Transflective fringe-field switching liquid crystal display without any retarder

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Abstract: Conventional transflective liquid crystal displays (LCDs) with single cell-gap requires optical compensation films or patterned retarders to balance the optical path-length difference between transmissive and reflective regions. In this paper, novel single cell-gap transflective LCDs driven by fringe electric field without using the compensation film or in-cell retarder have been proposed. The liquid crystal director is aligned parallel to analyzer but makes an angle of 45° with respect to analyzer in reflective region. In addition, the surface pretilt angle in the reflective region is controlled by vertical field and polymerization of an UV curable reactive mesogen at the same time and thus, the effective cell retardation in the reflective region becomes smaller than that in transmissive region. Consequently, without using any compensation film or in-cell retarder, the single cell-gap and single-gamma transflective LCD with high performance is realized.

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OCIS codes: (160.3710) Liquid crystals; (230.3720) Liquid-crystal devices.

References and links

1. J. Tanno, M. Morimoto, K. Igeta, H. Imayama, S. Komura, and T. Nagata, "A new transflective IPS-LCD with high contrast ratio and wide viewing angle performance," Proc. of the 13th International Display Workshop (Society for Information Display, Otsu, Japan), 635–638 (2006).
2. Y. Li, Z. Ge, and S.-T. Wu, "A simple transflective LCD for mobile display," SID Symposium Digest **15**, 1655–1657 (2009).
3. Y. P. Huang, M. J. Su, and H. P. David Shieh, "A single gap transflective color TFT-LCD by using image enhanced reflector," SID Symposium Digest **34**, 86–89 (2003).
4. H-I. Baek, Y-B. Kim, K-S. Ha, D-G. Kim, and S-B. Kwon, "New design of transflective LCD with single retardation film," Proc. Int. Disp. Workshops, 41–44 (2000).
5. K. Fujimori, Y. Narutaki, Y. Itoh, N. Kimura, S. Mizushima, Y. Ishii, and M. Hijikigawa, "New color filter structures for transflective TFT-LCD," SID Symposium Digest **33**, 1382–1395 (2002).
6. M. Jisaki, and H. Yamaguchi, "Development of transflective LCD for high contrast and wide viewing angle by using homeotropic alignment," Proc. Int. Disp. Workshops, 133–136 (2001).
7. Ch. Lo, T.-Ch. Yang, Ch.-J. Hu, Ch.-Sh. Cheng, Ch.-M. Chang, and F.-Y. Gan, "High Efficiency MVA-mode TR LCD," SID Symposium Digest **38**, 714–716 (2007).
8. T. B. Jung, J. C. Kim, and S. H. Lee, "Wide-Viewing-Angle Transflective Display Associated with Fringe-Field Driven Homogeneously Aligned Nematic Liquid Crystal Display," Jpn. J. Appl. Phys. **42**(Part 2, No. 5A), L464–L467 (2003).
9. M. O. Choi, J. H. Song, Y. J. Lim and S. H. Lee, "A Single Gap Transflective Display using a Fringe-Field Driven Homogeneously Aligned Nematic Liquid Crystal Display," SID symposium Digest **36**, 719–721 (2005).
10. J. H. Song, Y. J. Lim, M.-H. Lee, S. H. Lee, and S.-T. Shin, "Electro-optic characteristics and switching principle of a single-cell-gap transflective liquid-crystal display associated with in-plane rotation of a liquid crystal driven by a fringe-field," Appl. Phys. Lett. **87**(1), 011108 (2005).
11. H. Y. Kim, Z. Ge, S.-T. Wu, and S. H. Lee, "Wide-view transflective liquid crystal display for mobile applications," Appl. Phys. Lett. **91**(23), 231108 (2007).
12. 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, "Reflective liquid crystal display using a non-twist half-wave cell," Jpn. J. Appl. Phys. **39**(Part 2, No. 3A/B), L221–L224 (2000).

13. I. H. Yu, J. H. Song, Y. J. Lim, S. H. Lee, D. S. Kim, H.-S. Soh, W. Y. Kim, and S. D. Yeo, "Electro-optic characteristics of in-plane driven transflective LCD," Proc. Int. Disp. Workshops, 167–170 (2004).
14. J. H. Song, and S. H. Lee, "A single Gap transflective Display using In-Plane Switching Mode," Jpn. J. Appl. Phys. **43**(No. 9A/B), L1130–L1132 (2004).
15. M. Schadt, K. Schmitt, V. Kozinkov, and V. Chigrinov, "Surface-induced parallel alignment of liquid crystals by linearly polymerized photopolymers," Jpn. J. Appl. Phys. **31**(Part I, No. 7), 2155–2164 (1992).
16. J.-H. Lee, W.-H. Lee, D.-C. Shin, J.-H. Lim, K.-B. Park, J.-D. Lee, W.-S. Kim, M.-S. Yang, Y.-K. Hwang and I.-J. Chung, "The Advanced Transflective IPS LCD by Photo Alignment Technology," SID Symposium Digest **41**, 1791–1793 (2010).
17. P. Chaudhari, J. Lacey, J. Doyle, E. Galligan, S. C. A. Lien, A. Callegari, G. Hougham, N. D. Lang, P. S. Andry, R. John, K. H. Yang, M. H. Lu, C. Cai, J. Speidell, S. Purushothaman, J. Ritsko, M. Samant, J. Stöhr, Y. Nakagawa, Y. Katoh, Y. Saitoh, K. Sakai, H. Satoh, S. Odahara, H. Nakano, J. Nakagaki, and Y. Shiota, "Atomic-beam alignment of inorganic materials for liquid-crystal displays," Nature **411**(6833), 56–59 (2001).
18. T.-J. Chen, and K.-L. Chu, "Pretilt angle control for single-cell-gap transflective liquid crystal cells," Appl. Phys. Lett. **92**(9), 091102–091104 (2008).
19. Y. Kizu, R. Hasegawa, I. Amemiya, S. Uchikoga, and H. Wakemoto, "Analysis of electro-optical properties of polymer-stabilized OCB and the application to TFT-LCDs," J. Soc. Inf. Disp. **17**(8), 647–657 (2009).
20. Y. J. Lim, E. Jeong, M. H. Chin, J. H. Kim, S. S. Kim, and S. H. Lee, "Transflective liquid crystal display using UV curable reactive mesogen," Proc. of Spring Symposium KIEEME'08, 51–52 (2008).
21. Y. J. Lim, M. H. Chin, J. H. Kim, J. H. Her, H. S. Jin, B. K. Kim, and S. H. Lee, "A single-gap transflective liquid crystal driven by fringe and vertical electric fields," J. Phys. D Appl. Phys. **42**(14), 145412 (2009).
22. S. H. Jung, H. Y. Kim, S. H. Song, J.-H. Kim, S.-H. Nam, and S. H. Lee, "Analysis of optimal phase retardation of a fringe field- driven homogeneously aligned nematic liquid crystal cell," Jpn. J. Appl. Phys. **43**(3), 1028–1031 (2004).
23. A. Lien, "Extended Jones matrix representation for the twisted nematic liquid-crystal display at oblique incidence," Appl. Phys. Lett. **57**(26), 2767 (1990).

1. Introduction

Sunlight readability becomes a critical issue in image quality of LCDs because portable LCDs and public information displays are widely used nowadays. Present transmissive LCDs with adoption of wide-viewing-angle liquid crystal modes show excellent image qualities in wide viewing directions but the readability becomes very poor at outdoor uses. On the other hand, pure reflective LCDs exhibit a good visibility in outdoor uses, with additional better advantages such as thinness and low power consumption than those in transmissive LCDs. However, this display has a low visibility in indoor uses without a light source. Therefore, transflective LCDs, which show good visibility in any environmental light conditions and low power consumption as well as low cost, need to be developed. However, the commercialized transflective LCDs in early times need dual cell gap [1,2] with several compensation films and also show narrow viewing angle in the transmissive region. To solve these problems, the single cell-gap transflective LCDs have been proposed using several different LC modes, such as twisted nematic (TN) [3], electrically controlled birefringence (ECB) [4,5], vertical alignment (VA) [6,7], and fringe-field switching (FFS) [8–11] and in-plane switching (IPS) [12–14]. However, these devices still need to be improved because gamma curves between voltage-dependent reflectance and transmittance curves do not match well or optical light efficiency is not still satisfactorily. Besides, the compensation film or in-cell retarder is required and thus, electro-optic characteristics such as high image quality and light efficiency in transmissive region are sacrificed. Recently, the FFS mode becomes very popular being adopted by many LCDs, especially in Apple's iPad and iPhone.

In this paper, we propose a single cell-gap transflective LCD associated with FFS device in which the reflective region driven by either fringe or vertical electric field without using the compensation or in-cell retarder film is considered. To achieve the transflective LCD with single cell-gap, the homogenously aligned liquid crystal (LC) director is aligned parallel to analyzer in the transmissive region while it makes an angle of 45° with respect to analyzer in reflective region. In addition, surface pretilt angle in the reflective region is controlled to achieve retardation of λ/4.

2. Cell structure and switching principle of proposed transflective LCDs

Figure 1 shows a cross-sectional and top view of the proposed two kinds of single cell-gap transflective LCDs. Electrode structures in transmissive regions are the same each other while

they are different in reflective regions. In transmissive regions, both pixel and common electrodes exists on the bottom substrate with passivation layer between them, and pixel electrodes are patterned in slit form with an electrode width (w) and distance (l) between them. In reflective region, common electrode exists on the top substrate and two different electrode structures on bottom substrate are considered: (i) the same electrode structure like in transmissive region, (ii) just plane shape of pixel electrode. Ideally, embossing reflector is embedded in plane shape of electrode in reflective region. The alignment direction of an initial LC director is parallel to analyzer in the transmissive region but makes an angle of 45° with respect to analyzer in reflective region as shown in Fig. 1(a). This multi-alignment of LC at an initial state can be achieved using the photo-alignment method [15,16] or ion-beam irradiation on inorganic film [17]. In addition to dual orientation, the initial retardation of LC layer in the reflective region can be adjusted by controlling surface pretilt angle of LC. It was known that high surface pretilt angle of LC on homogenous alignment layer can be achieved by polymerization of the UV curable reactive mesogen (RM) under certain bias voltage as shown in Fig. 1(a) and 1(b) and thus, the effective cell retardation in the reflective region can become less than half of that in the transmissive region. In this way, the effective cell retardation with λ/2 and λ/4 in the transmissive and reflective regions, respectively, can be achieved. The bottom polarizer exists below bottom substrate with its transmission axis
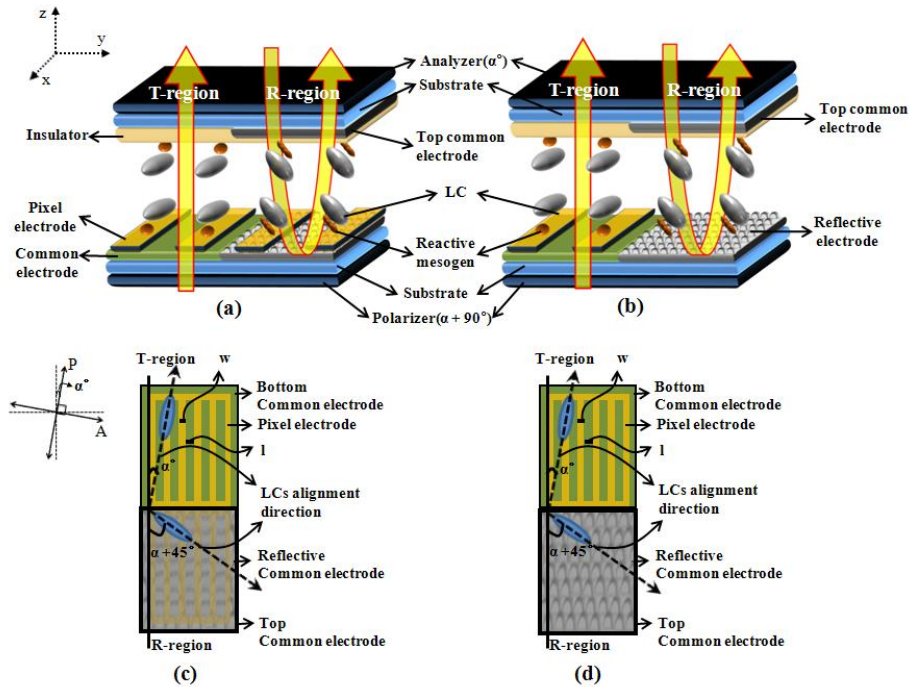

Fig. 1. Cell structure of two kinds of transflective LCDs associated with FFS mode having common electrode on top substrate only in reflective region. Electrode structures in reflective region are the same as that in the transmissive region (a) and a plane shape (b), respectively. (c) and (d) top view of electrode structure of bottom substrate of Fig. 1(a) and Fig. 1(b), respectively, in which the initial LC director in reflective region makes an angle of 45° with respect to that in transmissive region. Considering electric field direction given in the electrode structure of the reflective part in Fig. 1(a), both fringe and vertical fields control reorientation of LC director while only vertical field involves in Fig. 1(b).

orthogonal to analyzer. Another considered point when manufacturing dual oriented LC alignment is defect lines which could occur between transmittance and reflective regions, when the system is switched. However, it can be minimized with optimized pixel structure in a real application.

Describing more details how to obtain such different phase difference between transmissive and reflective region, we apply surface polymer stabilization using an UV curable RM [18–21]. At an initial state, the RM and the LCs are homogeneously aligned. Then, voltage satisfying phase retardation λ/4 is applied to the cell so that the RM as well as LC reorients with a certain tilt angle toward perpendicular to the substrate in response to vertical electric field in the reflective region. At this state, the reflective region only is exposed to the UV light while the transmissive region is covered with a mask. Then, after removing a mask, whole transflective cell is exposed to the UV light to fix constant surface pretilt angle and remove any remained monomer over whole areas. The device needs retardation of ∼0.4 μm in the transmissive region to maximize transmittance [22]. Therefore, in order for the $d\Delta n_{eff}$ of the LC layer in the reflective region to be λ/4, a high surface tilt angle is required. According to our calculation and also experiment, the pretilt angle of the reflective region should be 53°. Such a high tilt angle can be reduced to a smaller one if the retardation of the cell is lowered. In this way, different phase retardation in transmissive and reflective region is achievable with single cell-gap and also the LC director rotates in plane in the transmissive region so that the single cell-gap transflective LCD with wide viewing angle and without using any compensation film or in-cell retarder can be realized.

The optical configuration of the proposed single cell-gap transflective LCDs in initial state is shown in Fig. 2. For the transmissive region, one of transmission axes of the crossed polarizer axis is coincident with optic axis of the LC director. For the reflective region, the optic axis of LC layer with λ/4 retardation makes 45° with respect to analyzer, and the common electrode plays role of a reflector.

In the transmissive region, the normalized transmittance T/T_o is given by

$$T/T_o = \sin^2 2\psi(V)\sin^2(\delta/2)$$

where ψ is an angle between polarizer and LC director, and δ is phase difference between ordinary and extraordinary rays, defined by $\delta = 2\pi d\Delta n_{eff}/\lambda$ where d is cell gap and Δn_{eff} is voltage-dependent effective birefringence of LC layer, and λ is the wavelength of incident light. Therefore, in the absence of voltage, the linearly polarized light through the bottom polarizer pass through LC layer without change of polarization state, that is, ψ = 0°. Thus it is blocked by the analyzer, which results in a dark state. With bias voltage, LC director starts to rotate and when $d\Delta n_{eff}$ is equal to the half-wave and ψ is with an average twist angle of nearly 45°, the transmittance becomes maximum. On the other hands, the reflectance R in the reflective region in which LC layer exists above reflector under linear polarizer with assumption of initial LC's retardation value of λ/4 or π/2 could be defined as follows:

$$R_{i)} \propto\!\!> cos^2 2\psi(V) \quad \text{and}$$

$$R_{ii)} \propto cos^2 \delta(V)$$

In the case (i), the LC retardation is almost constant since the LC rotates in plane, whereas in the case (ii), ψ is fixed to 45° and the LC retardation changes according to applied voltage. Therefore, for the case i), when ψ is 45°, the device appears to be dark and when the LC director rotates by 45° to give rise to condition ψ = 0° by applied voltage, the R becomes maximal. In the case (ii), R is zero at an initial state, resulting in a dark state because δ equals to π/2. Then, when vertical electric field is applied, LC director tilts upward to perpendicular to the substrate, resulting in δ ≒ 0 so that an incident light does not feel phase retardation, that is, state of polarization is not changed, resulting in a white state. However, though we assume LC's retardation value is λ/4 at an initial state, it is strongly wavelength-dependent, so that to achieve a good dark state, $d\Delta n_{eff}$ should be optimized for each wavelength.
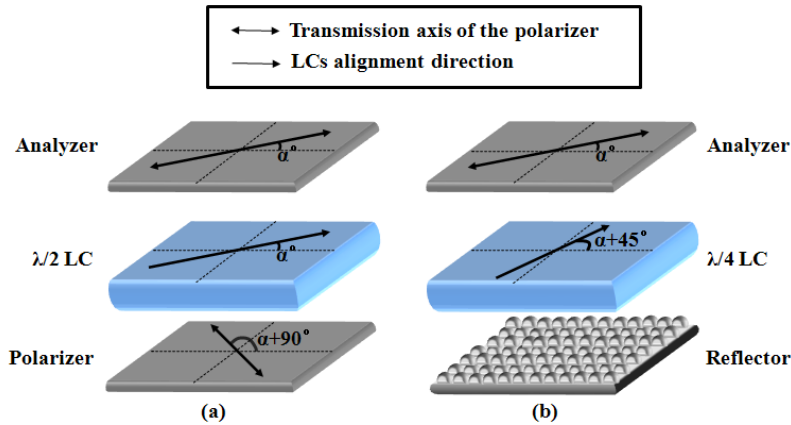
Fig. 2. Optical configurations of the proposed single cell-gap transflective LCDs in initial state: (a) transmissive region and (b) reflective region.

3. Calculated results and discussion

In order to obtain electro-optic performances of the proposed transflective display, commercially available software, a LCD master (Shintech, Japan) was used. Here, D65 is used as a light source. In the calculations, w and l were assumed to be 3 μm and 4.5 μm, respectively. Here, the LC with physical parameters, such as dielectric anisotropy $\Delta \varepsilon = 7.4$, elastic constants K1 = 11.7 pN, K2 = 5.1 pN, K3 = 16.1 pN, and birefringence $\Delta n = 0.1$ was used, and the surface tilt angle of the LC was 2° and 53° in transmissive and reflective region, respectively. Here, to calculate R and T, a 2 × 2 extended Jones matrix was used [23]. The transmittances for the single and parallel polarizer were assumed to be 41%, and 35%, respectively.

Since the surface pretilt angle of LC molecules is very high in the reflective region unlike in the transmissive region, the threshold voltage or operating voltage is expected to be different from that in the transmissive region. To match gamma curves of the reflective and the transmissive regions, voltage-dependent R and T curves for two suggested electrode structures are calculated according to thickness (I) of insulator layer on the top substrate in the reflective region, as shown in Fig. 3. As thickness of insulator layer increases from 0 μm to 2 μm in the electrode structure (i) and from 0 μm to 2.5 μm in the electrode structure (ii), driving and threshold voltage increases, so best matches in the voltage-dependent R and T curves between reflective and transmissive regions for both cases are achieved when thickness of insulator layer is 2 μm and 2.5 μm, respectively, as shown in Fig. 4. From this, we could realize a single gamma curve but the matching is better in the electrode structure (ii). In addition, the R of electrode structure (ii) is higher than that of the electrode structure (i). In the electrode structure (ii) which utilizes vertical electric field in the reflective region, the residual retardation is almost zero because LC director tilts upward almost perpendicular to the substrate along vertical field direction.
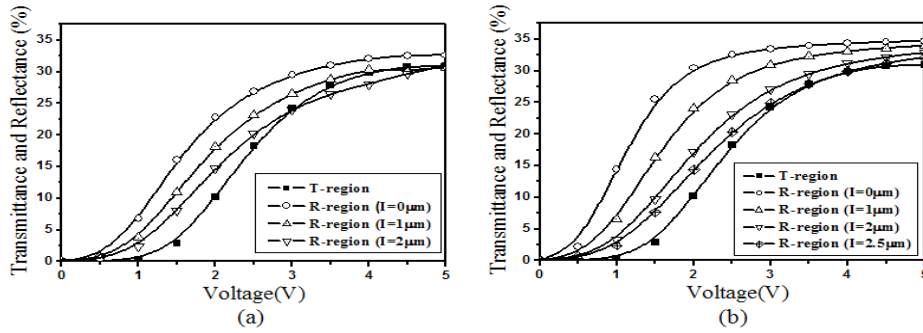
Fig. 3. Voltage-dependent reflectance and transmittance curves according to the thickness of insulator layer in the reflective region for the electrode structure (i) (a) and the electrode structure (ii) (b).
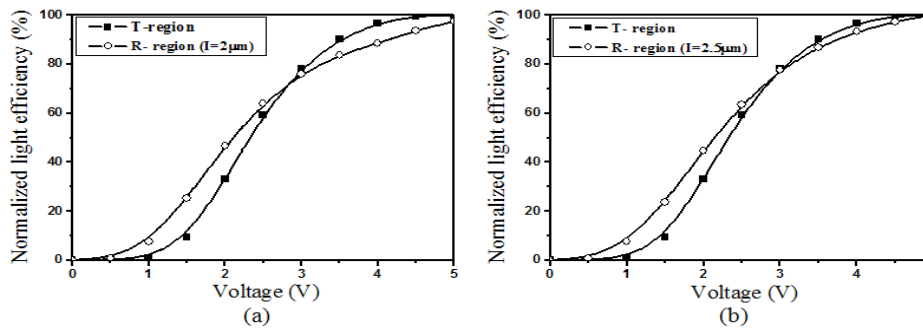

Fig. 4. Normalized voltage-dependent reflectance and transmittance curves when the thickness of insulator layer is 2μm and 2.5μm, respectively in the reflective region for the electrode structure (i) (a) and the electrode structure (ii) (b)

In order to realize high image quality of LCDs, having not only high transmittance and reflectance but also a good dark state is very important. Since the retardation has wavelength dispersion, it changes according to wavelength. As a result, if one wants to have effective retardation of λ/4, it is valid only in a single wavelength that is, a good dark state cannot be obtained, resulting in a light leakage which decreases contrast ratio in the reflective region. In order to minimize wavelength dispersion, we have applied different surface pretilt angles in each red (R), green (G), and blue (B) pixels, as shown Fig. 5. Different surface pretilt angle according to pixels can be achieved through polymerization of an UV curable RM by applying different voltages to R, G, and B pixels between top common and bottom pixel electrodes.
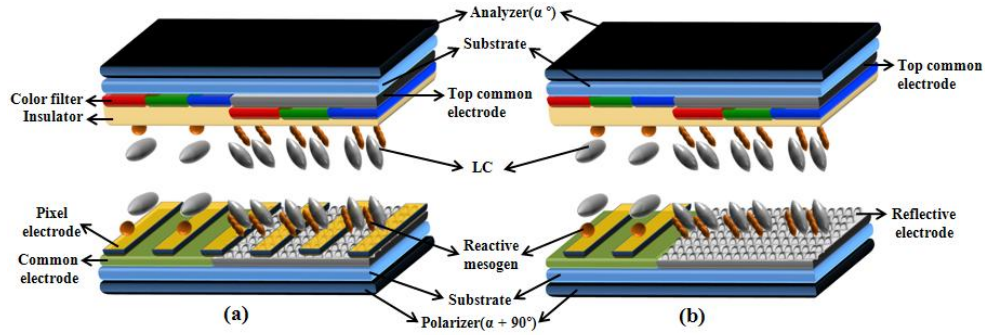
Fig. 5. Schematic cell structures of single cell-gap transflective LCD with different surface pretilt angles in R, G, and B pixels in electrode structure (i) (a) and electrode structure (ii) (b).

Figure 6 shows the level of light leakage according to surface pretilt angles of LC director at *R*, *G*, and *B* wavelength in reflective region. As indicated, optimization of the tilt angle in *R*, *G*, and *B* pixels greatly reduces the light leakage of dark state from 4.42% (the cell has 53° of pretilt angle at all wavelengths) to 0.0545%, 0.0192%, and 0.0734%, respectively. In addition, there is no sacrifice of reflectance since the electrode structure (i) and (ii) exhibit 31.02% and 32.1%, respectively. In this way, the contrast ratio in the reflective could be improved further without loss of reflectance.
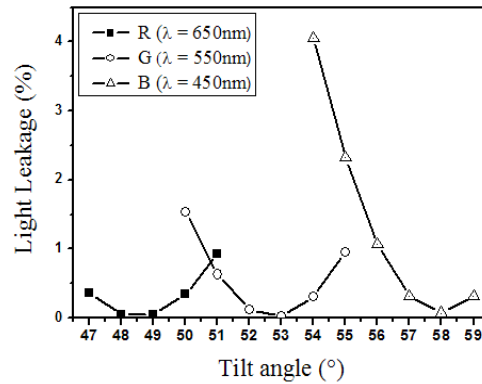

Fig. 6. Light leakage according to surface tilt angles at three different incident wavelengths *R*, *G*, and *B*.

4. Summary

In summary, single cell-gap transflective displays using the FFS mode without the compensation film or any retarder have been proposed. Fringe-electric field is used in the transmissive part while either fringe or vertical electric field is used in the reflective part. To achieve a single cell gap, a high pretilt angle has been formed in the reflective region through the polymerization of an UV curable RM monomer when the vertical field is applied. In addition, pretilt angles in each different color pixels can be tuned to minimize light leakage. The optimized cell structure provides a high performance single cell-gap transflective LCD. The proposed device has a potential application in portable displays for its high image quality in any light environmental conditions.

Acknowledgements