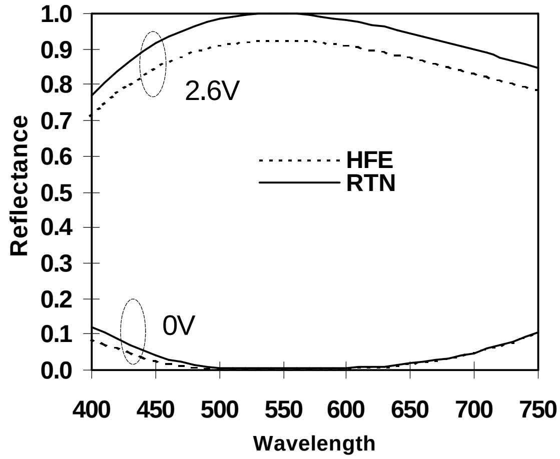

Fig. 5 Calculated reflectance spectra of the RTN and 45° HFE LCD.

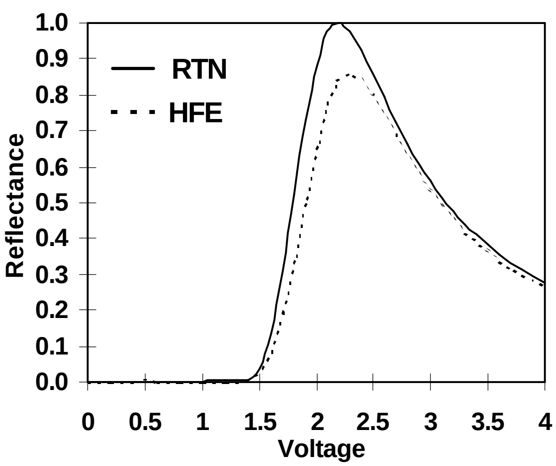

Fig. 6 Experimental RVCs of 45° and RTN sample cells.

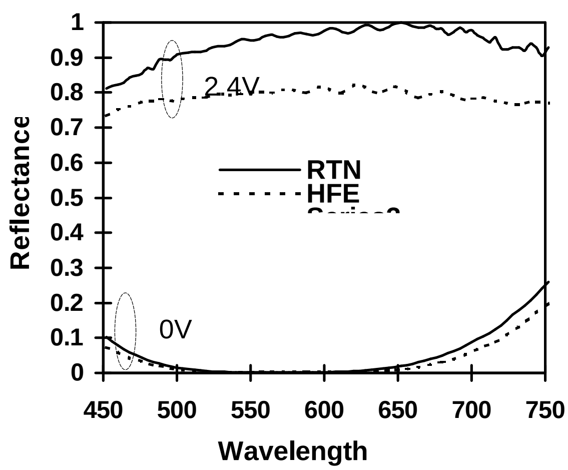

Fig. 7 Experimental reflectance spectra of the RTN and 45° HFE cells.

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 $\phi = 45^o$ (HFE) and 52^o (RTN), and $d\Delta n = 0.54\mu m$. The values of the elastic constants used for this calculation are those of a typical liquid crystal with a pretilt angle of 1^o. 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^o and 45^o cells is obtained. From Fig. 4, we find that the reflectance of the optimal cell is 10% greater than that of the 45 ^{o} cell. A wavelength of 550 nm is assumed in this calculation.