Optical approach to improve the γ curve in a vertical-alignment liquid-crystal cell

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In this Letter, we propose an optical configuration of a four-domain vertical-alignment (VA) liquid-crystal (LC) cell, which can improve the γ-curve distortion by using a pair of patterned *A* plates, without any change in cell structure. In order to find the optimal parameter value of the patterned *A* film, we calculated the polarization difference between the normal direction and the all-viewing direction as functions of the optical axes and the retardation (Δnd) under the voltage applied state. Based on the calculated results, the proposed LC cell showed an improvement in γ-curve distortion of more than 80% in each oblique viewing angle compared to a conventional wide-view VA LC cell, without any loss of optical performance in the dark state.

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For better electro-optical characteristics, many liquid-crystal (LC) display modes, such as the twisted nematic mode [1], the in-plane switching mode [2], the fringe-field switching mode [3], the multidomain vertical-alignment (MVA) mode [4], and the patterned vertical-alignment (PVA) mode [5], have been developed for the display market. In particular, the MVA and PVA modes are representative LC modes that show very high contrast ratios in the normal direction, in addition to wide-viewing angles [6]. In spite of the optical advantages of a VA LC cell, however, the optical performance still shows strong dependence on the observed direction in all gray scales, including the dark state [7]; therefore image distortions, which can be assessed by measuring the γ curve, occur in the middle gray level in the off-axis direction. In general this γ-curve distortion in the off-axis direction, several methods have been proposed to improve the viewing-angle properties in the gray scales by applying a novel electrode structure [8–10]. However, these methods require complex cell structures, such as two times the number of transistors compared to a conventional thin film transistor LCD [5], or a different electrode structure domain in the subpixel [6].

In this Letter, we studied an optical approach to improve the γ-curve distortion in a four-domain (4-D) vertical-alignment (VA) LC cell without any deterioration in the viewing angle or contrast ratio in the dark state by using a film-patterned retarder (FPR). In this Letter, we applied a pair of *A* plates, which consist of a positive *A* plate and a negative *A* plate, to the bottom and top substrates of a conventional wide-view PVA LC cell [11]. Optimization of the pair of *A* plates was performed in each domain (the directions of the LC director were 45°, 135°, 225°, and 315°) by calculating the polarization difference between the normal and oblique incidence under a voltage applied state on the Poincaré sphere as functions of the retardation and the optical axis of the pair of *A* plates [12].

In general, the optical improvement in the conventional wide-view VA LC cell was focused on the dark state. A good example of a conventional wide-view VA LC cell consists of a half-wave biaxial film ($Nz = 0.5$), LC cell, and a negative *C* plate between two crossed polarizers, as shown in Fig. 1(a) [11].

Figure 1(b) shows the LC director configuration in each domain in the 4-D VA LC cell. From the described optical structure, the V–T curve and the γ curve of the conventional wide-view PVA LC cell in the normal and oblique (polar angle $\theta = 60°$, azimuth angle $\phi = 0°$, 90°, 180°, and 270°) viewing angles can be calculated as shown in Fig. 2. In Fig. 2(a), we observe the gray inversion region between $V = 2$ V and $V = 3$ V, and this makes a serious γ-curve distortion, as shown in Fig. 2(b), especially in the middle gray levels, which are maximized at $V = 2.5$ V.

Figure 3 illustrates the polarization states of the light in front of the absorption axis of the output polarizer on the Poincaré sphere at the 90th gray level ($V = 2.5$ V). In the normal direction, the position P_{N1} represents the polarization state of light in front of the output polarizer in the domains of 45° and 225°, and P_{N2} represents the polarization position of light in the domains of 135° and 315°. In this case, the polarization difference (Δp) between the absorption axis of the output polarizer (S_1) and the polarization of light in front of the absorption axis of the output polarizer (P_{N1}, P_{N2}), in addition to the light intensity, are calculated as shown in Eq. (1) [12,13]:

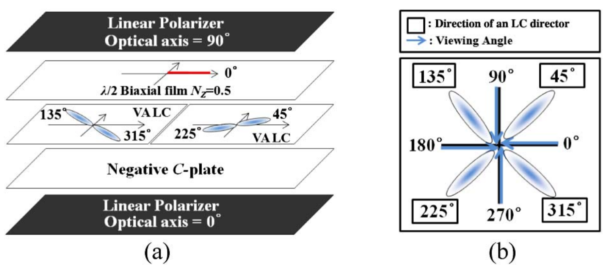

Fig. 1. (Color online) Example of the optical configuration of a conventional 4-D wide-view VA LC cell and the LC director configuration in each domain: (a) optical configuration and (b) LC director configuration.

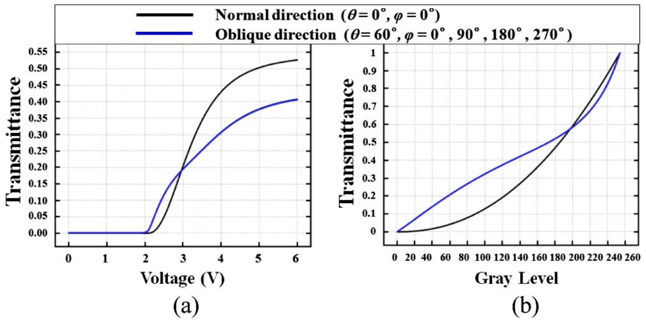

Fig. 2. (Color online) Calculated (a) V–T curve and (b) γ curve in a conventional wide-view PVA LC cell.

$$\Delta p = \sqrt{(S_{1(A)} - S_{1(p)}) + (S_{2(A)} - S_{2(p)}) + (S_{3(A)} - S_{3(p)})},$$

$$I = I_0 \cos^2\left(\frac{\Delta p}{2}\right), \qquad (1)$$

where $S_{1(A)}$, $S_{2(A)}$, and $S_{3(A)}$ represent the Stokes vector of the absorption axis of the output polarizer. $S_{1(p)}$, $S_{2(p)}$, and $S_{3(p)}$ are the Stokes vectors of the polarization positions in front of the absorption axis of the output polarizer. The calculated Δp for P_{N1} and P_{N2} is the same, and 0.5912 ($\lambda = 550$ nm), which is the light intensity in the normal direction in each domain, is also the same. The circle line j represents the equi-Δp line, which implies an equi-intensity line.

By way of contrast, the polarization states of light passing through the LC cell in the oblique direction ($\theta = 60°$) move to positions P_{O1}, P_{O2}, P_{O3}, and P_{O4}. The calculated Δp in the oblique direction is 1.3507 for P_{O1} and P_{O2}, and 0.3842 for P_{O3} and P_{O4}, respectively. These calculated results show a big difference between the normal incidence and the oblique incidence so that serious γ-curve distortion can be induced. Therefore, an improvement in the γ-curve distortion of the VA LC cell can be made by moving the deviated polarization positions P_{O1}, P_{O2}, P_{O3}, and P_{O4} to the goal polarization position, circle j, because this permits the same intensity in the normal direction.

In order to improve the γ-curve distortion of the VA LC cell, we applied a pair of A plates, which included a positive A plate and a negative A plate, to the bottom and top substrates of the conventional wide-view VA LC cell. In this configuration, optimization should be performed so that the proposed configuration is satisfied for the wide-view performance in both the dark state and all gray levels. We can describe the optical condition as follows:

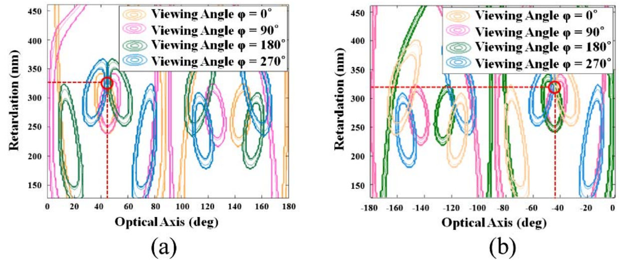

Fig. 4. (Color online) Calculated Δp of the pair of A plates at an all-viewing angle in (a) 45°, 225° and (b) 135°, 315° domain areas.

$$\sum \text{Retardation}(\text{VA LC} + \text{Negative } C) = 0, \qquad (2)$$

$$\sum \text{Retardation}(\text{Negative } A + \text{Positive } A) = 0. \qquad (3)$$

Equation (2) represents a condition for the excellent dark state in the all-viewing direction. In particular, Eq. (3) represents the optical conditions of the pair of A plates for improving viewing-angle properties in the gray scale without any loss of optical performance in the dark state.

Optimization of the pair of A plates was performed by calculating the polarization difference (Δp) as a function of the retardation value and the optical axis of the A plates at $V = 2.5$ V, as shown in Fig. 4. From the previous calculation, the Δp in the normal direction is 0.5912, so the optimization of the pair of A plates is obtained at the position shown in Fig. 4, which gives us the same Δp with normal incidence.

In order to investigate an optimized position for the optical films, we looked for the positions that could provide the Δp within ± 0.2 from 0.5912. Figures 4(a) and 4(b) show the calculated Δp in 45° and 225°, and 135° and 315°, domain areas, respectively. In Figs. 4(a) and 4(b), we observed that the optimized position was found at 45° of the optical axis and ± 320 nm of the retardation value for the 45° and 225° domains in the subpixel. For the 135° and 315° domains, the optimized value of the optical axis and the retardation were $-45°$ and ± 320 nm, respectively.

Figure 5 shows the calculated polarization positions of light in front of the absorption axis of the output polarized in each domain. Compared to the polarization state of the conventional wide-view VA LC cell shown in Fig. 3, we observed that the polarization distribution P_{O1}, P_{O2},

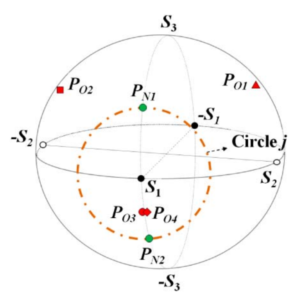

Fig. 3. (Color online) Polarization positions of light passing through the conventional wide-view PVA LC cell in normal and oblique directions in each domain at $V = 2.5$ V.

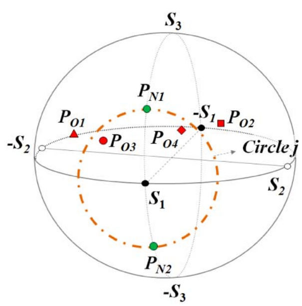

Fig. 5. (Color online) Polarization positions of light passing through the proposed 4-D VA LC cell in normal and oblique directions in each domain at $V = 2.5$ V.

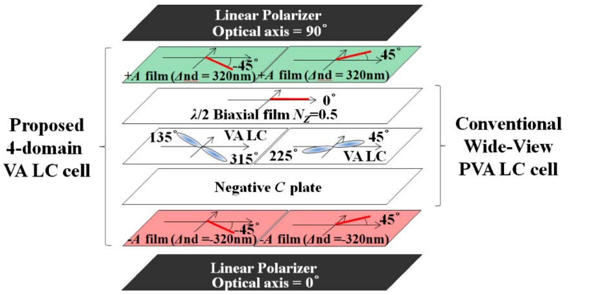

Fig. 6. (Color online) Proposed optical structure of the 4-D VA LC cell.

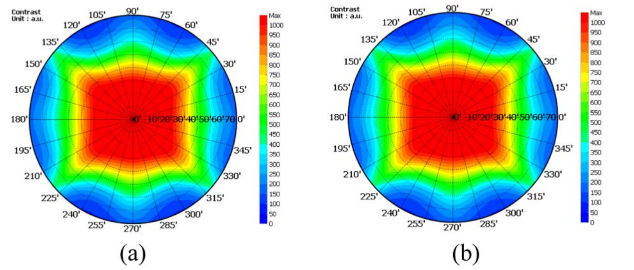

Fig. 8. (Color online) Comparison between the iso-contrast of (a) conventional wide-view PVA LC cell and (b) proposed 4-D VA LC cell.

P_{O3}, and P_{O4} in the oblique direction moved much closer to the goal position, circle j. From this, we assumed that the light intensity in the oblique direction could also be closer to the light intensity in the normal direction, thus improving the γ curve.

Figure 6 shows the completed optical configuration of the 4-D VA LC cell. The optimized configuration applies the FPR on both sides of the substrate because the optical axis of the pair of A plates for the 45° and 225° domains and the 135° and 315° domains should be +45° and −45°, respectively.

Figure 7 shows the calculated V–T curve and γ curve of the proposed and optimized optical configuration of the 4-D VA LC cell. We confirm that the gray inversion between 2 and 3 V in the oblique direction can be effectively removed by applying the pair of optimized A plates, as shown in Fig. 7(a). This improved V–T curve can provide an excellent γ curve for the 4-D VA LC cell at all viewing angles, as illustrated in Fig. 7(b).

The proposed optical configuration can also provide excellent viewing-angle properties because the optimized optical condition is satisfied with Eqs. (2) and (3). Figures 8(a) and 8(b) compare the calculated iso-contrast of the conventional wide-view 4-D VA LC cell and the proposed 4-D VA LC cell. We confirm that the proposed optical configuration also shows both excellent iso-contrast and an enhanced γ curve.

The γ-curve distortion can be quantitatively assessed by calculating the parameter GDI, i.e., the γ distortion index. The GDI is defined as follows [14]:

$$\mathrm{GDI} = \mathrm{AVG}\langle |L_{i(\text{on-axis})} - L_{i(\text{off-axis})}|\rangle_{i=0\sim255}, \qquad (4)$$

where $L_{i(\text{on-axis})}$ and $L_{i(\text{off-axis})}$ represent the brightness between the ith gray level in the on- and off-axis directions, and ⟨ ⟩ denotes the average for all cases of arbitrary gray levels. From the calculated results of the GDI, the γ-curve distortion of the proposed 4-D VA LC cell for each oblique viewing angle is improved by more than 80% compared to the conventional 4-D VA LC cell.

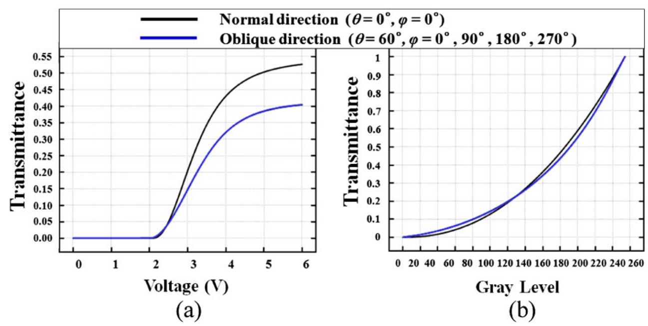

Fig. 7. (Color online) Calculated (a) V–T curve and (b) γ curve in the proposed wide-view 4-D VA LC cell.

In summary, we designed an optical configuration for a 4-D VA LC cell that can reduce the γ-curve distortion in the off axis without any loss of optical performance in the dark state. The proposed configuration applied a pair of A-type FPRs to the conventional wide-view configuration. We also confirm that the GDI of the proposed LC cell can be improved by more than 80% compared to a conventional 4-D VA LC cell.

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