Chapter 5

Image-Enhanced Reflector on Transflective LCDs for Transmissive Image Improvement

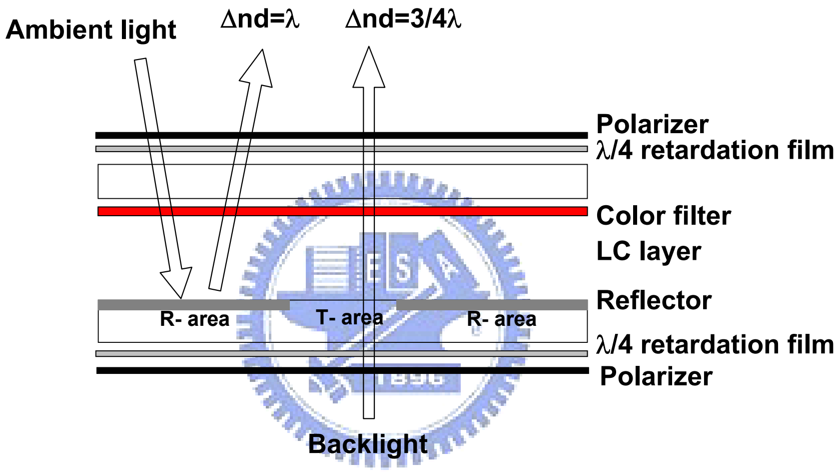
The transflective LCDs (TR-LCDs) become the most popular product in the portable display market. The LCFs, described in last chapter, cannot only be applied for reflective LCDs but also for transflective LCDs to much improve their reflective images. However, the transmissive images of a transflective LCD still suffer from the low transmittance, different response time, and unmatched color saturation. In this chapter, an "image-enhanced reflector (IER)" is proposed to be built above the transmissive region of liquid crystal cell, thus both reflective and transmissive portions achieve high optical efficiency, good contrast ratio, same response time, and matched color saturation.

Additionally, a full-color bistable transflective cholesteric liquid crystal display (Ch-LCD) is proposed using an imbedded image-enhanced reflector on top of each transmissive sub-pixel. The RGB colors are achieved by patterning conventional color filters on a black and white Ch-LCD. Consequently, the first full color transflective Ch-LCD in the world can be demonstrated.

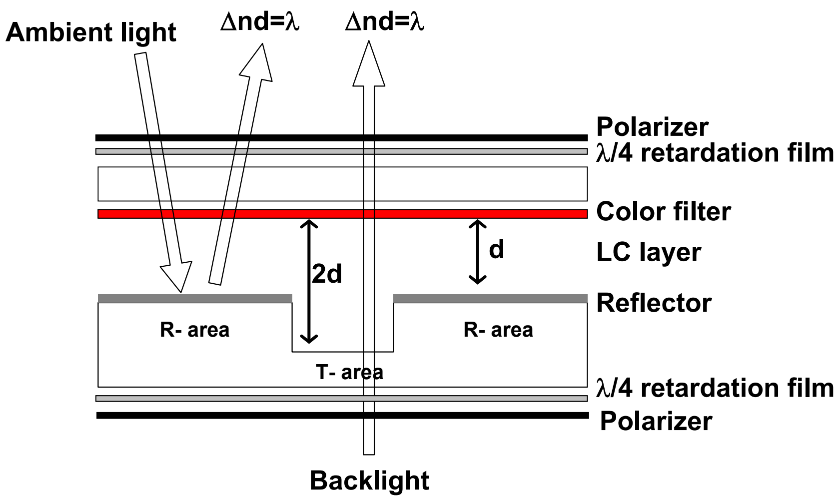
5.1 Introduction

5.1.1 Conventional transflective TFT-LCDs

The transmission-type liquid crystal display (LCD) exhibits a high contrast ratio and good color saturation. However, its power consumption is high due to the need of a backlight. At bright ambient, the display is washed out completely. On the other hand, a reflective LCD is using ambient light for reading displayed images. Since it does not require a back light, its power consumption is reduced significantly. However, its brightness is lower and contrast ratio much inferior to those of the transmission type. At dark ambient, a reflective LCD lost its visibility. In order to overcome the drawbacks of transmissive and reflective LCDs, two types of transflective LCDs, single[83] and double[22], [84] cell gap, as shown in Figs. 5-1(a) and (b), have been developed with good legibility under both bright and dark scenes.



(a)



(b)

Fig. 5-1. Schematic plot of transflective LCD using (a) single and (b) double cell gap.

In the single cell gap approach, the cell gap (d) for reflective (R) and transmissive (T) modes is the same. The cell gap is optimized for R-mode. As a result, the light transmittance for the T mode is lower than 50% because the light only passes the LC layer once. In the double cell gap approach, the cell gap is d and 2d for the R and T pixels, respectively. In this approach, both R and T have high light efficiency. However, the T mode has four times slower response time than that of the R mode. A common problem for the above-mentioned approaches is that R and T pixels have different color saturation. For R pixels, the incident light passes through the color filter twice, but for T pixels light only passes the color filter once. As a result, their color saturation is different. Therefore, we proposed a novel configuration for single cell gap transflective LCD[85], [86], which also allows the backlight to traverse the reflective region twice, similar to the ambient light. As a result, the optical efficiency, response time, and color saturation of T and R portion shall be similar to each other.

5.1.2 Conventional transflective cholesteric LCDs (Ch-LCDs)

Reflective cholesteric liquid crystal display (Ch-LCD)[87] is a bistable device which consumes less power than the general reflective STN or TFT displays. Due to its bistability, only refreshing the screen requires driving voltage. Thus, Ch-LCD is a strong contender for electronic newspapers and books.

The operation principle of a reflective cholesteric display is shown in Fig. 5-2. The left part of Fig. 5-2 (a) shows the bright state of a Ch-LCD. When an unpolarized light is incident into a right-hand cholesteric LC layer, the right-hand circularly polarized light within the bandwidth is reflected and the transmitted left-hand circularly polarized light is absorbed by the absorption layer. In an applied voltage state shown in the left part of Fig. 5-2 (b), the cholesteric LC layer is driven to a focal conic state. Thus, the incident light which passes through the LC layer is absorbed by the absorption layer, resulted in a dark state.

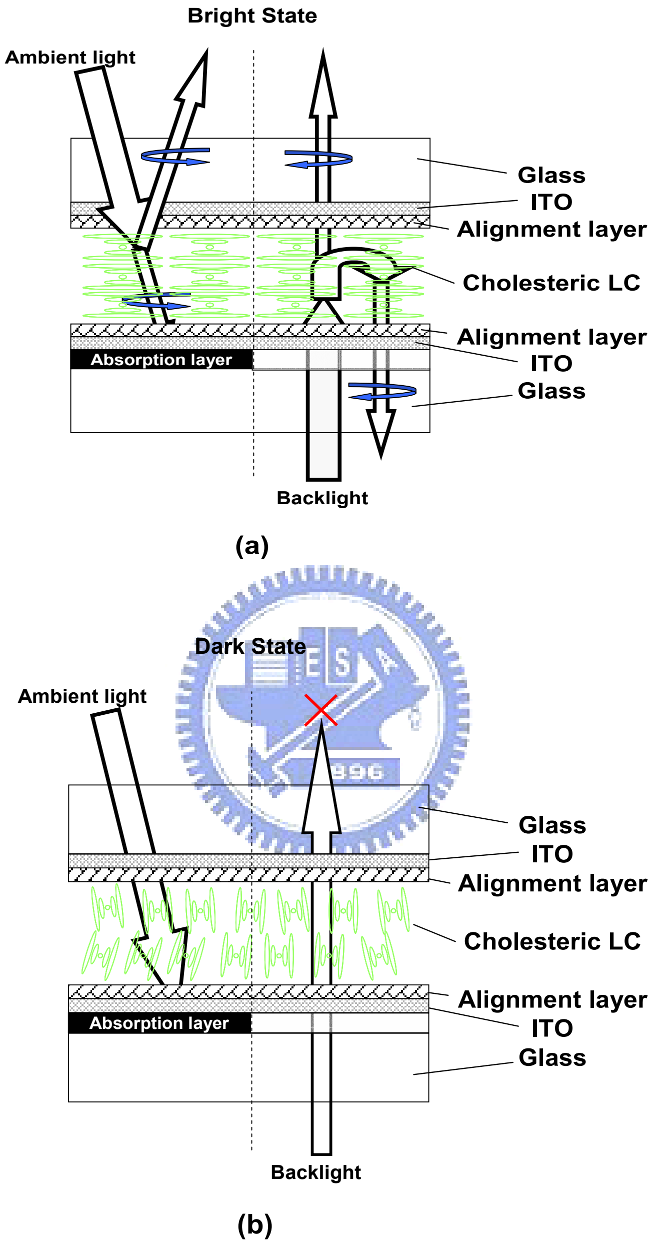


Fig. 5-2. Operation principle of reflective/transmissive cholesteric display. (a) Planar and (b) focal conic state.

To enable a display to be useable from dark to bright sunlight conditions, transflective display is a good option[88]. In a transflective STN or TFT LCD, each pixel is divided into transmissive and reflective sub-pixels. However, such a split pixel approach does not apply to the cholesteric display. As shown in the right part of Figs. 5-2(a) and (b), both reflective and transmissive sub-pixels display bright state, but lack of dark state. Additionally, several methods have been proposed to demonstrate a full color Ch-LCD, such as stacking cells with primary RGB colors,[89] exposing different UV intensity to generate different pitch lengths,[90] and doping different twist agents to create RGB color pixels.[91] Although these methods improve the display characteristics, the legibility of Ch-LCD remains an issue without adequate ambient light. In this chapter, we propose a first transflective Ch-LCD in the world that can display full color images.

5.2 Image-enhanced reflector (IER)

5.2.1 IER for TFT-LCDs

To allow the backlight to traverse the reflective region twice, similar to the ambient light, a bi-prism reflector named "Image-Enhanced Reflector (IER)" is built upon the transmissive region to guide the backlight to follow the similar path as the ambient light, as presented in Fig. 5-3. In addition, the light control films can also be laminated onto the top surface of a transflective LCD to improve the reflective images. Consequently, a single cell gap transflective LCD can utilize image-enhanced reflector[92] and light control film[72], [73], [74] to effectively enhance the image quality of transmissive and reflective region, respectively. The more advantages of this novel structure will be described in the following.

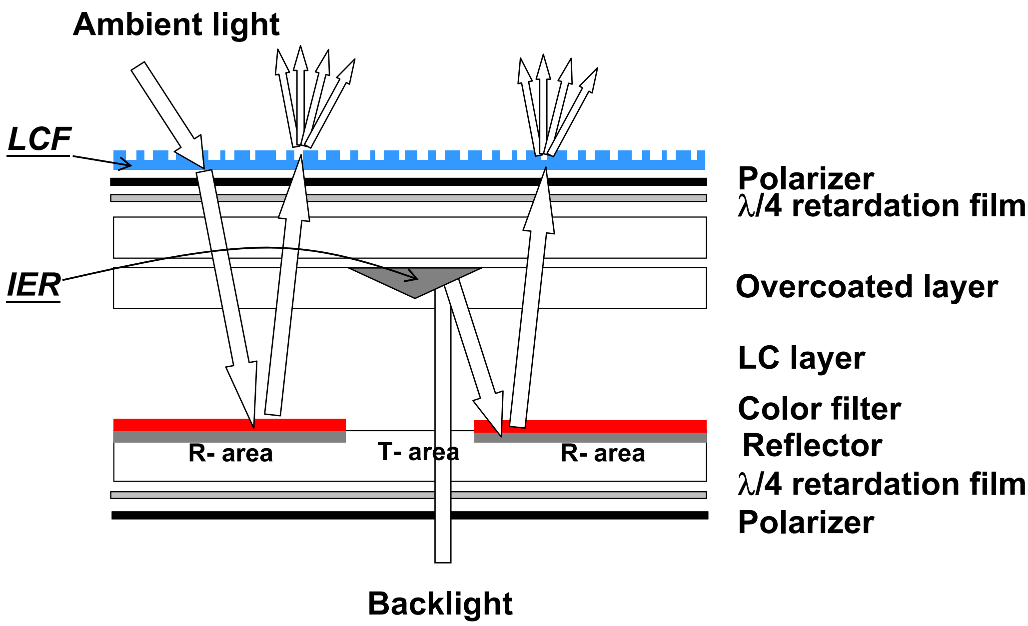


Fig. 5-3. Optical configuration of a novel transflective LCD with image-enhanced reflector (IER) and light control film (LCF).

(a) *High area utilization*

In a conventional transflective LCD, the aperture ratio is approximately 85%, due to the each electrode of each sub-pixel cannot be short to each other. However, in this novel structure, the liquid crystal in transmissive region should be designed as a quarter wave plate, and won't be modulated even turns the voltage on. Therefore, the ITO electrodes are not required in transmissive region, and the IER structure can be built around the reflective region to cover the gap between each sub-pixel and increase the area utilization, as shown in Fig. 5-4. In order to increase the percentage of backlight utilization, TFT and the metal lines can be built on the top glass and just above the IER structure, as shown in Fig. 5-5. Therefore, the useful pixel in conventional transflective LCDs can be utilized for reflective mode. By contrast, the area utilization of a single pixel in our design is increased to almost 100%.

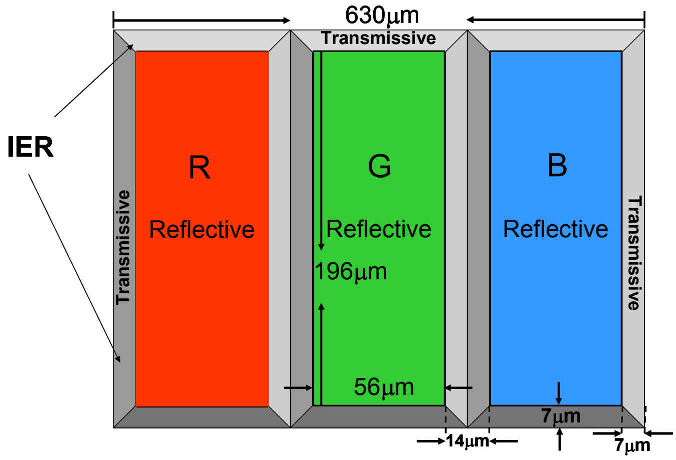


Fig. 5-4. A single cell gap transflective LCD employing image-enhanced reflector around reflective portion, where the dimension is for a typical RGB pixel.

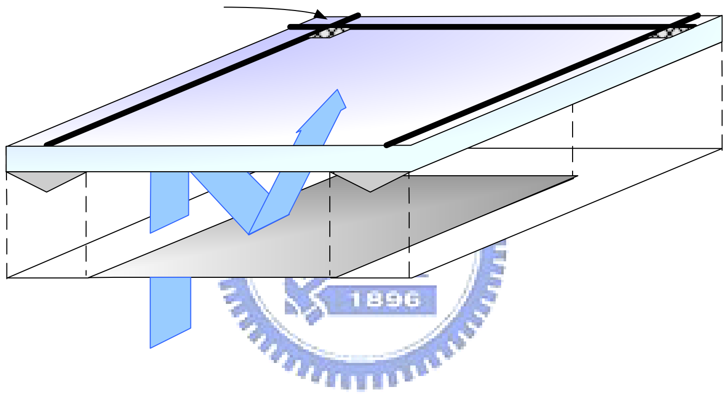
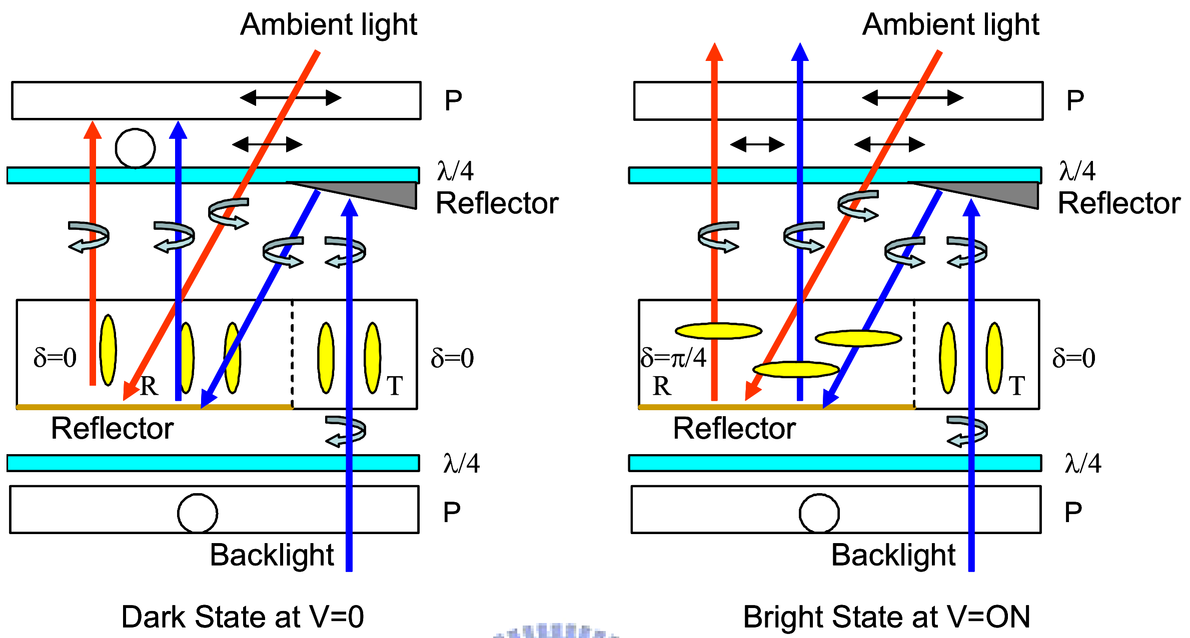


Fig. 5-5. TFT and metal lines on top glass for efficient area utilization.

(b) *High optical efficiency of LC layer*

The operating principles of the proposed transflective LCD with IER structure employing a vertical alignment LC cell for normally black display is shown in Fig. 5-6. In the voltage-off state (Fig. 5-6(a)), the LC directors are perpendicular to the glass substrates. The effective phase retardation is $\delta=0$. As a result, both ambient and backlight are blocked by the crossed polarizers. In the voltage-ON state (Fig. 5-6(b)), the transmissive part of the cell remains unaffected because of no electrode. However, the reflective sub-pixel is activated. The effective phase retardation is $\delta=\pi/4$ so that the light transmittance through the crossed polarizer is close to 100%. Therefore, both reflective and transmissive region can yield high optical efficiency of LC layer.



(a) (b)

Fig. 5-6. Operation principle of the proposed novel transflective LCD employing a vertical alignment LC cell.

(c) *Same response time*

For LCD technology, switching between different gray levels determines the real response time. From the small angle approximation[93], [94], the rise and decay times of an LC device are dependent upon the cell gap d, rotational viscosity γ_1, elastic constant K, threshold voltage V_{th}, bias voltage V_b, and applied voltage V as shown in Eqs. (5- 1) and (5- 2):

$$\tau_{rise} = \frac{\gamma_1 d^2 / K\pi^2}{(V/V_{th})^2 - 1} \tag{5- 1}$$

$$\tau_{decay} = \frac{\gamma_1 d^2 / K\pi^2}{\left|(V_b/V_{th})^2 - 1\right|} \tag{5- 2}$$

To display gray scale images, each pixel may have a different response time, depending upon the driving and bias voltages. In our consideration, we assumed the liquid crystal properties and the controlled voltage in each pixel are the same. From the equation, the response time is proportional to $1/d^2$. No doubt, the thicker the LC layer, the slower the response time. Therefore, for the conventional double cell gap transflective LCDs, the T sub-pixels have four times slower response time than that of the R sub-pixels, resulted in inferior image quality than those of the single cell gap structure. To achieve adequate response time, the single cell gap embodiment is chosen for our new transflective LCD structure.

(d) *Matched and higher color saturation*

It is helpful to describe the Beer Lambert Law before going on the color saturation task. The Beer-Lambert law (or Beer's law) [95], [96] is shown in Eq. (5-3)

$$T_2 = \exp^{-(a_\lambda B_2 \cdot C)} = \exp^{-(a_\lambda n B_1 \cdot C)} = \left[\exp^{-(a_\lambda B_1 \cdot C)}\right]^n = (T_1)^n \qquad (5\text{-}3)$$

. Here a_λ is a wavelength-dependent absorptivity coefficient (constituent), B is the light path length in the color filter, and c is the concentration of color filter. If the transmissive light has two different light path lengths (B_1 and B_2), and $B_2=nB_1$, n is integer constant. Hence, the transmittance of a color filter is proportional to the light path length in the color filter.

Therefore, we suppose that the concentration of the color filter is uniform. For conventional transflective LCD, backlight and ambient light pass through the color filter with different times, therefore, the transmittance of color filter in reflective sub pixels is square of that in transmissive sub pixels. By contrast, our new designed transflective LCD with IER structure can improve this problems and leads to high image quality. Once we have the transmissive spectrum of the color filter, we can calculate the transmittance under different wavelength. Therefore, the color saturation of the proposed TR-LCD can be compared with traditional one. These results will be demonstrated in the following section.

5.2.2 IER for Ch-LCDs

Except for using on TFT-LCDs, IER also applicable for a novel full color cholesteric LCD to yield similar image quality under any ambience. To achieve full color display, we select to use a broadband reflection cholesteric LCD. The reflection bandwidth of a cholesteric LCD is proportional to the birefringence (Δn) and pitch length (P) as $\Delta\lambda = p\Delta n$. Therefore, high birefringence LC is used to widen the reflective band width. Our approach is to achieve a broad reflection band covering the entire visible spectrum, from 450 to 650 nm. Under such a condition, a black and white cholesteric display can be realized. Since the reflected light is white, the conventional color filters can be patterned for obtaining full color displays.[97]

In this novel full color transflective cholesteric LCD, each pixel is divided into reflective and transmissive parts. In the transmissive part, an image-enhanced reflector (IER)[92] is placed to reflect the backlight into the reflection pixels. This IER design works equally well for both narrow and broadband cholesteric displays. Fig. 5-7 illustrates the operation mechanisms of the new transflective cholesteric display. In Fig. 5-7(a), an unpolarized ambient light is incident to the reflective pixels. Assumed the cholesteric layer is right-handed so that it reflects the right-hand (R) circularly polarized light and transmits the left-handed (L) part. The transmitted L light is absorbed by the absorption layer. As a result, a bright state is obtained. On the transmission channel from backlight, the R light is reflected back and L is transmitted to impinge onto the IER. Upon reflection, the L light becomes R and is reflected by the cholesteric LC layer to the viewer. Again, the bright state is achieved. The same bright state for both reflective and transmissive channels is critically important, as in a not-too-dark ambient, the backlight may be needed in order to enhance the readability.

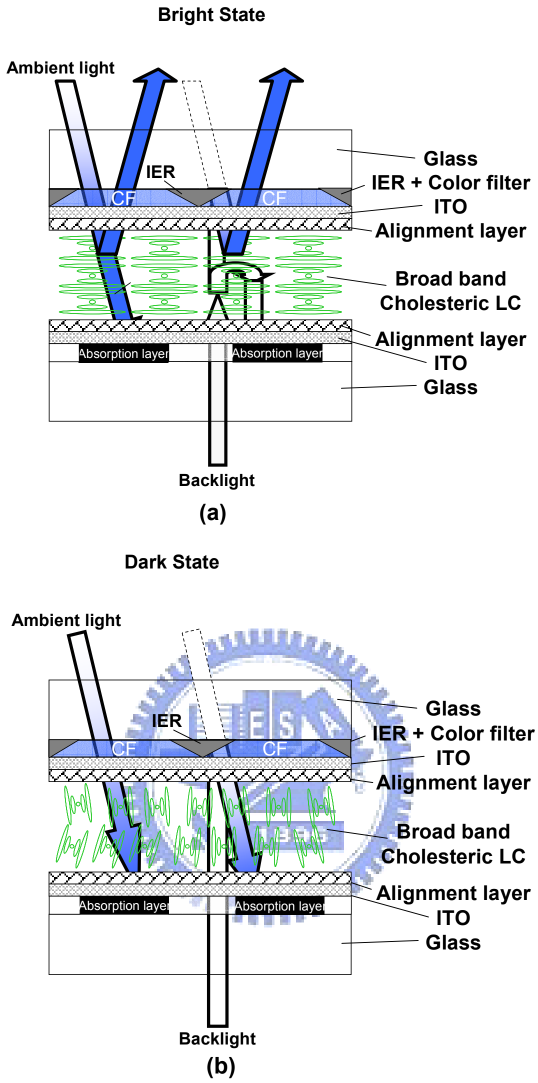


Fig. 5-7. Schematic plot of the proposed full color transflective cholesteric LCD with an IER and wide band reflective cholesteric liquid crystal. (a) Bright and (b) dark state.

However, the specular reflection of the Ch-LCD reflects the oblique incident light to its corresponding reflection angle, as illustrated in Fig. 5-7. Consequently, the viewers cannot perceive the brightest image near the normal direction, which is the typical viewing region for common viewers. To further improve the image quality of the novel Ch-LCD, we propose to use the light control films[71 - 74] to collect and redirect the oblique light into a lower-angle viewing region to increase the brightness, as illustrated in Fig. 5-8. Therefore, both reflective and transmissive sub-pixels exhibit a high optical efficiency in the normal viewing region.

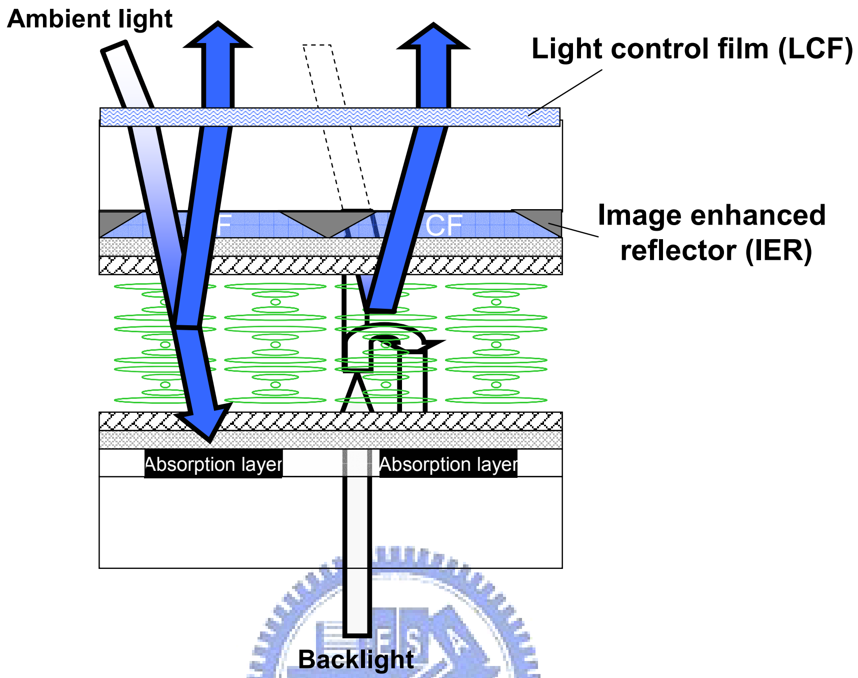


Fig. 5-8. Cross-sectional plot of the transflective Ch-LCD with image enhanced reflector (IER) and light control film (LCF).

5.3 Experiments

5.3.1 Fabrication of image-enhanced reflector

Many methods have been developed to fabricate a biprism structure. One of the commonly used methods is the photoresist thermal melting process. However, the approach is limited to a small linear dynamic range. Another method to fabricate the image-enhanced reflector is to use a half-tone mask exposed by an excimer laser. Excimer laser ablation is a rapid and effective way for micromachining a surface relief onto a substrate material such as photoresist. Besides, half-tone mask can modulate the incident light into gray levels. Therefore, by designing the gray levels of structure and controlling the laser energy, the biprism structure can be obtained. The detailed steps of the process are shown in Fig. 5-9. First, the photoresist AZP4620 was coated on the glass substrate. Second, the IER structure was fabricated by using half-tone mask equipped with excimer laser micromachining. Then, an aluminum film was evaporated. Finally, the Al layer outside the IER was etched off by using wet etching process.

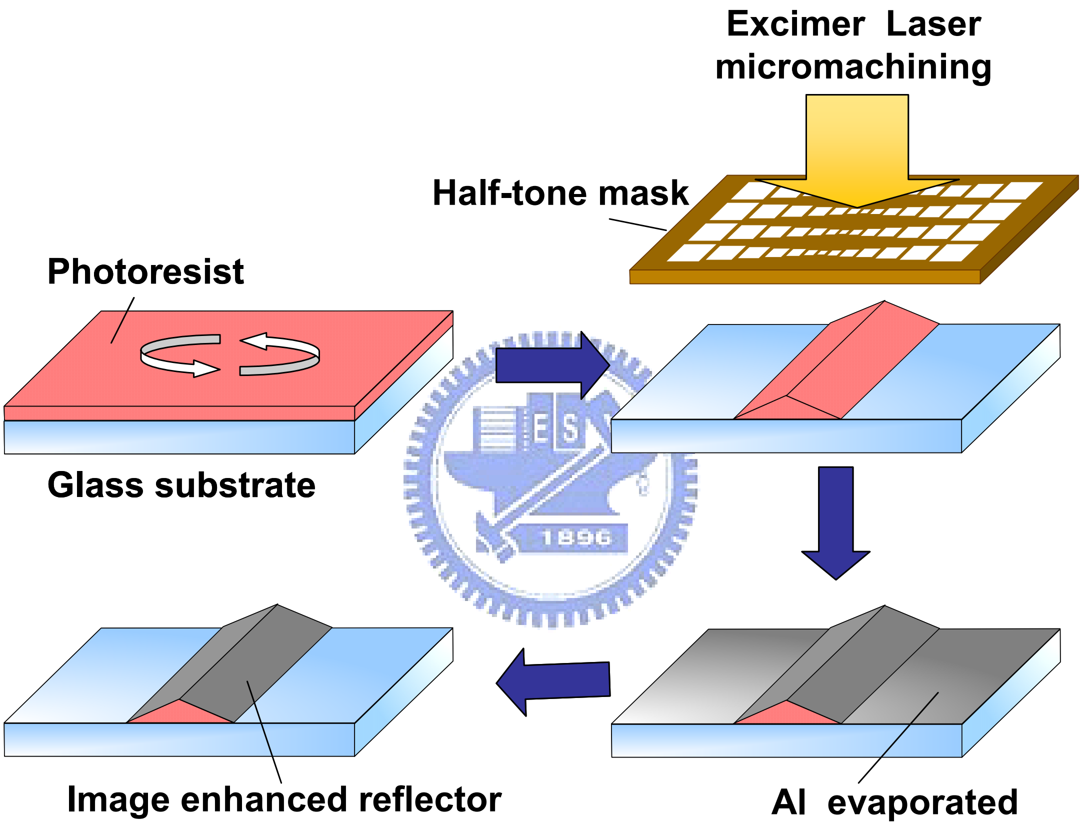


Fig. 5-9. Flow of the fabrication process of prototype IER.

5.3.2 Evaluation of morphological and optical properties

The surface structure and cross-sectional profile of IER were examined using a **Di** Dimension 3100 AFM. To measure the light utilization efficiency, a simple optical measurement system was setup, as shown in Fig. 5-10. A red laser was used as the light source. The collimated light was incident onto the fabricated structure. Therefore, the transmissive light utilization efficiency can be measured.

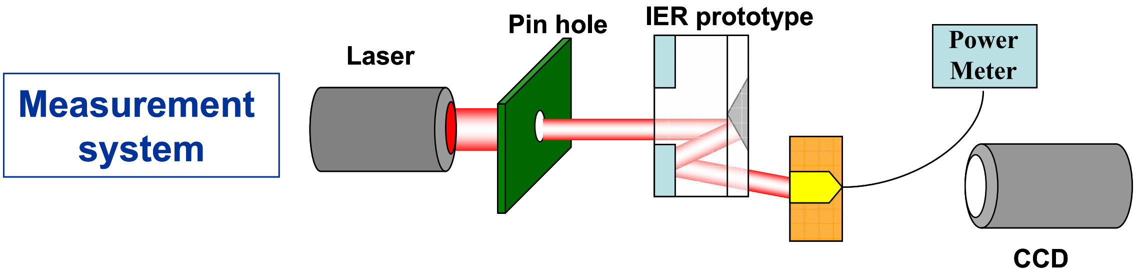
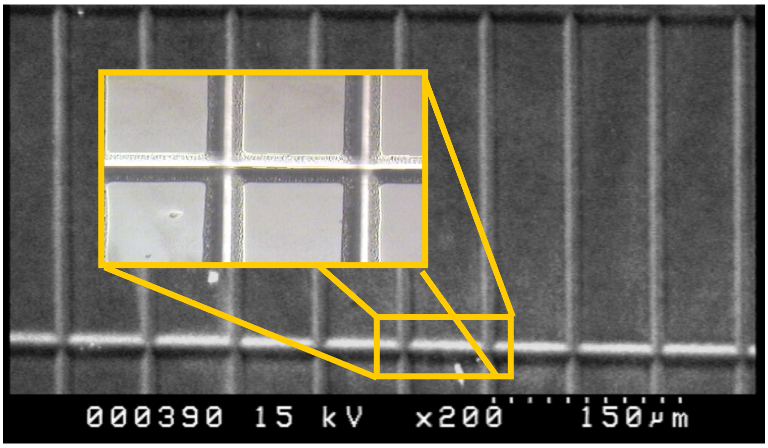


Fig. 5-10. Schematic diagram of the experimental setup for characterizing the light utilization efficiency of fabricated IER.

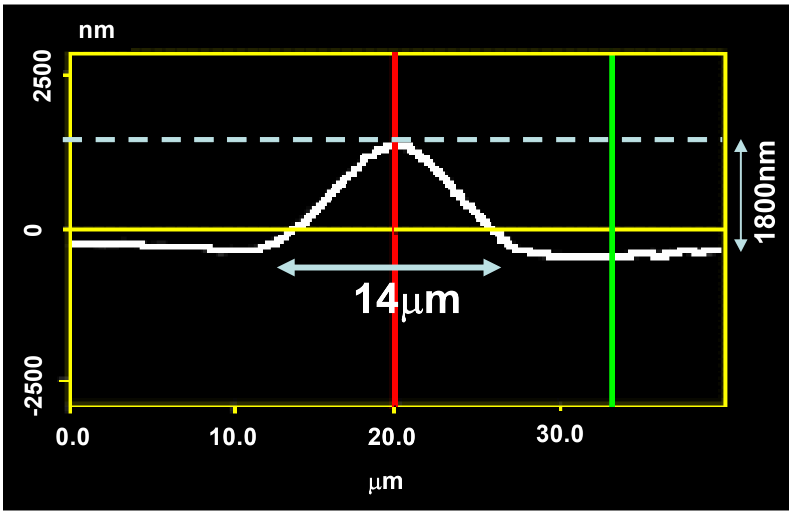
5.4 Simulation and experimental results

5.4.1 Results of IER in transflective TFT-LCDs

A simple transflective color TFT-LCD configuration was used to simulate and design the image-enhanced reflector. The angle of IER is set as 15° and will reflect the transmissive light to be 30° to the normal, which is the same angle as most of the ambient light incidence. By calculating both the width of IER and the distance from IER to bottom reflector the light utilization ratio of the transflective TFT-LCD with IER can be optimized. According to the conventional specification of 4-inches panel, the transmissive light utilization ration should be higher than 20%. Therefore, the width of IER was optimized from the simulation results to be 14μm, which achieves 23.89% transmissive light utilization ratio. The fabricated result measured by SEM and AFM are shown in Figs. 5-11(a) and (b), respectively. The width of the image-enhanced reflector is 14 μm and the depth is 1.8μm, which is close to the designed.



(a)



(b)

Fig. 5-11. (a) Top view and (b) literal view of fabricated image enhanced reflector measured by using SEM and AFM, respectively.

By using the fabricated IER structure, the transmissive light utilization of the novel TR-LCD was measured and compared with the simulation results of IER and the two conventional structures, as shown in Fig. 5-12. The IER structure is clearly indicated from the results to provide similar transmissive light utilization to the double cell gap structure and much higher than the single cell gap one.

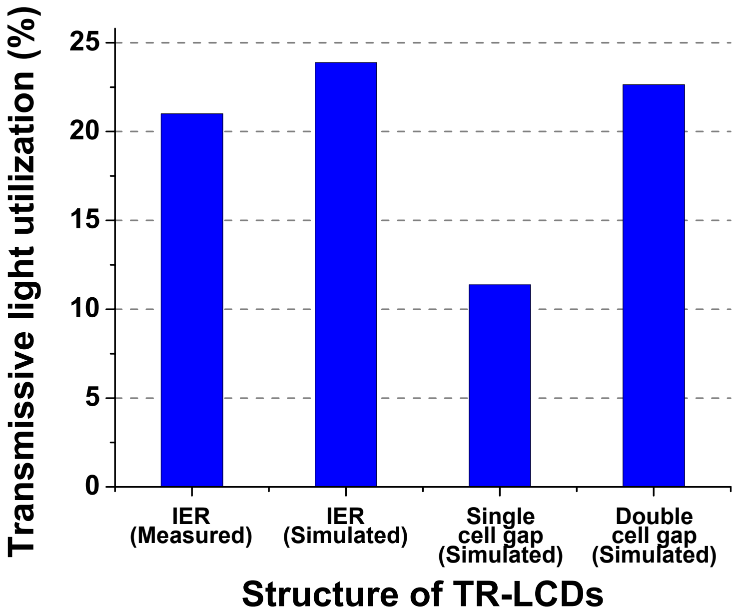
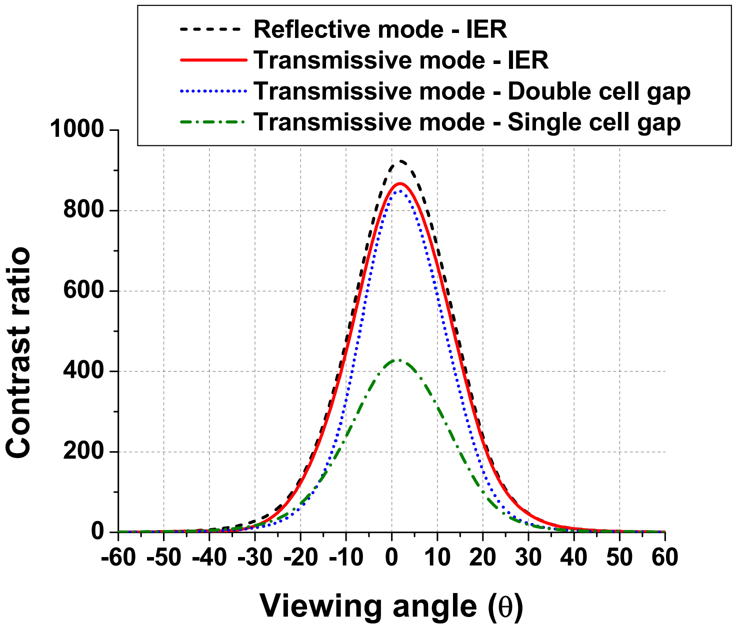
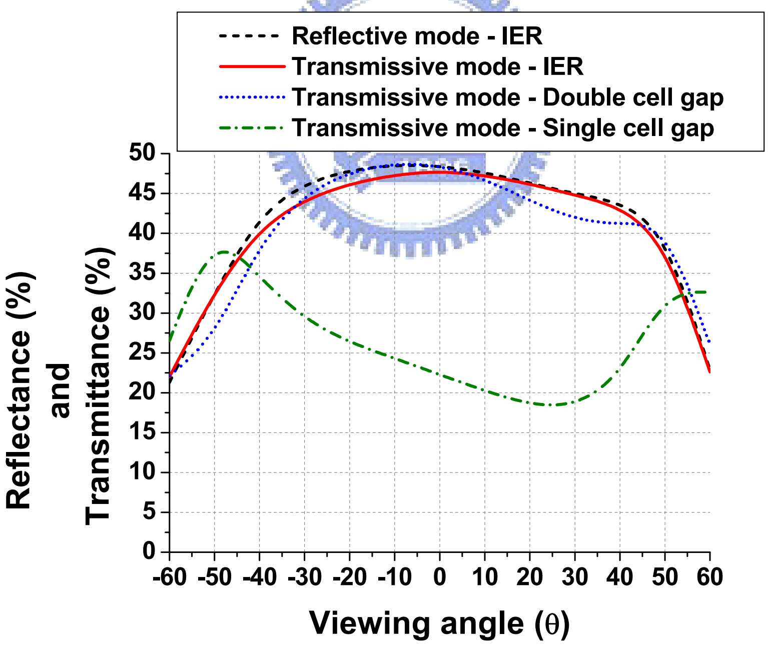


Fig. 5-12. The transmissive light utilization of the novel and conventional TR-LCDs.

A vertical aligned LC mode was used to simulate the optical properties of the novel TR-LCD and the single and double cell gap structure, as presented in Figs. 5-13(a) and (b), respectively. The results successfully demonstrate that since the backlight and ambient light follow the similar paths by using IER, the optical properties of the transmissive and reflective modes are similar. Furthermore, the optical properties of the transmissive mode with IER are quite close to that of the double cell gap structure and much better than the single cell gap one. Therefore, high image quality of transmissive and reflective mode can both be achieved once the IER structure is built above the transmissive region.



(a)



(b)

Fig. 5-13. The simulated (a) contrast profile and (b) reflectance and transmittance profile of the novel and conventional TR-LCDs.

The NTSC ratio of transmissive region in conventional and the novel transflective LCD was calculated and displayed in Fig. 5-14. By using IER structure, the transmissive light passes through the color filter twice which is the same as reflective light. Thus, the NTSC ratio can be increased to 19% that is much larger than conventional transmissive image, and can be matched with reflective region.

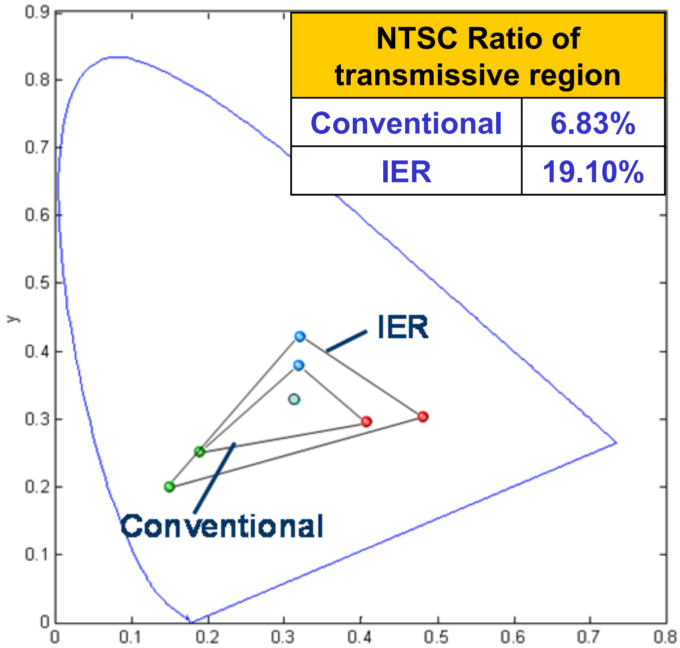


Fig. 5-14. The calculated NTSC ratio of transmissive region in conventional and with IER's transflective LCD.

5.4.2 Results of IER in full color transflective Ch-LCDs

By using finite element method (FEM)[98], the relationship between birefringence and reflection bandwidth of a cholesteric display was simulated, as shown in Fig. 5-15. The incident light was unpolarized and LC layer was right-hand circular cholesteric. The $\triangle$n values used for calculations are 0.2, 0.6 and 1.0, shown as dash, plus-dash and solid lines, respectively. Obviously, when the birefringence is larger than 0.6, the reflection bandwidth covers almost the entire visible spectrum with 50% reflectivity that can display black and white image. By implementing RGB color filters on the display, a full color cholesteric LCD with memory effect can be demonstrated.

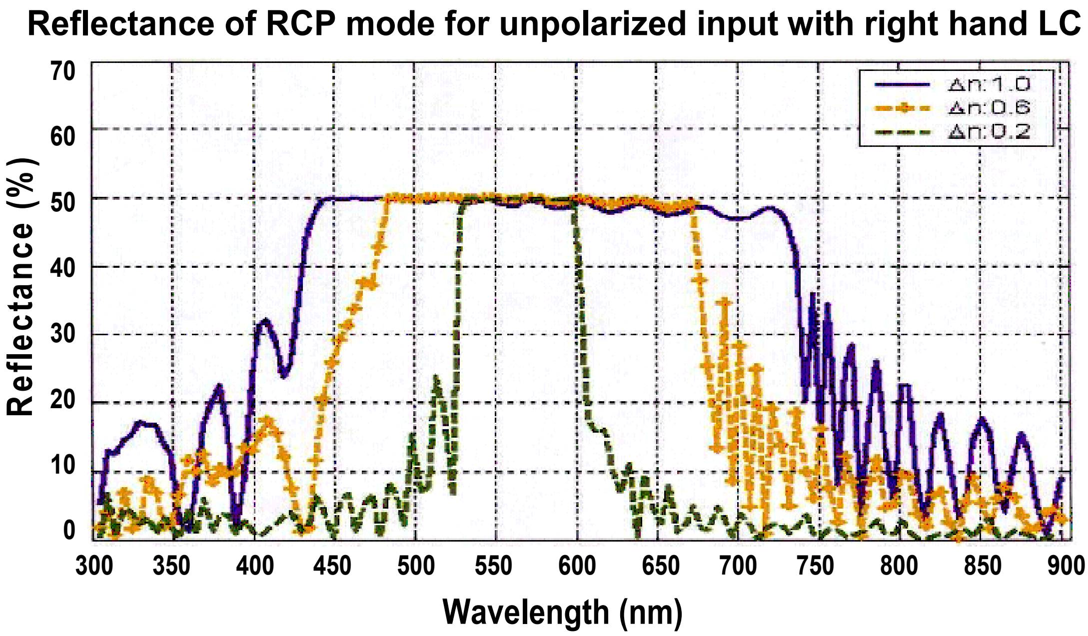
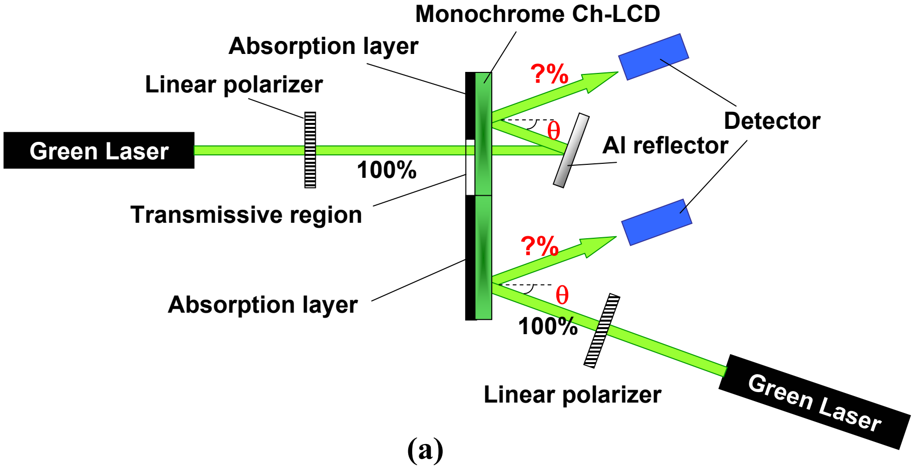
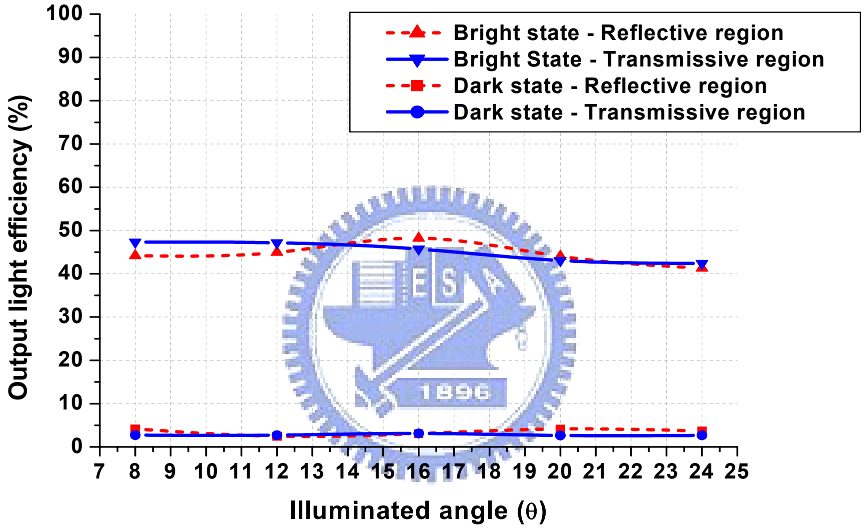


Fig. 5-15. Simulation results of the birefringence dependent reflection bandwidth of a Ch-LCD.

To examine the performance of IER on Ch-LCD, two linearly polarized He-Ne green lasers (λ=543 nm) were used to mimic backlight and ambient light, respectively, and to illuminate on a monochrome Ch-LC cell whose reflective bandwidth ranges from 530 to 590 nm, as shown in Fig. 5-16(a). An aluminum reflector which acts as an IER was set behind the Ch-LCD to reflect the transmitted light to the Ch-LCD. The output light efficiency of the transmissive and reflective portions was measured by the detectors at different illumination angle θ, and the results are shown in Fig. 5-16(b). From Fig. 5-16(b), the output light efficiency of the bright and dark states for the reflective and transmissive regions is similar. With different illumination angles of green lasers, both regions have output light efficiency higher than 40% for the bright state, and lower than 5% for the dark state. Therefore, by building IER above the transmissive portion, the transflective Ch-LCD shows a decent quality image for both reflective and transmissive modes.



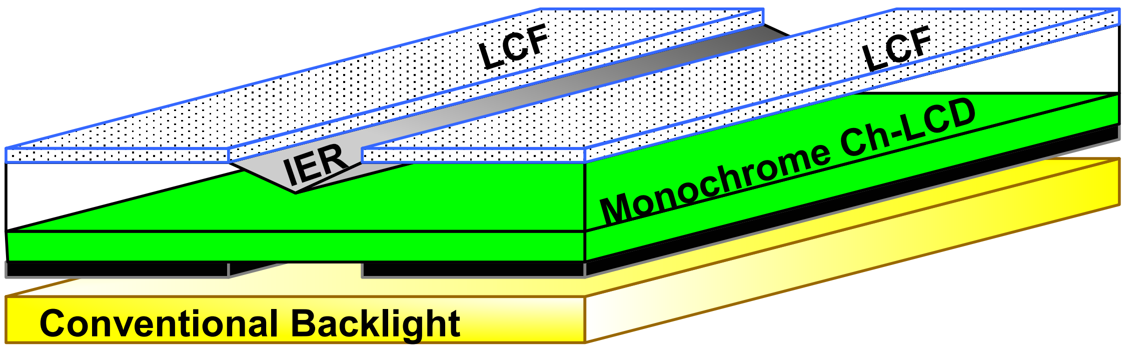
(a)



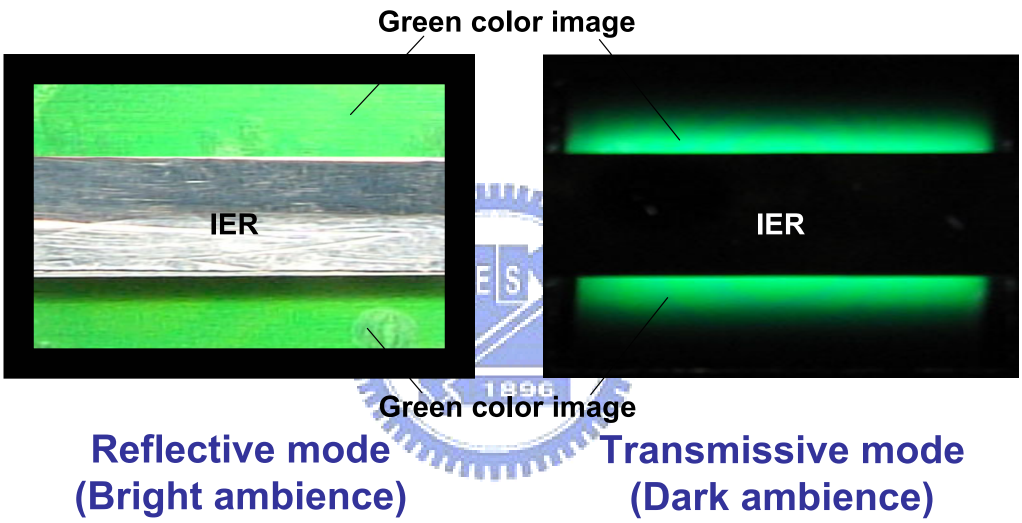
(b)

Fig. 5-16. (a) The experimental setup and (b) the measured output light efficiency of the IER function on Ch-LCD.

Prior to examine the function of IER, we prepared a simple monochrome Ch-LCD test sample with conventional backlight, as illustrated in Fig. 5-17(a). The images of reflective (left part) and transmissive (right part) mode are shown in Fig. 5-17(b). The demo photos successfully demonstrate that this novel transflective Ch-LCD can display same image color in any ambient condition. Accordingly, the Ch-LCD by using high birefringence LC and image-enhanced reflector is anticipated to yield high brightness full color images, which can be read in any ambience.



(a)



(b)

Fig. 5-17. (a) The schematic plot of a simple test sample of monochrome Ch-LCD with conventional backlight and (b) The demo photos of the same color images for both reflective (left part) and transmissive (right part) modes. (Color photos are shown in appendix)

5.5 Summary

For transflective TFT-LCDs, the significance of image-enhanced reflector is to solve their key issues, such as low optical efficiency in transmissive portion, different response time, and inadequate color saturation. Additionally, single cell-gap and high area utilization are also the advantages of the transflective TFT-LCD using image-enhanced reflector. From the experimental and simulation results, the novel transflective LCD can yield 22% transmissive light utilization which is similar to that of double cell gap approach. By using vertical alignment LC mode, the optical efficiency and viewing angle of reflective and transmissive image are almost the same. Additionally, its NTSC ratio of transmissive image is a factor of 3 to that of the conventional TR-LCDs.

Moreover, we demonstrated a novel cholesteric LCD which can easily display full color images by using high birefringence LC material ($\Delta n > 0.6$) with conventional color filter process. It also displays same color images both in reflective and transmissive modes, and maintains good readability in any ambience due to that the IER structure allows the paths of backlight similar to that of the ambient light. Additionally, the display has low power consumption because of the bistability of Ch-LC and high brightness due to elimination of polarizers. This transflective Ch-LCD is also the first approach in the world which can exhibit same color image for transmissive and reflective mode.

The IER structure fabricated by using half-tone mask and excimer laser micromachining process was successfully developed and demonstrated. Furthermore, the light control films can be laminated onto the top surface of the two proposed portable displays to enhance the image quality for both reflective and transmissive modes. Our results demonstrate that a much better image quality with excellent legibility under both bright and dark ambient conditions for transflective TFT-LCDs and Ch-LCDs can be achieved.