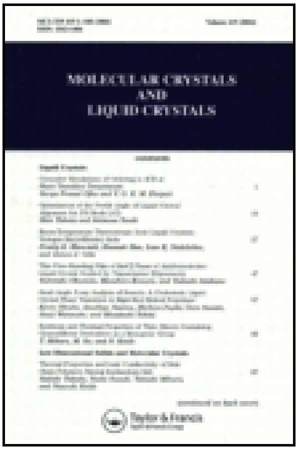

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A New Wide-Viewing-Angle Liquid Crystal Display without Grayscale Inversion

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A NEW WIDE-VIEWING-ANGLE LIQUID CRYSTAL DISPLAY WITHOUT GRAYSCALE INVERSION

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We examined the conditions that produce no grayscale inversion over a wide-viewing-angle. We also examined the optimum conditions for a retardation film that compensates for the retardation of all LC cells in the dark state. Using these conditions, we realized a wide-viewing-angle, high-contrast LCD with a simple structure and high brightness.

Keywords: compensation film; grayscale inversion; high contrast ratio; wide viewing angle

INTRODUCTION

Recently, several liquid crystal display (LCD) modes have been proposed to produce wide-viewing-angle LCDs, such as In-Plane Switching (IPS) [1], Multi-domain Vertical Alignment (MVA) [2], and Optically Compensated Bend (OCB) [3] modes. In these modes, an excellent dark state is maintained over a wide viewing-angle range, and a high contrast ratio is obtained. However, each of these modes has shortcomings. IPS has a low aperture ratio, MVA requires a multi-domain structure to prevent grayscale inversion, and OCB requires splay-bend transition. These problems cause low brightness and a complicated structure.

In order to realize a wide-viewing-angle LCD without such problems, it is required to prevent a grayscale inversion without using a multi-domain structure. Then, we examined the conditions required to prevent grayscale inversion. Furthermore, we examined the optimum conditions for a retardation film that compensates for the retardation of all LC cells in the dark state.

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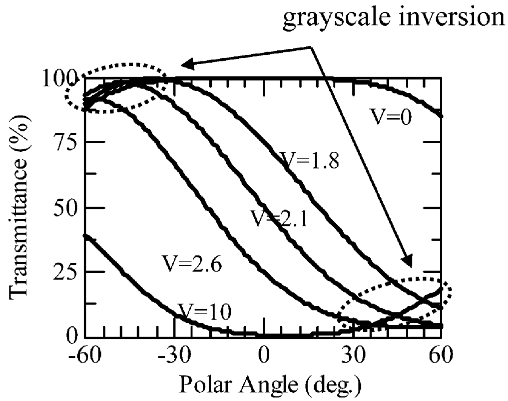

FIGURE 1 The viewing-angle properties of homogeneous cell transmittance.

THE CONDITIONS WITH NO GRAYSCALE INVERSION

The viewing-angle properties of the transmittance of a homogeneous cell are shown in Figure 1. In this figure, grayscale inversion arises in the high and low voltage ranges. Grayscale inversion becomes a problem when a homogeneous cell is applied to a display. Therefore, we examined a method of preventing grayscale inversion. The viewing-angle properties of retardation of a homogeneous cell calculated from the properties in Figure 1 are shown in Figure 2. This figure shows that the retardation curve crosses at the same points where grayscale inversion occurs. In order to prevent grayscale inversion, the retardation curves must not intersect in the viewing-angle range, and the change in retardation with voltage should always decrease or increase monotonously without depending on the viewing

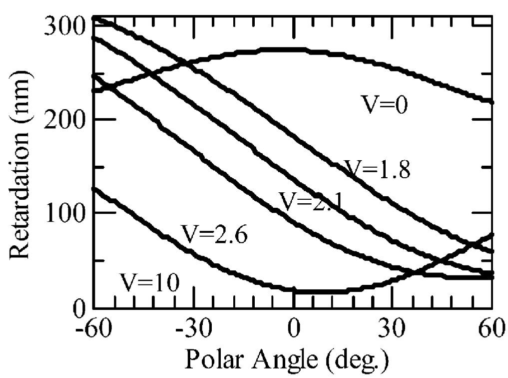

FIGURE 2 The viewing-angle properties of homogeneous cell retardation.

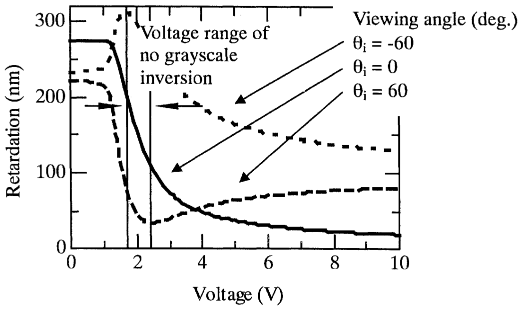

FIGURE 3 The change in retardation with voltage (The change decreases monotonously in the voltage range from 1.6 to 2.4 V).

angle. The change in retardation with voltage for three different viewing angles is shown in Figure 3. In this figure, the change in retardation of all the curves decreases monotonously in the voltage range from 1.6 to 2.4 V, so the retardation curves do not cross in the viewing-angle form −60 to 60 deg.; hence, there is no grayscale inversion in this voltage range. The viewing-angle properties of the retardation in this voltage range are shown in Figure 4. This figure shows that the retardation curves do not intersect by controlling the tilt angle of the liquid crystal with the voltage.

COMPENSATION OF RETARDATION IN THE DARK STATE

As shown in Figure 4, the voltage range over which there is no grayscale inversion is found. Over this voltage range, the retardation changes gradually with viewing angle, so transmittance changes with viewing angle, too. Change of transmittance causes a light leakage in a dark state, and leads

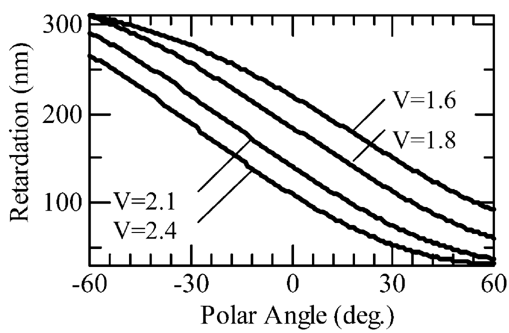

FIGURE 4 The viewing-angle properties of retardation without grayscale inversion.

to a low contrast, so it is necessary to compensate for the viewing-angle dependence of the retardation to obtain a dark state without light leakage. Then, we examined the optimum conditions of a retardation film to compensate for the viewing-angle dependence of a LC cell.

When voltage is applied to a cell, the tilt angle of the LC changes gradually with thickness (a non-uniform cell). We considered a LC cell as a collection of layers, in which the LC is oriented uniformly with thickness (uniform layer), and designed a compensation film for each layer. By stacking these compensation films, we can compensate for the viewing-angle dependence of a non-uniform cell in the dark state.

In order to compensate for changes in retardation of the uniform layer in all directions, it is necessary to satisfy the following equation, independent of the viewing angle.

$$\mathrm{Ret}_{\mathrm{LC}}(\theta_i) + \mathrm{Ret}_{\mathrm{film}}(\theta_i) = 0 \tag{1}$$

Where $\mathrm{Ret}_{\mathrm{LC}}$ is the retardation of the LC layer and $\mathrm{Ret}_{\mathrm{film}}$ is the retardation of the compensation film. The angles of the LC layer and the incident light are defined in Figure 5. Where, α is the tilt angle, ϕ_{LC} is the azimuthal angle of the LC, d is the layer thickness, θ_i is incident angle of light, and ϕ_i is the azimuthal angle of incident light. The retardation of the LC layer is given by the following equation:

$$\begin{aligned}\mathrm{Ret}_{\mathrm{LC}} = \Bigg\{ &\pm\sqrt{\left(1-\frac{p^2}{n_e^2}\right)\cdot\left(\frac{n_e^2}{q^2}-1\right)}\cdot\sin\theta_i. \\ &+\frac{p}{q}\sqrt{q^2-\sin^2\theta_i}-\sqrt{n_o^2-\sin^2\theta_i}\Bigg\}\cdot d(2)\end{aligned}$$

Here, n_o and n_e are the ordinary and extraordinary refractive indices, respectively. ϕ_{LC} is set to zero for simplification. The sign of the first

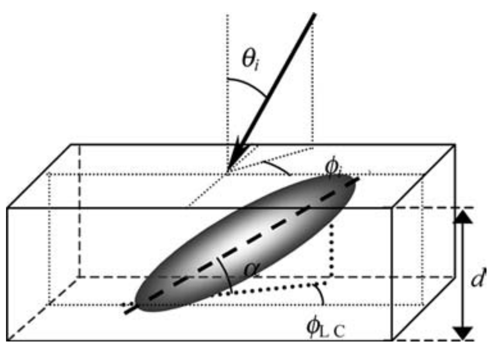

FIGURE 5 Definitions of the angles of the LC layer and incident light.

term is negative for $-90^\circ < \phi_i < 90^\circ$ and is positive for $90^\circ < \phi_i < 270^\circ$. Furthermore, p and q are given by the following equations:

$$\left\{\begin{array}{l} p = \frac{n_o \cdot n_e}{m} \\ q = \frac{n_e \cdot m}{n} \\ m^2 = n_o^2 \cos^2 \alpha + n_e^2 \sin^2 \alpha \\ n^2 = n_e^2 \cos^2 \phi_i + m^2 \sin^2 \phi_i \end{array}\right\} \quad (3)$$

The compensation film is defined in Figure 6. A and B are the ordinary and extraordinary refractive indices, respectively. D is the film thickness, β is the tilt angle, and ϕ_{film} is the azimuthal angle. In order to compensate for the retardation of the LC layer, parameters A, B, D, β and ϕ_{film} must satisfy Eq. (1) for all θ_i and ϕ_i. From the above, the conditions of a compensation film for a LC layer are given by:

$$\left\{\begin{array}{l} \beta = \mathrm{Arccos}\left(\sqrt{\frac{\mathrm{B}^2(\mathrm{A}^2-\mathrm{P}^2)}{\mathrm{P}^2(\mathrm{A}^2-\mathrm{B}^2)}}\right) \\ \mathrm{D} = \frac{p-a}{A-P} \cdot \mathrm{d} \\ \phi_{\mathrm{film}} = \phi_{\mathrm{LC}} \\ \text{P is expressed with the following equation:} \\ \frac{(\mathrm{A}+\mathrm{P}) \cdot (\mathrm{B}^2-\mathrm{P}^2)}{\mathrm{A}-\mathrm{P}} = \frac{\mathrm{A}^2 \cdot \mathrm{B}^2 \cdot (n_o+\mathrm{p}) \cdot (n_e^2-\mathrm{p}^2)}{n_o^2 \cdot n_e^2 \cdot (n_o-\mathrm{p})} \end{array}\right\} \quad (4)$$

Here, ϕ_{film} is the same as ϕ_{LC} for simplification.

Next, we show a method of compensating for the retardation of a non-uniform LC cell. An alignment of LC cell with an applied voltage is non-uniform, so it is necessary to stack compensation films for each layer so that the retardation of the LC layer is exactly zero. Figure 7 shows two ways of arranging the compensation films: on either one or both sides of the LC cell. In both cases, the LC and retardation film(s) form a pair with zero retardation. In the case of a twist cell, the direction angle ϕ_{film} of the compensation film corresponds to the azimuthal angle ϕ_{LC} of the LC, as shown in Figure 8.

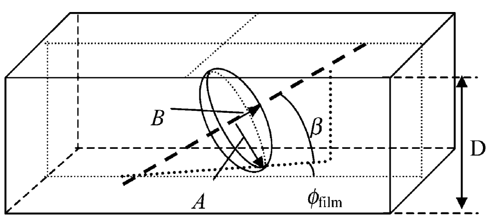

FIGURE 6 Definition of a compensation film.

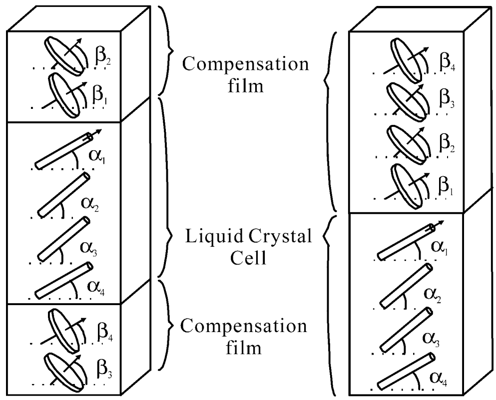

FIGURE 7 Methods of stacking compensation films for a LC cell.

We applied this method of compensation to a homogeneous cell, and calculated the viewing-angle properties in the dark state. As shown in Figure 9, in the case of no compensation film, there is light leakage in all directions, except in the normal direction. On the other hand, as shown in Figure 10, the compensated homogeneous cell has almost no light leakage (less than 1%) in all directions.

This method of designing a compensation film can be used for homogeneous, vertical, and bend alignment cells. Mori *et al.* reported that the viewing-angle properties of bend alignment can be compensated by using a hybrid discotic film that has the same director configuration with the bend alignment [4]. However, this configuration does not prevent light

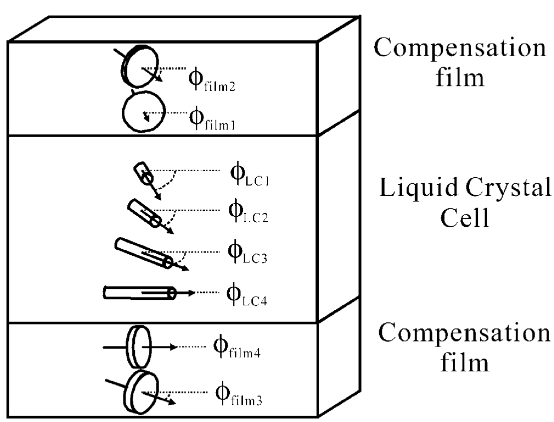

FIGURE 8 Method of stacking compensation films in a twist cell.

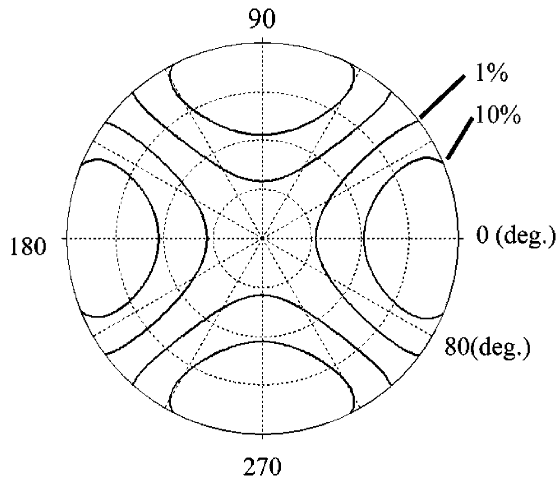

FIGURE 9 Iso-transmittance curve of a conventional homogeneous cell in the dark state.

leakage completely, so it is necessary to use other compensation films with this composition. By contrast, we optimized the tilt angle and thickness of a layer according to the tilt of bend alignment; as a result, light leakage can be suppressed perfectly over a wide viewing angle range.

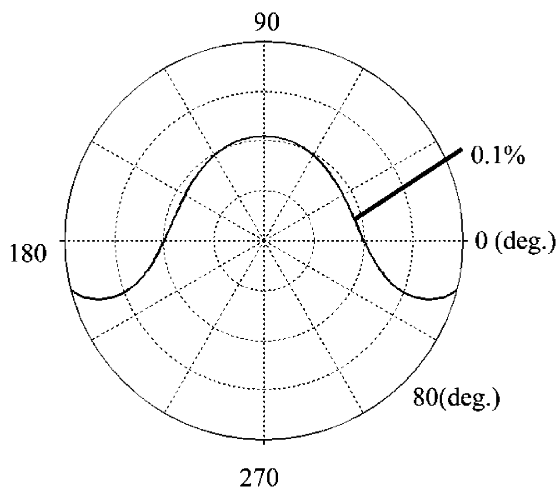

FIGURE 10 Iso-transmittance curve of a homogeneous cell using our new compensation film in a dark state.

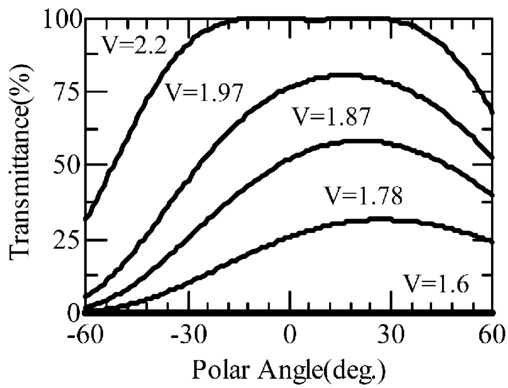

FIGURE 11 The viewing-angle properties of a compensated homogeneous cell, using the limited voltage range method and designed compensation film.

THE PROPERTIES OF A HOMOGENEOUS CELL USING THE NEW OUR DESIGN METHOD

We applied above-mentioned two design methods to a homogeneous cell. The viewing-angle properties of the transmittance are shown in Figure 11. In this figure, 100% is the intensity of incident light passed through parallel polarizers. The iso-contrast ratio curves are shown in Figure 12. Here, the value of Δn and thickness are 0.16 and 5 μm, respectively. These figures

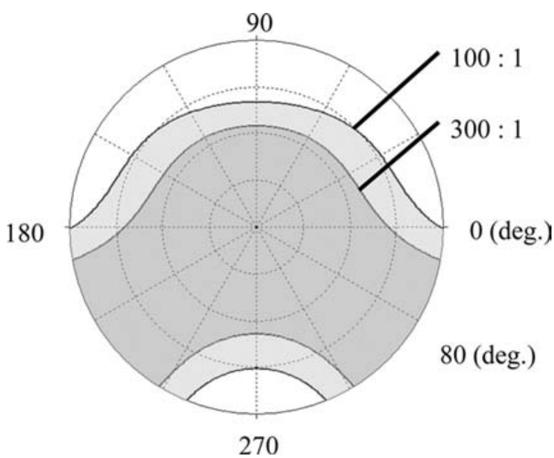

FIGURE 12 Iso-contrast curves of a compensated homogeneous cell, using the limited voltage range method and designed compensation film.

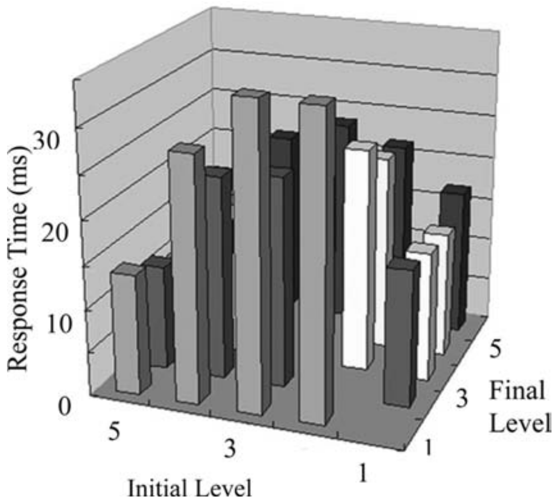

FIGURE 13 Response times of a homogeneous cell without acceleration.

show that grayscale inversion did not occur, and a high contrast ratio was obtained over a wide viewing-angle range.

RESPONSE SPEED OF THE NEW HOMOGENEOUS CELL

A new wide-viewing-angle LCD can be realized by limiting the tilt angle of the LC and using the newly designed compensation films. Like other LCD modes, however, our LCD has a problem with response speed. The response properties at five grayscale levels are shown in Figure 13. The response time

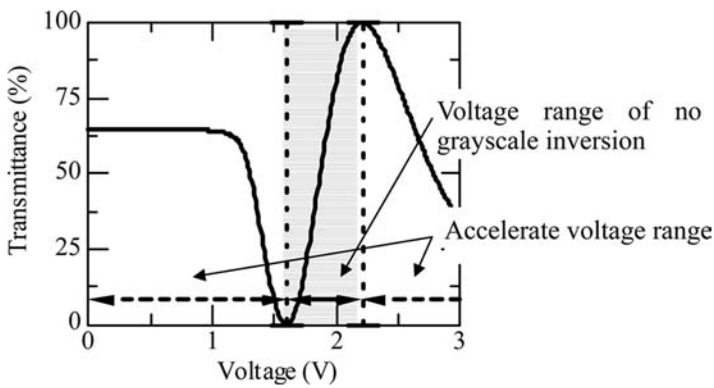

FIGURE 14 Accelerated voltage range of our homogeneous cell.

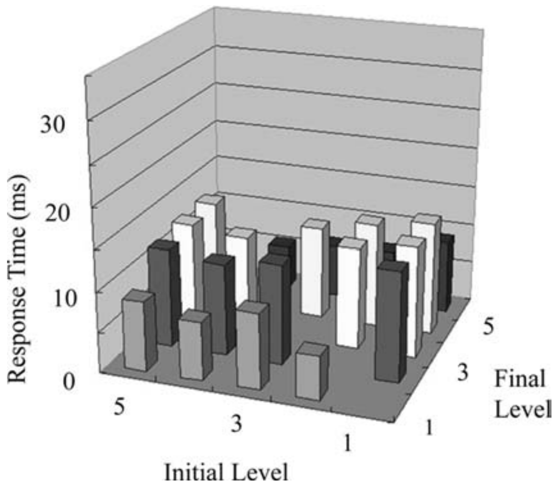

FIGURE 15 Response time properties of a homogeneous cell using the overdrive method (frame rate of 60 Hz).

is 35 ms, which is insufficient for showing a moving image. In order to improve the response time, a method that applies an accelerating voltage has been proposed [5,6]. We therefore applied this method to our LCD mode and examined the response properties. Although the accelerable range is either a rise or decay in other LCD modes, we can use the acceleration

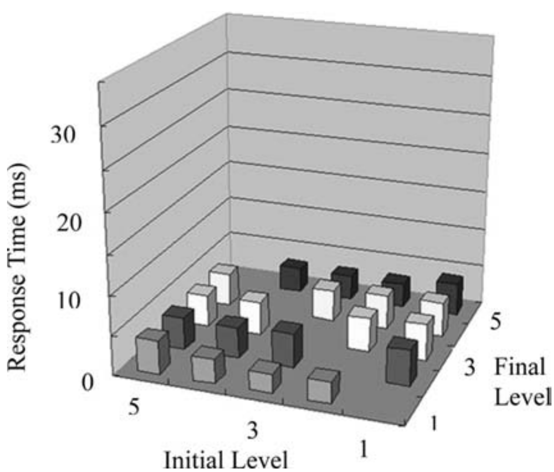

FIGURE 16 Response time properties of a homogeneous cell using the overdrive method (frame rate of 200 Hz).

voltage at both a rise and decay in our LCD mode, because this LCD is driven by using intermediate voltages, as shown in Figure 14. Figure 15 shows response time that is driven at a frame rate of 60 Hz. In this figure, the response time of a LC is less than 16 ms, so it shows that it is possible to show sharp moving image. Moreover, Figure 16 shows the response time when a frame rate of 200 Hz was applied to the homogeneous cell. From this figure, the response time was less than 5 ms, and our LCD mode can be applied to color field sequential LCDs.

CONCLUSION

We examined the cause of grayscale inversion and light leakage in the dark state. By controlling the tilt angle of the LC, we showed that grayscale inversion could be suppressed. Moreover, we clarified the optimum conditions of a retardation film to compensate the retardation of an LC cell in all directions, and realized the dark state without light leakage over a wide viewing-angle range. Consequently, we realized a wide-viewing-angle, high-contrast LCD with a simple structure and high brightness.

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