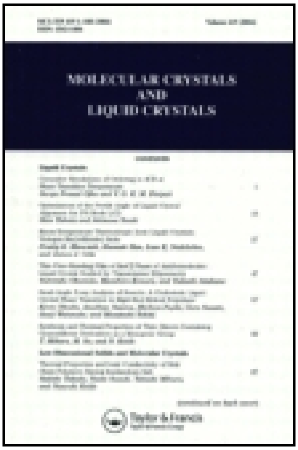

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We propose novel optical configurations of liquid crystal cells in double cell gap structure for transflective displays. The transmissive part as well as the reflective part is designed in the wide-band quarter-wave structure to achieve the good dark state. We found that in-plane switching of the proposed structure can provide a perfect bright state, although not only in-plane switching but also vertical switching can be used to achieve the bright state. It is also expected that wide viewing angle can be achieved at the same time by employing the in-plane switching mode.

Keywords: double cellgap; horizontal switching; liquid crystal; transflective

INTRODUCTION

Because of their advantages such as light weight, thinness, and low power consumption, reflective liquid crystal displays (LCDs) are becoming more and more important [1]. However, since reflective LCDs make use of the ambient light, they cannot show good display

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properties under dark indoor environments. On the other hand, transmissive LCDs show good performance under indoor environments, but do not under outdoor environments.

In order to obtain superior performance under indoor as well as outdoor environments, various types of transflective LCDs have been proposed [2–7]. The structures of transflective LCDs may be divided into two types: single cell-gap and double cell-gap. Single cell-gap transflective LCDs require complicated processes such as multiple rubbing, multiple domain, inner retardation layers, and so on. Moreover, it is difficult to find the optimal design conditions for both the reflective and the transmissive parts at the same time.

On the other hand, in double cell gap transflective LCDs, the cell gap of the reflective part is different from that of the transmissive part so that it is easy to find the optimal design conditions for each part [2,3]. As the process of fabricating the double cell gap structure is already established, it is not a big problem anymore.

Most of transflective LCDs in double cellgap structure are based on vertical switching of a homogeneously aligned liquid crystal cell, in which LC molecules are aligned horizontally in the voltage-off state [2,3]. By applying a vertical electrical field, LC molecules can be rearranged parallel to the electric field. A wide-band quarter-wave film, which consists of one half-wave film and on quarter-wave film, was used to achieve the dark state of the reflective part. One more wide-band quarter-wave film was added for phase compensation to realize the dark state of the transmissive part [8]. Although the conventional structure can provide good display performance as shown in Figure 1, they still need further improvement for rapidly increasing diverse mobile applications.

In this paper we propose two design methods of liquid crystal cells in double cell gap structure to improve the display performance of transflective displays. The reflective part is designed in wide-band quarter wave structure, while the transmissive part is designed in two method, which are the mirror image method and the compensation method. With the proposed configurations wavelength dispersion can be suppressed over the entire range of visible wavelengths so that high contrast ratio can be obtained. Moreover, they show an improvement of the bright state compared to the conventional double cell gap structure. Horizontal switching of the proposed optical configurations can be realized not only in nematic LCs but also in FLC (Ferroelectric Liquid Crystals), AFLC (Anti-Ferroelectric Liquid Crystals), and ECS (Electrically Commanded Surfaces) modes.

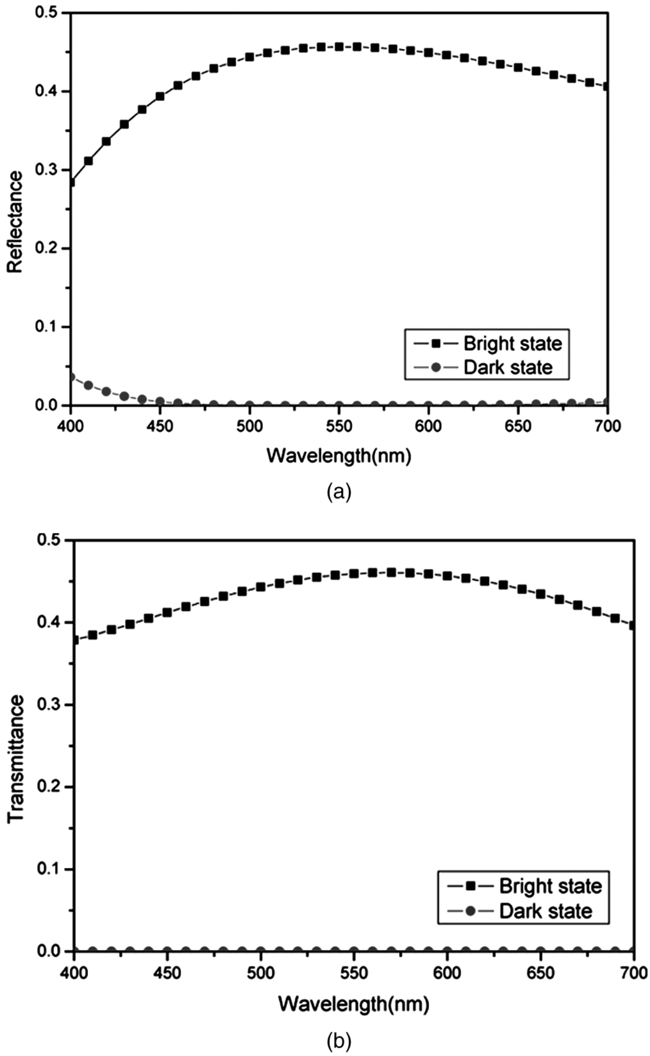

FIGURE 1 Spectral characteristics of a conventional transflective LCD. (a) reflective part, (b) transmissive part.

DESIGN PROCEDURE

The reflective part of a transflective display is designed in the wide-band quarter-wave structure to achieve the good dark state over the entire range of visible wavelengths. A polarizer, a half-wave film, and a quarter-wave LC layer are set to 0°, 15°, and 75°, respectively. In this optical condition, an LC cell shows a good dark state with little wavelength dispersion [9]. To achieve the bright state, we used three switching methods: vertical switching, horizontal switching to 30°, and horizontal switching to 120°.

Especially, in horizontal switching, voltages are applied between electrodes on the same substrate of the pixel structure. In the voltage-off state, LC molecules are untwisted and homogeneously aligned between two substrates. Since the cell is designed in the wide-band quarter-wave structure, it provides an excellent dark state. Applied horizontal electric field rotates LC molecules along the direction of the applied field, gradually increasing the optical transmittance over wide viewing angles [10,11].

Once the optical condition of the reflective part is determined, the transmissive part can be designed with the mirror image method and the compensation method as shown in Figure 2. In the mirror image method, upper and lower sides are symmetric with respect to the center of the half-wave LC layer. And, in the compensation method, the optic axes of upper and lower sides are set to be perpendicular to the center of the LC cell. Two polarizers, half-wave films, and a half-wave LC layer are set as shown in Table 1. To achieve the bright state, LC molecules can be switched by the same method as that of the reflective part. The proposed configurations are summarized in Table 1.

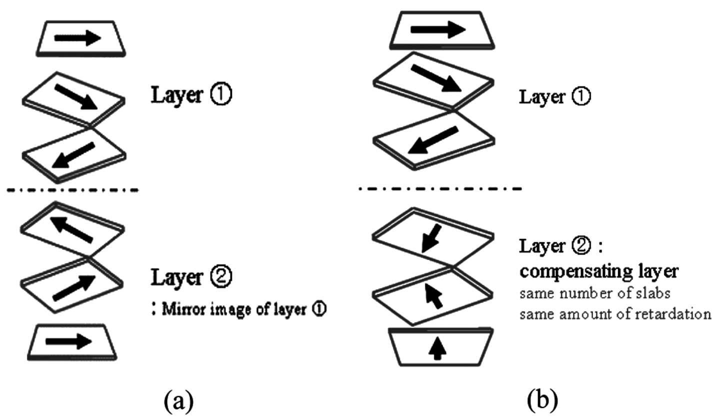

FIGURE 2 The schematic description of the mirror image method and the compensation method.

TABLE 1 Summary of the Proposed Double Cellgap Configurations

		Mirror image method			Compensation method		
Configuration		1	2	3	4	5	6
Top polarizer			0			0	
$\lambda/2$ Film			15			15	
LC layer	Dark			75			
	Bright	Vertical	30	120	Vertical	30	120
$\lambda/2$ Film			–			165	
$\lambda/2$ Film			15			105	
Bottom Polarizer			0			90	

PRINCIPLE OF OPERATION (MIRROR IMAGE METHOD)

In the reflective part, the unpolarized ambient light is 0° linearly polarized after passing through the polarizer. Then, its polarization direction is changed to 30° by passing through a half-wave film whose optic axis is oriented at 15°. By passing through a quarter-wave LC layer whose optic axis is set to 75°, the polarization state is changed to left-handed circular polarization. Since the optic axes of the half-wave film and the quarter-wave LC layer are set to 15° and 75°, respectively, these two layers play the role of a wide-band quarter-wave layer [9]. Round trip through these layers has the same effect as the single pass through two wide-band quarter-wave layers. The light is linearly polarized along the direction of 90° after the round trip through the reflective part, which will be blocked by the polarizer so that an excellent dark state can be realized.

As for the transmissive part, a half-wave LC layer is aligned along the direction of 75° in the voltage-off state. The structure of the transmissive part is the same as two wide-band quarter-wave layers in sequence. Since total retardation between two parallel polarizers is a half wave, 0° linearly polarized light is rotated to 90° linearly polarized light after passing through these layers. It is blocked by the top polarizer so that the dark state is achieved.

1. Vertical Switching (Configuration 1)

With a vertical electric field applied to the LC layer, LC molecules are reoriented parallel to the direction of the electric field. Since LC molecules are aligned vertically, there is no polarization change by the LC layer. In the reflective part, the 0° linearly polarized light passes through a half-wave film twice so that the polarization state remains unchanged. As a result, it can go through the polarizer freely so that the bright state can be achieved.

In the transmissive part, the cell structure under a vertical applied electric field is two half-wave layers in sequence. As the retardation change caused by the cell is just one wavelength, the incident light can pass through the top polarizer so that the bright state can be realized.

2. In-plane Rotation to 30° (Configuration 2)

With applying horizontal electric field, LC molecules can be rotated from 75° to 30° In the reflective part, the ambient light is polarized at the direction of 0° after passing through the polarizer. Then, it passes through a half-wave film at 15° so that polarization direction is rotated to 30°. After that, it meets a LC layer whose optic axis is set to 30°. The optic axis of the LC layer is parallel with the polarization direction of the light so that the polarization remains the same even after the round trip through the LC layer. Then, it passes through a half-wave film at 15° once more. The polarization is returned to 0° so that the bright state can be achieved.

As for the transmissive part, the polarization direction of the incident light passed through the bottom polarizer is 0°, which is changed to 30°, by the lower half-wave film at 15°. In the voltage-on state, LC director is rotated to 30°, in parallel with the polarization direction of the light having passed through the lower half-wave film. While passing through the half-wave LC layer, there is no change of the polarization state. Then, by the upper half-wave film, it is back to 0° linearly polarized light again. As a result, the final 0° linearly polarized light passes through the top polarizer to realize the bright state.

3. In-plane Rotation to 120° (Configuration 3)

With applying horizontal electric field, LC molecules can be rotated from 75° to 120°. In the reflective part, the ambient light is polarized at the direction of 0° after passing through the polarizer. Then, it passes through a half-wave film at 15° so that the polarization is changed to 30°. After that, it meets the LC layer whose optic axis is rotated to 120°. The optic axis of the LC layer is perpendicular to the polarization direction of the light so that the polarization state will not be changed like in-plane rotation to 30°. Then, as it passes through a half-wave film at 15° once more, the polarization is returned to 0° so that the bright state can be achieved.

As for the transmissive part, the polarization direction of the incident light passed through the bottom polarizer is 0°, which is rotated to 30° by the lower half-wave film at 15°. While propagating through the LC layer, there is no change of the polarization state because the optic axis is perpendicular to the polarization state. Then, by passing through the upper half-wave film at 15°, it is changed to 0° linearly polarized light again. After all, the final 0° linearly polarized light goes through the top polarizer to realize the bright state.

PRINCIPLE OF OPERATION (COMPENSATION METHOD)

In the reflective part, the principle of operations is exactly the same as that of the mirror image method. So, the following explains just the operation of the transmissive part.

As for the transmissive part, the optic axes of upper and lower sides from the center of a LC cell are set to perpendicular from each other in the voltage-off sate. The structure of the transmissive part is the same as two layers compensating each other in sequence. Since total retardation between two crossed polarizers is zero, the polarization state of the incident light remains the same after passing through all these layers. It is blocked by the top polarizer so that the dark state is achieved.

1. Vertical Switching (Configuration 4)

With the vertical electric field applied to the LC layer, LC molecules are realigned parallel to the direction of the applied electric field. Because LC molecules are aligned vertically, there occurs no retardation change by the LC layer.

In the transmissive part, by passing through the bottom polarizer, the unpolarized backlight is changed to the 90° linearly polarized light. Then, by passing through the third half-wave film, its polarization state is rotated to 120° linearly polarization state. By passing through the second half-wave film, its polarizing direction is rotated to 30°. Since there is no retardation change by a vertically aligned LC layer, it passes through the LC layer without any change of the polarization state. And, this 30° linearly polarized light goes through the first half-wave film to become 0° linearly polarized light. As a result, it can go through the top polarizer freely so that the bright state can be achieved.

2. Horizontal Switching to 30° (Configuration 5)

With applying a horizontal electric field, LC molecules can be rotated from 75° to 30° In the transmissive part, the polarization direction of the incident light passed through the bottom polarizer is 90°, which is changed to 30° after passing through the third and the second half-wave films whose optic axes are set to 105° and 165°, respectively. In the voltage-on state, LC director is rotated to 30° in parallel with the polarization direction of the light passed through the second half-wave film. Since its polarizing direction is the same as the optic axis of the LC layer, there occurs no change in polarization state. Then, by passing through the first half-wave film, it is changed to 0° linearly polarized light. After all, the final 0° linearly polarized light passes through the top polarizer to realize the bright state.

3. Horizontal Switching to 120° (Configuration 6)

With applying a horizontal electric field, LC molecules also can be rotated from 75° to 120°. As for the transmissive part, the polarization direction of the incident light passed through the bottom polarizer is 90°, which is rotated to 30° after passing through the third and the second half-wave films whose optic axes are set to 105° and 165°, respectively. In the voltage-on state, the LC director is rotated to 120° which is perpendicular to the polarization direction of the light having passed through the second half-wave film. Since its polarizing direction is perpendicular to the optic axis of the LC layer, there is no change in the polarization state. Then, by passing through the first half-wave film at 15°, it is changed to 0° linearly polarized light. After all, the final 0° linearly polarized light passes through the top polarizer to realize the bright state.

RESULTS AND DISCUSSION

Once the reflective part is designed, the transmissive part can be designed by one of the two methods, which are mirror image method and the compensation method as explained before. In case of the mirror image method, since the phase retardation upon the round trip through the reflective part is the same as that of the single pass through the transmissive part, spectral characteristics of the reflective part is exactly the same as that of the transmissive part, as shown in Figure 3. Figure 3(a) shows a little light leakage in the dark state. This can lower the contrast ratio, which is defined as the ratio of luminance between the brightest white that can be produced and the darkest black that can be produced. To get a high contrast ratio, improvement of the dark state is more important than the improvement of the bright state.

As for the compensation method, although the bright state becomes a little worse than that of the mirror image method, the dark state is

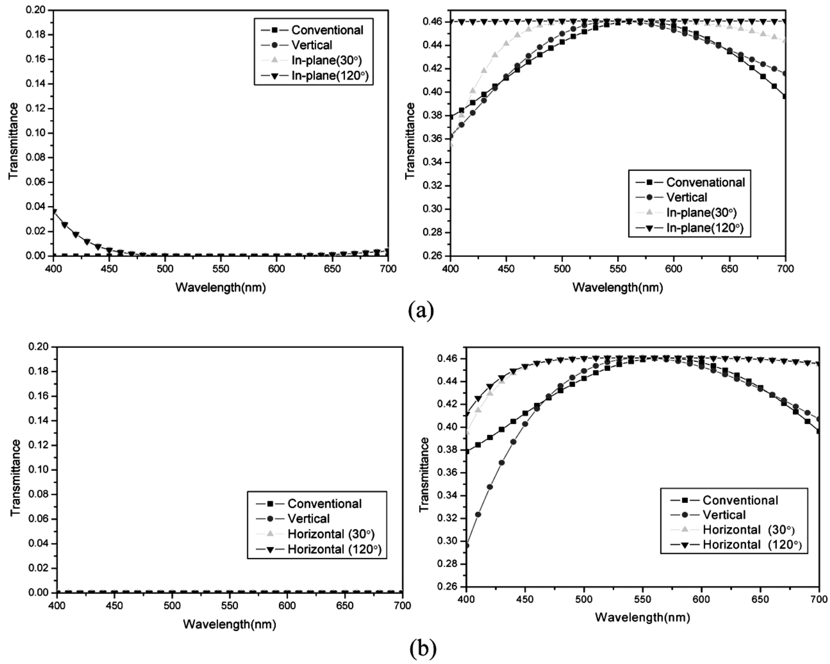

FIGURE 3 Spectral characteristics of the transmissive part. (a) Mirror image method, (b) Compensation method.

much improved so that we can get a higher contrast ratio. In short, the compensation method is more favorable than the mirror image method to get a high contrast ratio.

In this paper, since all of the proposed configurations are designed in wide-band quarter wave structure and the phase compensation method, they show little light leakage in the dark state as shown in Figures 3(b) so that high contrast ratio can be achieved. Figures 3 shows the improvement of the bright states of the proposed configurations compared with the conventional structure. Measured transmission spectra of the reflective and the transmittance parts show good agreements with calculated results, as shown in Figures 5.

But, as shown in Figures 3 and 4(b), the bright states of the horizontal switching are much better than those of the vertical switching. Since all the configurations are designed for the specific wavelength (550 nm), lights at shorter or longer wavelengths experience the retardation different from that at the design wavelength. That causes the reduction of the transmittance and the reflectance, which can be easily confirmed by calculations with the Mueller matrix [12]. The Mueller

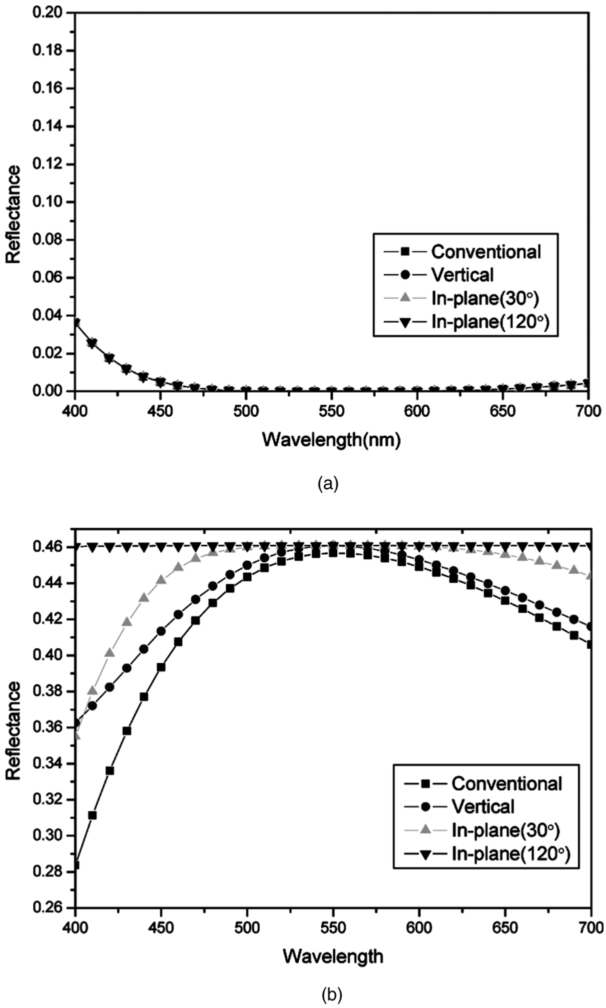

FIGURE 4 Spectral characteristics of the reflective part. (a) dark state, (b) bright state.

matrix of a retardation layer can be written as;

$$M(\theta,\beta)=\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos^2 2\theta+\cos\beta\sin^2 2\theta & (1-\cos\beta)\sin 2\theta\cos 2\theta & -\sin\beta\sin 2\theta \\ 0 & (1-\cos\beta)\sin 2\theta\cos 2\theta & \sin^2 2\theta+\cos\beta\cos^2 2\theta & \sin\beta\cos 2\theta \\ 0 & \sin\beta\sin 2\theta & -\sin\beta\cos 2\theta & \cos\beta \end{pmatrix} \quad (1)$$

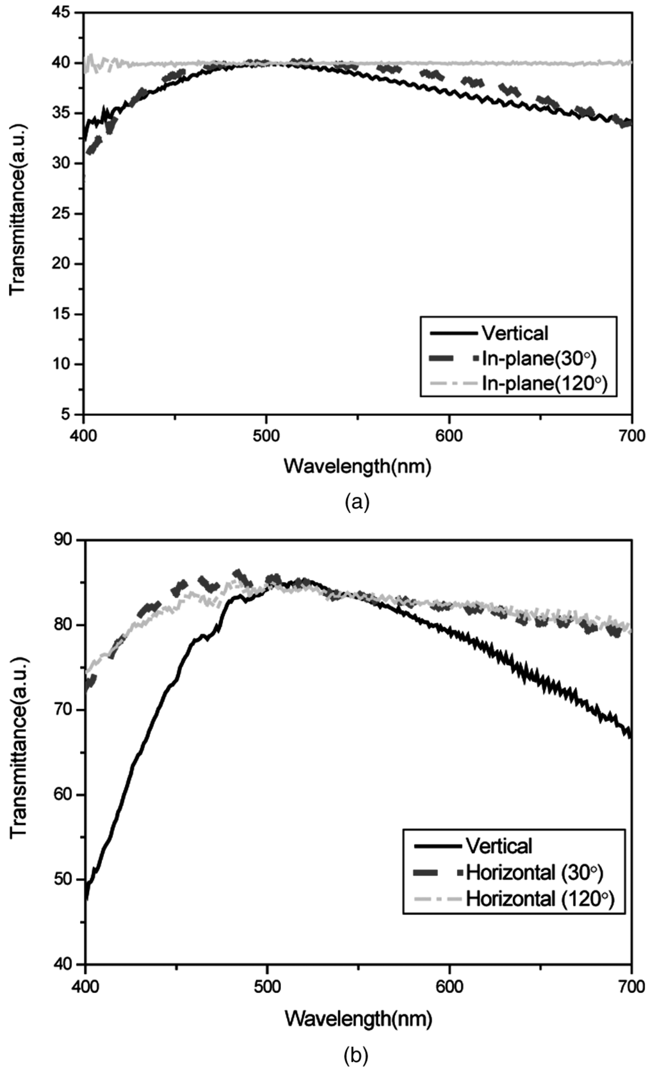

FIGURE 5 Measured transmission spectra of the bright state. (a) Mirror image method, (b) Compensation method.

θ: Direction of optic axis of the retardation layer
$\beta = 2\pi\Delta nd/\lambda$: Phase retardation of the retardation layer

In the above matrix, β is fixed at just one value for all visible wavelengths. But, in practice, the polarization state of the output

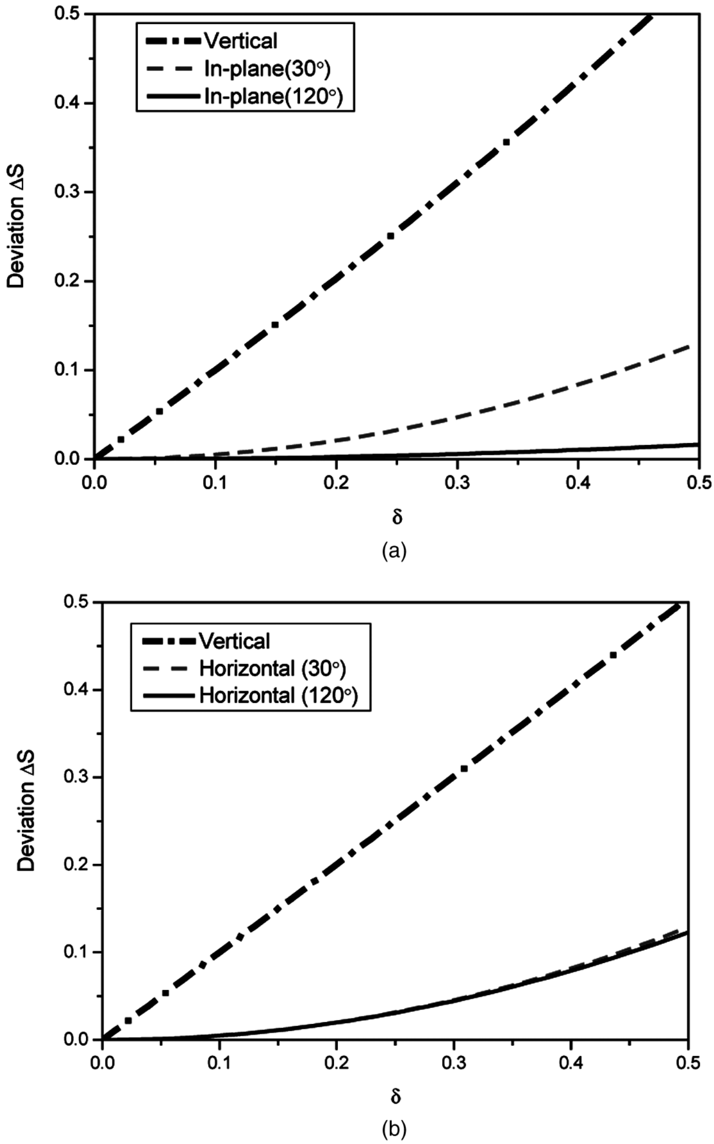

FIGURE 6 Dependence of the polarization deviation upon the value of δ in the bright state. (a) Mirror image method, (b) Compensation method.

light depends on wavelengths so that the phase retardation needs to be described as $\beta = \beta_o + \delta$, in which δ is the phase change due to the wavelength deviation. Mueller matrix that takes into account the wavelength deviation can be written as follows;

$$M(\theta,\beta_o+\delta)=$$

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos^2 2\theta+\left(\cos\beta_o\left(1-\frac{\delta^2}{2}\right)-\delta\sin\beta_o\right)\sin^2 2\theta & (1-\cos\beta_o\left(1-\frac{\delta^2}{2}\right)+\delta\sin\beta_o)\sin2\theta\cos2\theta & -\sin\beta_o\left(1-\frac{\delta^2}{2}\right)-\delta\cos\beta_o\sin2\theta \\ 0 & \left(1-\cos\beta_o\left(1-\frac{\delta^2}{2}\right)+\delta\sin\beta_o\right)\sin2\theta\cos2\theta & \sin^2 2\theta+\left(\cos\beta_o\left(1-\frac{\delta^2}{2}\right)-\delta\sin\beta_o\right)\cos^2 2\theta & \sin\beta_o\left(1-\frac{\delta^2}{2}\right)-\delta\cos\beta_o\cos2\theta \\ 0 & \sin\beta_o\left(1-\frac{\delta^2}{2}\right)-\delta\cos\beta_o\sin2\theta & -\sin\beta_o\left(1-\frac{\delta^2}{2}\right)-\delta\cos\beta_o\cos2\theta & \cos\beta_o\left(1-\frac{\delta^2}{2}\right)-\delta\sin\beta_o \end{pmatrix} \quad (2)$$

By using the Stokes vector, 0° and 90° linearly polarized incident lights are described as $S_i = (1,\ 1,\ 0,\ 0)$ and $S_i = (1,\ -1,\ 0,\ 0)$, respectively. The Stokes vector of the output light can be calculated by Mueller matrix calculation.

To investigate the wavelength dispersion, we should define the polarization deviation (ΔS) of the output Stokes vectors, $S_O = (S_0, S_1, S_2, S_3)$. The polarization deviation can be defined as $\Delta S = ((S_1-1)^2 + S_2^2 + S_3^2)^{1/2}$. Figure 6 shows the dependence of the polarization deviation upon δ in the bright state.

CONCLUSIONS

We proposed 6 optical configurations in which the transmissive parts are designed by the mirror image method and the compensation method. They show excellent spectral characteristics over the entire range of the visible wavelengths. We found that horizontal switching to 120° provides the best spectral characteristics among the proposed 6 configurations. Moreover, as the compensation method is employed, high contrast ratio can be achieved, which is very important in display performance. Moreover, by employing the horizontal switching mode, it is expected that wide viewing angle and high contrast ratio can be achieved at the same time. Horizontal switching of the proposed optical configurations can be realized not only by nematic LCs but also in FLC, AFLC, and ECS modes.

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