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Quasi-Achromatic and Wide Viewing Properties of a Reflective Liquid Crystal Display in In-Plane Optical Geometry

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In the in-plane optical geometry, the achromatic and viewing properties of reflective liquid crystal displays (LCDs) are studied within the framework of the 2×2 Jones matrix formalism. For obtaining high brightness, high contrast and good achromaticity, LCD cell parameters such as the molecular rotation angle of LC and the effective phase retardation through the LC layer are optimized in the geometry such that the average optic axis of the LC layer lies on the plane parallel to the substrates. The resultant viewing properties are consistent with previous experimental results for a reflective antiferroelectric LCD. [DOI: 10.1143/JJAP.41.5298]

KEYWORDS: in-plane optical geometry, reflective liquid crystal display, ferroelectric, antiferroelectric, achromaticity

1. Introduction

Reflective liquid crystal displays (LCDs) have attracted great interest for portable, low power consumption applications such as personal information systems. A variety of nematic-based reflective modes, such as the electrically controlled birefringence mode,[1] the mixed twisted nematic (TN) mode,[2] and the bistable TN mode,[3] have been studied so far. Under the optimized conditions, these nematic-based reflective LCDs exhibit enhanced brightness, contrast, and achromaticity to some extent.[4,5] However, they still suffer from slow response, low contrast, and narrow viewing characteristics for practical applications.

Recently, a new type of reflective LCD with a single polarizer using an antiferroelectric liquid crystal (AFLC) has been proposed[6,7] to achieve fast response for video-rate applications. In addition to fast response and viewing characteristics, the cell parameters of this reflective LCD must be optimized for high brightness and high contrast from the optical retardation and dispersion viewpoints.

In this work, we study the in-plane optical geometry for a fast reflective LCD in which the average optic axis of the cell, consisting of the LC layer and a series of optical films, changes on the plane parallel to the substrates. Using the 2×2 Jones matrix method, the cell parameters including the molecular rotation angle of LC and the effective phase retardation through the LC layer are optimized to obtain high brightness, high contrast ratio, and good achromaticity. Under the optimal conditions, the viewing properties of the reflective LCD can be calculated using the extended 2×2 Jones matrix method.[8] It is found that numerical results for the viewing characteristics of the in-plane optical geometry are consistent with our previous experimental results[6] for a reflective antiferroelectric liquid crystal display (AFLCD) where the average optic axis of the AFLC layer changes on the plane parallel to the substrates.

2. In-Plane Optical Geometry for a Reflective LCD

The fast, reflective LCD being studied is composed of a single polarizer, a LC layer, an ideal wide-band quarter (WQ) wave plate, and a reflector as shown in Fig. 1. The WQ wave plate practically consists of a half wave (HW) and a quarter wave (QW) plate with the fixed wavelength of 550 nm. As shown in Fig. 1, to achieve a completely dark state in the entire range of visible light, the optic axes of the HW and QW plates make angles of 75° and 15° to that of the polarizer, respectively. Note that the in-plane switching mode,[9] the surface-stabilized FLC mode,[10] and the AFLC mode[11] can be described semiquantitatively within our in-plane optical geometry where the average optic axis of the LC layer changes on the plane parallel to the substrates. For light propagating perpendicularly through a stack of uniform layers, a simple 2×2 Jones matrix method is suitable for calculating the optical transmission through it. The x and y components of light at the exit depend linearly on those at the entrance. Let the light propagating forward be represented by the 2×2 Jones matrix $\mathcal{J}$ and the light propagating backward by $\mathcal{J}^T$, the transpose of $\mathcal{J}$.[4)]

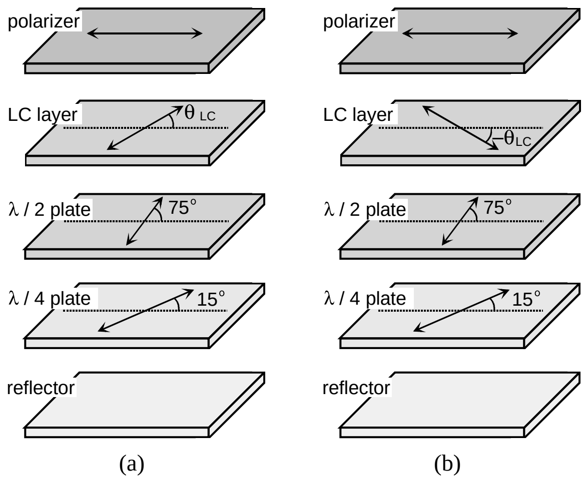

Fig. 1. Two in-plane optical geometries of a reflective LCD: (a) the counter-clockwise rotation and (b) the clockwise rotation of the average optic axis of the LC layer. A combination of the HW and QW plates is used for the WQ plate.

Assume that the dark state of the LC cell is obtained in the configuration such that a single WQ wave plate is placed between the polarizer and the reflector. If the optic axis of the LC layer is parallel to the polarizer, the total retardation matrix of the LC cell, $\mathcal{J}_{\mathrm{OFF}}$, can be expressed as

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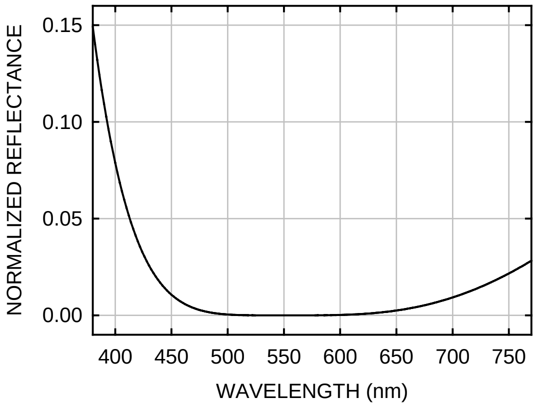

Fig. 2. Optical dispersion of the reflectance in the range of visible light for normal incidence when the optic axis of the LC layer is parallel to the polarizer.

$$\mathcal{J}_{\mathrm{OFF}} = \mathcal{P}_x^T \mathcal{J}_{\mathrm{WQ}}^T \mathcal{J}_{\mathrm{WQ}} \mathcal{P}_x, \tag{2.1}$$

where $\mathcal{P}_x$ is the Jones matrix of a linear polarizer along the x-axis and $\mathcal{J}_{\mathrm{WQ}}$ is the Jones matrix of the WQ wave plate composed of the HW and QW plates with a fixed wavelength. In other words,

$$\mathcal{J}_{\mathrm{WQ}} = \mathcal{R}(\theta_{\mathrm{Q}})\Gamma(\gamma_{\mathrm{Q}})\mathcal{R}(-\theta_{\mathrm{Q}})\mathcal{R}(\theta_{\mathrm{H}})\Gamma(\gamma_{\mathrm{H}})\mathcal{R}(-\theta_{\mathrm{H}}). \tag{2.2}$$

The above rotation matrix is given by

$$\mathcal{R}(\theta) = \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}, \tag{2.3}$$

where θ defines the rotation of the average optic axis of the relevant layer. The resultant retardation matrix is then expressed as

$$\Gamma(\gamma) = \begin{pmatrix} e^{i\gamma/2} & 0 \\ 0 & e^{-i\gamma/2} \end{pmatrix}, \tag{2.4}$$

where γ is the effective phase retardation through the relevant layer. For the in-plane optical geometry shown in Fig. 1, $\theta_{\mathrm{Q}} = 15^\circ$ and $\gamma_{\mathrm{Q}} = 90^\circ$ for the QW plate and $\theta_{\mathrm{H}} = 75^\circ$ and $\gamma_{\mathrm{H}} = 180^\circ$ for the HW plate. In this case, the reflectance from the LC cell is the square of a non-zero component of the total Jones matrix $\mathcal{J}_{\mathrm{OFF}}$. Figure 2 shows the optical dispersion of the reflectance in the entire range of visible light for normal incidence when the optic axis of the LC layer is parallel to the polarizer. In the range between 400 nm and 750 nm, a nearly ideal dark state is achieved.

3. Optimal Design of the LC Layer

For the reflective configuration shown in Fig. 1, the electrically tunable retardation is produced by the rotation of the optic axis of the LC layer with respect to the direction of the polarizer. The reflectance through the LC cell is given by the Jones matrix of the LC layer, $\mathcal{J}_{\mathrm{LC}}$, as follows.[12]

$$\mathcal{J}_{\mathrm{LC}} = \mathcal{R}(\theta_{\mathrm{LC}})\Gamma(-\gamma_{\mathrm{LC}})\mathcal{R}(-\theta_{\mathrm{LC}}), \tag{3.1}$$

where θ_{LC} defines the rotation of the average optic axis of the LC layer and $\gamma_{\mathrm{LC}} = 2\pi\Delta n_{\mathrm{LC}} d_{\mathrm{LC}}/\lambda$ where Δn_{LC}, d_{LC}, and λ are the birefringence, the thickness of the LC layer, and the wavelength of the incident light in vacuum, respectively. Thus, the total Jones matrix of the LC cell, $\mathcal{J}_{\mathrm{ON}}$, is expressed as

$$\mathcal{J}_{\mathrm{ON}} = \mathcal{P}_x^T \mathcal{J}_{\mathrm{LC}}^T \mathcal{J}_{\mathrm{WQ}}^T \mathcal{J}_{\mathrm{WQ}} \mathcal{J}_{\mathrm{LC}} \mathcal{P}_x. \tag{3.2}$$

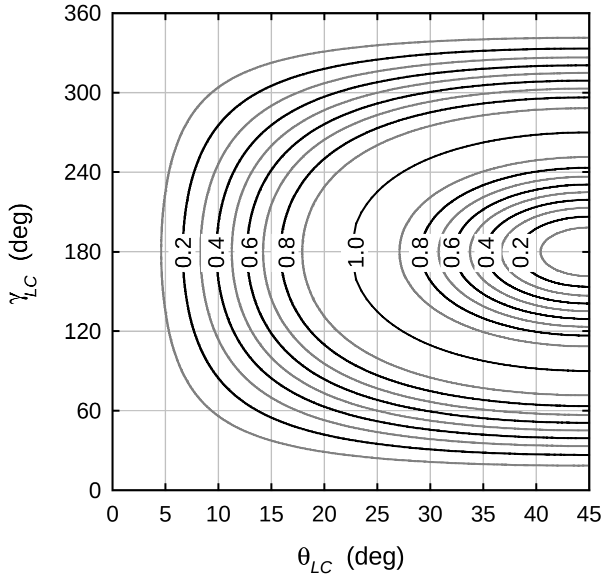

Fig. 3. Iso-reflectance curves given in the plane of the molecular rotation or the rotation of the average optical axis (θ_{LC}) and the phase retardation (γ_{LC}) of the LC layer for normal incidence.

For normal incidence, the reflectance is the square of a non-zero component of the Jones matrix, $\mathcal{J}_{\mathrm{ON}}$, and depends on both θ_{LC} and γ_{LC}.

Figure 3 shows the iso-reflectance curves given in the plane of θ_{LC} and γ_{LC} for normal incidence. The values of γ_{LC} are symmetric with respect to $\gamma_{\mathrm{LC}} = 180^\circ$ and those of θ_{LC} are symmetric to $\theta_{\mathrm{LC}} = 45^\circ$. The maximum reflectance occurs at $\theta_{\mathrm{LC}} = 22.5^\circ$ and 67.5°. From above 22.5° to 27.0°, high reflectance is obtained in a wide range of retardation γ_{LC}. However, for a larger θ_{LC} on approaching 45°, the range of retardation for high reflectance becomes narrower. At $\theta_{\mathrm{LC}} = 22.5^\circ$, the range of retardation for obtaining 90% reflectance is about 150° while at $\theta_{\mathrm{LC}} = 45^\circ$, it is about 50°. Since the retardation of the LC layer is proportional to the cell thickness, better achromaticity will be expected at $\theta_{\mathrm{LC}} \approx 22.5^\circ$.

Let us consider an ideal and simple case. Assume that the reflectance depends only on the retardation of the LC layer and the WQ wave plate is ideal in the entire range of visible light. For the ideal QW plate rotated from the polarizer by 45°, the reflectance from the LC cell, R^{MAX}, is written as

$$R^{\mathrm{MAX}} = 1 - \left[\cos^2 2\theta_{\mathrm{LC}} + \sin^2 2\theta_{\mathrm{LC}} \cos\gamma_{\mathrm{LC}}\right]^2. \tag{3.3}$$

The above equation, eq. (3.3), gives an analytical expression for the numerical results shown in Fig. 3. Moreover, the optimal conditions for the molecular rotation angle, $\theta_{\mathrm{LC}}^{\mathrm{MAX}}$, and the retardation, $\gamma_{\mathrm{LC}}^{\mathrm{MAX}}$, through the LC layer can be obtained using $R^{\mathrm{MAX}} = 1$.

$$\gamma_{\mathrm{LC}}^{\mathrm{MAX}} = \cos^{-1}(-\cot^2 2\theta_{\mathrm{LC}}^{\mathrm{MAX}}) + 2n\pi, \tag{3.4}$$

where $m\pi/2 + \pi/8 \le \theta_{\mathrm{LC}}^{\mathrm{MAX}} \le m\pi/2 + 3\pi/8$. Here, m and n are integers (0, ±1, ±2, \ldots).

4. Optical Dispersion of a Reflective LCD

Consider a reflective LCD consisting of the LC layer and the WQ wave plate with the fixed wavelength of 550 nm ($\lambda = 550$ nm) and calculate the optical dispersion of the reflectance. For the HW plate, $\Delta n_H d_H/\lambda = 1/2$ and for the QW plate, $\Delta n_Q d_Q/\lambda = 1/4$, where $\Delta n_{H,Q}$ and $d_{H,Q}$ are the birefringence and the thickness of the HW or QW plate, respectively. Once the maximum reflectance is determined for a fixed wavelength, the wavelength is accordingly varied to calculate the optical dispersion of the reflectance. Along the maximum reflectance line, $R^{MAX} = 1$ at the wavelength of 550 nm in Fig. 3, we calculate the reflectance as a function of the wavelength for given retardation γ_{LC} or molecular rotation angle θ_{LC}. In our calculations, the lower path for the line of $R^{MAX} = 1$ in Fig. 3 is selected since the upper path gives a much narrower range of wavelengths for obtaining high reflectance. Figure 4(a) shows the optical dispersion of the reflectance for the case of Fig. 1(a). In a wide region between $\theta_{LC} = 22.5°$ and $45.0°$, the reflectance is nearly achromatic for visible light.

Figure 4(b) shows the optical dispersion of the reflectance in the case of Fig. 1(b). For short wavelengths, the reflectance shows large optical dispersion from 95% to 50%. However, the achromaticity at $\theta_{LC} = -22.5°$ is superior to that at $\theta_{LC} = 22.5°$. This comes from the relative orientation of the LC layer to the WQ wave plate. It should be noted that the two cases in Fig. 1 are optically equivalent to each other in the absence of the wave plate. In bidirectional switching modes such as the normally black reflective AFLC mode,[6,7] the reflectance should be averaged over two switching angles. In the presence of an ideal QW plate, the optical dispersion of the reflectance will be identical for two switching angles as expected from eq. (3.3).

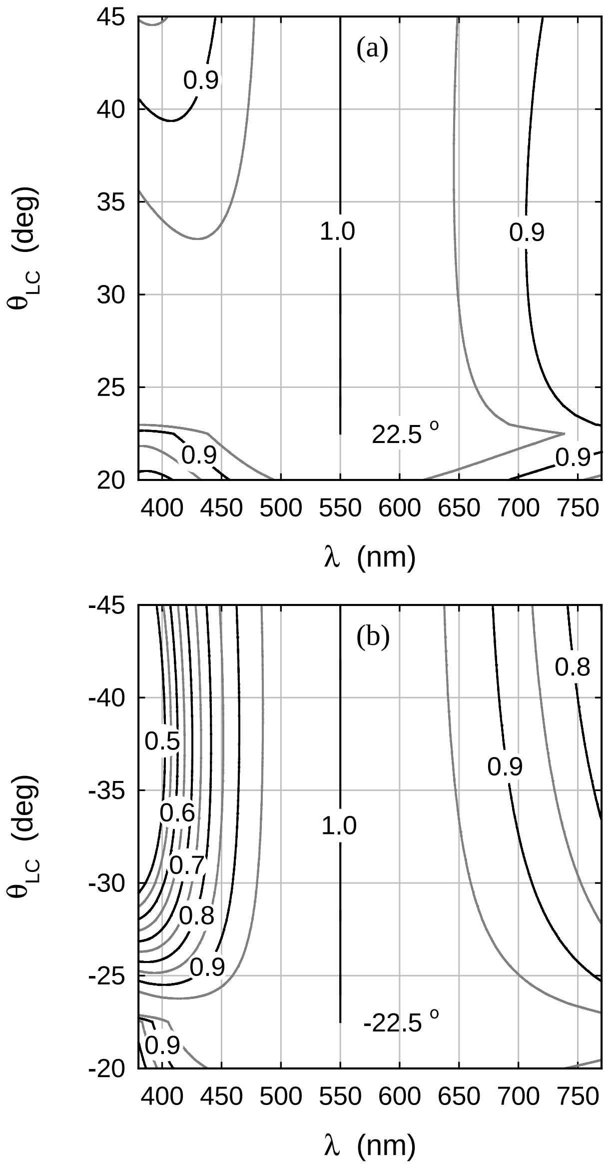

Fig. 4. Iso-reflectance curves for the two in-plane optical geometries as a function of the wavelength (λ). The calculations were performed along the maximum reflectance line obtained with fixed wavelength of 550 nm.

5. Viewing Properties of a Reflective LCD

For practical applications, the viewing property is one of the critical factors governing the display performances. We now calculate the iso-contrast map for the configuration of Fig. 1(b) at the wavelength of 550 nm which gives better achromaticity. The extended 2×2 Jones matrix[8] was used for calculating the iso-contrast map for obliquely incident light. As shown in Fig. 5, the viewing properties are nearly achromatic and symmetric for the entire range of visible light. The white solid curves represent the inversion lines of contrast at angles between $\pm 55°$ and $\pm 65°$ when viewed from two diagonal directions.

As shown in Fig. 3, two branches for the optical retardation exist with respect to $\gamma_{LC} = 180°$. One of them corresponds to γ_{LC}^{MAX+} for $\gamma_{LC} \geq 180°$ and the other to γ_{LC}^{MAX-} for $\gamma_{LC} \leq 180°$. The better viewing property and achromaticity for the reflectance can be obtained at γ_{LC}^{MAX-} as the thickness of the LC layer becomes thin ($\approx 2\,\mu$m). On the other hand, at γ_{LC}^{MAX+}, the viewing property and the achromaticity deteriorate with increasing thickness of the LC layer.

In a reflective AFLCD[6,7] having a definite threshold[13,14] in the multiplexing driving scheme, the average optic axis of the AFLC layer can be rotated by the magnitude of the

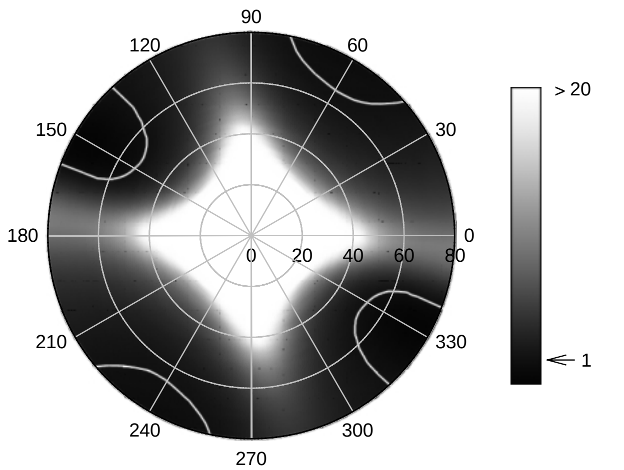

Fig. 5. Gray scale representation of the iso-contrast map for a reflective LCD cell with $\theta_{LC} = -22.5°$. The white solid curves represent the inversion lines of contrast.

molecular tilt on the plane parallel to the substrates. Thus, the optic axis swings from $\theta_{LC} = 22.5^\circ$ to $\theta_{LC} = -22.5^\circ$ when the polarity of the applied electric field changes alternatively. In this bidirectional switching mode, the iso-contrast contour can be calculated from the reflectance averaged over two switching angles relative to that at the zero angle for the fixed wavelength. It was found that our results are consistent with the previous experimental results[6] for the reflective AFLCD mode with CS4001 of Chisso Petrochemical Co., having $\theta_{LC} = 24.9^\circ$.

6. Conclusions

We presented the achromatic and viewing properties of reflective LCDs in the in-plane optical geometry. The 2×2 Jones matrix method was utilized for optimizing the LC cell parameters, such as the molecular rotation angle and the effective phase retardation through the LC layer, in such a reflective configuration. For practical applications, an ideal WQ wave plate can be replaced by an effective optical film consisting of the HW and QW plates with the fixed wavelength of $\lambda = 550$ nm. In the case that the reflectance of the LC cell depends solely on the retardation of the LC layer, the analytical expressions for the reflectance and the condition of the optimal retardation can be obtained in the range of θ_{LC} between 22.5° and 67.5°. The computational formalism presented here provides a basis for designing a new type of reflective LCD in the in-plane optical geometry. The dynamic properties of various reflective LCDs remain to be explored.

Acknowledgements

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1) T. Sonehara: Jpn. J. Appl. Phys. **29** (1990) L1231.
2) S.-T. Wu and C.-S. Wu: Appl. Phys. Lett. **68** (1996) 1455.
3) Z.-L. Xie and H. S. Kwok: Jpn. J. Appl. Phys. **37** (1998) 2572.
4) S. Stallinga: J. Appl. Phys. **86** (1999) 4756.
5) G.-D. Lee, G.-H. Kim, S.-H. Moon, J.-D. Noh, S.-C. Kim, W. S. Park, T.-H. Yoon, J. C. Kim, S. H. Hong and S. H. Lee: Jpn. J. Appl. Phys. **39** (2000) L221.
6) D.-H. You, J.-H. Lee, J.-H. Park and S.-D. Lee: J. SID **8** (2000) 277.
7) D.-H. You, J.-H. Lee, S.-S. Park and S.-D. Lee: Ferroelectrics **246** (2000) 203.
8) A. Lien: Appl. Phys. Lett. **57** (1990) 2767.
9) M. Oh-e and K. Kondo: Appl. Phys. Lett. **67** (1995) 3895.
10) N. A. Clark and S. T. Lagerwall: Appl. Phys. Lett. **36** (1980) 899.
11) Y. Yamada, N. Yamamoto, K. Mori, K. Nakamura, T. Hagiwara, Y. Suzuki, I. Kawamura, H. Orihara and Y. Ishibashi: Jpn. J. Appl. Phys. **29** (1990) 1757.
12) S. Chandrasekhar: *Liquid Crystals* (Cambridge University Press, New York, 1997) Chap. 4.
13) J. Li, X.-Y. Wang, E. Kangas, P. L. Taylor, C. Rosenblatt, Y. Suzuki and P. E. Cladis: Phys. Rev. B **52** (1995) R13075.
14) J.-H. Lee, C.-J. Yu and S.-D. Lee: J. Kor. Phys. Soc. **32** (1998) S1089.