# Optical Compensation in a Vertical Alignment Liquid Crystal Cell for Elimination of the Off-Axis Light Leakage

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## Abstract

*We propose an optical configuration for a vertical alignment (VA) liquid crystal (LC) cell to eliminate the off-axis light leakage in the dark state. The proposed compensation configuration consists of a positive A-film, a positive C-film and a negative C-film. The optical design is performed on a Poincaré sphere. This configuration has a better tolerance to the wavelength dispersion, as the polarization trace could self-compensate it. From calculations, we show that the proposed VA LC cell can improve the viewing angle characteristics by compensating for the light leakage in the diagonal direction.*

## 1. Introduction

Liquid crystal displays (LCDs) is one of the most important optical display systems for high performance flat panel displays. Recently, TV application has required a high picture quality in all directions including diagonal directions. In order to realize the LCD with a good optical performance, many display modes such as vertical alignment (VA) [1], in-plane switching (IPS) [2], and fringe field switching (FFS) [3] have been developed. In particular, the VA LC mode is applied in many advanced display devices because it yields an excellent contrast ratio in the normal direction due to zero phase retardation in the direction. However, the optical performance of the VA LC cell in the oblique direction deteriorates for several reasons, including changes in the polarization axis of the polarizer or changes in the phase retardation of the cell and the used films, particularly in the diagonal direction [4-5]. Light leakage in the oblique incidence can cause a serious decrease in the contrast ratio, especially, especially in the dark state.

In this paper, we introduce an optical configuration for the VA LC cell. This configuration can effectively eliminate light leakage in the oblique direction for a wide viewing angle. The proposed VA LC cell comprises an *A*-film and two *C*-films between crossed polarizers. In general, light leakage through the crossed polarizers in the oblique incidence is maximized at the azimuth angle $\phi = 45^\circ$ [6-8].

Therefore, we optimized the optical configuration of the proposed VA LC cell, particularly in the diagonal direction, in order to minimize the light leakage of the cell in the dark state. Optimization of the optical compensation films in the entire wavelength range in the dark state was performed on a Poincaré sphere [9-11] to achieve the optimized dispersion properties of each used film to get an excellent dark state. We compared the calculated optical properties of the proposed LC cell to the optical characteristics of the conventional LC cell to verify the outstanding optical characteristics of the proposed VA LC cell.

## 2.1 Optical principle for the oblique incidence

Light leakage in the dark state at the oblique incidence could occur for several reasons. One reason is the shift of the polarization axes of two crossed-polarizers and the shift of the optical axis of the optical film. This is dependent on the observation angle $\theta$ in an off-axis direction. Thus, the effective principle axis of the optical components deviates from the principle axis in the normal incidence by angle $\delta$. In terms of the polarizers, if we apply the very small birefringence approximation ($n_e \approx n_o$), the deviation angle $\delta$ in terms of $\phi$ and $\theta_o$ can be described as below [8,11]:

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

where $\phi$ is the azimuth angle of the polarization axis of the polarizer, and $\theta_o$ is the polar angle of the incident light in the LC layer. $n_e$ and $n_o$ represent the extraordinary and the ordinary refractive index of the polarizer and retardation film, respectively. From Eq. (1), the deviation angle $\delta$ is maximized in the diagonal direction ($\phi = 45^\circ$). Regarding the optical axis of the optical film, the effective angle of the optical axis of the retarder in the oblique incidence is changed as a function of the observation angle $\theta$. We can also calculate the effective optical axis of the *A*-film through Eq. (1). Thus, the optical axis of the *A*-film moves as much as the deviation angle $\delta$ from the optical axis in the normal incidence. In the case of the *C*-film and VA LC cell, the effective fast or slow axis moves to $90^\circ$ with respect to the projected angle of the incident *k* vector.

The second factor is a change in the retardation value of the compensation film in the oblique incidence. The effective retardation of the *A*-film, *C*-film and VA LC cell in the oblique incident angle can be described as below [12-13]:

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

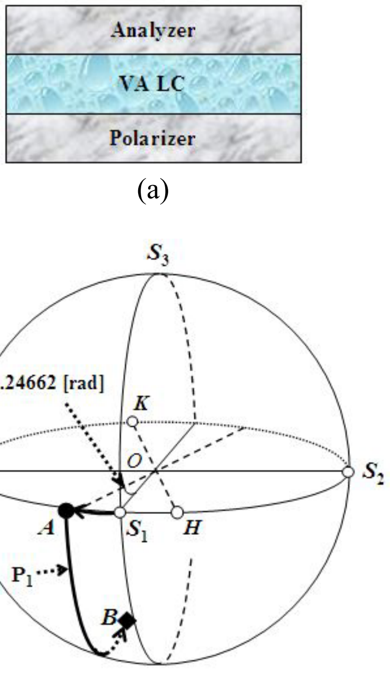
$$\Gamma_C = \frac{2\pi}{\lambda} n_o d \left[ \left( 1 - \frac{\sin^2\theta}{n_e^2} \right)^{1/2} - \left( 1 - \frac{\sin^2\theta}{n_o^2} \right)^{1/2} \right] \tag{3}$$

where $\Gamma_A$ and $\Gamma_C$ represent the phase retardation of the *A*-film and the *C*-film at the oblique incidence, respectively. $\theta$ represents the polar angle of the incident light in free space and $\phi$ is the azimuth angle of the incident angle. *d* represents the thickness of the film, and $\lambda$ represents the wavelength of the incident light.

The last issue is the dispersion of the refractive index of the optical components along the wavelength. In general, the dispersion is also dependent on the material property. The polarization states of the three primary colors (*R*, *G*, and *B*) usually differ from each other after passing through the LC cell and the retardation films because of the different material and wavelength dispersion properties. Therefore, to minimize light leakage at the oblique incidence in the dark state, the phase dispersion in the entire visible wavelength should be eliminated.

### 2.2 Optical compensation on the Poincaré sphere

For the optimal dark state, it is necessary to consider phase dispersion of the LC cell because the proposed configuration should satisfy the optical process in the entire wavelength range. A conventional VA LC cell comprises a VA LC layer and two crossed polarizers, as shown in Fig. 1(a). The LC director in the VA LC cell is vertically aligned to the substrate in the electrically off state. We assume that the optical axis of the VA LC cell in the absence of an electric field is the same as the optical axis of the positive *C*-film.



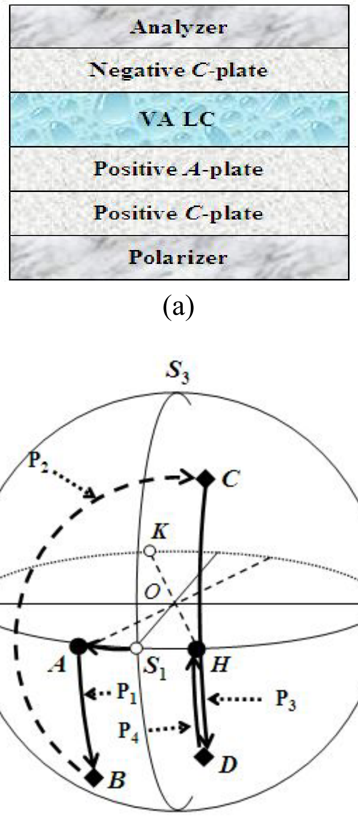
(a)

(b)

**Fig. 1. Optical configuration of the conventional VA LC cell and polarization states in the oblique incidence: (a) optical structure (b) polarization path on the Poincaré sphere in the oblique incidence**

Fig. 1(b) shows the polarization state of the light on the Poincaré sphere when the light obliquely passes through the cell in the diagonal direction. In the dark state, the oblique incident light experiences the deviated angle $\delta$ compared to the normal incidence when it passes the polarizer. Therefore, the position of the polarization axis of the polarizer will deviate by $2\delta$ from $S_1$, which is the polarization state of the polarizer in a normal direction on the Poincaré sphere. Therefore, the start polarization position in the oblique incidence becomes the position $A$. The polarization state of the light after passing through the VA LC with a position of the fast axis $Q$ is rotated to the polarization position $B$ along the circle path $P_1$. Here, the polarization position $B$ is quite different from the polarization position $H$, which is the perfect opponent position of the polarization axis of the analyzer in the oblique incidence. Therefore, we can assume that the large deviation between position $B$ and position $H$ will induce a serious off-axis light leakage in the dark state.

Optical compensation for the deviated polarization occurring in the 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 that can improve the viewing angle performance. The optical configuration of the proposed LC cell consists of a positive $A$-film, a positive $C$-film and a negative $C$-film [14]. The optical axis of the $A$-film is aligned with the absorption axis of the incident polarizer. An improved optical polarization path of the proposed LC cell is described on the Poincaré sphere, as shown in Fig. 2(b).



(a)

(b)

**Fig. 2. Optical configuration of the proposed VA LC cell and polarization states in the oblique incidence: (a) optical structure (b) polarization path on the Poincaré sphere in the oblique incidence**

Like the conventional VA LC cell, the start position in the oblique incidence ($\theta$=70° and $\phi$=45°) on the Poincaré sphere is position $A$ when the light passes through the polarizer. Then, the polarization state of the light passing through the positive $C$-film moves to position $B$ along the circle path $P_1$, centered at the point $Q$. The polarization position of the light moves to position $C$ along the circle path $P_2$ passing through the positive $A$-film which has a position $K$ for the optical axis. The polarization of the light passing through the VA LC layer moves to position $D$ along circle path $P_3$ with a centered position $Q$. Finally, the polarization state of the light passing through the negative $C$-film reversely rotates to proceed to position $H$ along path $P_4$. The position $H$ in front of the analyzer is exactly matched to the opponent position $K$ of the analyzer.

Therefore, the process of the proposed optical configuration can effectively move the polarization position of the light passing through the cell to the desired position, which should be the opponent position of the polarization axis of the analyzer in the oblique incidence. So that it can clearly eliminate the off-axis light leakage in the dark state.

## 3. Results and discussion

Fig. 3 represents the calculated transmittance of the VA LC cell in the oblique incidence in the dark state. The proposed configuration can effectively eliminate the transmittance in the dark state compared with the conventional configuration. We verified the improved viewing angle of the proposed VA LC cell by using commercial LC software *TechWiz LCD* by SANAYI System co. in Korea instead of performing experiments because each optimized film requires very long time to be supported. Fig. 4 shows the comparison of the luminance of the proposed LC cell to the luminance of the conventional LC cell in the dark state and. Fig. 5 compares the normalized iso-contrast contour of the conventional configuration with the proposed configuration. The dashed line represents the position of the half-contrast ratio compared with the contrast ratio in the normal incidence.

From the calculated results in Fig. 4 and 5, we confirmed that the proposed VA LC cell effectively eliminates light leakage in the dark state so that the off-axis contrast ratio of the proposed LC cell can increase far beyond that of the conventional LC cell in calculations.

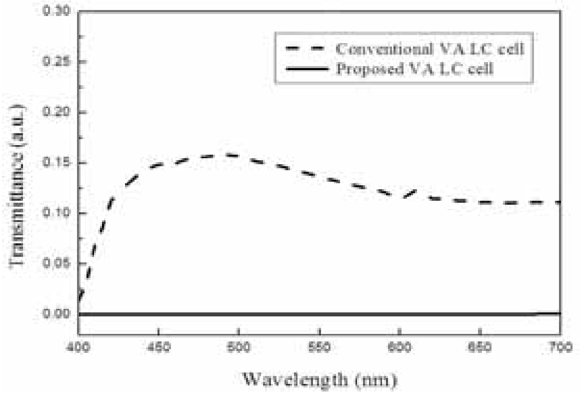
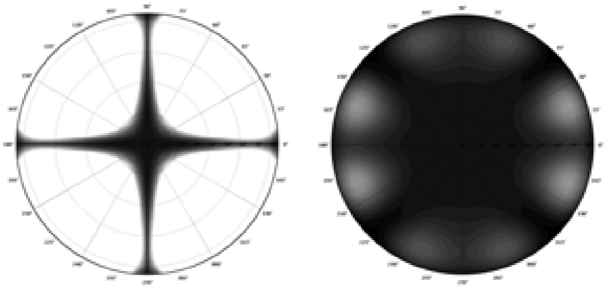
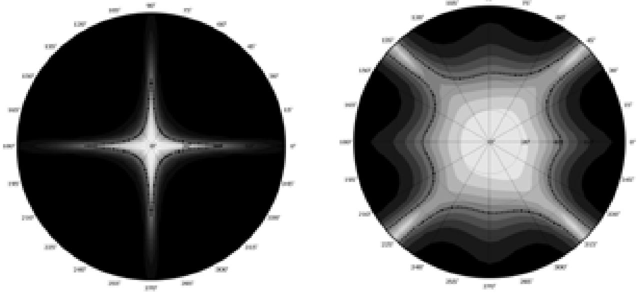


**Fig. 3. Optical transmittance as a function of wavelength at $\theta = 70^\circ$ and $\phi = 45^\circ$ in the dark state**



(a) (b)

**Fig. 4. Calculated luminance in the dark state: (a) the conventional VA LC cell (b) the proposed VA LC cell**



(a) (b)

**Fig. 5. Calculated normalized iso-contrast contour: (a) the conventional VA LC cell (b) the proposed VA LC cell**

## 4. Summary

We propose an optical configuration of a VA LC cell with an *A*-film and two *C*-films. In order to compensate for phase dispersion of entire wavelengths and to achieve an excellent dark state, we optimized phase dispersion of the compensation films on the Poincaré sphere. Numerical calculations show that the proposed structure has wide viewing angle characteristics by compensating for light leakage in diagonal directions.

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