Improvement of Gamma Curve Distortion in VA LCD by using Optical Film Patterned Retarder

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Abstract

In this paper, we improved the γ-curve distortion at off-axis direction in a 4-domain (4-D) patterned vertical alignment (PVA) liquid crystal (LC) cell by applying a pair of the film patterned retarder (FPR) system with the A-film property at the conventional wide-view (WV) PVA LC cell. In order to achieve the excellent γ-curve in the 4-domain LC cell, we optimized the parameter of the pair of the patterned A-film by using the two-dimensional parameter space method, which calculates the polarization difference between the normal direction and the all viewing directions under voltage applied state. As a result, we confirmed that the gamma distortion index (GDI) of the proposed optical structure is reduced to over 80% without any loss of the optical luminance and the contrast ratio in the dark state.

Author Keywords

Vertical alignment; γ-curve distortion; film patterned retarder; wide viewing angle; transmittance

1. Introduction

For better electro-optical characteristics, many liquid crystal (LC) display modes such as twisted nematic (TN) mode [1], in-plane switching (IPS) mode [2], fringe field switching (FFS) mode [3], multi-domain vertical alignment (MVA) mode [4] and patterned vertical alignment (PVA) mode [5] have been developed in the display market. In particular, the MVA mode and the PVA are representative LC modes that can show very high contrast ratio in normal direction in addition to wide viewing angle [6]. In spite of the optical advantage of VA LC cell, however, the optical performance still shows strong dependence on the observed direction in all gray scales including dark state [7]. So image distortions which can be assessed by measuring the γ-curve occur in the middle gray level in the off-axis direction. In order to reduce this γ-curve distortion in the off-axis direction, several methods have been applied for improving the viewing angle property in the gray scales by applying the novel electrode structure so far [8, 10, 11]. However, these methods require complex cell structure such as two times the number of the transistor compared to the conventional TFT LCD [5] or different electrode structure domain in the sub-pixel [6].

In this paper, we study an optical approach to improve γ-curve distortion in 4-D VA LC cell by using optical compensation films without any deterioration of the viewing angle and contrast ratio in the dark state. Generally, γ-curve of the LCD is induced by the voltage-transmittance (V-T) curve in observed direction, so the distortion of the V-T curve in oblique incidence can cause the γ-curve distortion in oblique incidence direction. In this paper, we apply the pair of the A-plates, which consists of a positive A-plate and a negative A-plate, to the bottom and up side of the conventional wide-view PVA LC cell that consists of a negative C-plate and a ¼/2 biaxial plate [9]. The optimization of the pair of the A-plates was performed in each domain (the direction of a LC director equal to 45°, 135°, 225° and 315°) by calculating the polarization difference between the normal incidence and the oblique incidence under voltage applied state on the Poincaré sphere as functions of the retardation and the optical axis of the pair of A-plates [12]. From the calculated result, we could propose an optical configuration of 4-D VA LC cell with a pair of the FPR that can improve off-axis γ-curve with high contrast ratio and wide viewing angle.

2. Electro-optical characteristics of the conventional wide-view 4-D VA LC cell

As I mentioned before, improvement of the optical performance in the conventional wide-view VA LC cell is focused on the dark state. A good example for the conventional wide-view VA LC cell consists of a half-wave biaxial retardation film (Nz = 0.5) and a negative C-plate in addition to a basic VA LC cell, which is composed of two crossed polarizer and a LC cell in Fig. 1(a) [9].

Figure 1. A conventional 4-D wide-view VA LC cell: (a) optical structure and (b) LC director configuration in each domain.

Figure 1(b) shows the LC director configuration in each sub-pixel of the 4-D VA LC cell in each domain. From the described optical structure, a V-T curve and a γ-curve of the conventional wide-view PVA LC cell in the normal (polar angle θ = 0°, azimuth angle φ = 0°) and oblique (polar angle θ = 60°, azimuth angle φ = 0°, 90°, 180° and 270°) viewing angle can be calculated as shown in Fig. 2. In the Fig. 2 (a), we can observe the gray inversion region between V = 2V and V = 3V. In general, when viewers are watching the display screen in normal direction, they can perceive high image quality and the vivid colors because the γ-curve has briefly 2.2 which is most fundamental γ index [10]. However, the γ-curve is deviated from the value of 2.2 in the oblique direction because the gray inversion in the V-T curve is caused by the transmittance difference in off-axis direction compared to the normal incidence. Thus, we can observe the serious γ-curve distortion in the wide-view PVA LC cell in Fig. 2 (b), especially in middle gray levels, which is around V = 2.5V.
curve distortion in the VA LC cell. In normal direction, the output polarizer with 2.5V. The calculated vector of the polarization positions in front of the absorption axis of the output polarizer on the Poincaré sphere.

The calculated \( S_1(A) \) and \( S_2(A) \) for \( V = 2.5V \) on the Poincaré sphere.

\[
\Delta P = \sqrt{(S_{1(A)} - S_{1(p)})^2 + (S_{2(A)} - S_{2(p)})^2 + (S_{3(A)} - S_{3(p)})^2}
\]

where \( S_{1(A)} \), \( S_{2(A)} \) and \( S_{3(A)} \) represent the Stokes vector of the analyzer absorption axis \( P_A \) and \( S_{1(p)} \), \( S_{2(p)} \) and \( S_{3(p)} \) are the Stokes vector of the polarization positions in front of the absorption axis of the output polarizer with 2.5V. The calculated \( \Delta P \) for \( P_{N1} \) and \( P_{N2} \) is same and the value of the \( \Delta P \) is 0.5912 (\( \lambda = 550\text{nm} \)). This implies the light intensity in all viewing angle in normal direction are same because they have same \( \Delta P \). A circle line \( j \) represents the equ-\( \Delta P \) line that can give us same \( \Delta P \), which implies equ-intensity line.

On the contrary, the polarization states of the light passing through the LC cell move to the position \( P_{O1} \), \( P_{O2} \), \( P_{O3} \) and \( P_{O4} \) with the red colored symbols \( \triangle, \Box, \bigcirc, \bigtriangledown \) and \( \bigotimes \) from the \( P_{N1} \) and \( P_{N2} \) in oblique direction. The calculated \( \Delta P \) in oblique direction are 1.3507 for \( P_{O1} \), \( P_{O2} \) and 0.3842 for \( P_{O3} \), \( P_{O4} \), respectively. These calculated results can make a big difference between the normal incidence and the oblique incidence under 2.5 voltage applied state, so that serious \( \gamma \)-curve distortion can be induced. Therefore, in order to improve the \( \gamma \)-curve distortion of the VA LC cell, we need to move the polarization position in oblique incidence to the goal polarization position (circle \( j \)), which can provide the same intensity with the normal incidence.

3. An optical configuration for improving the \( \gamma \)-curve distortion and optimization

In order to improve the \( \gamma \)-curve distortion of the VA LC cell, we applied a pair of \( A \)-plates to the bottom and top substrate of the conventional wide-view VA LC cell. Here, the optimization should be performed so the proposed configuration as to be satisfied for optical performance in both the dark state and all gray levels. And we can also derive the optical conditions which can produce the excellent wide-view property in the gray-level as well as in the dark state as follows,

\[
\sum \text{Retardation (VA LC + Negative C)} = 0
\]

\[
\sum \text{Retardation (Negative A + Positive A)} = 0
\]

Equation (2) represents a condition of the conventional wide-view PVA LC cell for the excellent dark state along the viewing direction. Equation (3) represents the relationship between the pair of a negative \( A \)-plate and a positive \( A \)-plate for improving the viewing angle property in the gray scale. We can assume that, if two equations above are satisfied, optical performance in the dark state will not be affected by the pair of \( A \)-plates, so that we can optimize the pair of \( A \)-plates without any deterioration of the optical performance in the dark state.

\[
\Delta P = \frac{1}{2} I_0 \cos^2 \left( \frac{\Delta P}{2} \right)
\]

Figure 3 illustrates the polarization states of the light in front of the absorption axis of the output polarizer in the conventional wide-view VA LC cell in normal and oblique directions in each domain at \( V = 2.5\text{V} \) on the Poincaré sphere.

\[
\Delta P = \sum \text{Retardation (A)} = 0
\]

\[
\sum \text{Retardation (Negative A + Positive A)} = 0
\]

Equation (2) represents a condition of the conventional wide-view PVA LC cell for the excellent dark state along the viewing direction. Equation (3) represents the relationship between the pair of a negative \( A \)-plate and a positive \( A \)-plate for improving the viewing angle property in the gray scale. We can assume that, if two equations above are satisfied, optical performance in the dark state will not be affected by the pair of \( A \)-plates, so that we can optimize the pair of \( A \)-plates without any deterioration of the optical performance in the dark state.

\[
\Delta P = \frac{1}{2} I_0 \cos^2 \left( \frac{\Delta P}{2} \right)
\]

Figure 4. Optimization conditions of the pair of \( A \)-plate at the all viewing angles in (a) 45°, 225° and (b) 135°, 315° domain areas.

Optimization of the pair of the \( A \)-plates was performed by calculating the polarization difference \( \Delta P \) as functions of retardation value and the optical axis of the \( A \)-plates as shown in Fig. 4. From the results, we compared the polarization difference between the normal direction and the oblique direction. From the previous calculation, optical parameters of the pair of the \( A \)-plates can be optimized at the condition that can give us similar \( \Delta P \) in that case of normal incidence, which is 0.5912 of \( \Delta P \). In order to investigate the optimized position of the optical films, we look for the positions that can provide the \( \Delta P \) within ±0.2 from 0.5912, which is \( \Delta P \) in the normal direction. Figure 4 (a) and (b) shows...
the calculated \( \Delta p \) in 45°, 225° domain area and 135°, 315° domain area, respectively. In the Fig. 4 (a) and (b), we can confirm that the optimized condition is found at 45° of the optical axis and the ±320nm of the retardation value for 45° and 225° domain in the sub-pixel. And, for 135° and 315° domain, the optimized value of the optical axis and the retardation are -45° and the ±320nm, respectively.

Figure 5 shows the calculated polarization positions of the light in front of the absorption axis of the output polarized in all viewing angle. Compared to the polarization state of the conventional wide-view VA LC cell, we can observe that the polarization distribution is very closer to the goal position, circle \( j \). Therefore, we can assume that this can make a similar light intensity with the light intensity in the normal direction, which implies the improved \( \gamma \)-curve.

Figure 5. Polarization position of the light passing through the proposed 4-D VA LC cell in normal and oblique directions in each domain at \( V = 2.5V \) on the Poincaré sphere.

In the calculated results, however, the optimized optical configuration is different from each domain area, which is 45° of the optical axis and the ±320nm of the retardation value for 45° and 225° domain, and -45° of the optical axis and the ±320nm of the retardation value for 135° and 315° domain. Therefore, we can understand the pair of \( A \)-plates should be patterned in each sub-pixel as shown in Fig. 6. Figure 6 shows the completed optical configuration of a film patterned retarder (FPR) type 4-D VA LC cell. The patterned \( \pm A \)-film is applied to the top and the bottom of a conventional wide-view configuration with the optimized value.

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

Figure 7. The calculated (a) V-T curve and (b) \( \gamma \)-curve of a proposed 4-D VA LC cell in each viewing angle.

The proposed optical configuration can also provide excellent dark state and iso-contrast because the optimized optical condition is satisfied with Eq. (2) and (3). Figure 8(a) and 8(b) compare the calculated iso-contrast of the conventional wide-view 4-D VA LC cell and of the proposed 4-D VA LC cell as shown in Fig. 6. And we can confirm the proposed optical configuration also shows excellent iso-contrast in addition to enhanced \( \gamma \)-curve.

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

The \( \gamma \)-curve distortion can be quantitatively assessed by calculating the parameter GDI, which is \( \gamma \) distortion index. The GDI is defined as follow [13],

\[
GDI = \text{AVG} \left( \frac{L_{i(\text{on-axis})} - L_{i(\text{off-axis})}}{L_{i(\text{on-axis})}} \right)_{i=0-255}
\]

(4)

where \( L_{i(\text{on-axis})} \) and \( L_{i(\text{off-axis})} \) represent the brightness between \( i \)th gray level at the on and off-axis direction. And, \( < > \) denotes the average for all cases of arbitrary gray levels. As the calculated results of the GDI, the \( \gamma \)-curve distortion of the proposed 4-D VA LC cell for each oblique viewing angle is improved over 80% compared to the conventional 4-D VA LC cell.
4. Conclusion
In summary, we designed an optical configuration for the 4-domain VA LC cell that can reduce the \(\gamma\)-curve distortion in off-axis and perform the enhanced wide viewing angle, simultaneously. The proposed configuration applied a pair of \(A\)-type film patterned retarder to the top and the bottom side of the conventional wide-view configuration. Optimization of the pair of the \(A\)-plates was performed by calculating the polarization difference \(\Delta p\) as functions of the optical axes and the retardation. After comparing the \(\Delta p\) between the normal direction and the oblique direction in all viewing angle, we could finally calculate the optimal value of the optical axes and the retardation of the pair of the \(A\)-plates. In calculation, the proposed 4-D VA LC cell can show the excellent \(\gamma\)-curve in middle gray level without any loss of the wide-view property of conventional PVA cell in the dark state. We also confirm the GDI of the proposed LC cell can be improved over 80% compared to the conventional 4-D VA LC cell. Therefore, we believe that the proposed 4-D VA LC cell can enhance image distortion of the VA LC cell by improving the \(\gamma\)-curve.

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6. References