Twisted-nematic liquid-crystal displays with small grayscale inversion and wide viewing angle

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This work proposes a twisted-nematic liquid-crystal display (TN-LCD) with a small grayscale inversion and wide viewing angle. The electro-optical properties of a tilted TN cell are studied to develop the proposed TN-LCD. Calculations reveal that when the applied voltage exceeds a critical voltage, the effective optical property of the tilted TN cell is optically uniaxial with the effective optical axis parallel to the bisector of the twist angle. This bisector effect is used to improve the grayscale inversion of TN-LCDs. A viewing angle of over the entire 80° viewing cone of the proposed TN-LCD is also demonstrated theoretically and experimentally. © *2009 American Institute of Physics*. [DOI: 10.1063/1.3133864]

Liquid-crystal displays (LCDs) are widely used in televisions, desktop monitors, notebook computers, and mobile phones. For LCDs, high transmittance, wide viewing angle, small grayscale inversion, and fast response time are critical requirements. Among various LCDs, twisted-nematic liquid-crystal displays (TN-LCDs) are the most extensively adopted because of their high transmittance, fast response, and low cost of manufacture.[1] The TN-LCD, however, exhibits a serious grayscale inversion and narrow viewing angle, which limit its range of applicability. Several optical compensation methods have been proposed to improve the viewing angle of the TN-LCDs.[2–4] Among various optical compensation methods, hybrid discotic LC films, which are so-called wide-view (WV) films,[2] have been developed for the TN-LCD to obtain a viewing angle of over the entire 80° viewing cone.[3] However, its grayscale inversion and color shift are needed to be improved. Another optical compensation method based on two crossed nematic LC polymer films has been developed for the TN-LCD to obtain an excellent WV angle and low color shift.[4] However, the grayscale inversion still exists in the downward viewing direction. Recently, a beam steering optical film has been proposed to improve the grayscale inversion of the TN-LCD.[5] However, the low transmittance leads to a high power consumption, which is not suitable for mobile applications.

This work proposes a simple TN-LCD with a small grayscale inversion and wide viewing angle without sacrificing the advantages of a TN-LCD. The electro-optical properties of the TN cell at oblique viewing direction are studied to improve the grayscale inversion. A viewing angle of over the entire 80° viewing cone of the proposed TN-LCD is also demonstrated theoretically and experimentally.

Figure 1 depicts the basic cell configuration of the proposed TN-LCD. The proposed structure comprises crossed polarizers whose transmission axes are parallel and normal to the bisector of the twist angle, respectively, two WV films are inserted between the polarizer and the TN cell, a tilted negative C-plate is inserted on the outer side of the top WV film, and one biaxial $\lambda/2$ plate is inserted between the top polarizer and the tilted negative C-plate with its slow axis parallel to the transmission axis of the top polarizer.

In this work, the extended Jones matrix method is used to calculate the electro-optical properties of the TN cell at oblique viewing angles.[6] A special tilted TN cell configuration, consisting of crossed polarizers and a tilted TN cell, as shown in Fig. 2(a), is designed for the calculations. To exclude the off-axis light leakage effect of the crossed polarizers,[7] the planes of the crossed polarizers in Fig. 2(a) are designed to be always normal to the propagation direction of light. The finite difference method is adopted to calculate the LC director distributions. Neglecting the reflections at the interfaces between the air and the polarizer (analyzer), the transmitted wave, having passed through the tilted TN cell, is related to the incident wave as

$$\begin{pmatrix} E_{\parallel,\mathrm{out}} \\ E_{\perp,\mathrm{out}} \end{pmatrix} = J_{\mathrm{anal}} J_{\mathrm{ext}} J_N J_{N-1} \ldots J_3 J_2 J_1 J_{\mathrm{ent}} J_{\mathrm{pol.}} \begin{pmatrix} E_{\parallel,\mathrm{in}} \\ E_{\perp,\mathrm{in}} \end{pmatrix}, \quad (1)$$

where J_N, $J_{\mathrm{pol.}}$ and J_{anal} are the extended Jones matrices of the Nth layer of the tilted TN cell, the polarizer and the analyzer, respectively, J_{ent} and J_{ext} are the correction matrices, considering for the reflections at the air-glass and the glass-air interfaces, respectively. Approximating the light inside the tilted TN cell as a plane wave, J_N is given by[8]

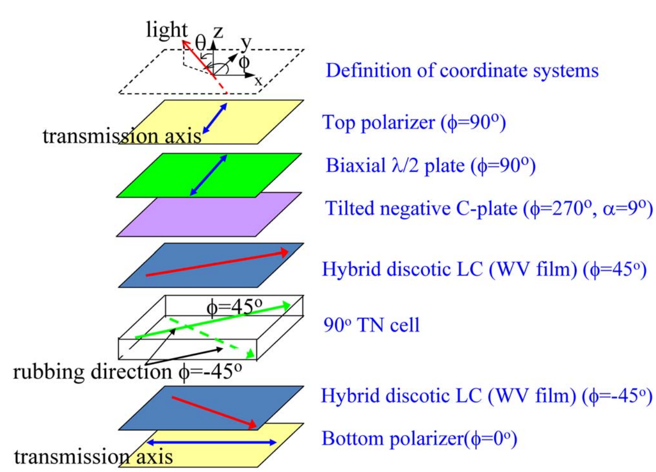

FIG. 1. (Color online) Basic cell configuration of proposed TN-LCD.

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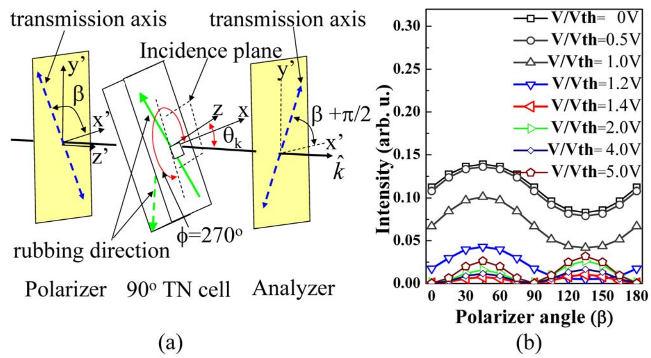

FIG. 2. (Color online) (a) Schematic configuration of tilted TN cell. Coordinate (x',y',z') is defined with z'-axis parallel to propagation direction of light and x'-axis is normal to incidence plane. θ_k is tilt angle of TN cell; β is angle of polarizer axis with respect to x'-axis. (b) Electro-optical properties of tilted TN cell at $\phi=270°$ and tilt angle $\theta_k=60°$ under different β. LC parameters used in the calculation are as follows; $\varepsilon_{\parallel}=13.6$, $\varepsilon_{\perp}=3.8$, $K_{11}=8.9\times10^{-12}N$, $K_{22}=5.5\times10^{-12}$, $K_{33}=12\times10^{-12}$, $n_e=1.624$, and $n_o=1.495$ and cell gap $d_{\mathrm{LC}}=4$ μm.

$$J_N=\begin{pmatrix}\cos\psi & -\sin\psi\\ \sin\psi & \cos\psi\end{pmatrix}\times\begin{pmatrix}e^{-j(2\pi/\lambda)(d/\cos\theta_N)n'_e} & 0\\ 0 & e^{-j(2\pi/\lambda)(d/\cos\theta_N)n'_o}\end{pmatrix}\times\begin{pmatrix}\cos\psi & \sin\psi\\ -\sin\psi & \cos\psi\end{pmatrix}, \quad (2)$$

where λ is the light wavelength, d is the thickness of the Nth layer, θ_N is the angle of light inside the Nth layer, n'_e and n'_o are the refractive indices of the Nth layer, and ψ is the angle between $E_{//}$ and the projection of the optical axis of the Nth layer on the wave plane. The electro-optical properties of the tilted TN cell from an azimuthal viewing angle of $\phi=270°$ are calculated; this is the direction of the most serious grayscale inversion. Without loss of generality, calculations are made with a tilt angle of $\theta_k=60°$ under various polarizer axis β in Fig. 2(b). From Fig. 2(b), the tilted TN cell exhibits a combination of a wave-guiding effect and a birefringence effect in the low voltage regime.[1,9] When the applied voltage exceeds 1.4 times the threshold voltage of the TN-LC V_{th},[1] the transmittance is minimal at polarizer axis $\beta=0°$ (180°) and 90° (270°), and maximal at $\beta=45°$ (225°) and 135° (315°). When a uniaxial optical medium is inserted between crossed polarizers, the transmittance is given by[9]

$$T=\sin^2(2\beta')\sin^2(\delta/2), \quad (3)$$

where β' is the included angle between the polarizer axis and the optical axis of the optical medium, and δ is the phase retardation of the optical medium. From Eq. (3), when δ is assumed to be constant, the transmittance of the uniaxial optical medium is minimal at $\beta'=0°$ (180°) and 90° (270°), and maximal at $\beta'=45°$ (225°) and 135° (315°), which results are the same as the calculations for $V\geq1.4V_{\mathrm{th}}$ as shown in Fig. 2(b). This indicates that the effective optical property of the tilted TN-LC is optically uniaxial when the applied voltage $V\geq1.4V_{\mathrm{th}}$. The effective optical property of a TN cell is optically uniaxial in the dark state at normal viewing direction because of the small phase retardation of the dark state.[10] However, for the tilted TN cell, the small phase retardation is achieved while the average orientation of the directors is pointed toward the propagation direction of light at an intermediate voltage. Thus, the critical voltage ($1.4V_{\mathrm{th}}$) for the optically uniaxial (OU) regime, shown in Fig. 2(b), is smaller than the dark state voltage ($>3V_{\mathrm{th}}$). Notably, although the effective optical property of the tilted TN-LC is optically uniaxial for $V\geq1.4V_{\mathrm{th}}$, the director distribution of the TN-LC is still twisted in this voltage regime.[11] Since the directors of the TN cell are distributed from $\phi=225°$ to 315°, the orientation of the effective optical axis for this OU regime is defined at $\beta=90°$ (270°), which corresponds to the bisector of the twist angle. It is also noted that the transmittance, shown in Fig. 2(b), does not decrease monotonically as applied voltage increases in the OU regime. This grayscale linearity problem of the OU regime leads to the grayscale inversion of a TN-LCD.

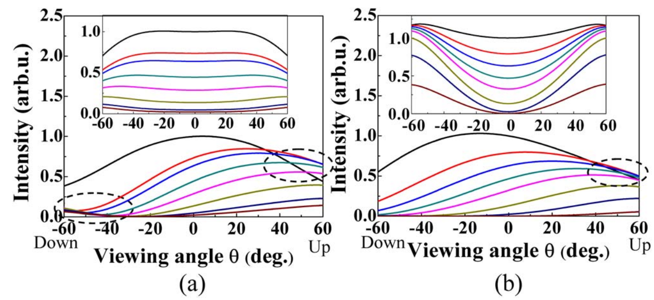

FIG. 3. (Color online) Calculated eight gray level characteristics in horizontal and vertical viewing directions for (a) conventional WV TN-LCD and (b) proposed TN-LCD. Dashed ellipses represent gray levels at which grayscale inversion occurs.

Based on the above analysis, the axes of the top polarizer and the bottom polarizer of the proposed TN-LCD, shown in Fig. 1, are designed to be parallel and normal to the bisector of the twist angle, respectively, to improve the grayscale inversion. Since the bottom polarizer axis is normal to the effective optical axis of the OU regime, i.e., $\beta'=90°$ in Eq. (3), the optical effect of the OU regime, which is mainly responsible for the grayscale inversion, could be eliminated, suppressing the grayscale inversion of the TN-LCD. Figures 3(a) and 3(b) show the calculated eight gray level characteristics for the conventional WV TN-LCD using WV films and the proposed TN-LCD, respectively. As expected, the proposed TN-LCD exhibits less grayscale inversion than the conventional WV TN-LCD, especially in a downward viewing direction.

To widen the viewing angle of a LCD, it is needed to reduce the off-axis light leakage of the dark state resulting from the LC and the crossed polarizers.[7,8] In our study, two WV films are utilized to cancel the residual LC phase near the substrate surfaces. A biaxial λ/2 plate, which is used to compensate for the multidomain vertical alignment LCD,[7] is used to compensate for the off-axis light leakage of the crossed polarizers. Calculations (not shown here) reveal that the bulk LC of the dark state behaves like a tilted positive C-plate with the effective optical axis oriented at $\phi=270°$, which results from the fact that the directors in the bulk area are not perfectly normal to the substrates in the dark state. Thus, a tilted negative C-plate with its optical axis oriented at $\phi=270°$ is used to effectively cancel the residual phase of the bulk area. The phase retardation $\Gamma_{t\text{-}C}$ and the tilt angle of the optical axis α of the proposed tilted negative C-plate strongly depend on the residual phase of the bulk LC. By

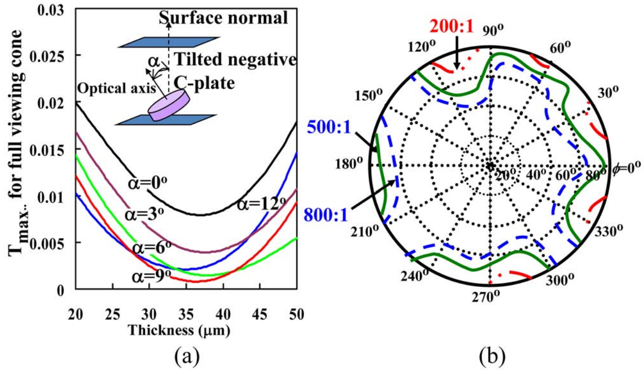

FIG. 4. (Color online) (a) Maximal dark state light leakage of full 80° viewing cone for proposed TN-LCD with different tilt angles and film thicknesses of tilted negative C-plate. (b) Simulated viewing angle characteristics of proposed TN-LCD.

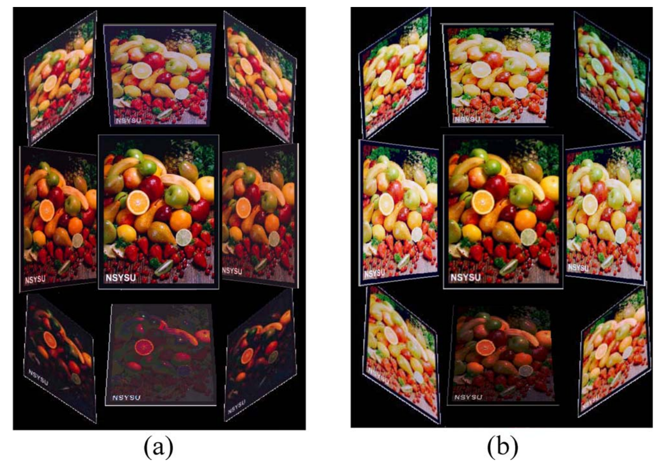

FIG. 5. (Color online) Comparison of photographs of (a) conventional WV TN-LCD and (b) proposed TN-LCD from different viewing directions.

minimizing the dark state transmittance of the full 80° viewing cone, the optimal parameters of the tilted negative C-plate can be obtained.

Based on the above method, the following material parameters of the tilted negative C-plate, the biaxial $\lambda/2$ plate and the WV film are employed in the proposed structure; $n_{e\ -c}=1.5089$ and $n_{o\ -c}=1.5124$, $n_{x\ \lambda/2}=1.5110$, $n_{y\ \lambda/2}=1.5095$, and $n_{z\ \lambda/2}=1.5102$ with thickness $d_{\lambda/2}=184$ μm, and $n_{e\ \mathrm{DLC}}=1.543$ and $n_{o\ \mathrm{DLC}}=1.6035$ with two pretilt angles $\theta_{\parallel}=24°$ and $\theta_{\perp}=79°$, and thickness $d_{\mathrm{DLC}}=1.95$ μm. For this design, the calculation, shown in Fig. 4(a), reveals that when the tilt angle α and the thickness d_{-C} of the tilted negative C-plate are 9° and 37 μm, respectively, the proposed TN cell has the minimal LC light leakage in the dark state for the full 80° viewing cone. Based on this result, the proposed TN-LCD then theoretically has a viewing angle of over the entire 80° viewing cone for CR$>$100:1 (CR denotes contrast ratio) as shown in Fig. 4(b). In the experiment, a TN-LCD with a cell gap of 4 μm was filled with a commercial LC mixture, ZTO-5059 (Chisso), with $\Delta n=0.13$ at 550 nm. A polarizer sample, consisting of a biaxial $\lambda/2$ plate (Nitto Denko), two WV films and a handmade tilted negative C-plate, fabricated by attaching a negative C-plate to a wedge-shaped glass with a wedge angle of 9°, with $\Gamma_{t\text{-}C}\sim 130$ nm at 550 nm, based on the proposed structure was prepared. Notably, the tilted negative C-plate in the proposed TN-LCD can be made of a discotic LC material in practical applications.[12] Measurements reveal that the proposed TN-LCD can achieve a viewing angle of over the entire 80° viewing cone for CR$>$20:1. The experimental iso-CR curves are lowered because the ideal parameters may not be precisely controlled. Furthermore, defects of the handmade polarizer, LC alignment distortion near spacers and pixel edges also reduce the contrast ratio. Figure 5 compares photographs of the conventional WV TN-LCD and the proposed TN-LCD from different viewing directions. From Fig. 5, the proposed TN-LCD clearly exhibits a small grayscale inversion in the downward viewing direction, which is consistent with our calculations in Fig. 3. The proposed TN-LCD theoretically has a larger color dispersion because of the large included angle (45°) between the polarizer axis and the front LC director.[9] This color dispersion can be reduced by using the method of three individual gamma curves for red, green, and blue pixels in practical applications.

In conclusion, this work proposes a simple TN-LCD with a small grayscale inversion and wide viewing angle. The grayscale inversion of the proposed TN-LCD is significantly improved by making the two polarizer axes parallel and normal to the bisector of the twist angle. Additionally, the proposed TN-LCD is compensated optically to achieve a viewing angle of over the entire 80° viewing cone theoretically and experimentally. We believe that the proposed simple TN-LCD with a small grayscale inversion and wide viewing angle will suffice for future mobile multimedia applications.

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