Full-color transflective cholesteric LCD with image-enhanced reflector

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Abstract — A full-color bistable transflective cholesteric liquid-crystal display (Ch-LCD) was demonstrated by using an imbedded image-enhanced reflector (IER) on top of each transmissive subpixel. The RGB colors were achieved by patterning conventional color filters on a black-and-white Ch-LCD. In addition, the IER on top of each transmissive subpixel provides similar paths for the transmissive backlight and the reflected ambient light. A simple transflective Ch-LCD was demonstrated.

Keywords — *Full color, transflective, cholesteric LC, image-enhanced reflector, light control film.*

1 Introduction

A reflective cholesteric liquid-crystal display (Ch-LCD)[1] is a bistable device which consumes less power than conventional general reflective STN or TFT displays. Due to its bistability, only the refreshing of the screen requires a driving voltage. Thus, the Ch-LCD is a strong contender for electronic newspapers and books.

The operation principle of a reflective cholesteric display is shown in Fig. 1. The left part of Fig. 1(a) shows the bright state of a Ch-LCD. When unpolarized light is incident to a right-handed cholesteric LC layer, the right-handed circularly polarized light within the bandwidth is reflected and the transmitted left-handed circularly polarized light is absorbed by the absorption layer. In an applied-voltage state shown in the left part of Fig. 1(b), the Ch-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, resulting in a dark state.

Several methods have been proposed to demonstrate a full-color Ch-LCD, such as stacking cells with primary RGB colors,[2] exposing different UV intensities to generate different pitch lengths,[3] and doping different twist agents to create RGB color pixels.[4] Although these methods improve the display characteristics, the legibility of a Ch-LCD remains an issue without adequate ambient light.

For a display to be useable from dark to bright-sunlight conditions, a transflective display is a good option.[5] In a transflective STN- or TFT-LCD, each pixel is divided into transmissive and reflective subpixels. However, such a split pixel approach does not apply to a cholesteric display. As shown in the right part of Figs. 1(a) and (b), both reflective and transmissive subpixels display in the bright state, but

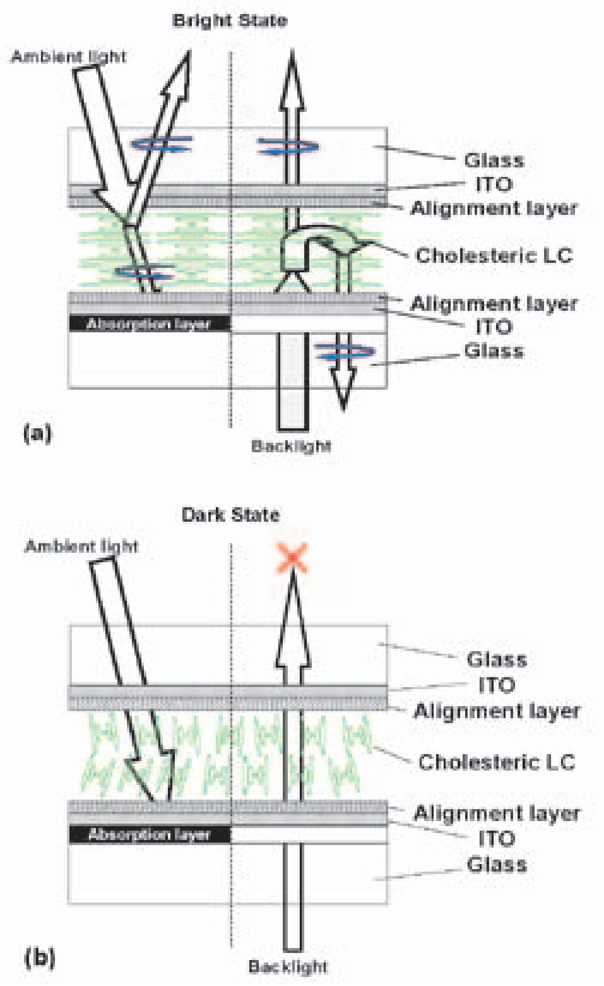

FIGURE 1 — Operation principle of a reflective/transmissive cholesteric display. (a) Planar and (b) focal-conic state.

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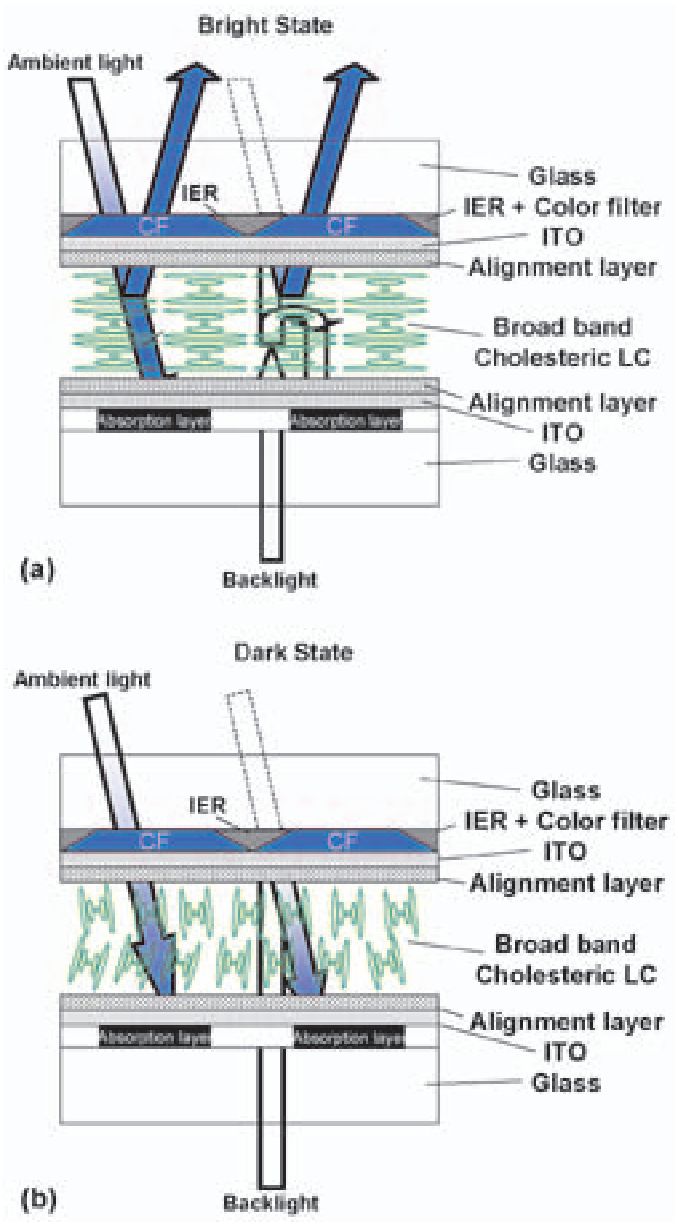

FIGURE 2 — Schematic plot of the proposed full-color transflective cholesteric LCD with an IER and wideband reflective cholesteric liquid crystal. (a) Bright and (b) dark state.

lack a dark state. In this paper, we demonstrate a simple transflective Ch-LCD that can display full-color images.

2 Full-color transflective cholesteric LCDs

To achieve a full-color display, we deceided to use a broadband reflective Ch-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, a high-birefringence LC was used to widen the reflective bandwidth. Our approach was to achieve a broad reflection band covering the entire visible spectrum, from 450 to 650 nm. Under such conditions, a black-and-white cholesteric display can be realized. Since the reflected light is white, the conventional color filters can be patterned to obtain full-color displays.[6]

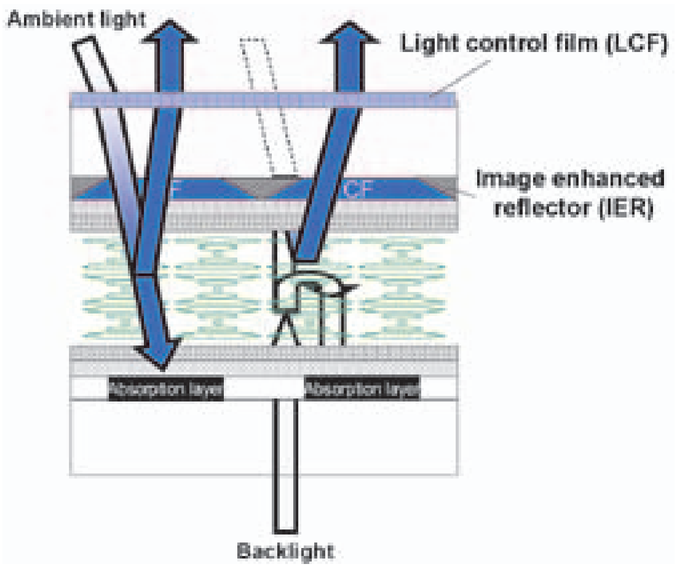

FIGURE 3 — Cross-sectional plot of the transflective Ch-LCD with image-enhanced reflector (IER) and light control film (LCF).

In this novel full-color transflective Ch-LCD, each pixel is divided into reflective and transmissive parts. In the transmissive part, an image-enhanced reflector (IER)[7] is positioned to reflect the backlight into the reflection pixels. This IER design works equally well for both narrow and broadband cholesteric displays. Figure 2 illustrates the operation mechanisms of the new transflective cholesteric display. In Fig. 2(a), unpolarized ambient light is incident to the reflective pixels. We assumed that 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 light L is absorbed by the absorption layer. As a result, a bright state was obtained. On the transmission channel from the backlight, the R light is reflected back and L is transmitted to impinge onto the IER. Upon reflection, the L light becomes R light and is reflected by the cholesteric LC layer to the viewer. Again, a 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 to enhance readability.

However, the specular reflection of the Ch-LCD reflects the oblique incident light to its corresponding reflection angle, as illustrated in Fig. 2. 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 a "light control film" to collect and redirect the oblique light into a lower-angle viewing region to increase the brightness, as illustrated in Fig. 3. The light control film can be made by multi-directional asymmetrical microlens arrays[8,9] or random gratings.[10] Therefore, both reflective and transmissive subpixels exhibit a high optical efficiency in the normal viewing region.

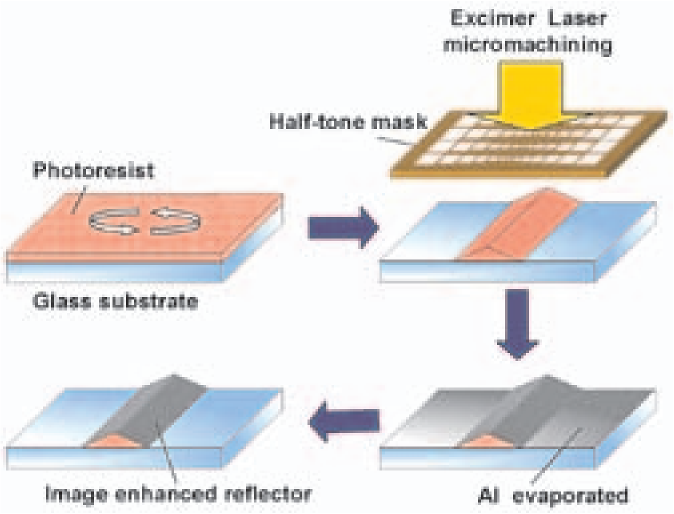

FIGURE 4 — Flow of the fabrication process of a prototype IER.

3 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 used to fabricate the image-enhanced reflector is to use a halftone 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 a photoresist. Besides, a halftone mask can modulate the incident light into gray levels. Therefore, by designing the gray levels of the structure and controlling the laser energy, a biprism structure can be obtained. The detailed steps of the process are shown in Fig. 4. First, the photoresist AZP4620 was coated on the glass substrate. Second, the IER structure was fabricated by using a halftone mask equipped with excimer laser micromachining. Then, an aluminum film was evaporated. Finally, the Al layer outside the IER was etched off by using a wet-etching process.

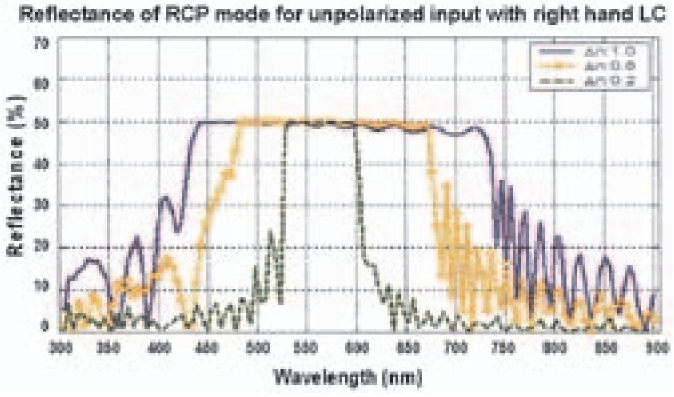

FIGURE 5 — Simulation results of the birefringence-dependent reflection bandwidth of a Ch-LCD.

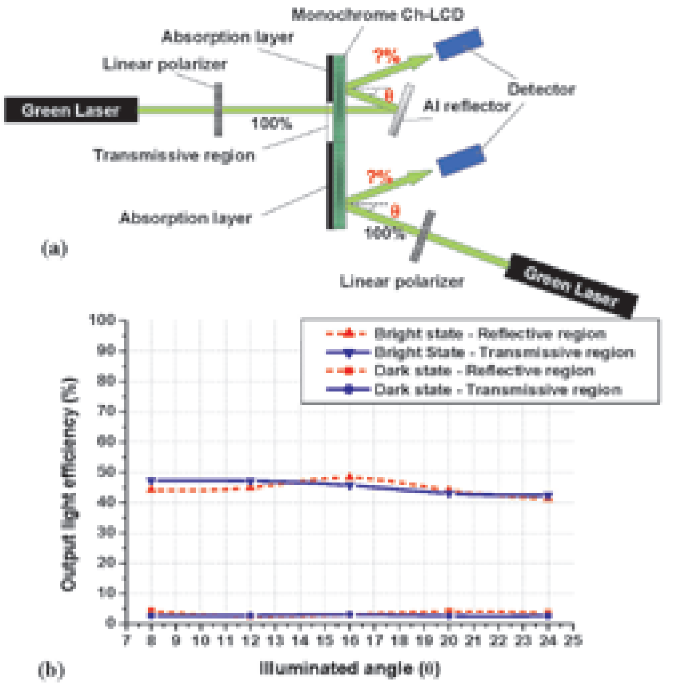

FIGURE 6 — (a) The experimental setup and (b) the measured output light efficiency of the IER function for a Ch-LCD.

4 Simulation and experimental results

By using the finite-element method (FEM),[11] the relationship between the birefringence and reflection bandwidths of a cholesteric display was simulated, as shown in Fig. 5. The incident light was unpolarized and the LC layer was a right-handed circular cholesteric. The calculated Δn values used were 0.2, 0.6, and 1.0, shown as dashed, plus-dashed, 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 a black-and-white image. By implementing RGB color filters on the display, a full-color cholesteric LCD with memory effect can be demonstrated.

To examine the performance of IER on a Ch-LCD, two linearly polarized He–Ne green lasers (λ = 543 nm) were used to mimic the 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. 6(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 a different illumination angle θ, and the results are shown in Fig. 6(b). From Fig. 6(b), the output light efficiency of the bright and dark states for the reflective and transmissive regions is similar. With different illumination angles for green lasers, both regions have an 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

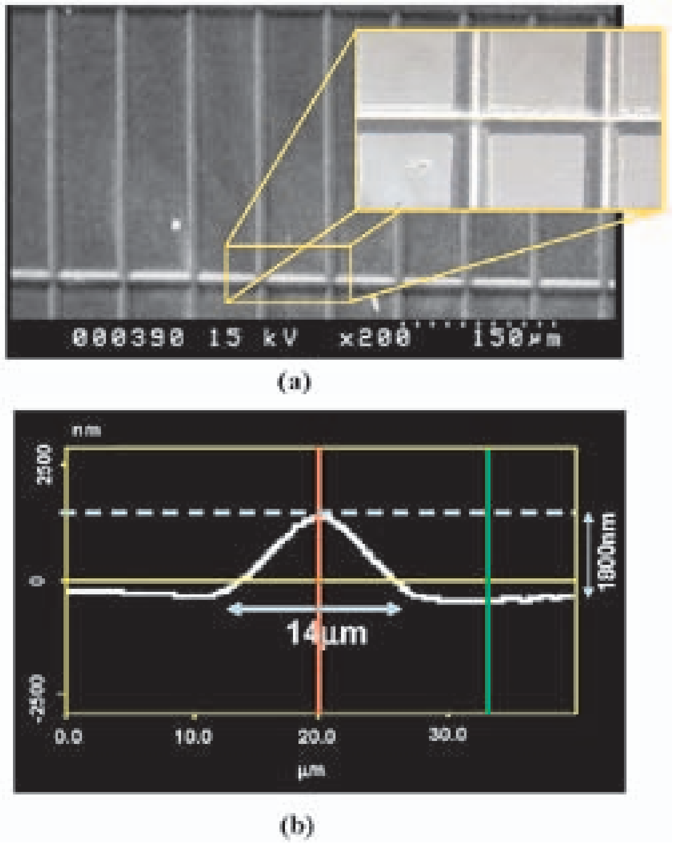

FIGURE 7 — (a) Top view and (b) literal view of the fabricated image-enhanced reflector measured by using SEM and AFM.

shows a decent quality image for both reflective and transmissive modes.

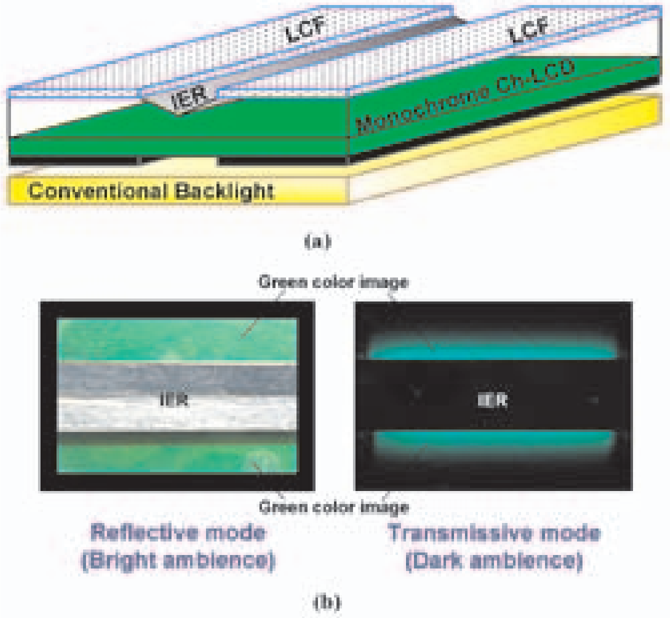

FIGURE 8 — (a) The schematic plot of a simple test sample of monochrome Ch-LCD with a conventional backlight and (b) the demo photos of the same color images for both reflective (left part) and transmissive (right part) modes.

The halftone mask technology equipped with excimer-laser micromachining was used to fabricate the prototype IER structure on a glass substrate. The fabricated structure was measured by using scanning electron microscopy (SEM) and atomic force microscopy (AFM), as shown in Figs. 7(a) and 7(b), respectively. From the results, we successfully demonstrated that the IER structure can be easily fabricated by a conventional well-developed process. In a completed device, the image-enhanced reflector can be integrated into the full-color Ch-LCD.

Prior to examining the IER function, we prepared a simple monochrome Ch-LCD test sample with a conventional backlight, as illustrated in Fig. 8(a). The images of the reflective (left part) and transmissive (right part) modes are shown in Fig. 8(b). The demo photos successfully demonstrate that this novel transflective Ch-LCD can display the same image color in any ambient condition. Accordingly, a Ch-LCD, using high-birefringence LC and an image-enhanced reflector, is anticipated to yield high-brightness full-color images which can be read in any ambience.

5 Conclusions

The proposed novel cholesteric LCD can easily display full-color images by using high birefringence LC material with a conventional color-filter process. It also displays the same color images in both the reflective and transmissive modes, and maintains good readability in any ambience due to the IER structure that allows the paths of the backlight to be 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 the elimination of the polarizers. The IER structure fabricated by using a halftone mask and excimer-laser micromachining was successfully demonstrated. The fabrication processes for this full-color transflective Ch-LCD are compatible with that of conventional LCDs. Furthermore, the light control films can be laminated onto the top surface of the proposed display to enhance the image quality for both reflective and transmissive modes. The results demonstrate that a full-color image with excellent legibility under both bright and dark ambient conditions for a Ch-LCD can be achieved.

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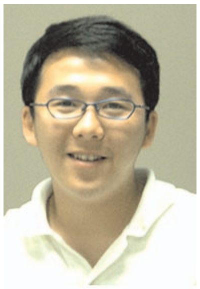

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