

An Optical Configuration for Vertical Alignment Liquid Crystal cell with Wide Viewing Angle

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Abstract

We propose an optical configuration of a vertical alignment (VA) liquid crystal (LC) cell to eliminate the light leakage in the diagonal direction. VA LC cell has an excellent contrast ratio in the normal direction due to the no phase-retardation. However, change of the phase-retardation occurs in all directions, which causes the light leakage and deteriorates the characteristics of the dark state. We designed the LC cell structure composed of multiple combinations with two A-plates and two C-plates in order to achieve wide viewing property on the Poincaré sphere. From calculations, we show that the proposed structure can improve the viewing angle characteristics by compensating for the light leakage in all directions.

Keywords : Vertical alignment LC cell, Light leakage, Optical compensation, Poincaré sphere

1. Introduction

Recently, many studies have been performed to improve the optical properties in Liquid Crystal Display (LCD) industry. Wide Viewing angle in LC cell, especially, is one of the most important properties that are required from users for excellent image quality which can be applied to TV application. In order to realize the LCD with good quality, many LC modes such as Optical compensated bend (OCB) mode [1], axial symmetric micro-cell (ASM) mode, in-plane switching (IPS) mode [2], fringe field switching (FFS) [3] mode and patterned vertically alignment (PVA) mode [4] have been studied. In this paper we propose an optical configuration that can exhibit wide viewing angle in VA mode. We applied two A-plates and two C-plates for achromatic black level in all direction. Optimization of the optical configuration of the proposed LC cell has been performed on a Poincaré sphere to get wide viewing angle. In order to verify the optical characteristics of the proposed LC cell, we compared the calculated optical properties of the proposed LC cell with conventional LC cell.

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2. Basic concept of the optical properties

There are several reasons for the light leakage of the vertical alignment LC cell in the diagonal direction with oblique incidence. The first reason for the light leakage is change in the effective angle of the polarization axes of two crossed polarizers, which increases with the polar angle of the observation angle θ in off-axis direction. So polarization axis of the polarizer deviates from normal incidence by angle δ. In case of small birefringence (i.e. $|n_e - n_o| \ll n_e, n_o$), the deviation angle δ in terms of ϕ and θ_o can be described as below [5-6]:

$$\delta = -\arcsin\left[\frac{\sin 2\phi \sin^2(\theta_o/2)}{\sqrt{1-\sin^2\theta_o \sin^2\phi}}\right] \quad (1)$$

Where the ϕ is azimuth angle of the polarization axis of the polarizer, the θ_o is polar angle of the incident light in the LC cell layer. The n_e and n_o represent extraordinary and ordinary refractive index of the polarizer, respectively. From equation (1), the deviation angle δ is maximized in the diagonal direction (ϕ =45°). We can also calculate the effective slow and fast axis of uni-axial film through equation (1). In general, the effective angle of the optical axis of the retarder in oblique incidence is changed as the observation angle θ is changed. A-plate moves to δ from the angle of a normal incidence. In case of the positive C-plate and VA LC cell, the effective fast or slow axis moves to 90° with respect to the projected angle of the incident *k* vector.

The second factor is the change of retardation in each optical film. The effective retardation of the A-plate, C-plate and VA LC cell in the oblique incident angle can be described as below [7]:

$$\Gamma_A = \frac{2\pi}{\lambda} d \left[n_e \left(1 - \frac{\sin^2\theta \sin^2\phi}{n_e^2} - \frac{\sin^2\theta \cos^2\phi}{n_o^2} \right)^{1/2} - n_o \left(1 - \frac{\sin^2\theta}{n_o^2} \right)^{1/2} \right] \quad (2)$$

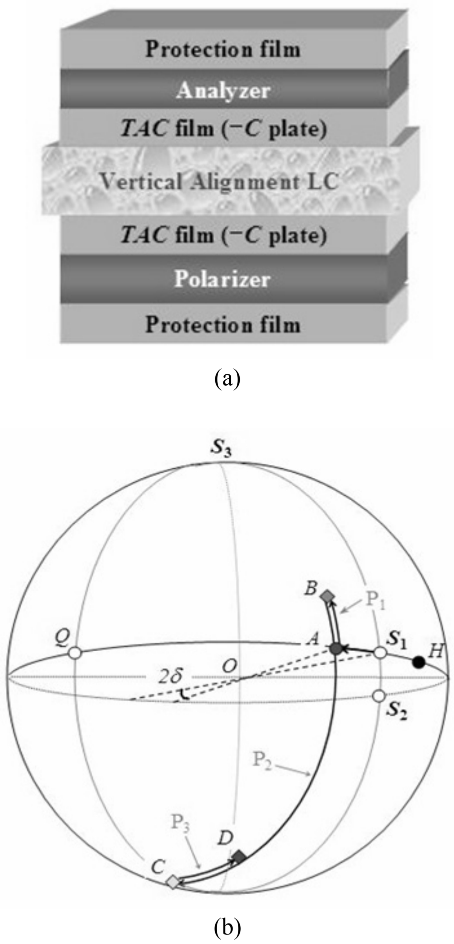
$$\Gamma_C = \frac{2\pi}{\lambda} \frac{d}{\cos\theta_o} \left[\left(\frac{n_o^2 n_e^2}{n_o^2 \sin^2\theta_o + n_e^2 \cos^2\theta_o} \right)^{1/2} - n_o \right] \quad (3)$$

Where Γ_A and Γ_C represent the retardation of the A-plate and C-plate at oblique incidence, respectively. The d represents the thickness and the λ represents wavelength of the incident light. From the equation (2), (3) we can calculate that retardation of the A-plate changes within 5% even though the oblique angle at the diagonal direction increases to 90°, whereas the C-plate has a large change in retardation compared to the A-plate.

The last issue is phase dispersion of the refractive index along the wavelength. The dispersion is dependent on the material property. The polarization states of the three primary colours (R, G, B) differ from each other after passing through the LC cell and retardation films because of the different material and wavelength dispersion. To minimize light leakage at oblique incidence in the dark state, the phase dispersion in all visible wavelengths should be eliminated. In this paper we introduce a design method using the Stokes parameters on the Poincaré sphere for an achromatic black state in all directions.

3. Results and discussion

The conventional LC cell consists of vertical alignment LC and two tri-acetyl-cellulose (TAC) films (negative C-plate ≈ -42nm) on the crossed polarizers as shown in Fig. 1(a). LC director in the VA LC cell is homeotropically aligned to the substrate in the electric field off state. We assume that the optical axis of the VA LC cell in the absence of electric field is the same as the optical axis of C-plate. Fig. 1(b) shows the polarization state of the light obliquely passing through the cell in the diagonal direction on the Poincaré sphere. In the dark state, oblique incident light in the diagonal direction will have a deviated polarization angle δ compared with normal incident light. The polarization position of the polarizer will deviate by 2δ from S_1 which is the polarization state of the polarizer in a normal direction. Therefore, the start position for the oblique incident is position A. The light passing through the lower TAC film with slow axis OQ has polarization position B along the circle path P_1. Next, the polarization state of the light will move to position C along the circle path P_2 by experiencing the vertical aligned LC cell. Finally, the upper TAC film will move the polarization state to position D from the position C with path P_3. From Fig. 1(b) we can observe that the polarization position of the light is quite different from the polarization position D in front of the output polarizer H. Therefore we can assume that the deviation between position D and position H will cause serious light leakage in the dark state.

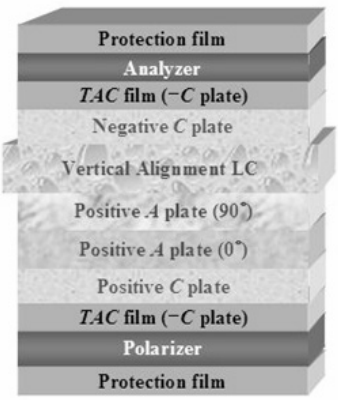


(a)

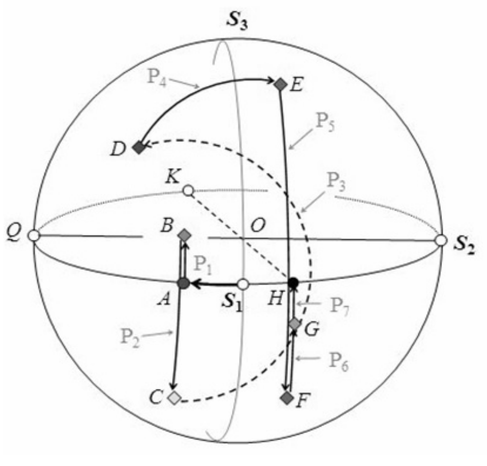
(b)

Fig. 1. Optical configuration of the conventional vertical alignment LC cell and polarization state of the oblique incident light in the LC cell; (a) optical structure (b) polarization path on the Poincaré sphere.

The Compensation for the deviated polarization occurred in oblique incidence can be achieved by adding several retardation films to the conventional LC cell. Fig. 2(a) shows the proposed optical configuration of the VA LC cell, which can improve the viewing angle in all directions. The optical configuration of the proposed LC cell consists of two A-plates, two C-plates, and vertical alignment LC cell. The optical axis of the lower A-plate is aligned with the transmission axis of the incident polarizer, and the optical axis of the upper A-plate is aligned along that of transmission axis of the analyzer. An improved optical polarization path of the proposed LC cell is described on the Poincare spheré as shown in Fig. 2(b). The application of the Poincaré sphere is particularly simple and provides the polarization state after passing through each media. Optimization of



(a)



(b)

Fig. 2. Optical configuration of the proposed vertical alignment LC cell and polarization state of the oblique incident light in the LC cell; (a) optical structure (b) polarization path on the Poincaré sphere.

the optical configuration in this paper has been performed at the diagonal direction, ϕ=45° because the light leakage in the dark state is maximized at ϕ=45°.

In the proposed configuration, the polarization state in front of the output polarizer can coincide with the absorption axis of the output polarizer through seven-paths (P_1−P_7). The polarization of the light passing through the lower TAC film and positive C-plate moves to position *C* along the circle path P_1 and P_2, which is centered at the same point *Q*. The polarization of the light approaches to the position *D* along the circle path P_3 after passing through the lower positive A-plate with the optical axis *OA*. Then the polarization of the light passing through the upper A-plate moves to position *E* along the circle path P_4 because the optical axis of the upper A-plate is aligned parallel with the absorption axis of the analyzer. The next polarization state of the light after passing through VA LC cell with fast axis *OQ* will rotate to position *F* along path P_5. Finally, the polarization state passing through the negative C-plate and upper TAC film reversely rotates to proceed to the position *H* by way of the position *G* along path P_6 and P_7. The position *H* is exactly matched with the opposite position *K* of the polarization state of analyzer. The process of the proposed optical configuration effectively moves the polarization position to the polarization position of the analyzer for the oblique incident direction, so that it clearly eliminates the light leakage in the dark state.

However, for the best dark state, we should consider phase dispersion of the LC cell because the proposed configuration should satisfy the above principle along the range of the entire wavelength. We need to optimize the retardation value of the used compensation films. Elimination of phase dispersion represents the coincidence of the polarization states among *R* (630 nm), *G* (550 nm) and *B* (450 nm) wavelength on the Poincaré sphere in front of the output polarizer. Fig. 3 shows the optical principle of the proposed VA LC cell to remove the phase dispersion through the wavelength *R*, *G* and *B* on the Poincaré sphere. The symbol ● represents the polarization at the longest wavelength *R*, ■ represents the polarization at the middle wavelength *G* and ◆ represents the polarization at the shortest wavelength *B*. To gather the polarization positions on the entire wavelength to position *H*, we need to satisfy two conditions as below.

The first condition is that the polarization positions for R, G and B wavelength after passing through the upper

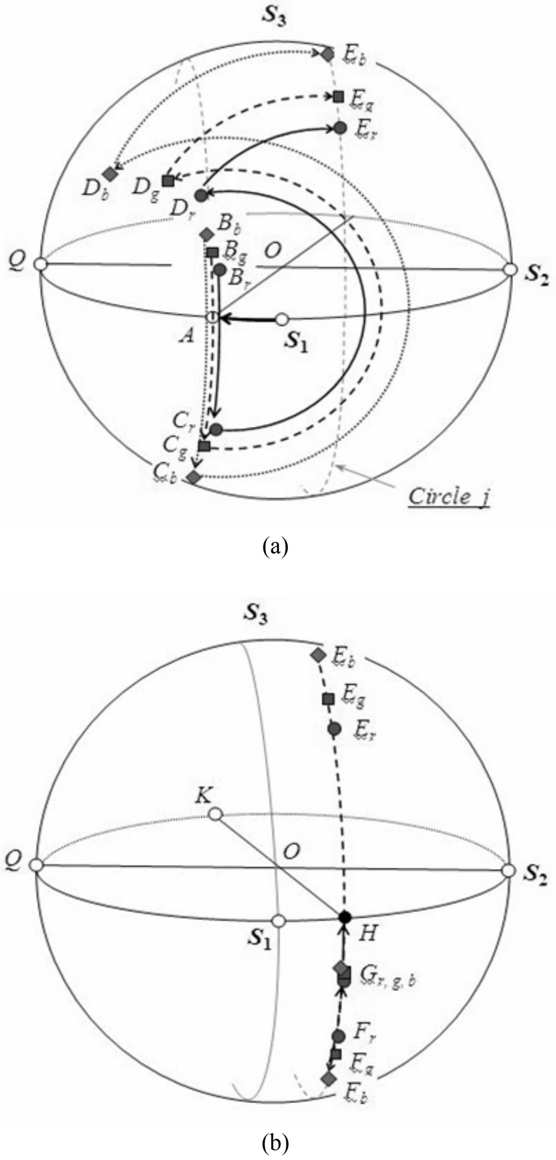


Fig. 3. Polarization state for wavelength R, G and B on the Poincaré sphere; (a) polarization state of the light after passing through the lower TAC film, positive C-plate and two A-plates, (b) polarization state of light after passing through VA LC, negative C-plate and upper TAC film.

A-plate should be on the circle j as shown in positions E_r, E_g, and E_b in Fig. 3(a). The subscript of the letter for each position represents the position of each R, G, and B wavelength. The aligned polarizations of the entire wavelength on the circle j can be gathered by adjusting the retardation of the positive C-plate and two A-plates. To satisfy the first condition, we need to calculate Stokes parameters along three wavelengths after passing through each retardation film. For the calculation, we assume that TAC film has flat material dispersion, because it has very small retardation difference among three wavelengths. We applied the Muller matrix and the Stokes vector to find the optimum retardation of two A-plates which move the polarization position to be on the circle j on the Poincaré sphere as shown below [8-9]:

$$S' = R(-2\theta)\cdot M(\Gamma)\cdot R(2\theta)\cdot S(input)$$
$$= \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos^2 2\theta + \cos\Gamma\sin^2 2\theta & (1-\cos\Gamma)\sin 2\theta\cos 2\theta & \sin\Gamma\sin 2\theta \\ 0 & (1-\cos\Gamma)\sin 2\theta\cos 2\theta & \sin^2 2\theta + \cos\Gamma\cos^2 2\theta & -\sin\Gamma\cos 2\theta \\ 0 & \sin\Gamma\sin 2\theta & \sin\Gamma\cos 2\theta & \cos\Gamma \end{pmatrix} \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} = \begin{pmatrix} S_0' \\ S_1' \\ S_2' \\ S_3' \end{pmatrix} \quad (4)$$

Where $S(input)$ is the Stokes vector of the incident beam, S' is the Stokes vector of the beam emerging, and S_0, S_1, S_2 and S_3 are the Stokes polarization parameters. R(2θ) is the rotating matrix to laboratory axis, R(-2θ) is rotating matrix to principal axis with rotation angle θ, and M(Γ) is the Muller matrix for rotated polarizing components with phase retardation Γ. In order to move polarization state of the light for all wavelengths to be on the circle j, the component S_2' of the Stokes polarization parameters after passing through upper A-plate should be 0.24413, which is matched with the component S_2 of the Stokes parameter for the analyzer.

The second condition to optimize is to determine the retardation of the negative C-plate considering the VA LC cell and upper TAC film. The process for removing the phase dispersion of the LC cell can be performed on the circle j. After passing through the upper A-plate, the light will experience the VA LC, negative C-plate and TAC film. The final positions of the polarization sate of the light along wavelength R, G, B should be coincident to the same position. Therefore optimization of the negative C-plate is dependent on the retardation value of the VA LC and upper TAC film of the analyzer. The process for the optimization on the Poincaré sphere is illustrated in Fig. 3(b) which shows the polarization states of the light passing through the VA LC, negative C-plate, and upper TAC film. To get an achromatic colour performance in the dark sate, the polarization state of the light passing through the final upper TAC film must move from E_r, E_g, and E_b to H which is desired final destination of the tri-stimulus wavelength for the dark state. The Stokes vector of point H is $(1, 0.96974, 0.24413, 0)^T$, so we can easily calculate the retardation of the negative C-plate by using the equation (4).

Fig. 4 shows the calculated optimum phase dispersions of two positive A-plates, positive and negative C-plate. In terms of the material dispersion, the positive C-plate is normal dispersion, the lower A-plate is reverse dispersion, the upper A-plate and negative C-plate are flat dispersion. Fig. 5 represents the calculated transmittance of the LC cell with the oblique incident light (ϕ=45°, θ=70°) in the dark state. The proposed configuration can eliminate the transmittance in the dark state significantly compared to the conventional configuration. We verified the improved viewing angle of the proposed VA LC cell using the commercial LC software *DiMOS*. Fig. 6 shows a comparison of the calculated iso-dark contour between the conventional configuration and the proposed configuration. We confirm that the maximum light leakage in diagonal direction is effectively eliminated in the proposed configuration, so that the viewing angle property can be improved more over 80% compare to the conventional configuration.

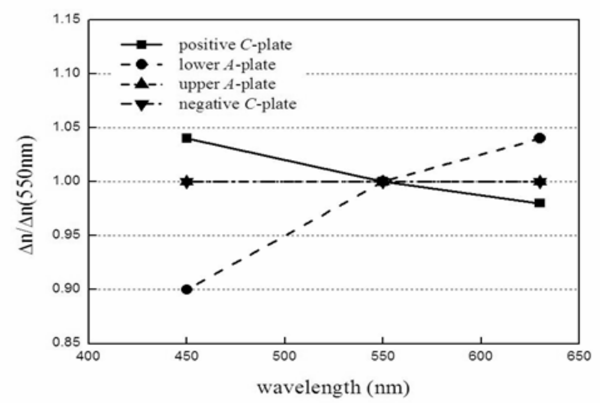


Fig. 4. Calculated material dispersion of the positive C-plate, lower A-plate, upper A-plate and negative C-plate.

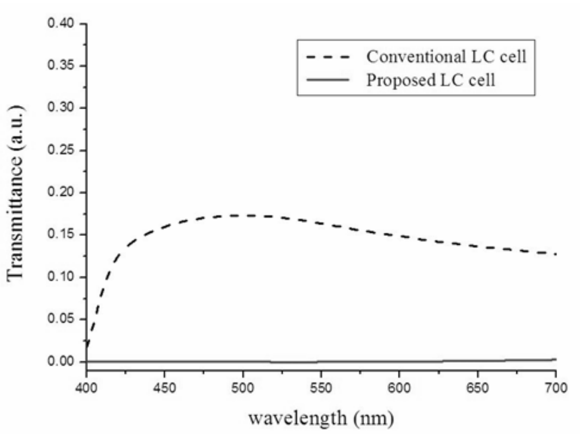
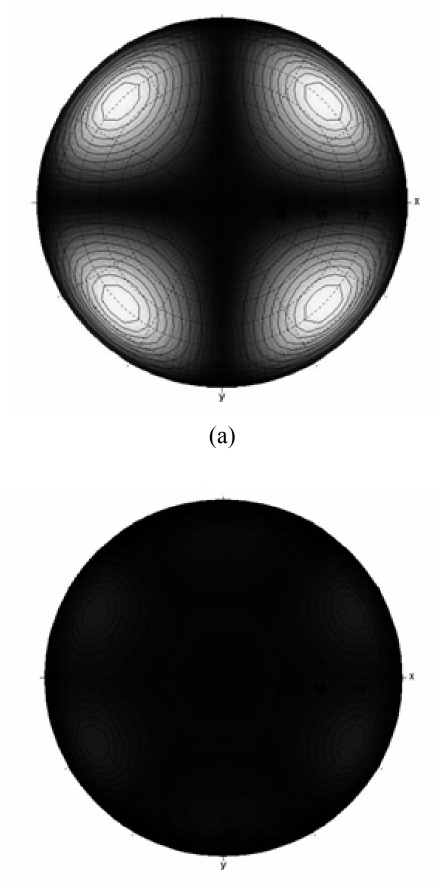


Fig. 5. Comparison of optical transmittance of the proposed LC cell with that of the conventional LC cell.



(a)

(b)

Fig. 6. Normalized iso-dark contour of the vertical alignment cell; (a) conventional LC cell, (b) proposed LC cell.

4. Conclusions

In conclusion, we propose an optical configuration of vertical alignment LC cell with two A-plates and two C-plates, which can improve the viewing angle in the diagonal direction. In order to compensate for phase dispersion of the entire wavelengths and achieve excellent dark state, we optimized phase dispersion of the retarders by using the Stokes vector and the Muller matrix on the Poincaré sphere. From calculations, we show that the proposed structure has the wide viewing angle characteristics by compensating for the light leakage in all directions.

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