분과초청V2

한국광학회 2001년도 동계학술발표회 (2001. 2. 15~16)

반사형 LCD의 광학설계
Optical Configurations for a Reflective LCD

Tae-Hoon Yoon, Gi-Dong Lee, and Jae Chang Kim
Department of Electronics Engineering, Pusan National University, Pusan, 609-735, Korea
thyoon@hyowon.pusan.ac.kr

With the increasing demands for hand-held devices with lightweight and low-power-consumption displays, the role of reflective liquid crystal displays (LCDs) is becoming more and more important. Especially, the single polarizer mode is considered as a suitable structure for reflective LCDs[1-12] because it can provide high brightness. However, the single-polarizer LCDs have demerit in that the contrast is lower than double-polarizer LCDs because of the light leakage in the dark state. To increase the contrast in a reflective LC cell, many efforts have been focused on reducing the light leakage in the dark state by making the reflected light polarized linearly over the entire visible spectra, which may block the light over the entire visible ranges.

In general, in order to make the reflected light polarized linearly over the entire visible spectra in the dark state, two-kinds of optical configuration could be used. The first could be achieved by using a wide-band quarter-wave film[4-6] that consists of a half-wave film and a quarter-wave film. The second is an optical configuration that could exhibit the wide-band property without using a wide-band film[6]. A wide-band film that consists of two retardation films requires fabrication cost higher than a conventional film. To obtain the wide-band property without using a wide-band film, we have to find an optical configuration of a reflective cell so that the cell could exhibit the wide-band property by using a LC layer and a conventional retardation film only.

In this work, we introduce optical configurations for single-polarizer reflective LCDs by using non-twisted cells. Especially, optical configurations that can provide high contrast and high reflectance without using a wide-band quarter-wave film are proposed.

Figure 1 shows the optical principle of a single-polarizer reflective LCD. It is composed of a polarizer, a metallic reflector, and retardation layers between them. The dark state can be obtained by the double pass through a quarter-wave layer. The linearly polarized light passed through the polarizer will be changed to the circularly polarized light as it passes through the layer with a quarter-wave retardation. The polarization of the reflected light changes to 90° -rotated linearly polarization by propagating through the quarter-wave retardation layer once more. The final polarization of the reflected light is perpendicular to the transmission axis of the polarizer, so that the polarizer will block the reflected light. As a result, we could achieve the dark state. However, it does not mean that we can obtain the perfect dark state, since this condition can be satisfied only at a single design frequency. Therefore, we have to find optical configurations of retardation layers that satisfy the above optical condition for the perfect dark state over the entire visible wavelength range.

For the bright state, the total retardation must be a multiple of a half-wave. Then, the polarization of the reflected light double-passed through the retardation layers is the same as the input polarization, so that the final polarization is coincident with the transmission axis of the polarizer. As a result, we could achieve the bright state. If phase dispersion over the entire visible wavelength range is small, we can expect high brightness.

In a single polarizer reflective LCD, retardation layers consists of a LC layer and a retardation film, as shown in Fig. 2. The optical configuration depends on whether we use a wide-band retardation film or not, and if we use a quarter-wave LC layer or a half-wave LC layer. Using the optimized configuration that consists of a LC layer and a retardation film, wide-band property would be obtained in the dark state, so that we could achieve the high contrast. To search for the optimum device configurations, we calculated the reflectance in the dark and bright state as a function of optical parameters, such as the retardation of the cell $d\Delta n$, and the angle of the LC director α with or without an applied electric field, and the optic axis β of the retardation film. The transmission axis of polarizer is chosen as the reference angle.

A non-twist reflective LC cell with a wide-band quarter-wave film[4] could be designed by using a quarter-wave LC layer or a half-wave LC layer. A non-twist quarter-wave LC cell with a wide-band retardation film consists of a quarter-wave LC layer and a wide-band quarter-wave film as shown in Fig. 2 (no. 1). In this case, we can obtain the dark and bright state regardless of the position of a quarter-wave LC layer. For this configuration the dark state can be obtained by making the LC layer not visible. We align a non-twist quarter-wave LC layer 1) coincident with or perpendicular to the transmission axis of the polarizer ($\alpha = 0°$ or $\alpha = 90°$)-this condition can be applied only when the quarter-wave LC layer is located just in front of the reflector, 2) vertically, or 3) highly-twisted and a wide-band quarter-wave film along an angle 45° ($\beta = 45°$). Together with this, to achieve the bright state, we align a quarter-wave LC layer homogeneously along an angle 45° ($\alpha = 45$). Then, the final polarization of the reflected light will return to the original polarization state that is coincident with the transmission axis of the polarizer. As a result, the bright state is obtained.

Optical configuration of a non-twist quarter-wave LC cell with a wide-band retardation film could be applied to all switching modes. Table 1 shows the application summary of non-twisted quarter-wave LC cells with a wide-band film in the normally black mode. Normally white mode could be realized by exchanging the optical configurations in the dark state with that in the bright state.

A non-twist half-wave LC cell with a wide-band retardation film[5] consists of a half-wave LC layer and a wide-band quarter-wave film, as shown in Fig. 2 (no. 2). The dark state can be obtained by the same principle as in a quarter-wave cell with a wide-band quarter-wave film. For the bright state, we align the half-wave LC layer to an angle α. Then, the linear polarization of the incident light will be rotated by an angle 2α by propagating through the half-wave LC layer. If the polarization angle 2α is in parallel with the optic axis β of the quarter-wave film, the light will keep the polarization during the double pass through the quarter-wave film. And then, the polarization of the reflected light will be rotated by an angle -2α by propagating through the LC layer once more. As a result, the polarization of the reflected light will return to the original polarization state, so that the bright state is achieved. Therefore, an optimized optical configuration is achieved at a condition $\beta = 2\alpha$. Since we have to fix the angle $\beta = \pm 45^\circ$ for the perfect dark state, $\alpha = \pm 22.5^\circ$ and $\beta = \pm 45^\circ$ is an optimized configuration for the bright state in a half-wave cell. We can also obtain the bright state with the optical configuration of $\beta = 2\alpha \pm 90^\circ$: the optic axis of LC layer is $\mp 22.5^\circ$ ($\alpha = \mp 22.5^\circ$).

Optical configurations of a non-twist half-wave cell in the NB mode are summarized in Table 2. NW mode could be also realized easily by exchanging the optical configurations in the dark state with that in the bright state. This configuration will suffer from parallax problem because a wide-band quarter-wave film is located between the LC layer and the reflector.

Wide-band property in the dark state could be achieved without a wide-band quarter-wave film. In order to achieve the completely dark state over the entire visible wavelength ranges without a wide-band quarter-wave film, a combination of a non-twisted LC layer and a conventional retardation film plays the role of a wide-band quarter-wave film, so that we can achieve the high contrast. On the other hand, to achieve the bright state, we have to change the total retardation of a non-twist LC cell to be a multiple of a half-wave by re-aligning the LC director properly.

Optical configuration of a non-twist quarter-wave LC cell without a wide-band quarter-wave film[7,12] is shown in Fig. 2 (no. 3). In the dark state, the polarization of the incident light will be rotated by an angle 2β by propagating through the half-wave film. Then, the polarization of the light double passing through the quarter-wave LC layer will experience a half-wave retardation, which results in polarization rotation by an angle of $-2(2\beta-\alpha)$. Therefore, the reflected light is polarized at an angle $2\beta - 2(2\beta-\alpha) = -2\beta + 2\alpha$. After the double pass through the LC layer, the polarization of the reflected light will be rotated by an angle $2((-2\beta + 2\alpha) - \beta) = 2(-3\beta + 2\alpha)$ by propagating once more through the half-wave film. As a result, the reflected light will be polarized at an angle $(2\beta - 2\alpha) + 2(-3\beta + 2\alpha) = -4\beta + 2\alpha$. To block the reflected light perfectly, the polarization angle of the reflected light has to equal to $\pm 90^\circ$ ($-4\beta + 2\alpha = \pm 90^\circ$). By choosing β and α appropriately, we can achieve the completely dark state over the entire visible wavelength spectra. The optimum angles of β and α with which a combination of a LC layer and a half-wave film plays the role of a wide-band quarter-wave film are found to be $\beta =$ 5° , and $\alpha = \pm 75^\circ$ by using the Mueller matrix calculation[11], if the phase dispersion of a quarter-wave LC layer and a half-wave film is assumed to be the same over the entire visible wavelength range[6]. For the bright state, we align the LC layer vertically or highly-twisted. In a horizontal switching cell, the bright state can be obtained by aligning the optic axis of a LC layer along an angle $\alpha = 2\beta$ ($\alpha = \pm 30^\circ$) or vertically with an angle $\alpha = 2\beta \pm 90^\circ$ ($\alpha = \pm 120^\circ$). The principle of operation is the same as a non-twist half-wave cell with a wide-band quarter-wave film in the bright state.

A non-twisted quarter-wave LC cell can be realized in most of switching modes. Table 3 shows the summary of optical configurations of the applicable switching modes in the NB mode. For the NW mode, we exchange the optical configurations in the dark state with that in the bright state.

A half-wave LC cell can be realized also without using a wide-band quarter-wave film[10]. A half-wave LC cell consists of a half-wave LC layer and a quarter-wave retardation film as shown in Fig. 2 (no. 4). A half-wave LC layer in front of a quarter-wave film is aligned along an angle of ±15° (α = ±15°) and the optic axis of a quarter-wave film is ±75° (β = ±75°). Therefore, in the dark state, the proposed configuration is the same as that of a quarter-wave LC cell without a wide-band quarter-wave film in the dark state. The bright state could be achieved by rotating the alignment of LC layer to an angle of ±37.5° or ∓7.5° horizontally. Then, the polarization of light is not affected by a quarter-wave film because the condition $\beta = 2\alpha$ or $\beta = 2\alpha \pm 90°$ is satisfied.

The above configuration with a half-wave cell can be applied only to horizontal switching modes because the LC layer should be aligned horizontally. Table 4 shows summary of optical configurations of horizontal switching cells in the NB mode. NW mode can also be obtained by exchanging the optical configurations in the dark state with that in the bright state. Compared with a quarter-wave LC cell, the proposed configuration has the double retardation value, so that manufacturing is easier than a quarter-wave LC cell. However, it will suffer from the parallax problem because a quarter-wave film should be located at the backside of a half-wave LC layer.

As mentioned before, we designed optical configurations so that the optical reflectance in the dark state exhibits the wide-band property. Wide-band property is obtained by making the polarization over the entire visible wavelength range very close to the polarization at the optical design wavelength (for example: 550 nm). Actually, the principle of operation of the introduced 4 configurations are the same in the dark state because all of them have the configurations composed of a half-wave retardation layer with ±15° and a quarter-wave retardation layer with ±75° . The optical reflectance in the dark state in each case is also nearly same, theoretically. However, the optical reflectance in the bright state is different from each other because of their different polarization paths in the bright state, which may cause the different phase dispersion in the bright state. We have shown the phase dispersions and reflectances of the possible bright state from the Table 1 to 4[10]. In general a non-twist quarter-wave LC layer without a wide-band quarter-wave film is more suitable for reflective mode because it can reduce a film. Therefore, we will investigate the polarization state and reflectance of horizontal and vertical switching mode of no. 3 and no. 4 in Fig. 2

To investigate the phase dispersion in the vertical or horizontal switching mode, we calculated the polarization state of the reflected light at the inner surface of the polarizer by using the Mueller matrix method[13]. To take into account the phase dispersion, we introduce $\delta = 2\pi d[\Delta n(\lambda)/\lambda - \Delta n(\lambda_o)/\lambda_o]$ that represents the deviation from the phase retardation at the design wavelength λ_o. When $\Delta\lambda = \lambda - \lambda_o << \lambda_o$, δ can be divided into two components: $\delta = \Delta n[(d(\Delta n)/d\lambda)/\lambda - \Delta n(\lambda)/\lambda^2]$. $\delta_M = \Delta\lambda((d(\Delta n)/d\lambda)/\lambda)$ represents phase dispersion due to the wavelength dependence of Δn and $\delta_W = -\Delta\lambda(\Delta n(\lambda)/\lambda^2)$ represents phase dispersion when $d(\Delta n)/d\lambda = 0$.

Now, we investigate the Stokes vectors S_o of the reflected light of the vertical switching mode and the horizontal switching mode with $\alpha = 2\beta$ or with $\alpha = 2\beta \pm 90°$ at the inner surface of the polarizer in case of no. 3 in Fig. 2. For simplicity of calculation, we used the approximation $\cos\delta \approx 1 - \delta^2/2$, $\sin\delta \approx \delta$. The calculated output Stokes vectors S_o are as follows;

$$S_o \approx \begin{pmatrix} 1 \\ 1 - 2\delta_W^2 \sin^2 2\beta \\ \delta_W^2 \sin^2 4\beta \\ -2\delta_W \sin 2\beta \end{pmatrix} \qquad \text{(Vertical)} \quad (2a)$$

$$\begin{pmatrix} 1 \\ 1+(\delta_W+\delta_M)^2\sin^2 2\beta\cos^2 4\beta \\ -(\delta_W+\delta_M)^2\sin 2\beta(1+\cos^3 2\beta+\frac{1}{2}\sin 6\beta\sin 4\beta) \\ 0 \end{pmatrix} \quad (\alpha = 2\beta) \text{ (2b)}$$

$$\begin{pmatrix} 1 \\ 1+(\delta_W+\delta_M)^2\sin^2 2\beta\cos^2 4\beta \\ (\delta_W+\delta_M)^2\sin 2\beta(1-\cos^3 2\beta-\frac{1}{2}\sin 6\beta\sin 4\beta) \\ 0 \end{pmatrix} \quad (\alpha = 2\beta\pm 90^\circ) \text{ (2c)}$$

when $\Delta\lambda << \lambda_0$.

In order to investigate the polarization state of the reflected light, we defined the polarization deviation factor s that represents the deviation of polarization from linear polarization whose Stokes vector is (1, 1, 0, 0). For the output Stokes vector S_o = $(1, S_{11}, S_{22}, S_{33})^T$, we define the polarization deviation Δs = $((S_{11}-1)^2 + S_{22}^2 + S_{33}^2)^{1/2}$. Figure 3 shows the dependence of the polarization deviation in the bright state upon the optic axis of the half-wave film. In numerical calculation, we assumed that δ_W = δ_M = 0.25 radian. As shown in Fig. 3, horizontal switching mode can provide very low polarization deviation. Optimum results can be obtained when $\alpha = 2\beta \pm 90^\circ$ for $\beta < 20^\circ$ or $\alpha = 2\beta$ for $\beta > 70^\circ$ in the horizontal switching mode, which can provide very high reflectance in the bright state.

As mentioned before, the half-wave film should be oriented along an angle ±15° for low reflectance in the dark state. Then, the LC layer should be aligned along an angle $2\beta \pm 90^\circ = 120^\circ$ for optimum bright state, so that very high reflectance can be expected. Figure 4 shows the dependence of polarization deviation in the bright state upon the value of when $\beta = 15^\circ$. Figure 4 shows that the very low polarization deviation can be obtained when $\alpha = 2\beta \pm 90^\circ$, so that we can achieve the very high reflectance over the entire visible wavelength range.

Experimental results, which are obtained by placing a half-wave layer (±15°) and a quarter-wave layer (∓120°) between a polarizer and a reflector, show good agreement with calculated reflection spectra, as shown in Fig. 5. For precise numerical calculation, we have taken into account the phase dispersion of Δnd of the LC layer. Reflectance in the bright state can be increased remarkably over the whole visible wavelength by using horizontal switching of the proposed configuration. Moreover, horizontal switching is expected to improve the color performance since the reflection spectrum of the bright state in the horizontal switching mode is much flatter than that in the vertical switching mode.

In case of no. 4 in Fig. 2, we can easily confirm that optical condition of $\beta = 2\alpha \pm 90^\circ$ (α = -7.5° and β = 75°) is superior to the condition of $\beta = 2\alpha$(α = 37.5° and β = 75°) for the bright state by far because of the result of Fig. 3. as shown in Fig. 6. This condition may be very good for a reflective LC cell because of high Δnd of the LC layer. However, it will suffer from the parallax problem. Prallax ploblem may be overcome if the quarter-wave film can be substituted by a coated film at inside of the cell.

We introduced various optical configurations for single-polarizer reflective LCDs using non-twisted cells. We summarized optical configurations for display applications not only in vertical switching modes but also in horizontal switching modes. In order to increase the contrast, we optimized optical configurations in the dark state with or without a wide-band quarter-wave film. We also found that high brightness in the bright state can be obtained by aligning a LC layer horizontally. By numerical calculation and experiments, we confirmed the validity of our design.

Acknowledgement

This work was supported by grant No. 2000-1-30200-014-3 from the Basic Research Program of the Korea Science & Engineering Foundation.

References

1. T. Ogawa, S. Fujita, Y. Iwai, and H. Koseki, *SID 98 Digest*, pp. 217-220, May 1998.
2. S.-T. Wu and C.-S. Wu, *Appl. Phys. Lett.* **68,** 1455-1457(1996).
3. Y. Saitoh, Y. Yoshida, and H. Kamiya, *SID 97 Digest*, pp. 651-654, May 1997
4. G.-D. Lee, G.H. Kim, S.H. Moon, J.-D. Noh, S.-C. Kim, W. S. Park, T.-H. Yoon, J. C. Kim, S. H. Hong, and S. H. Lee, *Jpn. J. Appl. Phys.*, **39,** L221-224(2000).
5. G.-D. Lee, G.-H. Kim, T.-H. Yoon, and J. C. Kim, *Jpn. J. Appl. Phys.*, **39,** 2716-2720(2000).
6. G.-D. Lee, H.-I. Baek, T.-H. Yoon, J. C. Kim, and E.-S. Lee, 19*th IDRC(Euro Display* 99) *Digest,* pp. 307-310, Sept. 1999.
7. T.-H. Yoon, G.-D. Lee, and J. C. Kim, *ILCC 2000 Abstracts*, p. 15, July 2000.
8. T.-H Yoon, G.-D. Lee, G.-H. Kim, S.-C. Kim, W. S. Park, J. C, Kim, and S. H. Lee, *SID 00 Digest*, pp. 750-753, 2000.
9. T.-H. Yoon, S.-H. Moon, G.-D. Lee, and J. C. Kim, *IDW 00 Digest*, pp. 153-156, Nov. 2000.
10. G.-D Lee, T.-H. Yoon, and J. C. Kim, *Displays*, Feb. 2001.(scheduled for publication).
11. T.-H. Yoon, G.-D Lee, and J. C. Kim, *Mol. Cry. Liq. Cry.*, (2001) (accepted for publication).
12. T.-H. Yoon, G.-D Lee, and J. C. Kim, *Opt. Lett.*, **25**, 1547-1549(2000).
13. E. Collett, *Polarized Light Fundamentals and Applications,* (Marcel Dekker, New York, 1993) pp. 219-253.

Table 1. Summary of optical configurations for quarter-wave LC cells with a wide-band quarter-wave film. (HO: Homogeneous, HE: Homeotropic)

Mode		Horizontal Switching		Vertical Switching		Bistable Switching	
		V_{off}	V_{on}	V_{off}	V_{on}	V_{off}	V_{on}
		Dark	Bright	Dark	Bright	Dark	Bright
LC layer	Alignment	HO		HE	HO	180° Twisted	
	O.A. (α)	0° , ±45°	±45°	-	±45°	-	±45°
	Twist	0°	0°	0°	0°	360°	0°
O.A. of $\lambda/4$ film (β)		±45°					
Applicable mode		IPS, FFS, FLCD, AFLCD, etc		π -cell, VA cell, etc		BTN LCD	

Table 2. Summary of optical configurations for half-wave LC cells with a wide-band quarter-wave film. (HO: Homogeneous, HE: Homeotropic)

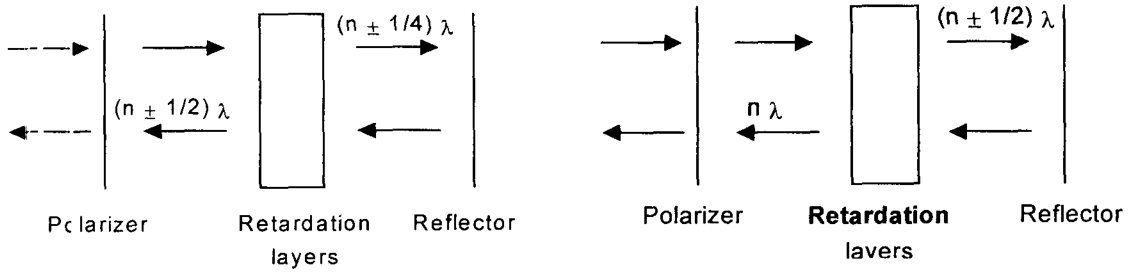
Mode		Horizontal Switching		Vertical Switching		Bistable Switching	
		V_{off}	V_{on}	V_{off}	V_{on}	V_{off}	V_{on}
		Dark	Bright	Dark	Bright	Dark	Bright
LC layer	Alignment	HO		HE	HO	180° Twisted	
	O.A. (α)	0°, ±90°	±22.5°	-	±22.5°	-	±22.5°
	Twist	0°	0°	0°	0°	360°	0°
O.A. of $\lambda/4$ film (β)		±45°					
Applicable mode		IPS, FFS, FLCD, AFLCD, etc		π-cell, VA cell, etc		BTN LCD	

Table 3. Summary of optical configurations for quarter-wave LC cells without a wide-band quarter-wave film. (HO: Homogeneous, HE: Homeotropic)

Mode		Horizontal Switching		Vertical Switching		Bistable Switching	
		V_{off}	V_{on}	V_{off}	V_{on}	V_{off}	V_{on}
		Dark	Bright	Dark	Bright	Dark	Bright
LC layer	Alignment	HO		HE	HO	180° Twisted	
	O.A. (α)	±75°	±30° ±120,°	±75°	-	±75°	-
	Twist	0°	0°	0°	0°	360°	0°
O.A. of $\lambda/2$ film (β)		±15°					
Applicable mode		IPS, FFS, FLCD, AFLCD, etc		π-cell, VA cell, etc		BTN LCD	

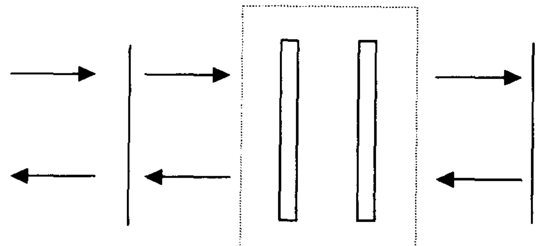
Table 4. Summary of optical configurations for half-wave LC cells without a wide-band quarter-wave film. (HO: Homogeneous, HE: Homeotropic)

Mode		Horizontal Switching	
		V_{off}	V_{on}
		Dark	Bright
LC layer	Alignment	HO	
	O.A. (α)	±15°	±37.5°, ∓7.5°
	Twist	0°	0°
O.A. of $\lambda/4$ film (β)		±75°	
Applicable mode		IPS, FFS, FLCD, AFLCD, etc	



(a) (b)

Fig. .. Optical principle of a single polarizer reflective LCD. (a) in the dark state, (b) in the bright state. *n* is an integer.



No	Layer 1	Layer 2
1	Wide-band λ/4 film	λ/4 LC
2	λ/2 LC	Wide-band λ/4 film
3	λ/2 Film	λ/4 LC
4	λ/2 LC	λ/4 Film

Fig. 2. Optical configuration of a single polarizer reflective LCD.

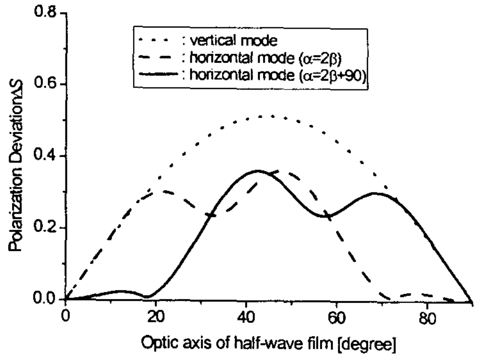


Fig. 3. Dependence of polarization deviation in the bright state upon the optic axis of the half-wave film.

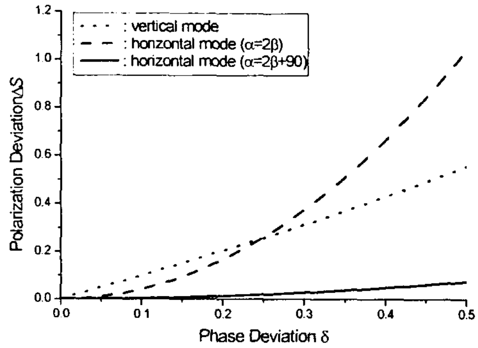


Fig. 4. Dependence of polarization deviation in the bright state upon the value of δ.

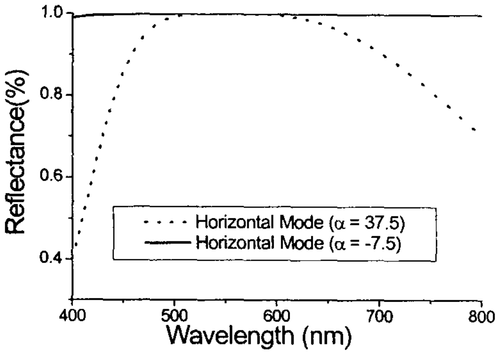
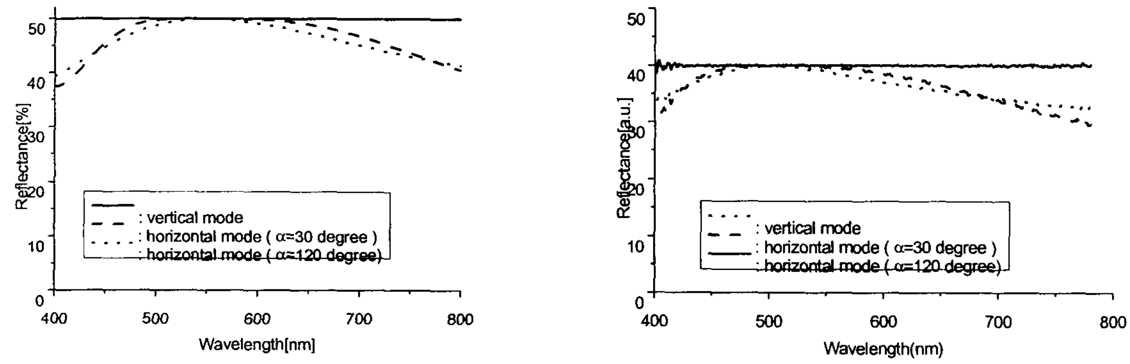


Fig. 6. Calculated reflection spectra of the bright state (no. 4 in Fig. 2)



(a) (b)

Fig. 5. Reflection spectra of the bright state; (a) calculated, (b) measured. (no. 3 in Fig. 2)