Wideband quarter-wave liquid crystal cell with wide viewing angle for the reflective mode with single polarizer

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In this letter, the authors propose an optical configuration for the reflective liquid crystal (LC) cell with single polarizer, which can show the wideband property for high contrast in oblique incidence. The cell consists of a biaxial, a half-wave retarder, a quarter-wave LC cell, and a positive *C* plate in addition to a reflector. They optimize the configuration of the reflective LC cell on the Poincaré sphere using trigonometric calculation. In order to verify the optical performance, the authors experimentally compare the optical characteristics of the proposed LC cell with those of the conventional LC cell. © *2007 American Institute of Physics*. [DOI: 10.1063/1.2767236]

Generally, the reflective liquid crystal display (LCD) mode can be applied to mobile display devices because of their low power consumption and lightweight.[1–4] Especially, a single-polarizer mode is considered a suitable structure for reflective liquid crystal (LC) cells as it shows greater brightness than the double-polarizer mode. However, the single-polarizer LCD has the demerit of having a lower contrast than that of double-polarizer LCDs because of light leakage in the dark state. To overcome this disadvantage in a reflective cell, an optical configuration which is sequentially stacked by a polarizer, a half-wave retarder and a quarter-wave LC cell and a reflector, has been proposed in the previous paper.[5] This study showed that the proposed, single-polarizer LC cell effectively removes the phase dispersion along the visual wavelength range, thereby satisfying the twin criteria of high contrast and high brightness. However, the optical configuration of the previous LC cell does not consider the viewing angle performance because the luminance in the oblique incidence definitely decreases in all directions compared to the normal direction in the dark state.

Generally, several reasons lead to the decreased contrast ratio, the most important of which is the movement of the polarizer's absorption axis and optical axes in each optical film by change of the polar angle θ and the azimuthal angle ϕ in the observation direction. In the case of small birefringence (i.e., $|n_e-n_o| \ll n_e,n_o$), the deviation angle δ of the effective angle of absorption axis of the polarizer and the optical axes of the *A* plate from the normal direction can be expressed as[6,7]

$$\delta=\psi-\arcsin \times\left\{\frac{\sin\phi_c\cos\phi_c\cos\theta_0-\cos\theta_c\sin\theta_0}{[1-(\sin\phi_c\cos\phi_c\cos\theta_0+\cos\theta_c\cos\theta_0)^2]^{1/2}}\right\}, \quad (1)$$

where ϕ_c and θ_c are the azimuth and the polar angle of the optical axes of the *A* plate and polarizer and θ_0 is the polar angle of the incident light for the LC cell layer, respectively.

In the case of positive *C* plate, the effective fast axis moves to 90° with respect to the projected angle of the incident *k* vector. Equation (1) can also be applied to the deviation angle δ of the biaxial film with the assumption of the small birefringence material ($|n_j-n_i| \ll n_x,n_y,n_z,\ i,j=x,y,z$).

The second reason for the decreased contrast ratio is the change of retardation in each optical film in the oblique direction and the changed retardation along the incident angle can be easily calculated.[7,8]

Figures 1(a) and 1(b) explain the light leakage in the dark state on the Poincaré sphere. Figure 1(a) shows the principle of the compensation of the phase retardation for the wideband property in the normal direction. Polarization

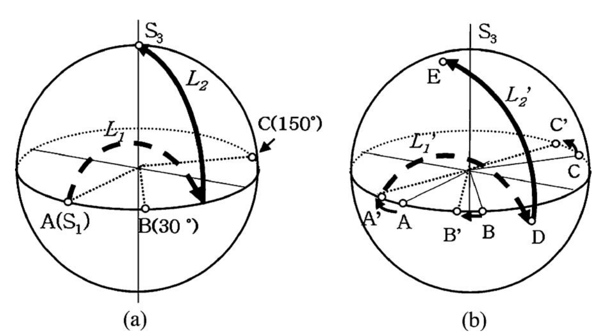

FIG. 1. Optical principle of the conventional reflective LC cell with single polarizer on the Poincaré sphere: (a) in the normal direction and (b) in the oblique direction.

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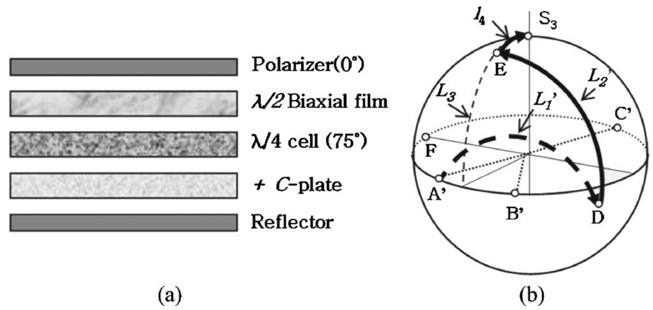

FIG. 2. Optical configuration of the proposed reflective LC cell with single polarizer: (a) optical configuration and (b) optical principle for phase compensation of the light in front of the mirror on the Poincaré sphere.

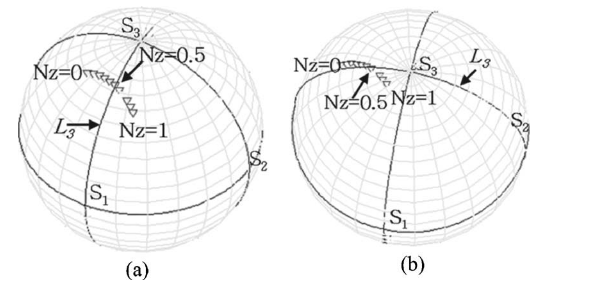

FIG. 3. Polarization distribution of the light passing through the half-wave biaxial retarder and the quarter-wave LC cell as a function of N_z factor: (a) for ϕ=45°, θ=70° and (b) for ϕ=0°, θ=70°.

paths L_1 by the half-wave retarder and L_2 by the quarter-wave LC layer effectively compensate for the phase dispersion along the full visual range, so that all the polarization positions of all the wavelengths proceed to position S_3 in front of the mirror. Positions A, B, and C in Fig. 1(a) represent the polarization position of the polarizer, the half-wave retarder, and the quarter-wave LC cell, respectively. On the contrary, the polarization path of all the wavelengths in the oblique direction may not proceed to S_3, as shown in Fig. 1(b). As noted above, the polarization axis of the polarizer and the optical axis of each optical film have the deviation angle δ from the normal direction. In Fig. 1(b), δ_1, δ_2, and δ_3 represent the deviation angle of the polarizer, the half-wave retarder, and the quarter-wave LC layer, respectively. As a result, positions A, B, and C move to the deviated positions $A'(=-2\delta_1)$, $B'(=30°-\delta_2)$, and $C'(=150°+\delta_3)$, respectively. Path lengths L_1 and L_2 are also changed to L_1' and L_2' by the changed retardation of each retardation layer. In the oblique direction, the polarization of the light passing through the polarization proceeds to A' with deviation angle δ_1. By passing through the half-wave retarder, the polarization state of the light proceeds to position D with circle path L_1', which has centering position B'. The polarization of the light passing through the quarter-wave LC layer proceeds to E with circle path L_2', which is centered at position C'. As a result, the polarization of the light in front of the mirror obviously deviates to E from the desired destination S_3.

The optical improvement in the oblique direction for the reflective LC cell can be achieved by using several optical films, as shown in Fig. 2(a). The optical configuration of the proposed LC cell consists of a positive C plate, a quarter-wave LC layer, and a half-wave biaxial film instead of the half-wave A plate. In order to place the polarization position of the light in front of the mirror on the S_3 position in the oblique incidence, the following two conditions for the polarization of the light in the Fig. 2(b) should be satisfied.

First is that the polarization of the light passing through the biaxial film and the LC layer should be on the circle path L_3, which is centered at position of the slow axis of the C-plate F. Second is that the optimized retardation of the positive C plate should make the polarization state of the light E proceed to S_3 with circle length l_4.

The optical configuration is optimized in the diagonal and horizontal directions (ϕ=45° and 0°) with polar angle θ=70° at wavelength λ=550 nm. In order to satisfy the first condition, we calculate the polarization position of the light as a function of parameter $N_z[=(n_x-n_z)/(n_x-n_y)]$ after the light passes through the half-wave biaxial film and the quarter-wave LC cell. Figures 3(a) and 3(b) show the calculated polarization position of the light. In the case of ϕ=45° and 0°, the polarization position of the optical axis of the C plate lies on the opposite position of S_2 and S_1, respectively, so that L_3 on the Poincaré sphere can be expressed, as shown in Figs. 3(a) and 3(b). From the calculated result, we confirmed that the first condition for compensation for the oblique incidence can be satisfied with the biaxial half-wave retarder with $N_z\approx 0.5$.

The second condition can be calculated with trigonometric calculation. Figure 4(a) shows the Poincaré sphere on the S_1-S_2 plane in the case of ϕ=45°, and we can calculate the retardation of the C plate on the triangle GEC'. Position G represents the projected position on the equator along the circle path L_5, which is centered at position S_1, so that the desired path length l_4 can be described as path length $\widehat{GS}_2$. From the figure, $\widehat{GS}_2$ is calculated by $\widehat{GC'}-\widehat{S_2C'}$. Therefore, once $\widehat{GC'}$ is calculated, then we can easily calculate $\widehat{GS}_2$ because the value of $\widehat{S_2C'}$ has already been obtained as the optical axis of the LC cell. The length $\widehat{GS}_2$ can be described by the following simple trigonometric equation:

$$\widehat{GS}_2=\widehat{GC'}-\widehat{S_2C'}=\sin^{-1}[\tan(\widehat{EG})/\tan(\angle EC'G)]-\pi/3. \quad (2)$$

The retardation of the positive C plate $\Gamma_{c\text{-plate}}$ can be calculated as about 105 nm.

Figure 4(b) shows the Poincaré sphere on the S_1-S_2 plane in the case of ϕ=0°. In this case, the projected position G on the equator is rotated along the circle path L_5, which is centered at position S_2, so that desired path length l_4 can be described as path length $\widehat{GS}_1$. C'' and D' represent the opposite position of the optical axis of the LC layer on the equator and the encountered position of L_1 to the equator. $\widehat{GS}_1$ is simply calculated by $\widehat{C''S_1}-\widehat{C''G}$. First of all, we calculate

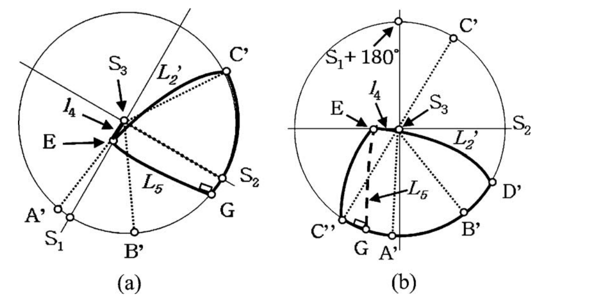

FIG. 4. Spherical triangle on the Poincaré sphere for determining the retardation of positive C plate: (a) for ϕ=45°, θ=70° and (b) for ϕ=0°, θ=70°.

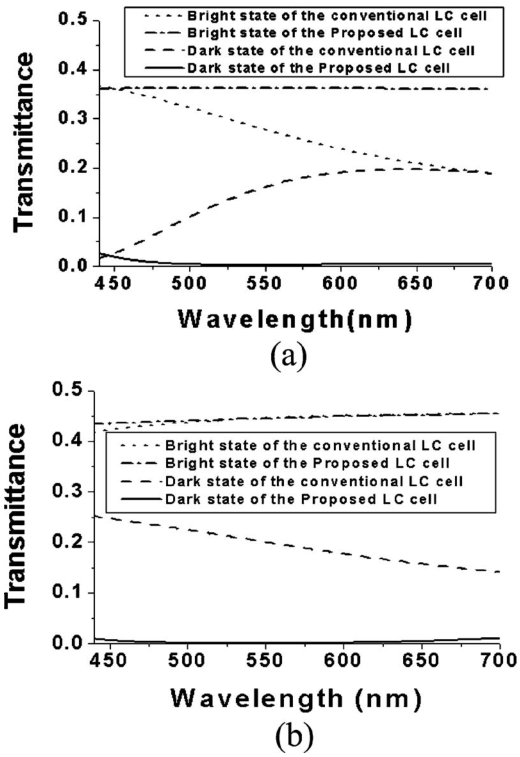

FIG. 5. Comparison of the calculated transmittance between the conventional and the proposed LC cells: (a) for ϕ=45°, θ=70° and (b) for ϕ=0°, θ=70°.

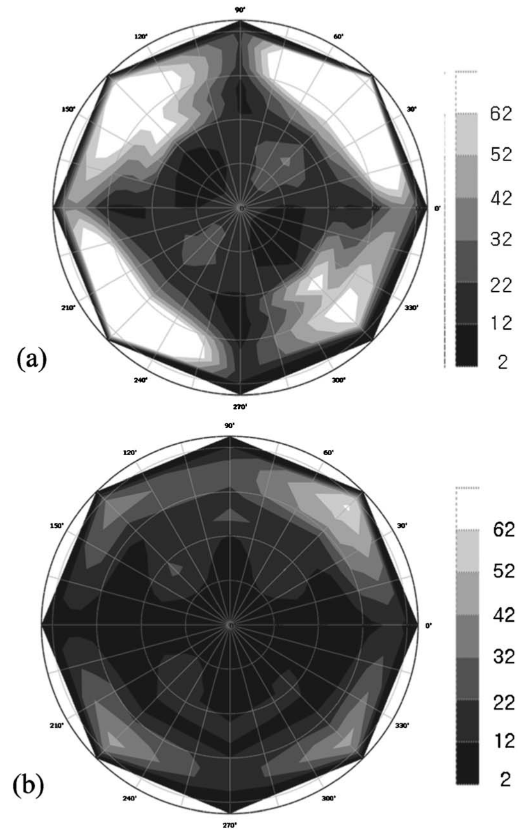

FIG. 6. Measured isoluminance in the dark state: (a) for the conventional LC cell and (b) for the proposed LC cell.

$\hat{GE}$ and $\angle EC''D'$ by using the known values of $\hat{ED'}$, $C''\hat{D'}$ and $\angle ED'G$ in order to calculate $C''\hat{G}$. From the result, we can easily calculate $\hat{GS_1}$ as

$$\hat{GS}_1 = C''\hat{S}_1 - C''\hat{G} = \pi/6 - \sin^{-1}[\tan(\hat{EG})/\tan(\angle EC''G)].$$

Through the optimization, we obtain the optimized value of the biaxial, the biaxial half-wave retarder ($N_z \approx 0.5$), and the positive C plate ($\approx$105 nm).

Figures 5(a) and 5(b) compare the calculated optical transmittance between the conventional and proposed configurations in the diagonal and horizontal directions (ϕ =45° and 0°) with polar angle θ=70°, respectively. Figure 5 shows that the proposed optical configuration can provide an excellent viewing angle property compared to the conventional configuration. The calculation was performed by the DIMOS program (made by autronic-MELCHERS in Germany). Figure 6 compares the measured iso-luminance between the conventional and proposed configuration in the dark state. For the proposed configuration, the used LC is ZLI-4119 (made by Merck Co.). The biaxial half-wave retarder has 0.5 of the N_z (n_x=1.499, n_y=1.502, n_z=1.501, thickness is 100 μm), and the retardation of the positive C plate is 105 nm. In the figure, dark state in the diagonal direction is slightly worth compared to the darkness in the horizontal direction. We think that this may be induced by the manufacturing error of the sampled films from companies for experiments. The figure confirms that the proposed optical configuration provides an excellent dark state in all the viewing directions compared to the dark state of the conventional LC cell, so that the proposed configuration can improve over 60% wider viewing angle in terms of contrast ratio.

In conclusion, we have proposed an optical configuration of the reflective LC cell with single polarizer for viewing angle characteristics. By applying the biaxial half-wave retarder and the positive C plate to the previous reflective LC cell, we simultaneously achieved the wideband property and wide viewing angle characteristics. For optimization, we calculated the optimized retardation value of the biaxial half-wave retarder ($N_z \approx 0.5$) and the positive C plate ($\approx$105 nm). We confirmed that the proposed configuration provides very low light leakage in the dark state and a good viewing angle property.

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