

P-116: Wider Viewing Angle in In-Plane Switching Mode Liquid Crystal Displays by Self-Compensated Phase Retardation Films

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Abstract

We propose a Self-compensated Phase Retardation (SPR) film as a compensation film for in-plane switching liquid crystal displays. Numerical calculations show that SPR film suppress the light leakage significantly to achieve the contrast ratio higher than 290:1 for all viewing angle, compared to the conventional film having the contrast ratio 120:1. Color difference from D65 at black state is also decreased from $\Delta u'v'=0.3031$ to 0.1646 at viewing angle $(\theta, \phi)=(60^\circ, 45^\circ)$ when we replace the conventional films to SPR ones.

Key Words: in-plane switching mode, wide viewing angle, compensation film, dispersion in wavelength.

1. Introduction

Viewing angle has been a key parameter evaluating the image quality of liquid crystal displays (LCDs). There have been two approaches to improve the viewing angle performance of LCDs. First approach is to design the liquid crystal mode including the structure of electrodes and the condition of surface alignment [1-4]. Second approach is to use the retardation films to compensate the change of polarization state due to the change of effective polarizer absorption axis and residual optical retardation of liquid crystal layers at off-axis viewing angle [5-7]. Patterned vertical alignment (PVA) mode and in-plane switching (IPS) mode have been employed by major LCD industries to achieve the wide viewing angle performance. In those commercial LCDs, the contrast ratio is only about 10 at some viewing angles even with the help of compensation films because of the wavelength dispersion of the optical birefringence. Light leakage at off-axis viewing angle in black state of IPS mode especially is sensitive to the wavelength dispersion of compensation films [8,9].

Previously we proposed a self-compensated phase retardation (SPR) film as an achromatic compensation film for wide-viewing transmissive LCDs and reflective LCDs with vertical surface alignment at SID '08[10] and IDRC '08[11], respectively. It was shown that, compared to conventional films where optical anisotropy satisfies Cauchy dispersion relation, SPR films worked well as compensation films to suppress the light leakage efficiently at off-axis viewing angle. In this paper, we report the results when we apply the SPR films to IPS mode. We find that in IPS mode SPR films give not only high contrast ratio at off-axis viewing angle but also reduced color shift at off-axis viewing angle in black state. It should be noticed again here that optical birefringence of SPR films is nearly proportional to wavelength, which make the optical phase retardation be constant. SPR films are not composed of new materials which has reverse dispersion in wavelength like WRF (wide-band retardation film) [12], but composed of optical films following normal Cauchy dispersion relation [13,14].

2. Basic Concept of Self-Compensated Retardation (SPR) Film

The optical phase retardation governing the optical transmittance of LCDs is given by

$$\Delta\phi = \frac{2\pi\Delta n d}{\lambda}, \quad (1)$$

where Δn is optical birefringence, d is thickness of a sample and λ is wavelength of light in vacuum. This equation leads that, in order to keep the transmittance to be constant in wavelength, the Δn should be proportional to the wavelength. By contrast, the optical birefringence of conventional optical film decrease with increasing wavelength satisfying the Cauchy dispersion formula. The SPR film is a solutions to this problem.

A SPR film is composed of two films that have opposite sign of retardation value. Fig. 1 depicts the schematic of SPR film for a positive C plate. The absolute value of optical birefringence of the films decreases with increasing wavelength. Thus, by tuning the slope of the curves, we can obtain the dispersion curve nearly proportional to wavelength. As shown in Fig. 1(a), sum of optical birefringence curves of two films is nearly linear in wavelength. This strategy can be applied to other types of compensation films such as C-, A+, A-, and biaxial plates.

Let us consider a positive SPR C plate comprising a positive C plate and a negative C plate. The wavelength dispersions of optical birefringence of the two films are given by the simple Cauchy relation as

$$\Delta n_1 = a_1 + \frac{b_1}{\lambda^2}, \quad -\Delta n_2 = a_2 + \frac{b_2}{\lambda^2}, \quad (2)$$

then, the net optical retardation is

$$\begin{aligned} \Delta\phi &= \frac{2\pi\Delta n_1 d_1}{\lambda} + \frac{2\pi\Delta n_2 d_2}{\lambda} \\ &= 2\pi \left[(a_1 d_1 - a_2 d_2) + \left(\frac{b_1 d_1}{\lambda^2} - \frac{b_2 d_2}{\lambda^2} \right) \right] \frac{1}{\lambda} \\ &\stackrel{\text{let}}{=} 2\pi \frac{(A+B/\lambda^2)}{\lambda} \end{aligned} \quad (3)$$

where $A=a_1 d_1 - a_2 d_2$ and $B=b_1 a_1 - b_2 d_2$. The values of A and B can be obtained by minimizing the following quantity.

$$\begin{aligned} F &= \int_{\lambda_{\min}}^{\lambda_{\max}} \left(\frac{\Delta\phi}{2\pi} - \frac{\Delta\phi_0}{2\pi} \right)^2 w(\lambda) d\lambda \\ &= \int_{\lambda_{\min}}^{\lambda_{\max}} \left(\frac{R_{\text{eff}}}{\lambda} - \frac{\Delta\phi_0}{2\pi} \right)^2 w(\lambda) d\lambda, \end{aligned} \quad (4)$$

where $\Delta\phi_0$ is the desired phase retardation, $R_{\text{eff}}=A+B/\lambda^2$, and $w(\lambda)$ is a weighting function. λ_{\max} and λ_{\min} are the boundary value of visible wavelength region, i.e., 780 nm and 380 nm, respectively. After integration and differentiation with respect to A and B , we can obtain A and B for a given $\Delta\phi_0$. For example, if we set $w(\lambda)=1$, we obtain

$$A = R_0 \frac{su - qt}{ps - q^2}, \quad B = R_0 \frac{-qu + pt}{ps - q^2}, \quad (5)$$

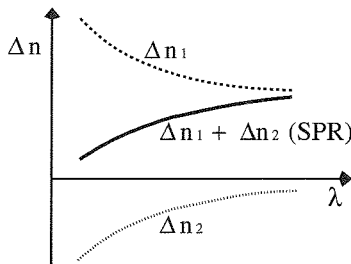
where $R_0 = \Delta\phi_0 / 2\pi$ and

$$p = 1/\lambda_{\min} - 1/\lambda_{\max}, \quad q = (1/\lambda_{\min}^3 - 1/\lambda_{\max}^3)/3, \quad (6)$$

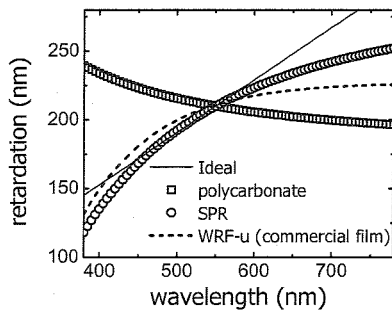
$$s = (1/\lambda_{\min}^5 - 1/\lambda_{\max}^5)/5$$

$$r = \ln|\lambda_{\max}/\lambda_{\min}|, \quad t = (1/\lambda_{\min}^2 - 1/\lambda_{\max}^2)/2.$$

Optimized optical retardation of the SPR film is shown in Fig. 1(b) in comparison with the wavelength dispersion curves of the conventional polycarbonate film and WRF film [12]. SPR film has the curve nearly proportional to wavelength as desired. Here, the retardation values of the films are set to 210 nm at wavelength 550 nm. In the case of biaxial plate, we have to calculate the *A* and *B* parameters in Eq. (3) for in-plane and out-of-plane, independently. Then we get the dispersion relations of three principal refractive indices.



(a) Principle of SPR film



(b) Wavelength dispersion of SPR film

Fig. 1. Basic concept of self-compensated phase retardation (SPR) Film.

3. Numerical Calculation of Optical Transmittance of IPS mode LCDs

Numerical calculations are performed to evaluate the performance of SPR films for IPS mode liquid crystal display. Fig. 2 shows the schematic drawing of optical layers of film-compensated IPS mode LCD [6]. Coordinate system is chosen such that *x*-axis is along absorption direction of bottom polarizer and *z*-axis is perpendicular to the optical films and parallel to propagation direction of light for normal incidence. Liquid crystal director on the cell substrates is anchored to be along *x*-axis. Optical compensation for off-axis viewing angle is carried out by a positive C plate and a positive A plates where the slow axis is parallel to *x*-axis. Throughout this paper, θ and ϕ represent the polar angle and azimuthal angle of propagation direction of light,

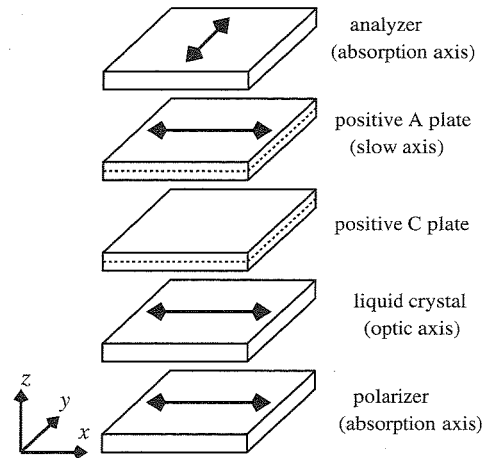


Fig. 2. Layer structure of optical components in IPS mode LCD.

respectively. The faster Berreman method is used to calculate the optical transmittance [15]. The dispersion of optical birefringence of conventional compensation films is assumed to satisfy Cauchy dispersion relation with following form.

$$\Delta n = 0.00875 + \frac{892.527}{\lambda^2}, \quad (7)$$

where λ is wavelength in unit of nm. Thickness of the films are determined by the retardation values giving the minimum luminance of leaked light at $\theta = 60^\circ$ and $\phi = 45^\circ$.

3.1 Mechanism of compensation

Fig. 3 shows the evolution of polarization state on the Poincare sphere for a finite polar angle and azimuthal angle 45° . It is noticed to avoid confusion that three unit vectors defining a propagation frame are $(\cos\theta \cos\phi, \cos\theta \sin\phi, -\sin\theta)$, $(-\sin\phi, \cos\phi, 0)$ and $(\sin\theta \cos\phi, \sin\theta \sin\phi, \cos\theta)$. And $\exp[i\omega t]$ is used as a phase convention, where ω is angular frequency of light and t is time. Point *Q* represents the polarization state of light just after passing through bottom polarizer, while point *A* is the extinction point of analyzer. Thus, the polarization state should move from *Q* to *A* by the retardation of the liquid crystal layer and compensation films. In fact, there is no change in polarization state when the light passes through the liquid crystal layer because point *Q* is on the rotation axis of the liquid crystal layer Ω_{LC} as shown in Fig. 3 (b) [6]. By the positive C plate, the polarization state evolves from point *Q* to point *M*. Then, the polarization state moves to *A* by the positive A plate whose slow axis is along *x*-axis. However, the path explained above is true only for single wavelength unless the optical birefringence of compensation films is proportional to wavelength. As shown in Fig. 1, most compensation films have dispersion in wavelength satisfying Cauchy form. Thus, we need to replace the evolution trajectory of polarization state of light shown in Fig. 3 (b) with that shown in Fig. 3 (c). Red (Blue) light has smaller (larger) rotation angle than green light because optical retardation of red(blue) light is smaller (larger) than that of green one when the dispersion of optical birefringence of the film satisfy the Cauchy's form. Thus the polarization states of red and blue light is not at the point *A*, which cause some amount of light leakage. Therefore, in order to suppress the leaked light for all visible light, it is inevitable to use

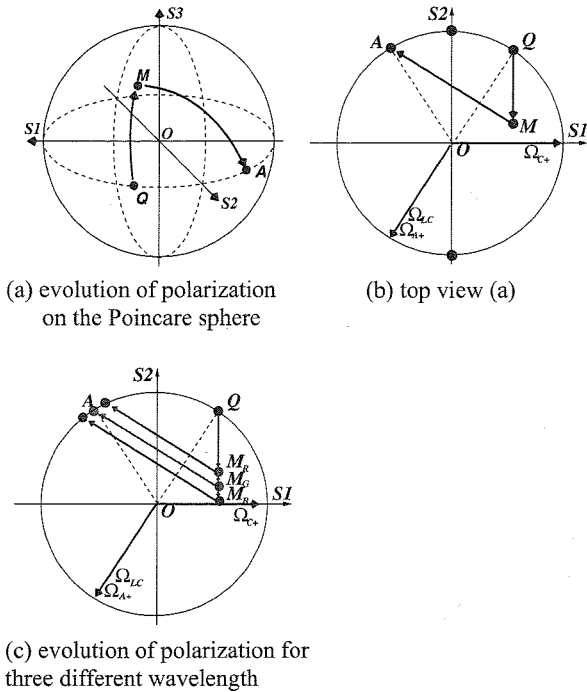


Fig. 3. The evolution of polarization state on the Poincare sphere.

the compensation films where the birefringence of optical retardation in wavelength is proportional to wavelength when we employ IPS mode and compensation film structure as shown in Fig. 2. It is why we use the SPR film for IPS mode LCDs.

3.2 Numerical Calculation Results

As a first step we tune the optical retardation values of the positive C plate and the positive A plate to obtain the minimum leaked luminance condition of black state at $\theta=60^\circ$ and $\phi=45^\circ$. To mimic real device situations, we use the spectrum of conventional Cold Cathode Fluorescence Lamp (CCFL) as a light source and the transmittance spectrum of conventional color filter. Luminance and color coordinates of transmitted light are calculated using the tristimulus function of human eye. Liquid crystals are parallel to x direction at black state and along diagonal direction (45°) at white state.

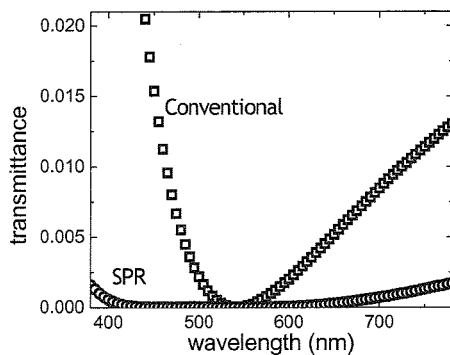
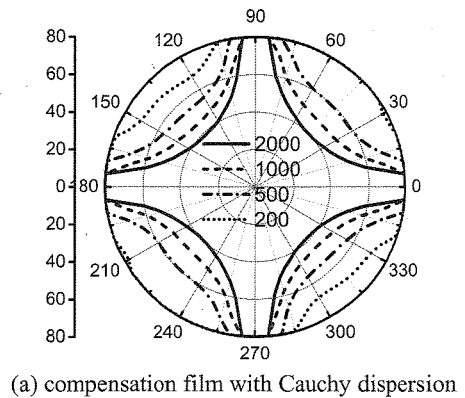


Fig. 4. Transmittance of leaked light of black state at polar angle 60° and azimuthal angle 45°

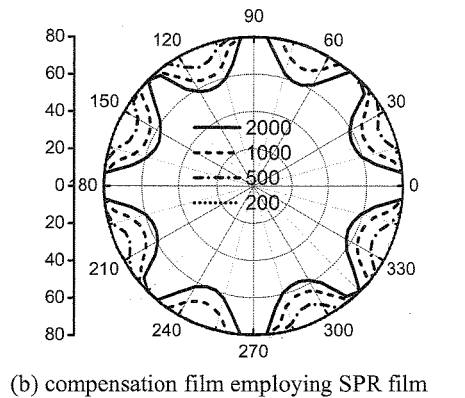
Optimized retardation value of a positive C plate and a positive A plate are 86 nm and 138 nm at wavelength 550nm, respectively, for the case of conventional compensation films satisfying Cauchy dispersion relation Eq. (7). SPR films have minimum leaked luminance at 86 nm and 142 nm at 550nm, which are almost same with the condition of conventional films.

Fig. 4 shows the curves of transmittance of leaked light of black state at an incident angle $\theta=60^\circ$ and $\phi=45^\circ$. We can see that the leaked light is much suppressed when we employ the SPR films, compared to the case that conventional compensation films are used. Curve of SPR films has almost zero value for all range of wavelength of visible light. In contrast, the curve of conventional films has low value only around 550 nm as is described in the section 3.1. The high leaked transmittance comes from the Cauchy dispersion of optical retardation.

Fig. 5 shows the isocontrast curves. In (a), the isocontrast curve is shown when the conventional compensation films are applied. Contrast ratio at off-axis is higher than that of IPS mode LCDs commercially available in the market because we ignore the tri-acetyl-cellulose(TAC) layer which is widely used as a base film of polarizer absorption layer. TAC films are worked optically as a negative C plate with small biaxiality. Inserting the TAC layer between the bottom polarizer and the liquid crystal layer, and the positive C plate and top analyzer, we need to modify the compensation scheme [4]. However, TAC film with nearly zero birefringence was developed by a company, which has brand name FUJI FILM 'Z-TAC@[16].



(a) compensation film with Cauchy dispersion



(b) compensation film employing SPR film

Fig. 5. Isocontrast curve

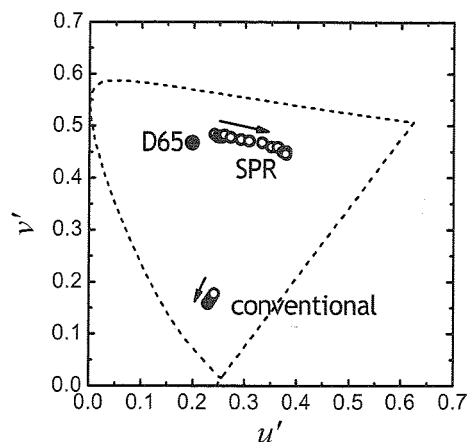


Fig. 6. Color shift performance

Thus, we can improve the viewing angle performance by employing the compensation scheme shown in Fig. 2 and utilizing conventional compensation films and 'Z-TAC®. Contrast ratio is higher than 120 for all viewing angles. However, as shown Fig. 6, the color coordinate of IPS LCD utilizing conventional compensation films is strongly pushed to blue region. Arrow in the figure shows the increment direction of polar angle. The azimuthal angle ϕ is fixed at 45° . The color coordinate for $\theta=60^\circ$ and $\phi=45^\circ$ is dislocated from that of standard white light source D65 by 0.3031 in $u'v'$ color coordinate system ($\Delta u'v'=0.3031$). Blue shift in dark state of LCDs are not ignorable problem because human eye is more sensitive to blue light in dark luminance condition, which is called the Purkinje effect [17].

Fig. 5 (b) shows the isocontrast curve when SPR films are applied to compensation films. Compared to the conventional films, SPR films give much higher contrast value. The contrast is beyond 290 for all viewing angles. If we limit the polar angle θ less than 60° , we can obtain the contrast ratio higher than 1000 for all azimuthal angle. Furthermore, as shown in Fig. 6, color coordinate is much closer to that of D65, compared to conventional case. Color difference from D65 is 0.1646, which is almost a half of conventional case. Thus we can see that SPR films shows excellent viewing angle property in not only contrast ratio but also color shift.

4. Conclusion

We propose a self-compensated phase retardation (SPR) film for reducing light leakages stemming from wavelength dispersion as a new compensation film for IPS mode liquid crystal displays. SPR films are not composed of new material, but simply composed of two optical films with simple Cauchy dispersion relation, of which the sign of optical anisotropies are opposite each other. Our numerical calculations show that SPR film significantly reduce the light leakage of IPS LCDs for off-axis

viewing angle. This leads to anomalous increment of contrast ratio and suppression of color shift at off-axis viewing angle. This study directs the new way to develop the optical compensation films.

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5. References

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