Journal of Information Display, vol. 7, no. 1, 2006 © 2006 KIDS

Optical Configurations for an Achromatic Transflective Liquid Crystal Cell

Gak-Seok Lee[**a], **Jae-Chang Kim**[a], **Tae-Hoon Yoon**[*a],
Young-Sik Kim[b], **Won-Seok Kang**[b], **and In-Byeong Kang**[*b]

Abstract

We propose optical configurations of a double-cellgap liquid crystal cell for transflective displays with wide viewing angle and high contrast ratio. The reflective part is designed in the wide-band quarter wave structure to achieve good dark state. For the transmissive part, the compensation method is applied to achieve the super-achromatic dark state, and three switching methods are used : which are vertical switching, horizontal switching to 30° and horizontal switching to 120°, to achieve the bright state.

Keywords : liquid crystal, transflective, double cell gap, horizontal switching

1. Introduction

Liquid crystal displays (LCDs) is considered as a leading candidate for next generation display devices. Their merits include the following : They are light, thin, requires low power, and little space. They can be used as an alternative to cathode ray tube (CRT) and so are usually found in computer monitors and televisions. In addition, they are suitable for mobile display devices such as mobile phones, portable media players (PMPs), and personal digital assistants (PDAs).

With the increasing popularity of mobile display devices, LCDs [are required to show the performance as much as computer monitors and televisions]. For this, various types of transflective LCDs have been proposed [1-5]. The structures of transflective LCDs can 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, etc., to manufacture them. Moreover, it is difficult to find the optimal design conditions for both the reflective and the transmissive parts at the same time. Particularly, when realizing a single cellgap transflective LCD in horizontal switching, a retardation layer is always placed under the LC layer [so that the parallax problem can be avoided]. To overcome this problem, an inner retarder should be used [5].

In contrast, in the case of the double cell gap transflective LCDs, the cell gap of the reflective part is different from that of the transmissive part in that it is easy to find the optimal design conditions for each part [1]. As the fabrication process of the double cell gap structure is already established, [it is not a big problem anymore.]

In a transflective LCD in double cell gap, two methods can be used to design the transmissive part: the mirror image method and the compensation method. In the mirror image method, the upper and lower sides of the transmissive part are symmetric with respect to the center of the LC layer [6]. Although they show good spectral characteristics enough to get a high contrast ratio, there is still room to improve the quality of the dark state. In the compensation method, optic axes of upper and lower sides of the transmissive part are set to be perpendicular to the center of the LC layer. While they show spectral characteristics of the bright state on a level of those of the mirror image method, they can achieve a perfectly dark state to get higher contrast ratio.

In this paper, we propose three optical configurations of liquid crystal cells in double cell gap structure for high performance transflective displays. The reflective part is designed in wide-band quarter wave structure, while the transmissive part is designed in the compensation method.

Manuscript received February 13, 2006; accepted for publication March 15, 2006.
This work was supported by LG-Philips LCD.
[*] Members, KIDS; [**] Student Members, KIDS.
Corresponding Author : Gak Seok Lee
[a] Department of Electronics Engineering, Pusan National University Busan 609-735, Korea.
[b] Panel Design 4 Team, LG Philips LCD Gumi-si, Gyungsangbuk-do 730-726, Korea
E-mail : neodol@pusan.ac.kr **Tel** : +051 510-1700 **Fax** : +051 515-5190

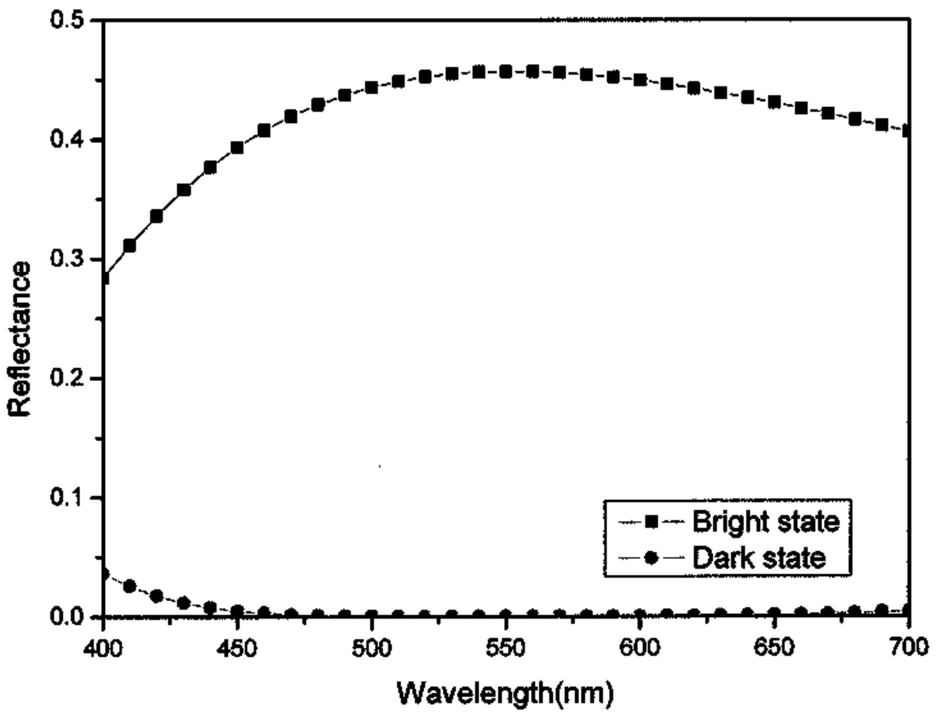
With the proposed configurations, not only can the wavelength dispersion be suppressed over the entire range of visible wavelengths but also high contrast ratio can be obtained. Moreover, compared to the conventional double cell gap structure, we can see an improvement in the bright state. Furthermore, 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 [7-9].

2. Design Procedure

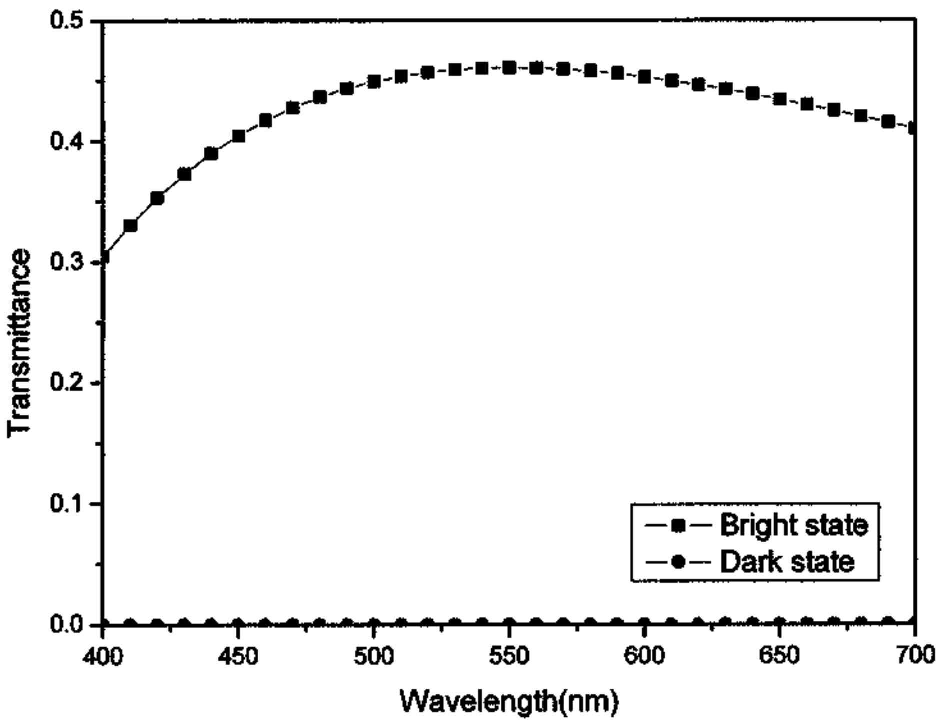
Most of transflective LCDs are based on vertical switching of a homogeneously aligned liquid crystal cell in double cellgap structure, in which LC molecules are aligned horizontally in the voltage-off state. By applying a vertical electrical field, LC molecules can be realigned parallel to the applied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

In this paper, 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 [10]. To achieve the bright state, we use three switching methods: vertical switching, horizontal switching to 30°, and horizontal switching to 120°.

In horizontal switching, electric currents are made to flow 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 in the direction of the applied field, gradually increasing the optical transmittance over wide viewing angles [11,12].



(a) the reflective part



(b) the transmissive part

Fig. 1. The spectral characteristics of the conventional structure.

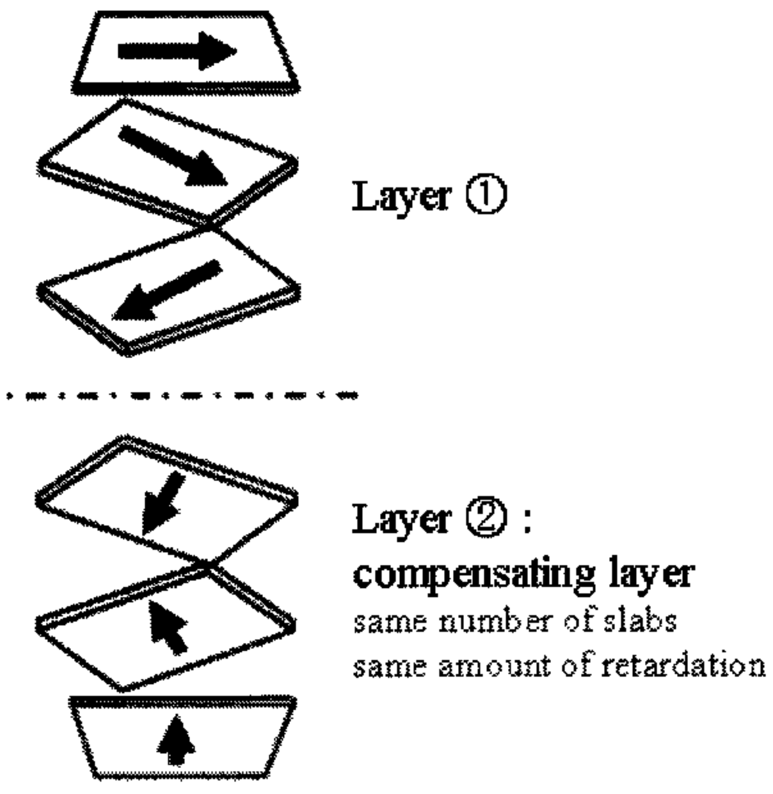


Fig. 2. The schematic description of the compensation method.

Once the optical condition of the reflective part is determined, the transmissive part can be designed with the compensation method. In the compensation method, the optic axes of upper and lower sides are set to be perpendicular to the center of the LC cell as shown in Fig. 2. Two polarizers, three half-wave films, and a half-wave LC layer are set as shown in Table 1. To achieve the bright

Table 1. Summary of the proposed double cell gap configurations.

Configuration		1	2	3
Top Polarizer		0°		
First $\lambda/2$ Film		15°		
LC Layer	Dark	75°		
	Bright	Vertical	30°	120°
Second $\lambda/2$ Film		165°		
Third $\lambda/2$ Film		105°		
Bottom Polarizer		90°		

state, LC molecules can be switched in the same way as that of the reflective part. The proposed configurations are summarized in Table 1.

3. Operation Principle

In the reflective part, 0° linearly polarized passed through the polarizer changes its polarization direction to 30° while passing through a half-wave film whose optic axis is oriented at 15°. Then, 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 act as a wide-band quarter-wave layer [10]. A round trip through these layers has the same effect as passing through a 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 consequently become blocked by the polarizer so that an excellent dark state can be realized.

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

3.1 Vertical switching

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 is no [retardation 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 can remain the same. This allows it to through the polarizer freely to achieve the bright state.

In the transmissive part, after passing through the bottom polarizer, the unpolarized backlight is changed to the 90° linearly polarized light. Then, when it passes through the third half-wave film, its polarization state is rotated to 120° linearly polarization state. Finally, when it passes 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 to the polarization state. This 30° linearly polarized light goes through the first half-wave film to become the 0° linearly polarized light. This allows it to go through the top polarizer freely to achieve the bright state.

3.2 Horizontal switching to 30°

By applying a 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 changed to 30°. After that, it meets a LC layer whose optic axis is set to 30°. The optic axis of the LC layer is set to be parallel with the polarization direction of the light so that the polarization remains unchanged even after the round trip through the LC layer. Then, it passes through a half-wave film at 15° again. Finally, the polarization is returned to 0° so that the bright state can be achieved.

In the transmissive part, the polarization direction of the incident light passing through the bottom polarizer is 90°, which is changed to 30° after passing through the third and the second half-wave films at 105° and 165°, respectively. In the voltage-on state, LC director is rotated to 30°, 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 is no change in the polarization state. However, when passing through the first half-wave film, it is changed to 0° linearly polarized light. Finally, the final 0° linearly polarized light passes through the top polarizer to realize the bright state.

3.3 Horizontal switching to 120°

By applying a 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 polarization direction is rotated to 30°. After that, it meets a LC layer whose optic axis is set to 120°. The optic axis of the LC layer is perpendicular to the polarization direction of the light so that the polarization remains the same after the round trip through the LC layer. Then, it passes through a half-wave film at 15° again. 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 is passed through the bottom polarizer at 90°, which is changed to 30° after passing through the third and the second half-wave films at 105° and 165°, respectively. In the voltage-on state, the LC director is rotated to 120°, perpendicular to the polarization direction of the light passing 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 rotated to 0° linearly polarized light. In the end, the final 0° linearly polarized light passes through the top polarizer to realize the bright state.

4. Results and Discussion

In this paper, since all of the proposed configurations have been designed in wide-band quarter wave structure and the phase compensation method, they show a slightly light leak in the dark state as shown in Figs. 3(a) and 4(a) so that high contrast ratio can be achieved. Figs. 3(b) and 4(b) show improvements of the bright states of the proposed configurations compared with the conventional structure.

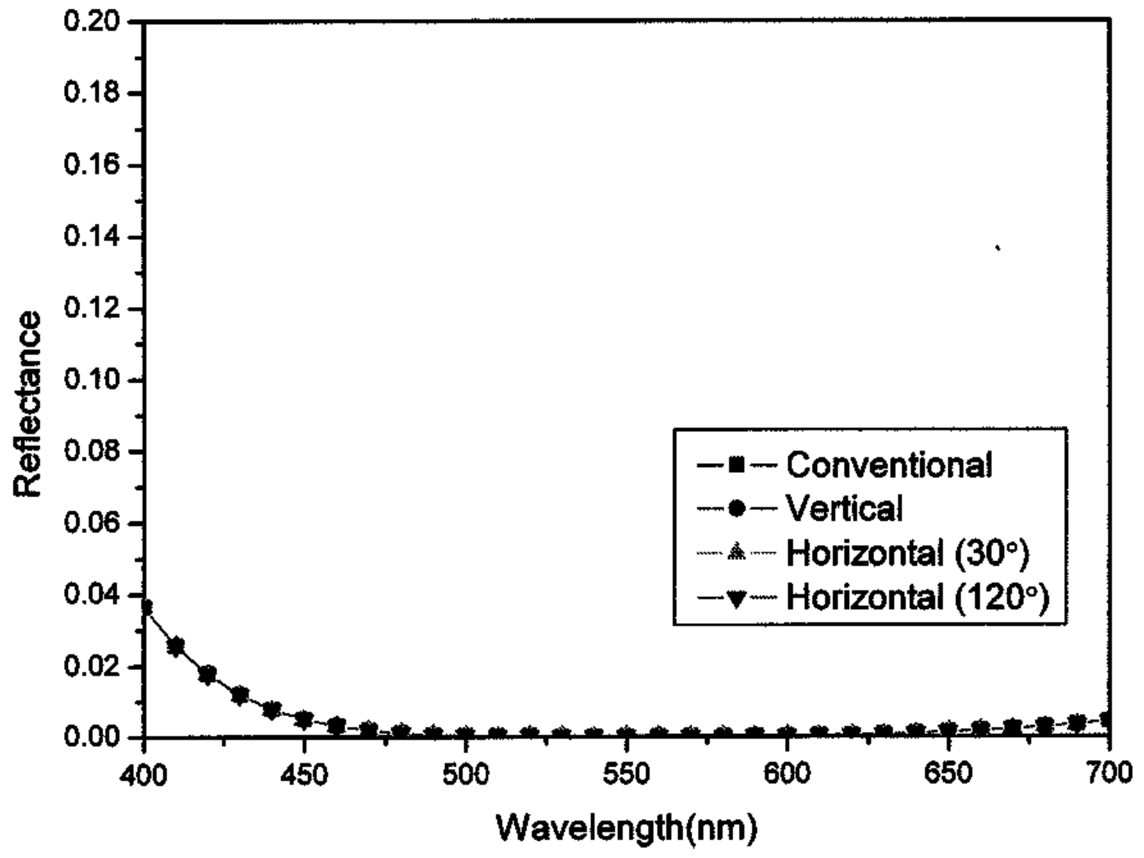
As shown in Figs. 3(b) and 4(b), the bright states of the horizontal switching are much better than those of the vertical switching. Since all the configurations are designed for the specific wavelength (550 nm), the lights at shorter or longer wavelengths experience etardation different from that at the design wavelength. This leads to reduction of the transmittance and the reflectance, which can be easily confirmed by calculations with the Mueller matrix [13]. The Mueller matrix of a retardation layer can be written as;

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

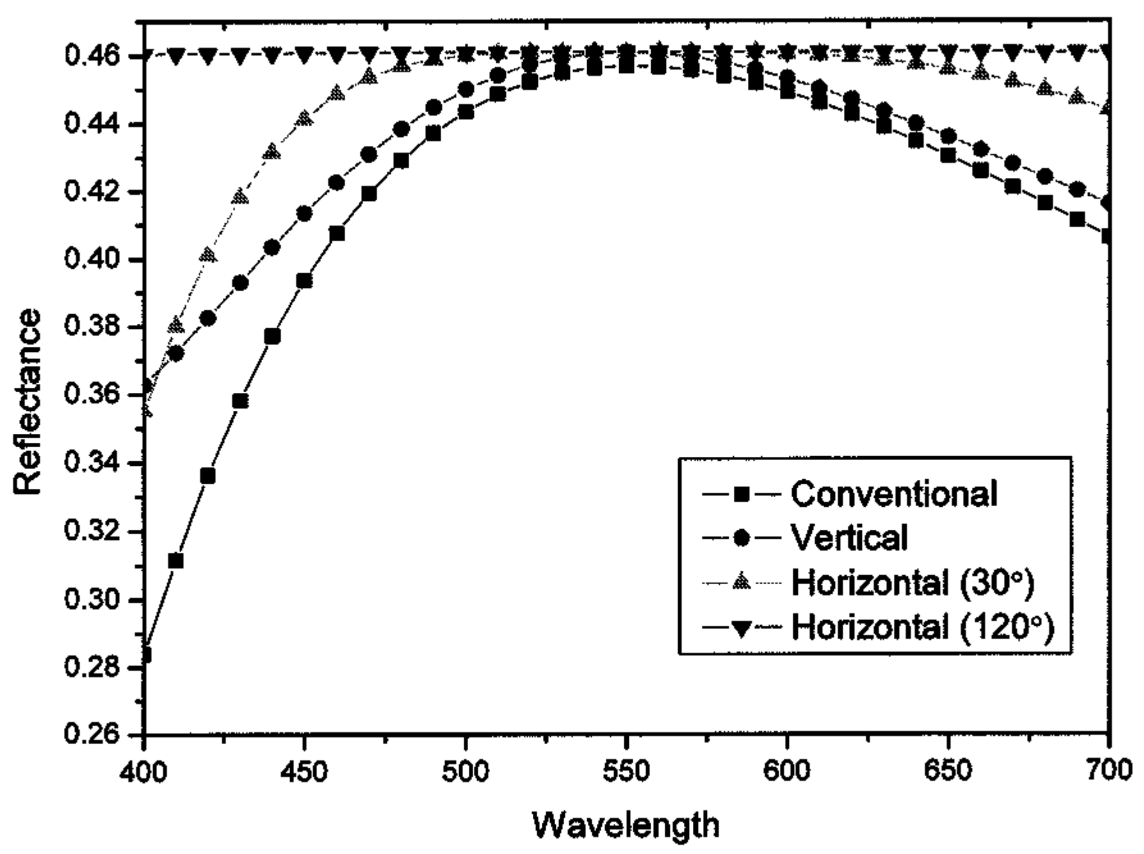
θ : Direction of optic axis of the retardation layer

$\beta=\dfrac{2\pi\Delta nd}{\lambda}$: Phase retardation of the retardation layer

Meanwhile, the polarization state of the output light depends on the wavelengths and thus the phase retardation needs to be described as $\beta=\beta_o+\delta$ where δ means the phase change due to the wavelength deviation. Mueller matrix that takes into account the wavelength deviation can be written as follows;

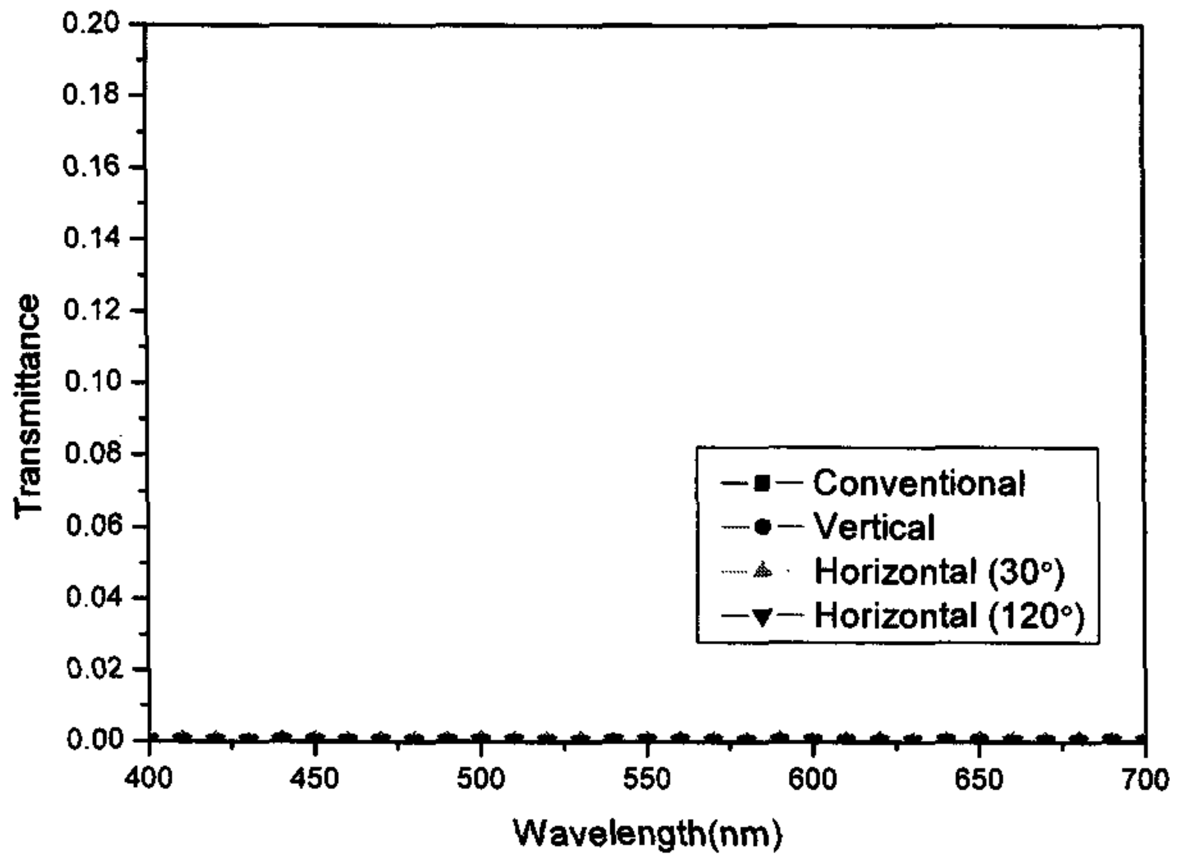


(a) the dark state

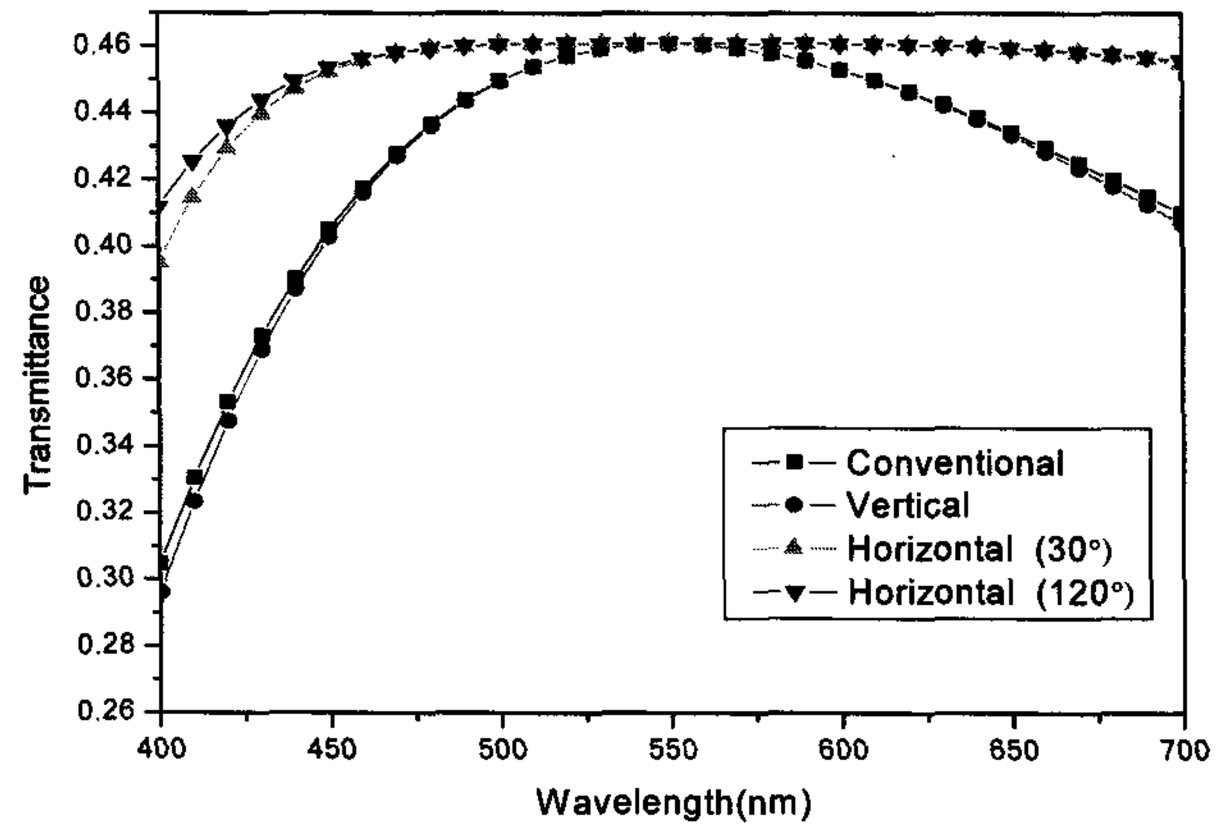


(b) the bright state

Fig. 3. Calculated spectral characteristics of the reflective part.



(a) the dark state



(b) the bright state

Fig. 4. Calculated spectral characteristics of the transmissive part.

$$M(\theta,\beta_o+\delta) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos^2 2\theta+\left(\cos\beta_o\left(1-\frac{\delta^2}{2}\right)-\delta\sin\beta_o\right)\sin^2 2\theta & (1-\cos\beta_o\left(1-\frac{\delta^2}{2}\right)+\delta\sin\beta_o)\sin 2\theta\ \cos 2\theta & -\sin\beta_o\left(1-\frac{\delta^2}{2}\right)-\delta\cos\beta_o\ \ \sin 2\theta \\ 0 & \left(1-\cos\beta_o\left(1-\frac{\delta^2}{2}\right)+\delta\sin\beta_o\right)\sin 2\theta\ \cos 2\theta & \sin^2 2\theta+\left(\cos\beta_o\left(1-\frac{\delta^2}{2}\right)-\delta\sin\beta_o\right)\cos^2 2\theta & \sin\beta_o\left(1-\frac{\delta^2}{2}\right)-\delta\cos\beta_o\cos 2\theta \\ 0 & \sin\beta_o\left(1-\frac{\delta^2}{2}\right)-\delta\cos\beta_o\ \ \sin 2\theta & -\sin\beta_o\left(1-\frac{\delta^2}{2}\right)-\delta\cos\beta_o\ \ \cos 2\theta & \cos\beta_o\left(1-\frac{\delta^2}{2}\right)-\delta\sin\beta_o \end{pmatrix} \tag{2}$$

By using the Stokes vector, 0° and 90° linearly polarized incident light is 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 using the following equation.

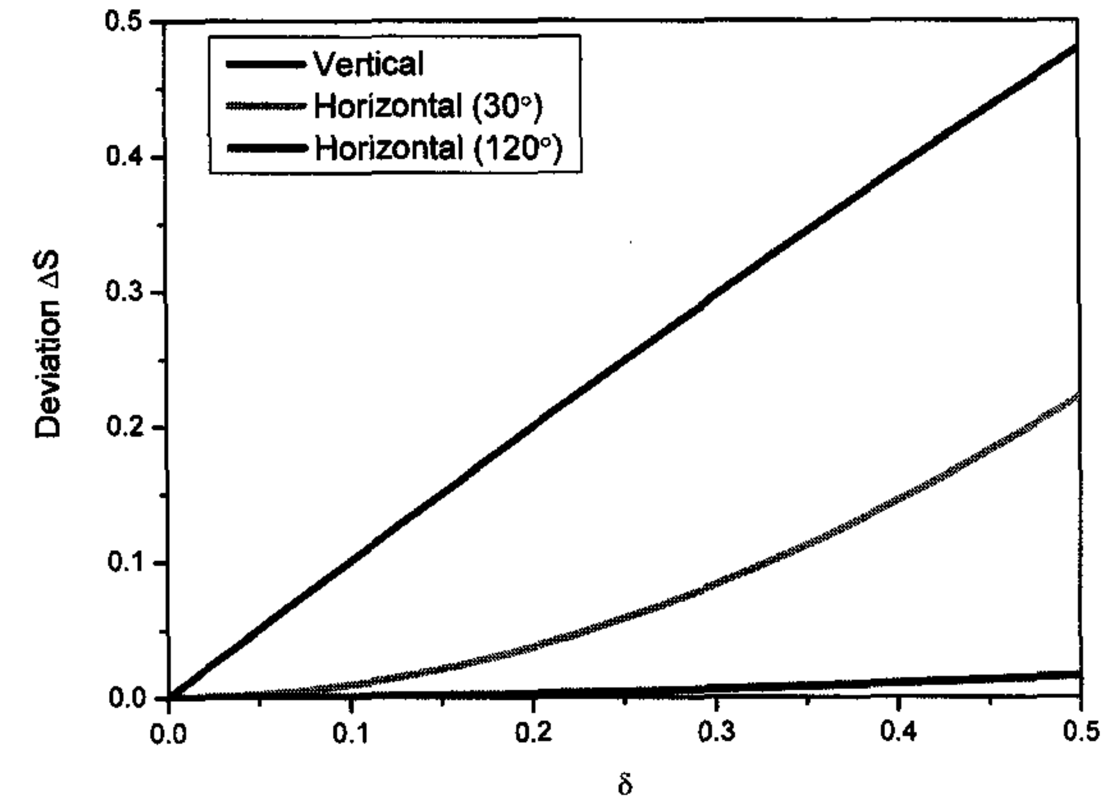
$$S_{o,ref} = M(\theta_{H1},\beta_H)M(\theta_{LC},\beta_{LC})M(\theta_{H1},\beta_H)S_i^T \tag{3}$$

$$S_{o,trans}=M(\theta_{H1},\beta_H)M(\theta_{LC},\beta_{LC})M(\theta_{H2},\beta_H)M(\theta_{H3},\beta_H)S_i^T \tag{4}$$

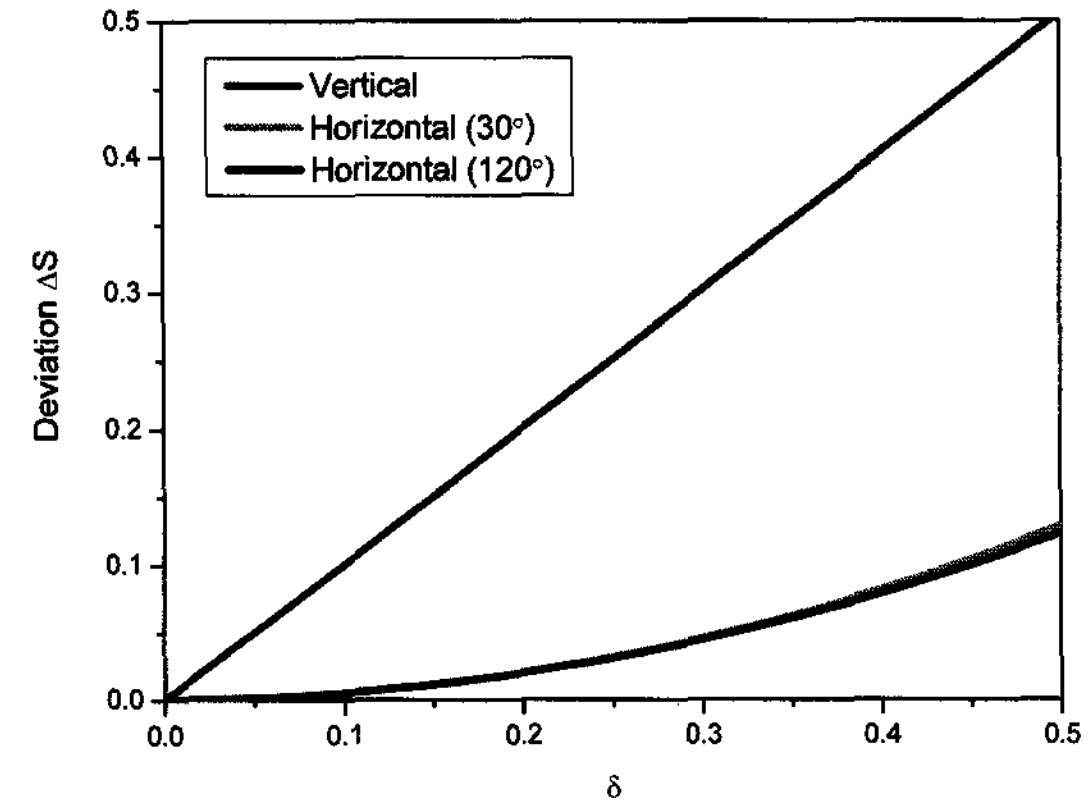
θ_{H1}, θ_{H2}, θ_{H3}, θ_{LC} : optic axes of the half-wave films and the LC layer,

β_H, β_{LC} : phase retardation of the half-wave film and the LC layer.

Equations (3) and (4) represent the Stokes vectors of the reflective and the transmissive parts, respectively. To investigate the wavelength dispersion, the polarization deviation (Δ S) of the output Stokes vectors $S_O=(S_0,S_1,S_2,S_3)$ need to be defined. The polarization deviation can be defined as $\Delta S=((S_1-1)^2+S_2{}^2+S_3{}^2)^{1/2}$. Fig. 5 shows the dependence of the polarization deviation upon δ in the bright state.



(a) the reflective part



(b) the transmissive part

Fig. 5. The dependence of the polarization deviation upon δ.

5. Conclusion

We proposed three optical configurations in which the transmissive parts are designed by the compensation method. They all showed excellent spectral characteristics over the entire range of the visible wavelengths. Among the three proposed configurations, the horizontal switching to 120° provided the best spectral characteristics. The reason why horizontal switching shows better spectra characteristics is explained by Mueller matrix. Moreover, when the compensation method was employed, a high contrast ratio was obtained, and this is very important as it determines the display performance. Especially, when the horizontal switching mode is employed, a 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.

References

[1] M. Kubo, T. Ochi, Y. Narutaki, T. Shinomiya, and Y. Ishii, J. Society for Information Display **8**, 299 (2000).

[2] H.-I. Baek, Y.-B. Kim, K.-S. Ha, D.-G. Kim, and S.-B. Kwon, Proc. International Display Workshop '00, 41 (2000).

[3] S. H. Lee, H. W. Do, G.-D. Lee, T.-H. Yoon, and J. C. Kim, Jpn. J. Appl. Phys. **42,** L1455 (2003).

[4] S. J. Roosendaal, B. M. I. van der Zande, A. C. Nieuwkerk, C. A. Renders, J. T. M. Osenga, C. Doornkamp, E. Peeters, J. Bruinink, and J. A. M. M. van Haaren, Society for Information Display Symposium '03 Digest, 78, (2003).

[5] K.-H. Park, J. C. Kim, and T.-H. Yoon, Jpn. J. Appl. Phys. **44,** 210 (2005).

[6] T. B. Jung, J. C. Kim, and S. H. Lee, Jpn. J. Appl. Phys. **42,** L464 (2003).

[7] N. A. Clark and S. T. Lagerwall, Appl. Phys. Lett. **36**(11), 899 (1980).

[8] A. D. L. Chandani, T. Hagiwara, Y. Suzuki, Y. Ouchi, H. Takezoe, and A. Fukuda, Jpn. J. Appl. Phys., Part 2, **27,** L729 (1999).

[9] L. Komitov, B. Helgee, J. Felix, and A. Matharu, Appl. Phys. Lett. **86,** 023502 (2005).

[10] T.-H. Yoon, G. D. Lee, and J. C. Kim, Opt. Lett. **25,** L1547 (2000).

[11] Oh-e. M and Kondo. K, Appl. Phys. Lett., **67,** L3895 (1995).

[12] Oh-e. M and Kondo. K, Liq. Cryst., **22,** 379 (1997).

[13] T.-H. Yoon, G.-D. Lee, and J. C. Kim, Society for Information Display Symposium '01 Digest, 898 (2001).