An O-Plate Compensated In-Plane Switching Liquid Crystal Display

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***Abstract*—Pretilt angle effect on the dark-state light leakage and viewing angle of in-plane switching (IPS) liquid crystal display is investigated. As the liquid crystal (LC) pretilt angle increases, the light leakage becomes more severe and the off-axis light leakage from the out-of-plane LC directors cannot be neglected. Introducing an oblique compensation plate (O-plate) reduces the off-axis light leakages from the crossed linear polarizers and the anisotropic LC media simultaneously which, in turn, improves the viewing angle of the IPS LCD.**

***Index Terms*—Compensation plate, in-plane switching (IPS), light leakage, liquid crystal display (LCD), wide viewing angle.**

I. Introduction

WIDE VIEWING angle along with high contrast ratio, fast response time, and small color shift have been the major technical challenges for large-screen liquid crystal (LC) televisions [1]. Several factors that influence the viewing angle of a liquid crystal display (LCD) include the off-axis light leakages of the crossed polarizers, optical anisotropy of the LC layer, light scattering from the LC layer, the surface of the polarizers or the color filters, light reflection from the device components (such as the substrates, polarizers, and color filters), and the collimation of the backlight [2], [3]. Among them, the off-axis light leakage is most critical and should be dealt with first.

A normally black in-plane-switching (IPS) LCD exhibits an inherently wide viewing angle because the LC directors are switched in the same plane by the transverse electric field [4], [5]. The uniaxial and biaxial compensation films have been used to further widen the viewing angle of the IPS LCDs [6]–[8]. Previous efforts mainly focus on compensating the off-axis light leakage from the crossed linear polarizers to improve the dark state while assuming the off-axis light leakage from the LC layer is negligible. On the contrary, Anderson *et al.* [9] point out that the light leakage from LC layer could be serious and the viewing angle would be degraded if the LC pretilt angle is larger than 3°.

In this paper, we investigate the pretilt angle effect on the light leakage and viewing angle of the homogeneous IPS mode LCD without/with the conventional uniaxial compensation plates. An oblique-plate (O-plate) is proposed to compensate the off-axis light leakages from the crossed polarizers and the anisotropic LC layer simultaneously. The viewing angle is widened by using the proposed O-plate. This effect is particularly evident for an increased pretilt angle.

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II. Viewing Angle and Off-Axis Light Leakage of an LCD

The contrast ratio (CR) of an LCD device at a certain light incident angle is defined as $\mathrm{CR} = T_{\mathrm{on}}/T_{\mathrm{off}}$, which is the ratio of light transmittance between the voltage-on (T_{on}) and the voltage-off (T_{off}) states. And the viewing angle is tied to CR by the iso-contrast bars on a defined viewing cone. Thus, it is crucial to minimize the off-axis light leakage and dark state transmission in order to improve the CR over a wide viewing angle. To reduce the off-axis light leakage, the phase compensation method plays an important role in different LCD modes, such as in-plane switching (IPS) [7] and multidomain vertical alignment (MVA) [6], [10], [11].

In an IPS mode, the bright state transmittance does not change too noticeably as long as the LC pretilt angle is lower than 5° (simulation results will be shown later). Here we mainly discuss the dark-state light leakage effect on the viewing angle. At first, let us take a look on the origin of the off-axis light leakages from the crossed linear polarizers and the anisotropic LC layer. These are the two major factors influencing the dark state of a LCD device.

A. Light Leakage From the Crossed Linear Polarizers

In the present LCD industry, the most commonly used linear polarizers are the O-type whose transmission axis is perpendicular to the c-axis [12]. In a conventional polar coordinates as shown in Fig. 1, the internal angle of propagation (θ, ϕ) of the incident wave-vector inside the polarizer media can be defined as [12], [13]

$$\vec{k} = k(\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta). \tag{1}$$

Therefore, the polarization state of the light transmitted through the first polarizer can be expressed as

$$\vec{T_1} = \frac{\vec{k}\times\vec{a}_1}{\left|\vec{k}\times\vec{a}_1\right|} \tag{2}$$

and the polarization state of the light passing through the second polarizer (i.e., the analyzer) can be written as

$$\vec{T_2} = \frac{\vec{k}\times\vec{a}_2}{\left|\vec{k}\times\vec{a}_2\right|} \tag{3}$$

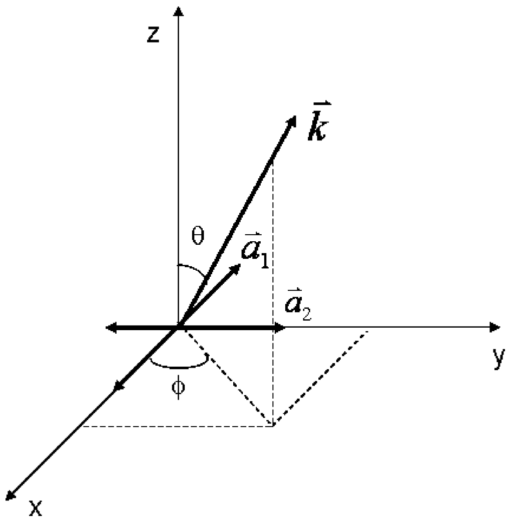

Fig. 1. Coordinate system used to analyze the light leakage from the crossed polarizers.

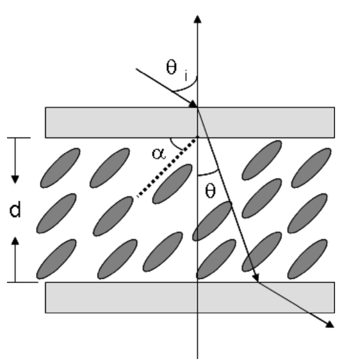

Fig. 2. Light path of a uniformly tilted liquid crystal cell at an oblique angle.

where $\vec{a}_1$ and $\vec{a}_2$ are the unit vectors representing the respective polarizer absorption axes. The off-axis light leakage through the crossed linear polarizers whose transmission axis is along $\phi = 0^\circ$ and $\phi = 90^\circ$, respectively, is given by

$$\begin{aligned} T_{\text{polarizer}} &= \frac{1}{2}\left|\vec{T}_1 \cdot \vec{T}_2\right|^2 \\ &= \frac{\sin^4\theta \cdot \sin^2\phi \cdot \cos^2\phi}{4(1-\sin^2\theta \cdot \sin^2\phi)(1-\sin^2\theta \cdot \cos^2\phi)}. \end{aligned} \quad (4)$$

From (4), the off-axis light leakage depends on the light transmission angle θ and azimuthal angle ϕ of the incident light, where θ is related to the external angle of incidence by Snell's law. In theory, there will be no light leakage at $\phi = 0^\circ$ or 90° when the incident light is parallel to one of the transmission axes of the polarizers, but will have the worst light leakage in the bisector planes ($\phi = 45^\circ$ and 135°).

B. Angular Dependent Phase Retardation of LC Layer

As shown in Fig. 2, Snell's law correlates the incident angle θ_i in the air to the exit angle θ in a uniform LC layer as

$$n_{\text{air}} \sin\theta_i = n \sin\theta. \quad (5)$$

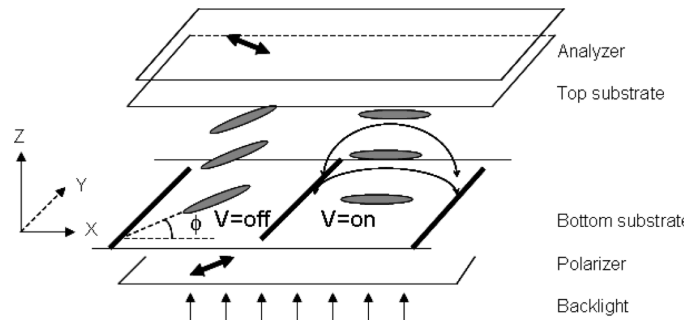

Fig. 3. Typical structure of IPS mode LCD with the homogeneous alignment.

The angular dependent phase retardation of the LC layer at a given wavelength λ is expressed as [14]

$$\delta(\theta, \phi, \alpha, V, \lambda) = \frac{2\pi(d \cdot \Delta n)_{\text{eff}}}{\lambda} \quad (6)$$

where

$$(d \cdot \Delta n)_{\text{eff}} = \frac{d}{\cos\theta}\left\{\frac{n_e n_o}{\sqrt{n_o^2 \sin^2(\theta \pm \alpha) + n_e^2 \cos^2(\theta \pm \alpha)}} - n_o\right\}. \quad (7)$$

In (5) and (7), n_o and n_e represent the ordinary and extraordinary refractive indices, $\Delta n = n_e - n_o$ the birefringence, $n = (n_e + 2n_o)/3$ the average refractive index of the LC material, d is the LC cell gap, ϕ is the azimuthal angle between the effective optic axis of the LC directors and the transmission axis of the polarizer, and α is the LC pretilt angle. The $\pm$ signs in (7) represent the light coming from left and right sides, respectively.

Correspondingly, the normalized light transmittance through the LC medium under the crossed linear polarizers has the following form [15]:

$$T_{LC} = \sin^2(2\varphi)\sin^2\left(\frac{\delta}{2}\right) = \sin^2(2\varphi)\sin^2\left[\pi \cdot \frac{(d \cdot \Delta n)_{\text{eff}}}{\lambda}\right]. \quad (8)$$

It indicates that the transmittance is closely related to the light incident angle, LC alignment angle, LC pretilt angle, the incident wavelength, and the applied voltage.

III. IPS-LCD Cell

Fig. 3 shows the typical device structure of a normally black IPS LCD. The transmission axis of the polarizer is parallel to the LC alignment (i.e., rubbing) direction. The LC rubbing direction, i.e., LC director, is at an angle of 90°-ϕ with respect to the IPS electrodes. The LC pretilt angle is defined as the angle α between the LC directors and the cell substrate. In the voltage-off state, the incident backlight is absorbed by the crossed analyzer resulting in a normally black state. As the applied voltage exceeds the threshold voltage, the LC directors are reoriented along the electric field direction. As a result, light transmits through the crossed linear polarizers.

In our simulations, we assume the dark state voltage is 0. In a practical LCD device, there is a small bias voltage (~ 0.5 $\mathrm{V_{rms}}$) originated from TFT. The threshold voltage of an IPS LCD is typically around 1.5 $\mathrm{V_{rms}}$. Therefore, this small bias voltage only slightly influences the response time [15] but does not affect the VT curves nor the contrast ratio of the display.

We used a 3-D simulator to obtain the LC director distribution first, and then calculate the electro-optical properties using the extended Jones matrix method, which considers the surface reflections from the cell substrates and the polarizers [16]. In the simulations, we chose the following parameters: LC cell gap $d = 4$ μm, electrode width $= 4$ μm, electrode gap(from center to center) $= 9$ μm and a positive LC mixture Merck MLC-6692 (birefringence $\Delta n = 0.085$, dielectric anisotropy $\Delta\varepsilon = 10.3$ and rotational viscosity $\gamma_1 = 0.1$ Pa · s). The glass substrate is 0.3 mm thick with dielectric constant of 6.8. The LC rubbing angle was chosen to be $\phi = 80^\circ$ for achieving high transmittance and low driving voltage. Since the pretilt angle of a practical IPS LCD is usually smaller than 5°, in our simulations we only consider the pretilt angle from 0° to 5°. In calculating the dark state light leakage and the viewing angle of the LCD, we used the RGB wavelengths ($R = 650$ nm, $G = 550$ nm, and $B = 450$ nm) at 3:6:1 weighting ratios to mimic the balanced white light. The employed polarizers are Nitto Denko HEG1425 high efficiency ones which are O-type sheet polarizers. The linear polarizer pair has a maximum light transmittance of 35%.

IV. Results and Discussion

A. Voltage-Dependent and Time-Dependent Transmittance Curves at Normal Incidence

Fig. 4 plots the voltage-dependent transmittance (VT) curves of the IPS-LCD with different LC pretilt angles at $\lambda = 550$ nm under normal incidence. The VT curves are quite inert to pretilt angle. The maximum transmittance appears at $\mathrm{V} = 4.75$ $\mathrm{V_{rms}}$. Very little change is observed with the increased pretilt angle due to the slight decrease of the effective LC phase retardation projected on the cell substrate.

Fig. 5 further plots the time-dependent transmittance curves of the IPS-LCD with different LC pretilt angles under normal incident angle at $\lambda = 550$ nm and $V = 4.75$ $\mathrm{V_{rms}}$. It can be found that the transmittance is firstly saturated at a lower LC pretilt angle which means there is more LC phase to be switched under the transverse electric field when the pretilt angle is low. We will choose the fully saturated transmittance time point of 150 ms at $V = 4.75$ $\mathrm{V_{rms}}$ as the bright state for the following viewing angle calculations.

B. Inherent Light Leakage and Viewing Angle of IPS LCD

Fig. 6 shows the dark-state light leakage of the homogeneous IPS LCD at different LC pretilt angles when no any compensation plate is added. For comparison purpose, the light leakage of the IPS cell with a virtual LC layer ($d = 0$ μm) is firstly calculated and results are depicted in Fig. 6(a) as benchmark. Next, we calculate the light leakage of the 4-μm IPS cell (with $\alpha = 0$) sandwiched between two crossed polarizers. Results are shown in Fig. 6(b). From Fig. 6(b), light leakage is evident in the

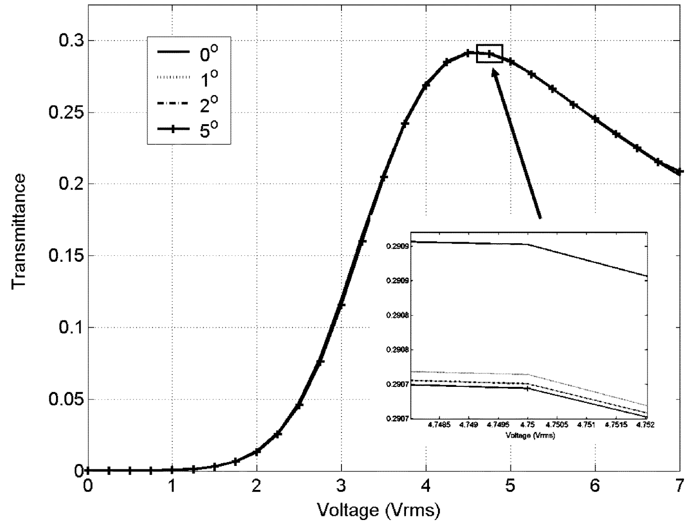

Fig. 4. Voltage dependent transmittance curves with the different LC pretilt angles at the wavelength of 550 nm under the normal incident angle.

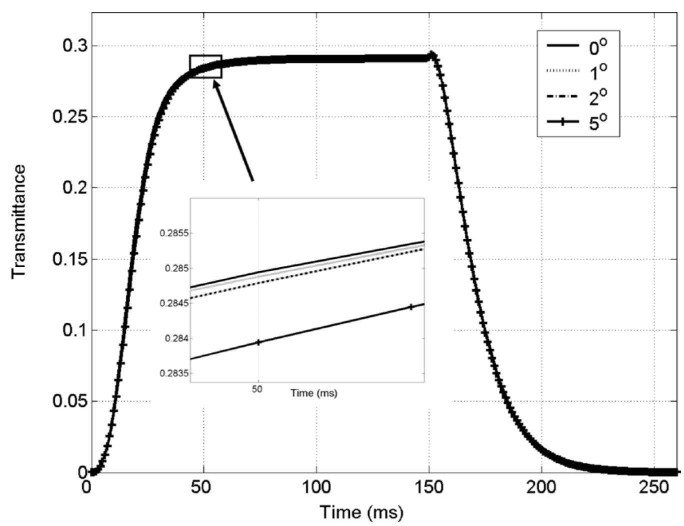

Fig. 5. Time-dependent transmittance curves with the different LC pretilt angles under the normal incident angle at the wavelength of 550 nm and the applied voltage of 4.75 $\mathrm{V_{rms}}$.

bisector planes of the polarizer's transmittance axes, whose azimuthal angle is at $\phi = 35^\circ, 125^\circ, 215^\circ$, and 305°, respectively. The equal transmittance bars have the same pattern and are symmetric along the above bisector planes of $\phi = 35^\circ$ and 125° under different polar angle θ. In addition, the dark-state light leakage is nearly the same as that shown in Fig. 6(a) where the LC effect is excluded completely. This indicates that the light leakage from the IPS LCD with zero pretilt angle ($\alpha = 0$) is mainly due to the off-axis light leakage of the crossed linear polarizers while the phase retardation effect of the homogeneous LC layer is blocked by the crossed polarizers even at oblique viewing angles [7].

As the LC pretilt angle increases, the light leakage at the 35° and 125° azimuthal angles increases, but decreases at 215° and 305°. The symmetric pattern of the equal transmittance bars as shown in Fig. 6(b) is broken along the bisector planes in Fig. 6(c)–(e) for the cases of $\alpha = 1^\circ$, 2°, and 5°, respectively.

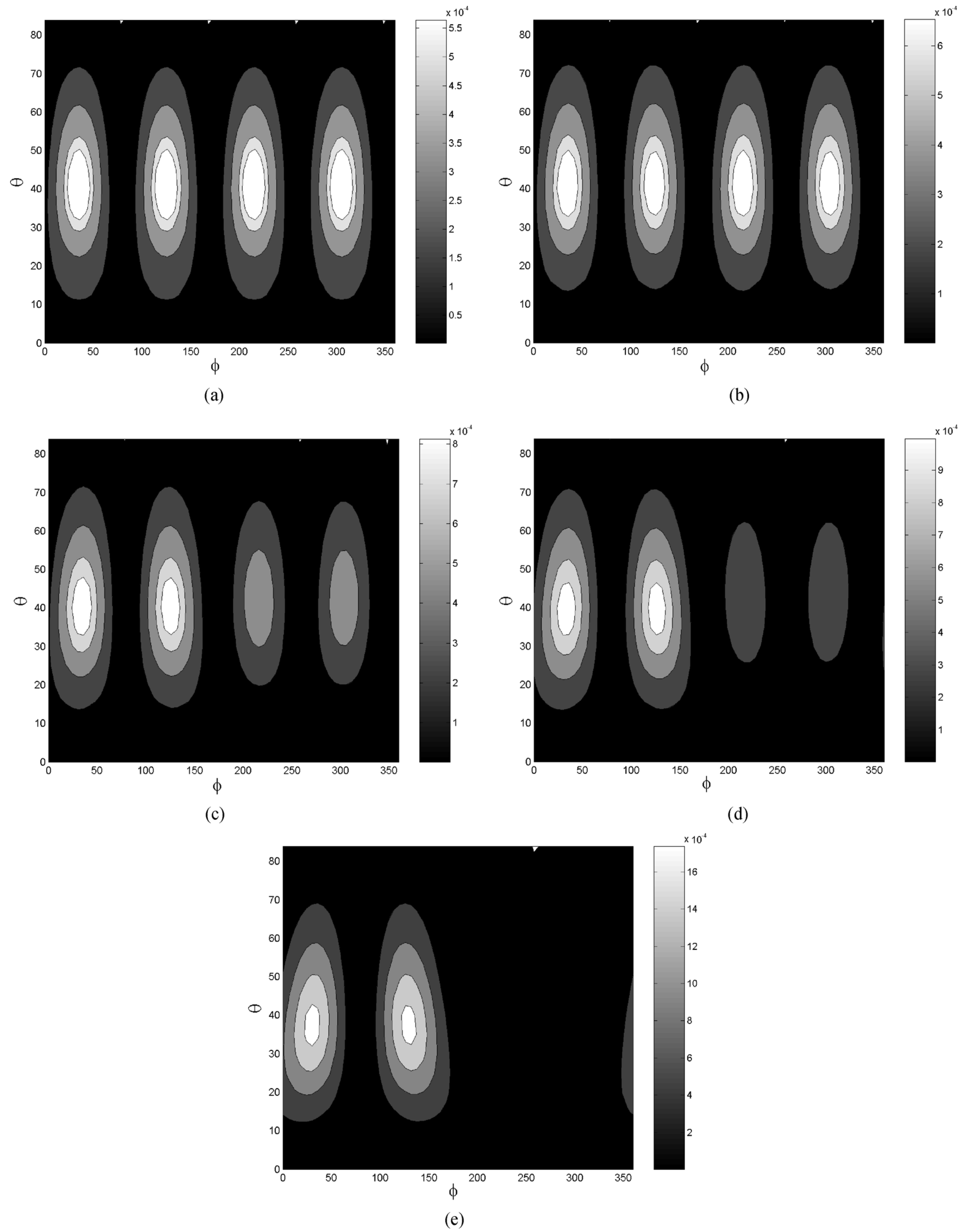

Fig. 6. Dark-state light leakages of the homogeneous IPS LCD with the different LC pretilt angles when no any compensation plate is added. (a) LC layer thickness $d = 0\ \mu$m. (b) $\alpha = 0^\circ$. (c) $\alpha = 1^\circ$. (d) $\alpha = 2^\circ$. (e) $\alpha = 5^\circ$.

This indicates the dark-state light leakage of the IPS LCD not only originates from the off-axis light leakage of the crossed polarizers but also from the LC layer as (8) shows. This phenomenon can be explained as follows. As the pretilt angle gets larger, the out-of-plane LC directors exhibit residual phase when viewed from off-axis positions because of the optical anisotropy resulting in an increased light leakage through the LC cell and deteriorated dark state. Therefore, when the pretilt angle of the IPS cell is not zero the dark-state light leakages from crossed polarizers and LC layer should be taken into consideration in order to obtain accurate simulation results.

Fig. 7 plots the pretilt angle effect on the iso-contrast contours of the IPS LCD. When the pretilt angle is zero [see Fig. 7(a)], the inherent viewing angle is relatively wide: $\mathrm{CR} \geq 500{:}1$ within the $\pm 25^\circ$ viewing cone and $\mathrm{CR} = 10{:}1$ contour line extends to $\pm 65^\circ$. The iso-contrast contour bars are symmetric along the rubbing direction (i.e., the azimuthal angle 80°) and its corresponding perpendicular direction, i.e., the azimuthal angle 170°.

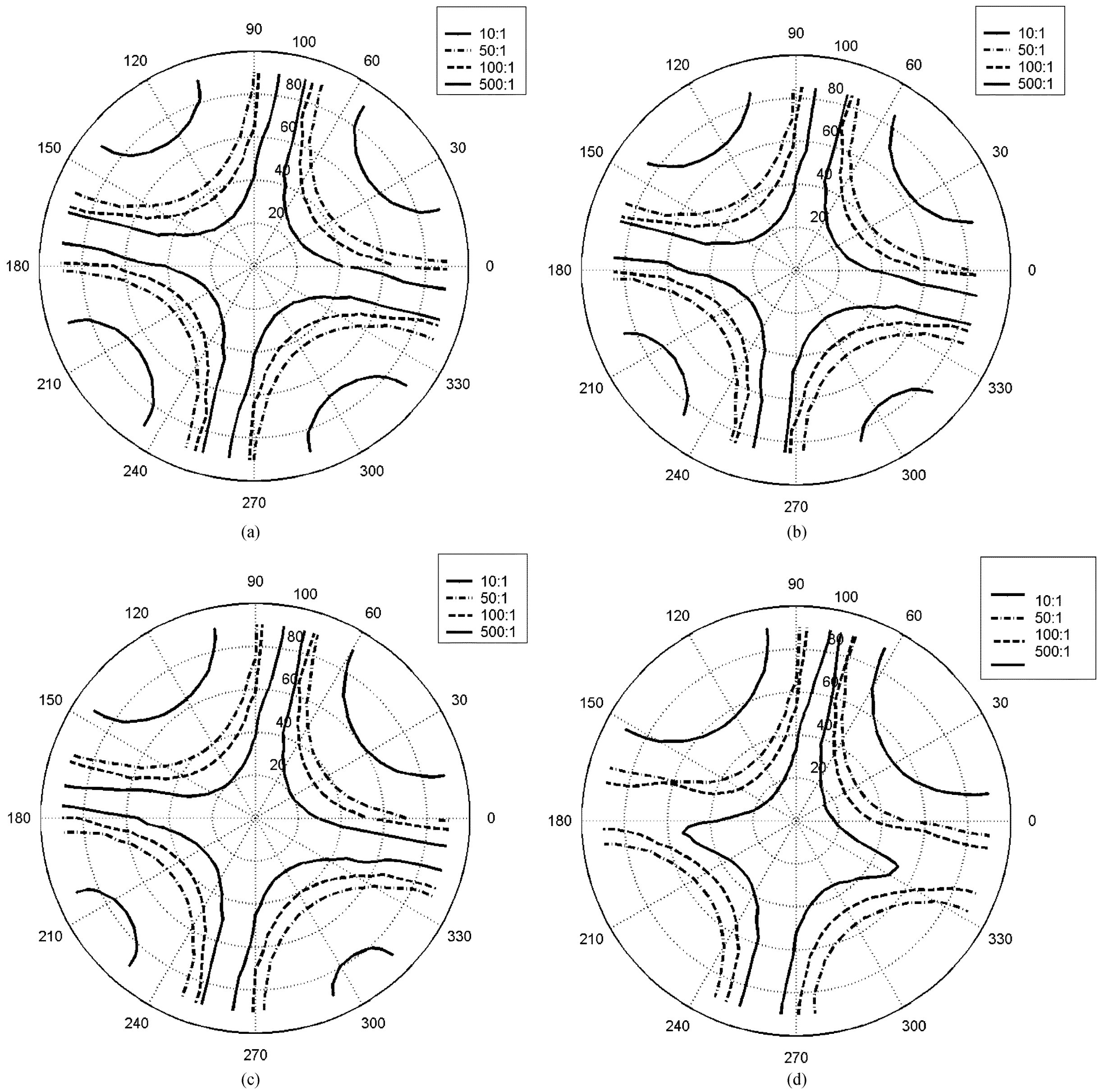

Fig. 7. Viewing angle of the IPS device under the different LC pretilt angles. (a) $\alpha = 0°$. (b) $\alpha = 1°$. (c) $\alpha = 2°$. (d) $\alpha = 5°$.

Because of the larger light leakages along the bisector planes, the corresponding CR is lower and the viewing cones narrower than the other azimuthal regions.

When $\alpha > 0$, the CR is symmetric only along the rubbing angle direction. The $\mathrm{CR} = 10$:1 iso-contrast contour bars in the first and second quadrants are shrunk along the bisector azimuthal angles 35° and 125°, respectively, but are expanded at the third and fourth quadrants at the azimuthal angles of 215° and 305°. The viewing cones for $\mathrm{CR} = 10$:1 are kept at ±65° for $\alpha = 1°$ [see Fig. 7(b)] and $\alpha = 2°$ [see Fig. 7(c)]. At 5° pretilt angle [see Fig. 7(d)], the high contrast viewing cone is drastically narrowed and the $\mathrm{CR} = 500$:1 contour line is reduced to around ±20°. Besides the dark-state light leakage from the crossed polarizers, the out-of-plane LC directors also contribute noticeably to the undesirable phase retardation. Therefore, pretilt angle effect should be taken into consideration for designing a wide view IPS-LCD.

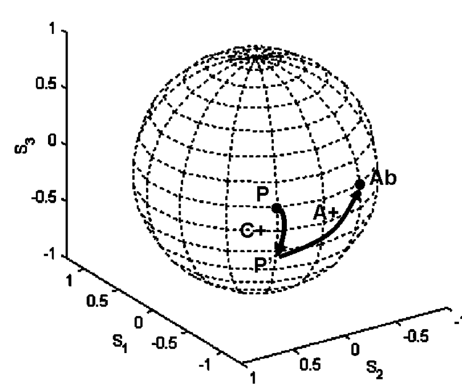

Fig. 8. Principle to compensate the off-axis light leakage from the crossed polarizers on the Poincaré sphere using positive A-plate and C-plate.

From our simulations, although the 0° pretilt angle leads to the widest viewing characteristics, in reality this condition is dif-

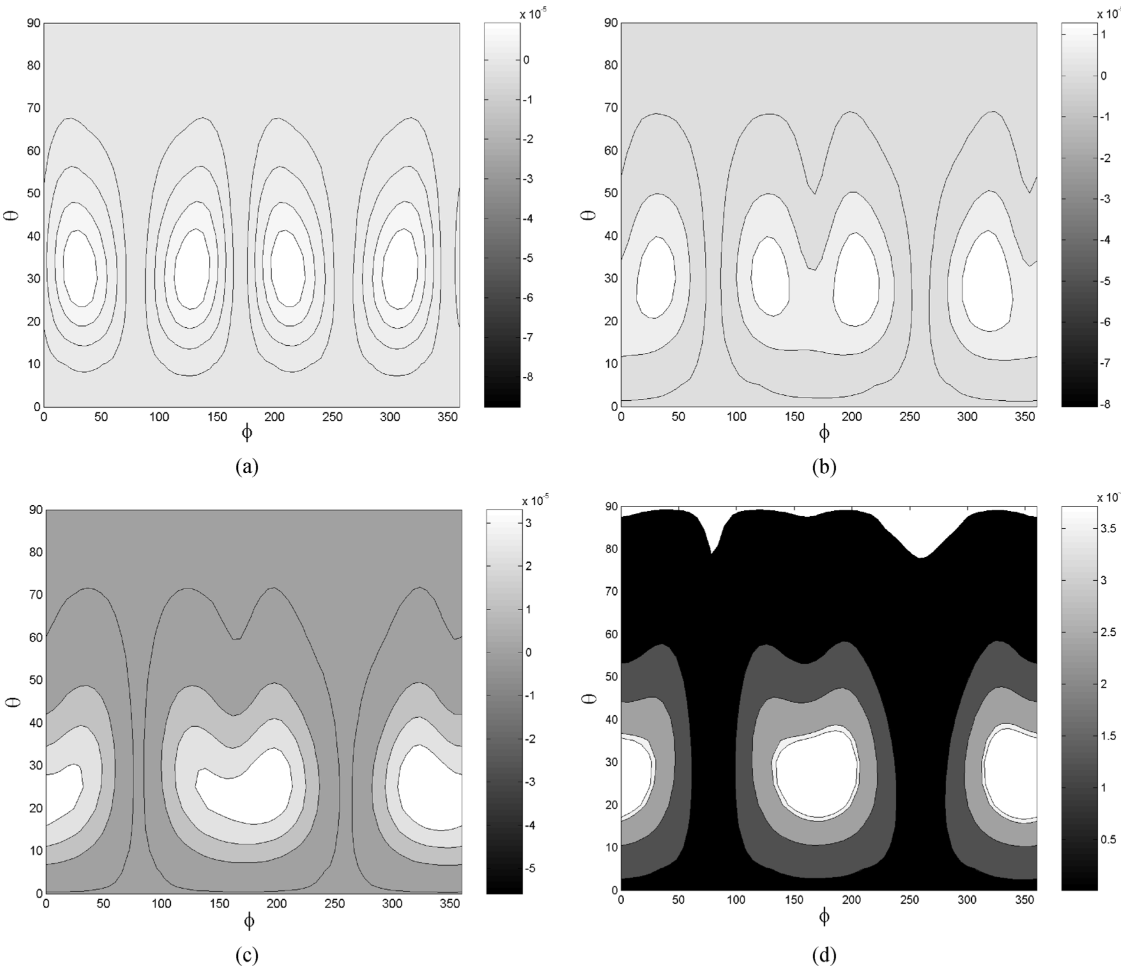

Fig. 9. Film-compensated dark-state light leakages of the homogeneous IPS LCD with the different LC pretilt angles using the optimized A/C-plates. (a) $\alpha = 0°$. (b) $\alpha = 1°$. (c) $\alpha = 2°$. (d) $\alpha = 5°$.

ficult to fulfill. The IPS cell requires rubbing process to provide uniform homogeneous LC alignment. The pretilt angle depends on the polyimide employed and the rubbing strength. Normally, the buffing-induced pretilt angle is around 1°–3°. Our studies indicate that minimizing the pretilt angle is helpful to improve the dark state light leakage and widen the viewing zone.

C. Phase Compensation With Uniaxial Plates

To improve contrast ratio and enhance viewing angle, we should lower the dark state transmittance because the contrast ratio is defined as $\mathrm{CR} = T_{\mathrm{on}}/T_{\mathrm{off}}$. From (4), the light leakage is inevitable from the crossed polarizers if the light incident angle θ is not zero. We previously optimized a series of positive A/C-plates to widen the viewing angle of the IPS LCD as proposed by Chen *et al.* [6], [17], where an A/C-plate is defined as a uniaxial birefringent plate with its optical axis parallel/perpendicular to the surface of the plate. The principle is to compensate the off-axis light leakage from the crossed linear polarizers based on the Poincaré sphere representation as shown in Fig. 8. The positive C-plate first moves the polarization state that exits through the analyzer from P to P', then the positive A-plate further rotates the polarization state from P' back to the equator and meets at the polarizer's absorption point, Ab. The polarization state P is converted back to Ab so that the exit light is completely blocked by the analyzer. As a result, the off-axis light leakage of the IPS LCD can be minimized.

Fig. 9 shows the dark-state light leakages of the film-compensated IPS LCDs with different LC pretilt angles. The optimized $d \cdot \Delta n$ value for the positive A-plate and C-plate films is 149.4 and 87.9 nm, respectively. Under such conditions, the light leakage of the IPS cell is relatively small (usually on the level of 10^{-5} within the entire viewing range) if the pretilt angle is kept at below 1°, as Fig. 9(a) and (b) shows. The light leakage of the film-compensated IPS cell is greatly improved as compared to that without any compensation films. At 2° [see Fig. 9(c)] and 5° [see Fig. 9(d)] pretilt angles, the light leakage is increased but the maximum leakage is still kept as low as 10^{-4}.

Fig. 10 plots the iso-contrast contour bars of the IPS LCD with the uniaxial A/C-plates under different LC pretilt angles. For the case of $\alpha = 0$ [see Fig. 10(a)], the 500:1 contrast ratio is expanded to $\pm 50°$ viewing cone and $\mathrm{CR} = 120{:}1$ to $\pm 80°$. Moreover, the iso-contrast contour bars are both symmetric along the rubbing angle direction and its corresponding perpendicular direction. This indicates the uniaxial plates have effectively widened the viewing angle of the IPS LCD. For the cases of $\alpha = 1°$ [see Fig. 10(b)] and 2° [see Fig. 10(c)], the $\mathrm{CR} = 500{:}1$ contrast ratio occurs at around $\pm 50°$ viewing cone, while the CR at $\pm 80°$ drops to 80:1 and 50:1, respectively. And

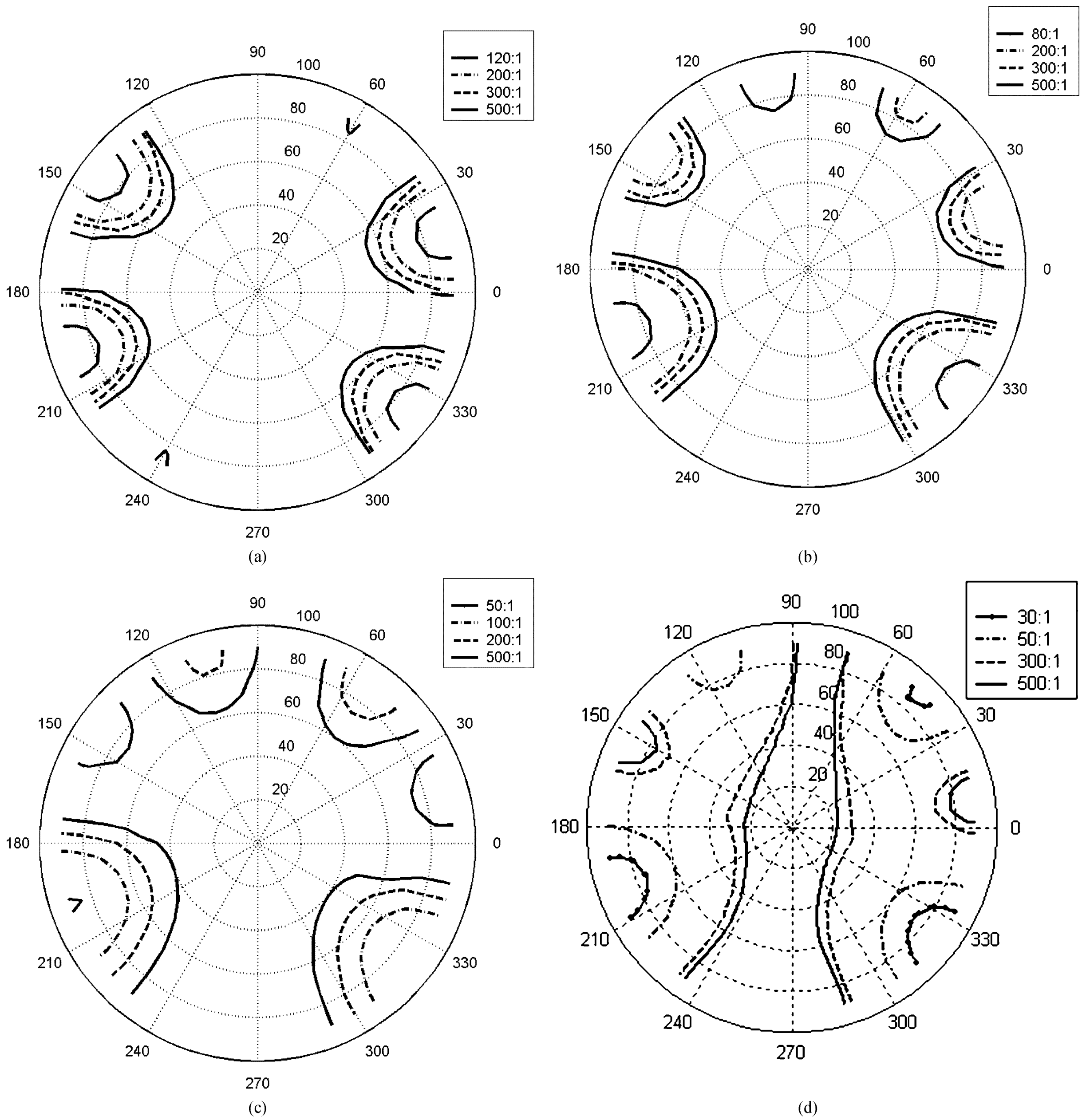

Fig. 10. Viewing angle of the IPS device with the uniaxial A/C-plates under the different LC pretilt angles. (a) $\alpha = 0°$. (b) $\alpha = 1°$. (c) $\alpha = 2°$. (d) $\alpha = 5°$.

the iso-contrast bars are symmetric only along the rubbing angle direction. As the pretilt angle increases to 5° [see Fig. 10(d)], the CR drops to 30:1 at the ±80° viewing cone. In addition, there are other 500:1 iso-contour bars outside the 300:1 ones at the 10° and 150° azimuthal angles. This reversed contrast phenomenon indicates that the conventional uniaxial plates can hardly meet the requirement of compensating the off-axis light leakages from the crossed polarizers and the LC media simultaneously when the pretilt angle is large. It requires a new compensation approach to overcome this reversed contrast issue.

D. Phase Compensation With an O-Plate

The positive O-plate we refer here is a positive birefringent film whose optic axis is oblique to the surface of the film; it is equivalent to a positive C-plate plus a tilted positive A-plate, as shown in Fig. 11 [12]. The purpose is to compensate the off-axis dark state light leakages from the crossed polarizers and the LC directors. Ideally, we should select a positive O-plate to cancel the residual phase retardation $(d \cdot \Delta n)_{\text{eff}}$ from the LC layer and from the polarizers $(d \cdot \overline{n})_{\text{polarizer}}$ at any oblique angle by satisfying the following equation:

$$(d \cdot \Delta n)_{\text{eff}} + (d \cdot \overline{n})_{\text{polarizer}} + (d \cdot \Delta n)_{O\text{-plate}} \approx 0 \qquad (9)$$

where $(d \cdot \Delta n)_{\text{eff}}$ is defined in (7). For simplicity, we assume the O-plate has the same birefringence properties as the LC material employed and a similar pretilt angle to the IPS LC cells. Correspondingly, the optimized O-plate has an effective $\mathrm{d} \cdot \Delta \mathrm{n}$ value that is comparable to a series of positive A/C-plates with the $d \cdot \Delta n$ value of 149.4 and 87.9 nm, respectively.

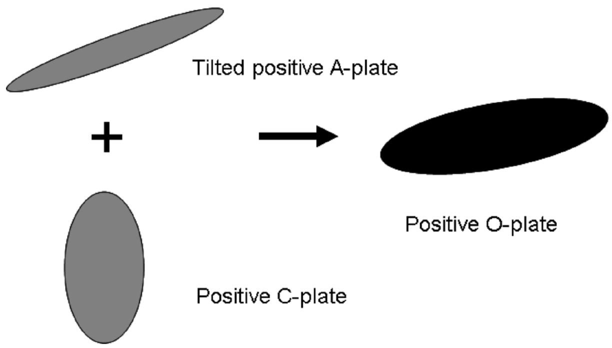

Fig. 11. Typical structure of the proposed O-plate.

With such an O-plate, the simulated light leakages for the IPS cells with nonzero pretilt angles are indeed lower than that of using the conventional A/C-plates. As plotted in Fig. 12, the light leakage of the O-plate-compensated IPS cell is reduced to the level of 10^{-5} even the pretilt angle is as large as 5°. That means the O-plate is more effective than the combined A/C plates in reducing the off-axis light leakage for the IPS LCD cells.

Fig. 13(a) shows the simulated viewing angle of the O-plate-compensated IPS cell with 1° pretilt angle. A high contrast with $\mathrm{CR} \geq 120{:}1$ is obtained within the entire $\pm 80^{\circ}$ viewing cone. This result is comparable to that of the IPS cell with $\alpha = 0^{\circ}$ while using the conventional A/C-plates. Most importantly, the iso-contrast contour bars are symmetric along the rubbing angle direction and along its perpendicular direction, which indicates that the O-plate has effectively compensated for the off-axis light leakage of the crossed polarizers and the off-axis light leakage of the LC layer simultaneously. Similar to the case of 1° pretilt angle, there is also noticeable improvement in viewing angle for the 2° pretilt angle Fig. 13(b), where the $\mathrm{CR} = 500{:}1$ is slightly narrower but the $\mathrm{CR} = 120{:}1$ contour line expands to $\pm 80^{\circ}$ viewing cone. This improvement is quite noticeable when compared to the IPS employing conventional uniaxial plates. Moreover, when the O-plate is used the reversed contrast observed in the IPS cell with 5° pretilt angle using the conventional A/C-plate compensation is suppressed completely as shown in Fig. 13(c). The CR at $\pm 80^{\circ}$ viewing cone is better than 40:1 and the CR is symmetric along the rubbing direction.

We have applied the O-plate to compensate the four-domain super-IPS mode, and found a similar improvement in the viewing angle when the IPS cell has a small pretilt angle. Therefore, the proposed O-plate is effective in widening the viewing angle of the IPS LCD by lowering the off-axis light leakage when the pretilt angle effect is not negligible. Meanwhile, different O-plate designs are possible in combination with different types of uniaxial plates or biaxial plates, which is a future research topic [18], [19].

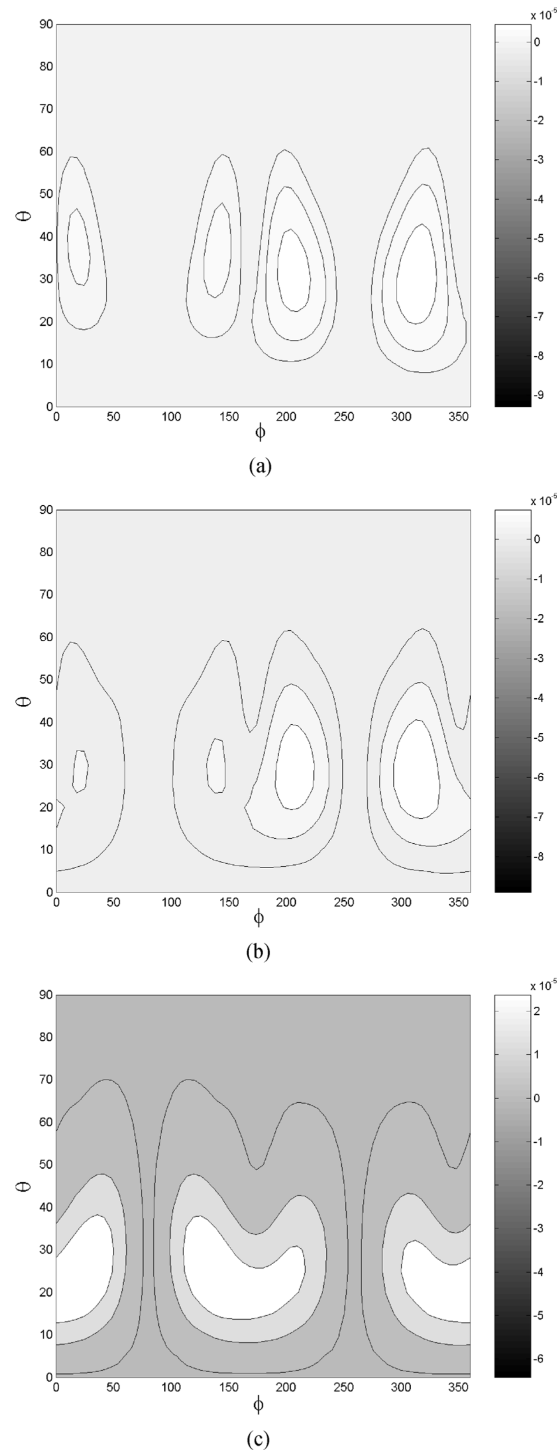

Fig. 12. Dark-state light leakages of the homogeneous IPS LCD with the different LC pretilt angles using the proposed O-plate. (a) $\alpha = 1^{\circ}$. (b) $\alpha = 2^{\circ}$. (c) $\alpha = 5^{\circ}$.

V. Conclusion

The inherent light leakage and viewing angle properties without any compensation plate, and those with conventional uniaxial A/C-plates are analyzed. The pretilt angle is found to have a significant effect on the IPS LCD. The off-axis dark-state light leakage from the crossed linear polarizers and the anisotropic out-of-plane LC directors cannot be neglected, especially when the LC pretilt angle is nonzero. An O-plate is proposed to lower the off-axis dark-state light leakage of the device. Simulation results indicate that, indeed this O-plate compensation is effective in overcoming the pretilt angle effect for widening the viewing angle of the IPS LCD. Specifically, when the LC pretilt angle is lower than 2°, a high contrast ratio of 120:1 over the $\pm 80^{\circ}$ viewing cone can still be obtained,

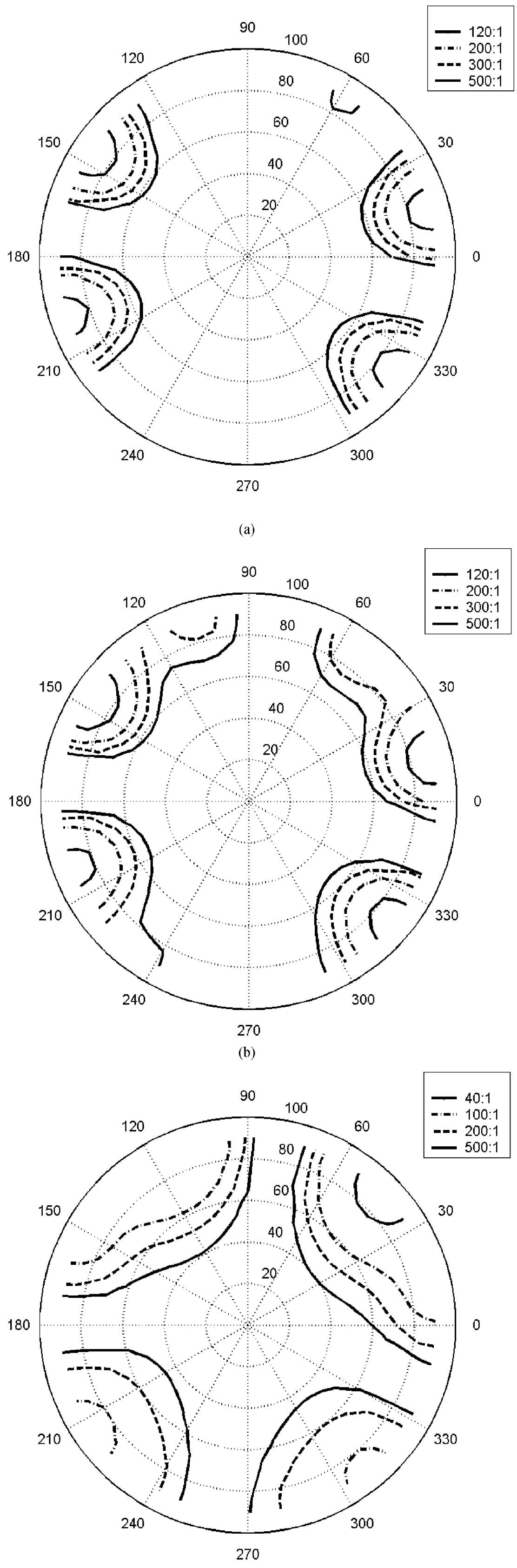

Fig. 13. Viewing angle of the IPS device with the O-plate under the different LC pretilt angles. (a) $\alpha = 1^\circ$. (b) $\alpha = 2^\circ$. (c) $\alpha = 5^\circ$.

where the iso-contrast contour bars are symmetric along the rubbing direction and its perpendicular direction.

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