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Sun, Yubao; Ma, Hongmei; Zhang, Zhidong; and Wu, Shin-Tson, "Reflective liquid-crystal display using an in-plane-switching super-twisted nematic cell" (2002). *Faculty Bibliography 2000s*. 3495.

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Cite as: Journal of Applied Physics **92**, 1956 (2002); <https://doi.org/10.1063/1.1496127>
Submitted: 13 February 2002 . Accepted: 01 June 2002 . Published Online: 30 July 2002

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Reflective liquid-crystal display using an in-plane-switching super-twisted nematic cell

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(Received 13 February 2002; accepted for publication 1 June 2002)

Two in-plane-switching (IPS) super-twisted nematic (STN) cells are proposed for reflective liquid-crystal displays. The IPS 180°-STN cell exhibits a normally black display with a relatively low-operating voltage, fast response time, and wide viewing angle. Potential applications for large screen reflective displays are foreseeable. © 2002 American Institute of Physics.

[DOI: 10.1063/1.1496127]

I. INTRODUCTION

Reflective liquid-crystal displays (LCD)¹ offer several advantages over the transmissive ones in low-power consumption, sunlight readability, and filmlike image quality. First, a reflective LCD uses ambient light for reading the displayed information. Since it does not require a backlight, both power consumption and panel weight are reduced. Second, reflective displays have superb sunlight readability. In a bright outdoor environment, the displayed images of a transmissive LCD could be washed out by sunlight. Because the reflective displays utilize ambient light as a reading source, the brighter the ambient light, the more vivid the displayed images. Third, the thin-film-transistors addressed reflective displays exhibits a large (90%) aperture ratio even for high-resolution devices. The displayed images have the filmlike quality.

Several reflective LC modes have been developed, e.g., twisted nematic cells with a twist angle ranging from 45° to 90° and super-twisted nematic (STN) cells with 180°–240° twist angle. Most of these displays are normally white, i.e., high reflectance at null voltage state. Their viewing angle is around ±40°. Most handheld displays are palm sized so that a ±40° viewing cone is usually adequate. However, as the panel size keeps on increasing, the demand for wider viewing angle will also increase.

In this article, we utilize the parameter space representation method^{2,3} to search for reflective LC modes that exhibit a wide viewing angle. In Sec. II, a brief description on the theoretical modeling is given. In Sec. III, the simulation results of two reflective in-plane-switching (IPS) modes using the 180° and 155° STN cells are presented. The IPS 180°-STN cell exhibits a normally black mode with a wide viewing angle.

II. THEORETICAL MODELING

Parameter space is a useful method for designing a LC cell configuration for reflective displays. The geometry of the

reflective LCD we studied is shown in Fig. 1. It consists of a polarizer, a quarter-wave film, and a liquid-crystal cell with reflective electrode imbedded in the inner side of the bottom substrate. The axis of the polarizer and the retardation film is at an angle α and χ with respect to the input director of the liquid-crystal cell. To reduce surface reflections, the polarizer and the phase retardation film can be laminated onto the LC cell. The reflectance (R) of this optical arrangement can be represented by²

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

where

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

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

and

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

In Eqs. (1)–(4), F is the square of the Jones matrix of the retardation film, and R_χ is the rotation matrix for transforming F to a proper coordinate system, HMH^{-1} represents the Jones matrix of the liquid-crystal cell with light

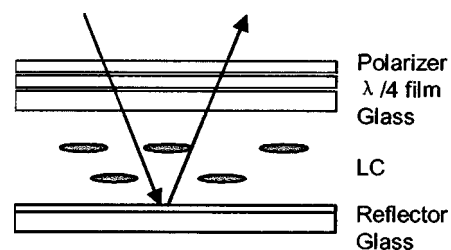


FIG. 1. Device structure of a reflective LCD used for simulations.

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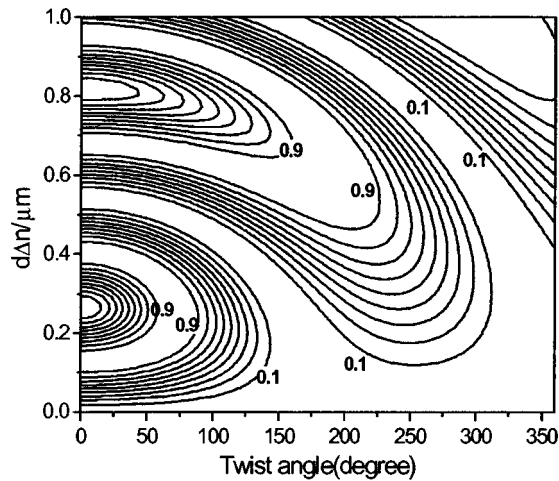


FIG. 2. Contour map of the reflectance of R-LCD as a function of $d\Delta n$ and twist angle ϕ .

traveling in the opposite direction and ϕ is the twist angle of the liquid-crystal cell. The reflectance of such a display is a unique function of the polarizer's angle α , film's angle χ , LC twist angle ϕ , and the cell gap-birefringence product $d\Delta n$. The reflectance of the LC cell can be plotted as a function of two parameters in the two-dimensional contour map by fixing other two parameters.

Figure 2 shows a contour map of the reflectance as a function of $d\Delta n$ and ϕ for the case of $\alpha=0^\circ$ and $\chi=45^\circ$. In our calculations, the input light wavelength λ is 550 nm and the LC pretilt angle is 1° . The retardation film is a quarter-wave film so that $\delta=\pi/4$. For the comparison purpose, we only calculate the normalized reflectance of the LC cell; the optical losses from polarizer, quarter-wave film, LC substrates, and reflective electrodes are all neglected. Retaining the angle between the polarizer and the fast axis of the quarter-wave film at 45° , the contour map of the reflectance does not change when we vary the polarizer angle. This is because the incident linearly polarized light is turned to circularly polarized after passing the $\lambda/4$ film once.

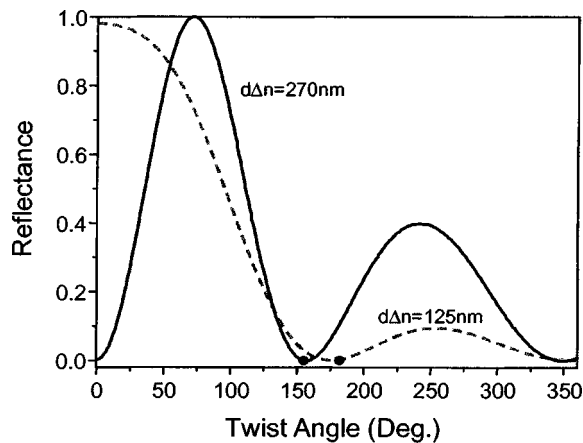


FIG. 3. Twist-angle-dependent reflectance at $d\Delta n=125$ and 270 nm. $R\sim 0$ occurs at $\phi=180^\circ$ and 155° , respectively.

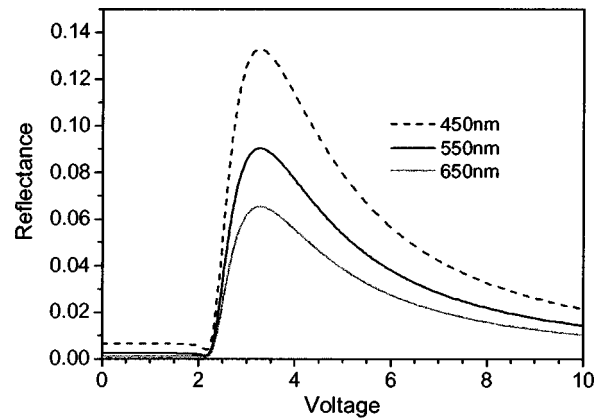


FIG. 4. Voltage-dependent reflectance of the 180° -STN cell. $d\Delta n=125$ nm. The electric field is in the longitudinal direction.

III. SIMULATION RESULTS

The calculated results in Fig. 2 represent the reflectance of a LC cell at the null voltage state. The traces of $R\sim 1$ are potential modes for realizing normally white displays and $R\sim 0$ for normally black. At a given twist angle, the vertical intersections with the contour lines imply to the $d\Delta n$ tolerance of the LC cell. From Fig. 2, two normally white modes $R=1$ occur at $[\phi, d\Delta n]=[63.6^\circ, 192 \text{ nm}]$, and $[191^\circ, 583 \text{ nm}]$, respectively. These two modes have been discussed and used for reflective light valves.^{4,5} A shortcoming of these two normally white modes is that their contrast ratio is low ($\sim 20:1$) because of lacking self-phase compensation. To improve contrast ratio, several mixed-mode twisted nematic (MTN) cells with $60^\circ \leq \phi \leq 90^\circ$ and $\alpha \sim 15^\circ - 30^\circ$ have been developed.¹

From Fig. 2, we notice that the smallest $d\Delta n$ corresponding to $R\sim 0$ occurs in the vicinities of $[\phi, d\Delta n]=[180^\circ, 125 \text{ nm}]$. Figure 3 plots the twist-angle-dependent reflectance at two $d\Delta n$ values: 125 and 270 nm. From the trace of $d\Delta n=125$ nm, $R\sim 0$ occurs at $\phi\sim 180^\circ$. And for $d\Delta n=270$ nm, $R\sim 0$ occurs at $\phi\sim 155^\circ$. These are the two normally black modes we report here for the wide view reflective displays.

A. Reflective 180° -STN mode

If we configure the 180° -STN cell in a conventional way, i.e., using the longitudinal electric field, the reflectance is less than 15%, as shown in Fig. 4. The longitudinal electric

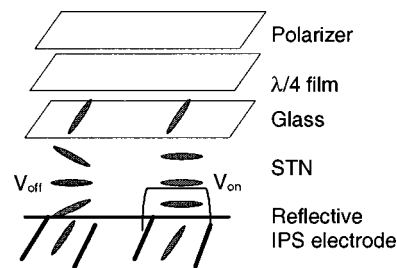


FIG. 5. Device structure of a reflective IPS mode.

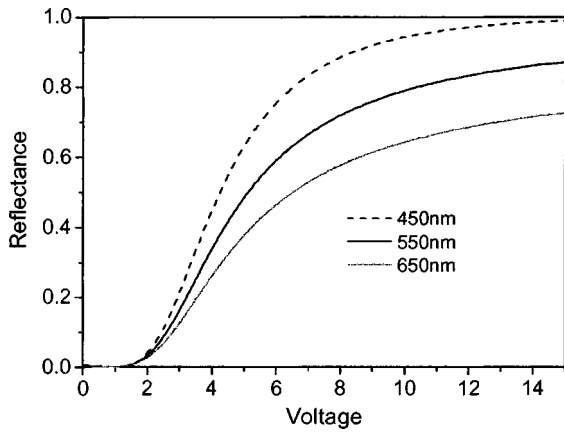


FIG. 6. Voltage-dependent reflectance of the IPS 180°-STN cell. $d\Delta n = 125$ nm.

field is also known to result in a narrow viewing angle. In order to boost reflectance and widen viewing angle, we use the lateral electric field, also called the in-plane-switching (IPS) mode,⁶⁻¹⁰ to drive the reflective 180°-STN cell.

The reflective IPS cell structure is shown in Fig. 5. In the voltage-off state (left), the LC directors are twisted by 180°. By controlling the $d\Delta n$ of the LC cell properly, a good dark state as shown in Fig. 3 can be obtained. In a voltage-on state, the LC directors are reoriented by the lateral electric field to be parallel to each other, as shown in the right side of Fig. 5. This molecular reorientation retards the phase of the incident and then returned beams. As a result, a bright state occurs.

Figure 6 plots the voltage-dependent reflectance of the reflective IPS 180°-STN cell at three wavelengths: $R = 650$, $G = 550$, and $B = 450$ nm. During simulations, the following LC cell parameters are used: $\epsilon_{\parallel} = 11.4$, $\epsilon_{\perp} = 3.6$, $K_{11} = 10$ pN, $K_{22} = 7$ pN, $K_{33} = 13.6$ pN, and 10 μm electrode gap. Unless otherwise mentioned, the cell gap used for simulations is $d = 6 \mu\text{m}$. We vary Δn to meet the specified $d\Delta n$ value.

From Fig. 6, a common dark state for RGB colors is observed at $V \leq 1.2$ V_{rms} . As the applied voltage increases,

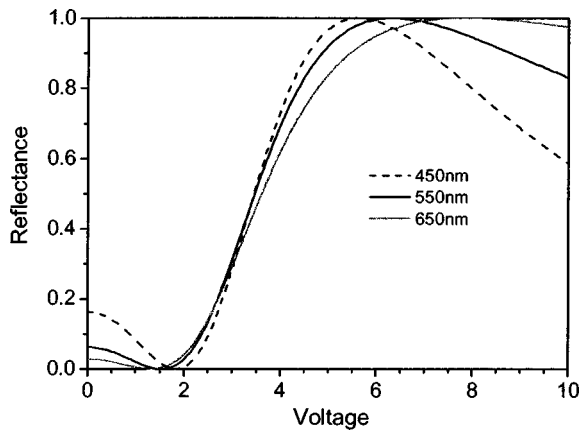


FIG. 7. Voltage-dependent reflectance of the IPS 180°-STN cell. $d\Delta n = 240$ nm.

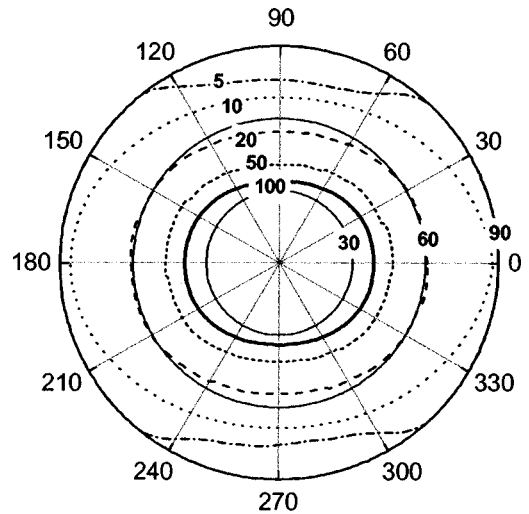


FIG. 8. Iso-contrast contours of the reflective IPS 180°-STN cell. $d\Delta n = 240$ nm.

reflectance increases. At 15 V_{rms} , the blue color reaches $R \sim 1$. This operating voltage is too high for most thin-film-transistor-based liquid-crystal displays.

To reduce the on-state voltage, we could increase either $\Delta\epsilon$ or $d\Delta n$, reduce the electrode gap, or properly combine these three parameters. Figure 7 repeats the plot as Fig. 6 except for a larger $d\Delta n$ value which is 240 nm. The dark and bright states occur at 1.6 and 6.0 V_{rms} , respectively. To keep on increasing $d\Delta n$ would lower the bright state voltage further. However, the common dark state for the RGB colors is gradually worsened so that the contrast ratio is reduced. Therefore, an optimal $d\Delta n$ value is around 200–240 nm.

The viewing angle of the reflective IPS 180°-STN cell was calculated. Results are shown in Fig. 8. As expected, the viewing angle exceeds $\pm 80^\circ$ at 5:1 contrast ratio. Although the IPS mode offers a very wide viewing angle, there are some tradeoffs, such as reduced aperture ratio, higher on-state voltage, and slower response time.¹

The present 180°-STN cell only requires $d\Delta n = 240$ nm, similar to most MTN cells. If the cell gap is maintained at $d = 6 \mu\text{m}$, then the required LC $\Delta n = 0.04$. The commercially available lowest birefringence TFT-LCD LC mixture has $\Delta n \sim 0.06$. Thus, a proper cell gap is $d = 4 \mu\text{m}$

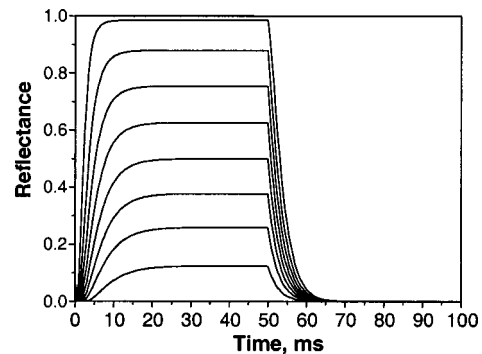


FIG. 9. Calculated response time for the eight-gray levels of the reflective IPS 180°-STN cell. $d = 4 \mu\text{m}$ and $\Delta n = 0.06$.

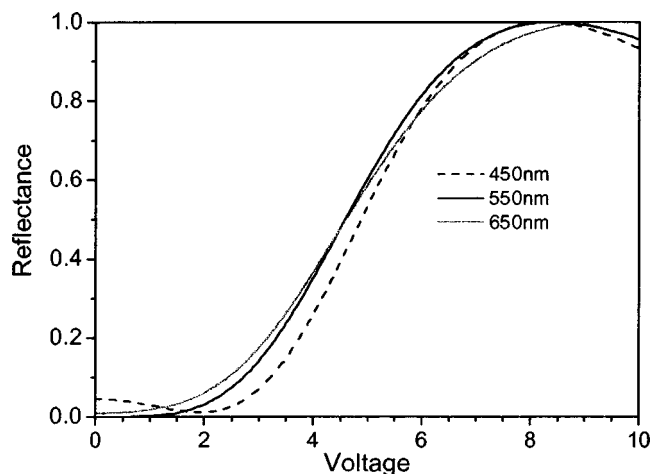


FIG. 10. Voltage-dependent reflectance of the IPS 155°-STN cell. $d\Delta n = 270$ nm.

which is comparable to a transmissive TN cell. We calculated the response time of the 4- μm -thick reflective IPS 180°-STN cell at eight gray levels. Results are shown in Fig. 9. For each gray scale, the frame time (rise+decay) is less than 30 ms.

B. Reflective 155°-STN mode

As shown in Fig. 3, another possible normally black mode takes place at $\phi = 155^\circ$ and $d\Delta n = 270$ nm. We have also investigated its performance for normally black display.

Figure 10 shows the voltage-dependent reflectance of such a reflective cell in the IPS structure. The dark and bright states occur at 1.5 and 8.0 V_{rms} , respectively. However, in the dark state, its color dispersion is more severe than that of 180°-STN cell. Thus, the 180°-STN cell would have a higher-contrast ratio.

IV. CONCLUSIONS

We have demonstrated two in-plane-switching STN cells for reflective liquid-crystal displays. These two reflective displays exhibit a wide viewing angle, relatively low-operating voltage, and fast response time. Potential applications for large screen reflective displays are anticipated.

ACKNOWLEDGMENT

The UCF group is indebted to AFOSR for financial support under Contract No. F49620-01-1-0377.

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