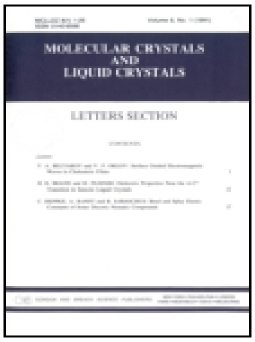

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Optical Design for Reflective Liquid Crystal Displays

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An optical design for a reflective LCD with a thicker cell gap that can have relatively higher productivity was examined theoretically. The proposed LCD was characterized by the optical axes of a half-wave retardation film, quarter-wave retardation film, and LC layer, which are 15°, −15° and 75° with the transmission axis of the polarizer, respectively. The LCs at the dark state lie down on the surface to produce half-wave retardation, whereas they rise up to produce quarter-wave retardation under an electric field in the white state. The proposed optical structure for the reflective LCD shows good dispersion characteristics at both the dark and white states.

Keywords Liquid Crystal Display; Reflective LC mode; Wider band; Dispersion Characteristics

Introduction

Various types of reflective liquid crystal display (LCD) modes have been proposed for use in laptop computers, tablet personal computers, smart phones, and digital cameras [1–23]. Reflective type LCDs can exhibit excellent electro-optical properties in outdoor environments, even in bright sunlight. Therefore, they have has advantages, such as low power consumption, light weight and better outdoor readability. On the other hand, this type of LCD has not been applied to industry because of the lower productivity caused by the low cell thickness and relatively low contrast ratio compared to transmissive type LCD modes. Currently, the optical axes of the optical film and LC layer in most proposed reflective LCDs are 15° and 75° with respect to the transmission axis of the polarizer, respectively [5]. In this optical structure, a very thin cell gap of approximately 1.5 μm should be used to satisfy the quarter-wave retardation when used with a half-wave retardation film. The thin cell gap can produce optically inferior goods in the fabrication process, which reduces the production rate.

This paper presents the theoretical optical structure of a reflective LCD that can be applied to a thicker cell gap with relatively higher productivity. In this optical configuration, a half-wave retardation film and a quarter-wave retardation film are used to satisfy simultaneously the good dispersion characteristics through a wide band and the condition of

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higher cell thickness (approximately 3 μm). The proposed optical structure for a reflective LC mode exhibits good dispersion characteristics at both the dark and white states, despite having a higher cell thickness.

Optical Design for Reflective LC Cell

The proposed cell structure was characterized by a half-wave retardation film, a quarter-wave retardation film, an LC cell, reflector, and a polarizer. In this optical configuration, the polarization of incident light in the optical components was examined. The linearly polarized light from the polarizer will become a rotated linearly polarized light after passing through the half-wave retardation film. The light must exhibit circular polarization at the reflector as it passes through the quarter-wave retardation film because the incident linearly polarized light must be rotated by 90° in front of the polarizer to obtain a dark state in the single polarizer. To obtain the circular polarization at the reflector, the angle, θ_H, between the optic axis of the half-wave retardation film and the transmission axis of the polarizer, the angle, θ_Q, between the optic axis of the quarter-wave retardation film and the transmission axis of the polarizer, and the angle, θ_L, between the optic axis of the LC layer and the transmission axis of the polarizer are needed.

Therefore, to determine the angles, the Mueller matrices were used for the LC layer and the retardation films, and the Stokes vector was used to express the polarization states. Generally, a 4 × 4 Mueller matrix that ties up the Stokes parameter in the optical layers can be expressed as

$$\begin{bmatrix} S_0' \\ S_1' \\ S_2' \\ S_3' \end{bmatrix} = \begin{bmatrix} m_{00} & m_{01} & m_{02} & m_{03} \\ m_{10} & m_{11} & m_{12} & m_{13} \\ m_{02} & m_{21} & m_{22} & m_{23} \\ m_{30} & m_{31} & m_{32} & m_{33} \end{bmatrix} \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix}. \quad (1)$$

where S_i' and S_i are the Stokes parameter of the outcoming and incoming light, respectively, and m_{ij} is the directional components of a retardation layer. m_{ij} components of the Mueller matrix in the parallel aligned molecular retardation layers can be expressed as

$$M(\theta, \Gamma) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos^2 2\theta + \cos\Gamma \sin^2 2\theta & (1-\cos\Gamma)\sin 2\theta \cos 2\theta & \sin\Gamma \sin 2\theta \\ 0 & (1-\cos\Gamma)\sin 2\theta \cos 2\theta & \sin^2 2\theta + \cos\Gamma \cos^2 2\theta & -\sin\Gamma \cos 2\theta \\ 0 & -\sin\Gamma \sin 2\theta & \sin\Gamma \cos 2\theta & \cos\Gamma \end{bmatrix} \quad (2)$$

where $\Gamma = 2\pi \Delta n d/\lambda$ (Δn and d are the birefringence and the thickness of the optical component, respectively, and λ is the wavelength of incident light) is the retardation of an optical birefringent material, and θ is the angle between the optic axis of the optical birefringent layer and the transmission axis of the input polarizer. Therefore, the Mueller expression of the half-wave retardation film whose retardation Γ is π can be expressed as

$$M(\theta, \pi) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 4\theta & \sin 4\theta & 0 \\ 0 & \sin 4\theta & -\cos 4\theta & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} \quad (3)$$

by inserting Γ is π into Eq. (2). In addition, the Mueller expression of the quarter-wave retardation film whose retardation Γ is $\pi/2$ can be described as

$$M\left(\theta, \frac{\pi}{2}\right) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos^2 2\theta & \sin 2\theta \cos 2\theta & \sin 2\theta \\ 0 & \sin 2\theta \cos 2\theta & \sin^2 2\theta & -\cos 2\theta \\ 0 & -\sin 2\theta & \cos 2\theta & 0 \end{bmatrix}, \tag{4}$$

by letting $\Gamma = \pi/2$ in Eq. (2). When the polarizer, half-wave retardation film, quarter-wave retardation film, and half-wave LC layer in order are adopted in a reflective LCD, the Stokes vectors can be expressed as

$$S_O = M_L(\theta_L, \pi)\, M_Q\left(\theta_Q, \frac{\pi}{2}\right) M_H(\theta_H, \pi)\, S_I., \tag{5}$$

where M_L, M_Q, and M_H are the Mueller matrices of the LC layer, the quarter-wave retardation film, and the half-wave retardation, respectively. Here S_I is $(1\ 1\ 0\ 0)^T$ because the incident light has linear polarization to the 0° direction and S_O must be expressed as $(1\ 0\ 0\ \pm1)^T$ because as mentioned previously, the light at the reflector must be circular polarization to obtain the dark state from a linear polarization rotated by 90° in front of the polarizer. Therefore, by inputting S_I, S_O, Eq. (3), and Eq. (4) into Eq. (5), Eq. (5) can be rewritten as

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 4\theta_H & \sin 4\theta_H & 0 \\ 0 & \sin 4\theta_H & -\cos 4\theta_H & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix}. \tag{6}$$

By calculating and rearranging Eq. (6), a simplified form can be obtained as follows:

$$\begin{bmatrix} 1 \\ \frac{1}{2}\left\{\cos 4(\theta_L - \theta_H) + \cos 4\left(\theta_L - \theta_Q + \theta_H\right)\right\} \\ \frac{1}{2}\left\{\sin 4(\theta_L - \theta_H) + \sin 4\left(\theta_L - \theta_Q + \theta_H\right)\right\} \\ -\sin 2\left(2\theta_H - \theta_Q\right) \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ \pm 1 \end{bmatrix}. \tag{7}$$

From the condition of $-\sin 2(2\theta_H - \theta_Q) = \pm 1$ in Eq. (7), the following can be induced

$$4\theta_H - 2\theta_Q = -90^\circ \text{or } 90^\circ. \tag{8}$$

Based on this condition, a wider band concept is applied to Eq. (5) to determine the relative optimized angles for the optic axes of each optical component. By applying the wider wavelengths, $\lambda = \lambda_0 + \Delta\lambda = \lambda_0(1+\delta)$ (here, $\delta = \Delta\lambda/\lambda_0$), instead of a single wavelength [3, 5], the retardation of the half-wave film, quarter-wave film, and half-wave LC layer are $\Gamma_H = \pi(1+\delta)$, $\Gamma_Q = \pi(1+\delta)/2$, and $\Gamma_L = \pi(1+\delta)$, respectively. Eq. (6) can be rewritten as

$$\begin{bmatrix} 1 \\ 0 \\ 0 \\ \pm 1 \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 4\theta_L & \sin 4\theta_L & -\delta\pi \sin 2\theta_L \\ 0 & \sin 4\theta_L & -\cos 4\theta_L & \delta\pi \cos 2\theta_L \\ 0 & \delta\pi \sin 2\theta_L & -\delta\pi \cos 2\theta_L & -1 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos^2 2\theta_Q - \frac{\delta\pi}{2}\sin^2 2\theta_Q & \left(1+\frac{\delta\pi}{2}\right)\sin 2\theta_Q \cos 2\theta_Q & \sin 2\theta_Q \\ 0 & \left(1+\frac{\delta\pi}{2}\right)\sin 2\theta_Q \cos 2\theta_Q & \sin^2 2\theta_Q - \frac{\delta\pi}{2}\cos^2\theta_Q & -\cos 2\theta_Q \\ 0 & -\sin 2\theta_Q & \cos 2\theta_Q & -\frac{\delta\pi}{2} \end{bmatrix} \tag{9}$$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 4\theta_H & \sin 4\theta_H & -\delta\pi \sin 2\theta_H \\ 0 & \sin 4\theta_H & -\cos 4\theta_H & \delta\pi \cos 2\theta_H \\ 0 & \delta\pi \sin 2\theta_H & -\delta\pi \cos 2\theta_H & -1 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix}.$$

By calculating and rearranging Eq. (9), a simplified form can be obtained as follows:

$$\begin{bmatrix} 1 \\ -\frac{1}{2}\pi\delta\left\{\sin 2\left(2\theta_L - \theta_Q\right)(2\sin 2\theta_H \mp 1) \mp 2\sin 2\theta_L\right\} \\ \frac{1}{2}\pi\delta\left\{\cos 2\left(2\theta_L - \theta_Q\right)(2\sin 2\theta_H \mp 1) \mp 2\cos 2\theta_L\right\} \\ \frac{1}{2}\pi^2\delta^2 (2\sin 2\theta_H \mp 1)\cos\left(2\theta_L - 2\theta_Q\right) \pm 1 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \\ 0 \\ \pm 1 \end{bmatrix}. \tag{10}$$

Here, a small band approximation ($\delta <<1$) for δ was used. From the fourth row of Eq. (10), the angle of the optic axis of the half-wave film, $\theta_H = \pm 15°$, can be obtained. By inserting this value into Eq. (8), the angle of the optic axis of the quarter-wave film, $\theta_{\mathrm{L}} = \pm\ 15°$, can also be obtained. Continuously, from these values, the angle of the optic axis of the half-wave LC layer can also be determined by Eq. (7) or Eq. (10) to be $\theta_{\mathrm{L}} = \pm 75°$. Under this condition, the incident light with 0° linear polarization by the polarizer will be almost 90° linear polarization through a wider wavelength range after the double pass of each optical component and be blocked by the polarizer through a wider band. Therefore, although the cell thickness is double that of the conventional reflective modes, this reflective type LC mode under this condition can generate an excellent dark state, which enhances the contrast ratio, one of most important optical factors in a display.

Under the condition of the bright state, the angles of the optic axes of the each optical component are fixed to $\theta_{\mathrm{H}} = \pm 15°$, $\theta_{\mathrm{L}} = \mp\ 15°$, and $\theta_{\mathrm{L}} = \pm 75°$, which is similar to the condition of the dark state. The retardation of the half-wave LC layer is changed only by the vertical electric field and maximum bright state occurs when it is $\pi/2$ (λ/4).

Simulation Results

Figure 1 shows the optical structure of the reflective LC cell showing schematically the calculated results.

Based on Fig. 1, the reflectance of the wavelength of 560 nm and the LC director profile at the bulk region according to applied voltages were simulated, as shown in Fig. 2. When LC directors lie down under 0 V, the reflectance is in a perfectly dark state. The reflective LC cell in 2 V does not show the maximum reflectance even though the LC directors of the bulk increase approximately 50° from the surface, which might be enough to become

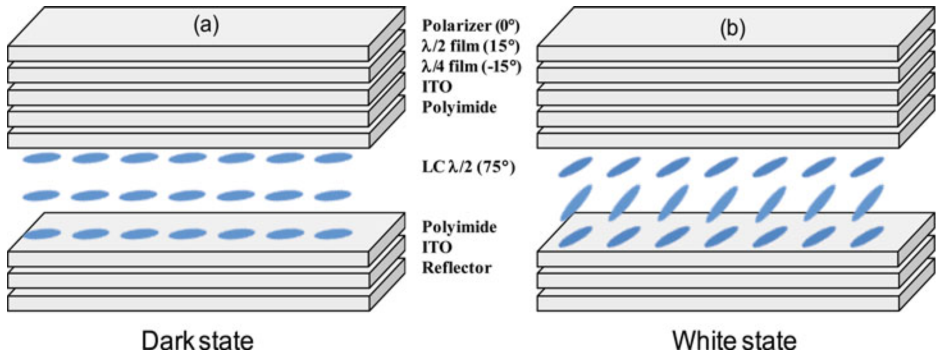

Figure 1. Schematic diagram of the optical structure of the proposed reflective LCD.

the retardation of $\pi/2$, which is the condition for maximum reflectance. This is caused by surface LC directors that do not move up by the electric field. Therefore, the retardation of the LC layer including the surface falls short of $\pi/2$, and the cell cannot show the maximum reflectance in 2 V. On the other hand, although the upward tilting of the bulk LC directors at 2.5 V is quite high at approximately 75°, which shows a very small retardation, it exhibits the maximum reflectance due to the surface LC directors, which contribute entirely to the generation of retardation. As a result of this simulation, the proposed reflective LC cell can have very low operation voltage, ~ 2.5 V.

To determine a more detailed result for the dispersion characteristics of the proposed LC cell, the reflectance was calculated according to wavelengths at each voltage. Figure 3 presents the reflectance as a function of the wavelength at various voltages, showing excellent dispersion characteristics at all voltages. In particular, the dark state shows a wider band property except for a portion of the visible region. Consequently, the proposed

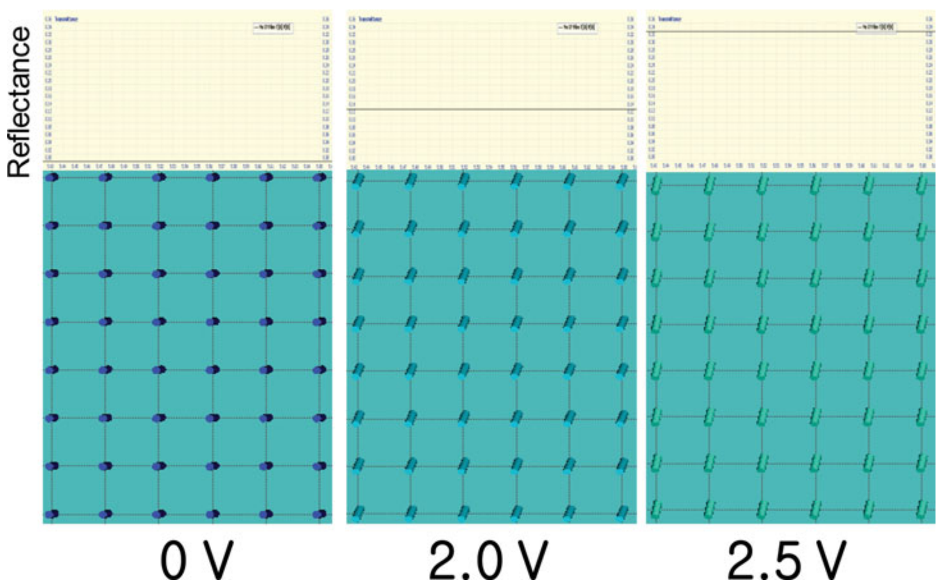

Figure 2. Reflectance and LC director profile according to the voltages.

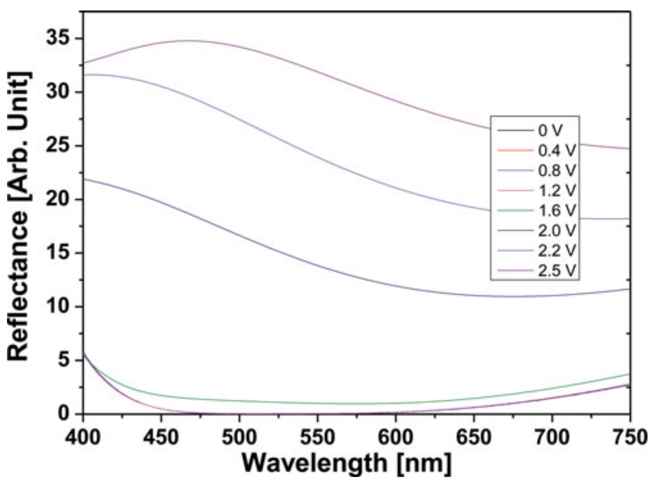

Figure 3. Calculated reflectance according to the wavelengths at various voltages.

reflective LC mode can apply a thicker cell gap with higher productivity and has excellent electro-optic characteristics. Therefore, this can be adopted in industries as a good reflective LC mode.

Conclusion

The optical structure for a reflective LCD with thicker cell gap, which can have relatively higher productivity, was presented and examined theoretically. The LCD was characterized by two retardation films and an LC cell, and the optical axes of the half-wave retardation film, the quarter-wave retardation film, and the LC layer were 15°, −15°, and 75° with the transmission axis of the polarizer, respectively. The LCs at the dark state lie down on the surface of the LC alignment layer (homogenous polyimide) to produce half-wave retardation, whereas they rise up to produce quarter-wave retardation under an electric field in the white state. The proposed optical structure for a reflective LC mode shows good dispersion characteristics in both the dark and white states despite the greater cell thickness. Consequently, the proposed reflective LCD mode exhibits excellent electro-optical properties.

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