The Optical Design Principle of Twisted-Vertically Aligned Mode LCD

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Abstract: Compared with normal VA mode LCD, twisted-vertically aligned (TVA) mode LCD gained more and more attention due to its high transmittance as well as high contrast ratio (CR). To realize the optimized electro-optical performance and low cost, this work revealed the optical design principle of TVA mode LCD by Jones Matrix and Computer simulations. Subsequently, the TVA mode sample with high transmittance under orthogonal polarizers was obtained by optimizing the design of the pixel electrode pattern and parameters of chiral LC materials.

1. Introduction
Among the various flat panel displays (FPDs), liquid crystal displays (LCDs) are still the most widely used one. The common LCD modes include VA, TN, IPS, and FFS modes. Facing the increasingly demand of high-resolution LCDs with low energy consumption, the requirement of high contrast ratio (CR) and high transmission is urgent. To meet the needs, researches have focused on the twisted vertically aligned (TVA) mode. This mode provides excellent CR because of the good dark state of the VA mode and high luminance resulting from optical rotation of the TN mode [1-4].

![Figure 1. the operating principle of TVA mode LCD](image)

Figure 1. the operating principle of TVA mode LCD

The typical structure and basic operating principle of TVA mode is shown in Figure 1. In the TVA-mode LCDs, LC molecules which composed of a negative nematic LC and a small quantity of chiral dopant, are vertically-aligned in the off state, while twisted alignment is obtained in the on state [5-7].
As known to all, the azimuth angle of LC in VA mode is usually set to 45 degree to realize maximum transmittance, and its typical pixel electrode is designed as Figure 2 [8]. However, as for the TVA mode with a twisted alignment on-state, the research about how to design the pixel electrode and how to match the polarizer setup to obtain maximum transmittance is rare and the theoretically optical design principle is also unknown.

![Figure 2. the typical pixel electrode pattern of VA mode LCD](image)

Based on the above, this work investigated the effects of the parameters of LCs and cell design on the electro-optical performance of TVA mode LCDs, and revealed the theoretically optical design principle by Jones matrix and computer simulations.

2. Experimental

2.1. Sample preparation

A series of samples with different LC and pixel electrode pattern were prepared as listed in Table 1. The used TVA liquid crystals which consisted of negative nematic liquid crystal, UV polymerized reactive monomer (RM) and chiral dopant, were purchased from JNC corporation. The typical process for fabricating PSVA test cell is shown in Figure 3. The cell gap was set to 3.2μm.

| Sample | LC  | Pitch/μm | Δnd/nm | Handedness | Pixel electrode design | Cell gap/μm |
|--------|-----|----------|--------|------------|------------------------|-------------|
| 1      | VA  | 0        | 350    | None       | Normal                 | 3.2μm       |
| 2      | TVA | 12.5     | 450    | Right-handed | Normal | New             |

2.2. Characterization

The VT curve and brightness were tested by FS-POL optical measurement system and CA310 color analyzer. Moreover, the twist angle and retardation of VA mode LC and TVA mode LC were measured by Axometrics measurement system.
3. Results and discussion

VA-mode LCD is a kind of mature product, which has already achieved mass production. And the normal pixel electrode pattern of VA LCD is shown as Figure 2. In order to thoroughly investigate the difference between TVA and VA modes, we firstly study the optical property of sample 1 with VA LC and sample 2 with TVA LC, and they were both filled into the test cell with normal pixel electrode pattern. Results revealed that under the same backlight whose luminance was 5020 cd/m², the maximum transmittance luminance of sample 1 and sample 2 was 252 cd/m² and 277 cd/m², respectively. Interestingly, the maximum transmittance of sample 2 was obtained by rotating the test cell while keeping the upper and bottom polarizers orthogonal, or rotating the upper analyzer while fixing the cell and bottom polarizer. As shown in Figure 4, the transmittance of sample 2 varied with the cell rotation angle, and there is a maximum transmittance. That is, the upper and bottom polarizers should be non-orthogonal or the pixel electrode pattern which determines the bottom azimuth angle of TVA LC should be modified to meet the maximum transmittance. However, the non-orthogonal polarizers mean the special cutting of polarizers, causing a significant increase in cost of TVA mode LCD. Therefore, the special pixel electrode pattern design for TVA to optimize the optical performance is required.

In order to efficiently find out the optical design principle of TVA mode LCD, Jones matrix and
computer simulation were used to evaluate the relationship among the twist angle of TVA LC, the slit angle of pixel electrode, the angle between the upper and bottom polarizers, and the transmittance. The layer-built structure of TVA cell is shown in Figure 5. For simplicity, the azimuth angle of the bottom polarizer is set to $0^\circ$, while the azimuth angle of the upper analyzer is set to $\Phi$. Thus, the angle between the two polarizers is $\Phi$. Typically, taking right-handed TVA LC as an example, set the starting azimuth angle of the LC layer on the lower substrate to $\Theta$, and the ending azimuth of the LC layer on the upper substrate to $(\Theta + \phi)$, respectively. That is, the twist angle of the TVA LC is $\phi$.

![Figure 5. The layer-built structure of TVA cell](image)

The Jones matrix expression of each layer is as follows:

(1) Incident light:

$$J_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 \\ 1 \end{pmatrix}$$

(2) Polarizer:

$$M_1 = \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

(3) LC layer:

$$M_2 = R(-\Theta) \begin{pmatrix} LC_{11} & LC_{12} \\ LC_{21} & LC_{22} \end{pmatrix} R(\Phi)$$

(4) Analyzer

$$M_3 = R(-\phi) \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix} R(\phi)$$

(5) Outgoing light:

$$M = J_0 M_1 M_2 M_3$$

Where,

$$LC_{11} = \cos \phi \left[ \cos X - i \frac{\Gamma \sin X}{2X} \right] + \sin \phi \left[ \frac{\sin X}{2X} \right]$$

$$LC_{21} = \sin \phi \left[ \cos X - i \frac{\Gamma \sin X}{2X} \right] - \cos \phi \left[ \frac{\sin X}{2X} \right]$$

$$LC_{12} = \cos \phi \left[ \frac{\sin X}{2X} \right] - \sin \phi \left[ \cos X + i \frac{\Gamma \sin X}{2X} \right]$$

$$LC_{22} = \sin \phi \left[ \frac{\sin X}{2X} \right] + \cos \phi \left[ \cos X + i \frac{\Gamma \sin X}{2X} \right]$$
According to Jones matrix calculation, the transmittance (T) of the above optical path could be calculated as the following formula:

\[ T = \frac{1}{2} \left\{ \cos(\phi - \varphi) \cos X - \varphi \sin(\phi - \varphi) \frac{\sin X}{\lambda} \right\}^2 + \left\{ \frac{\Gamma}{2} \cos(\phi - \varphi - 2\theta) \frac{\sin X}{\lambda} \right\}^2 \]  

(13)

Obviously, the maximum transmittance (Tmax) can be obtained when \( \phi - \varphi - 2\theta = n\pi \) or \( \phi = \varphi + 2\theta + n\pi \). Especially, to achieve the desirable orthogonal-polarizers configuration, the value of \( \Phi \) should be set to 90°. Subsequently, the transmittance can be described as Formula 14:

\[ T = \frac{1}{2} \left\{ \sin(\phi) \cos X - \varphi \cos(\phi) \frac{\sin X}{\lambda} \right\}^2 + \left\{ \frac{\Gamma}{2} \sin(\phi + 2\theta) \frac{\sin X}{\lambda} \right\}^2 \]  

(14)

Therefore, the starting azimuth angle of the LC layer (\( \Theta \), i.e. pixel electrode ITO slit angle) and the twist angle of the TVA LC (\( \phi \)) should be designed to follow the relationship of \( \phi + 2\theta = \frac{(2n+1)\pi}{2} \) to gain the maximum transmittance.

![Figure 6. The pre-twist angle (\( \Theta \)) dependence of the transmittance with different twist angle (\( \phi \))](image)

The software of 1D master, was used to verify the Jones matrix-based optical design principle of TVA mode. Results in Figure 6 revealed the relationship between Tmax and \( \Theta \) with different \( \phi \), agreeing with the Jones matrix calculation. Moreover, Sample 3 with new ITO pattern (slit angle that determines \( \theta \) equals 12.5°) was prepared to verify the Jones matrix-based optical design principle of TVA mode. Result in Figure 7 revealed that the maximum transmittance can be obtained under orthogonal polarizers without any rotation of cell, confirming the applicability of the as-calculated Jones matrix-based optical design principle of TVA mode.
Finally, the optical performance of normal VA mode sample 1 and TVA mode sample 2 were measured by CA310 color analyzer. As shown in Figure 8, it can be clearly seen that compared with sample 1, sample 2 shows a huge advantage in the transmittance, exhibiting 10% higher transmittance than that of sample 1.

4. Conclusion
In summary, the optical design principle of TVA mode LCD has been proposed and verified by Jones matrix calculation, computer simulation and experiment. By optimizing the design of the pixel electrode pattern and parameters of chiral LC materials, the TVA mode LCD with high transmittance under orthogonal polarizers was realized. The as-prepared TVA-mode sample can provide 10% higher transmittance than VA-mode sample, showing a large advantage in the application of future high-resolution LCDs.

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