High Image Quality Reflective Liquid Crystal Displays by Using Multi-directional Asymmetrical Microlens-Array Light Control Films

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ABSTRACT

The multidirectional asymmetrical microlens array light control film (MAMA-LCF) is developed to enhance the image brightness and contrast ratio of reflective liquid crystal displays. Through optimized designs and optical alignments, the MAMA-LCF which is constructed with asymmetrical microlens arrays, leads to a ~5x gain in brightness over the MgO standard white and 12:1 contrast ratio for color STN-LCDs, 10x gain and 11.5:1 contrast ratio for PDLC, and 9x gain over the conventional Ch-LCD. In each display, the light control film does not induce visible surface diffusion, moiré patterns and parallax.

INTRODUCTION

Reflective liquid crystal displays (LCDs)[1] are being widely used in portable personal digital assistants and mobile communications. Varieties of new applications, e.g., STN-LCDs for mobile phones, PDLC for smart cards, and cholesteric LCD for e-books have been considered. In such applications, low power consumption, high brightness, high contrast ratio, and low cost are critical. Most single polarizer-based reflective color LCDs still suffer from inadequate reflectivity and contrast ratio (CR).

Many methods, such as rough surface of reflector,[2] holographic reflector,[3] front scattering film,[4] and holographic light control film,[5,6] have been developed for improving the brightness and contrast ratio of reflective LCDs. We have developed a modified asymmetrical microlens array light control film (AMA-LCF)[7] by cutting along microlens array's diametric direction to form an off-axis one, and then laminated onto the front surface of reflective LCDs, is an effective, yet low cost method. As shown in Fig. 1, the oblique incident light can be reflected to the near normal viewing zone, and yields significant gain in brightness. The AMA-LCF shown in Fig. 2(a), however, was fabricated for uni-directional ambient illumination. The brightness and contrast ratio enhancement reduce if the light source doesn't illuminate from a designed orientation. Therefore, a multi-directional AMA-LCF (MAMA-LCF)[8], as shown in Fig. 2(b) with a fill factor of 100% was designed for typical ambient environment for much improved image quality. As a result, the viewing angle is widened and reflectance enhanced. Simple fabrication and low cost are the major advantages of the MAMA light control film. In this paper, we demonstrate the performances of MAMA light control film on three reflective LCDs: color STN, PDLC and Ch-LCD. Through optimized designs and alignments, the image quality of these displays is improved significantly.

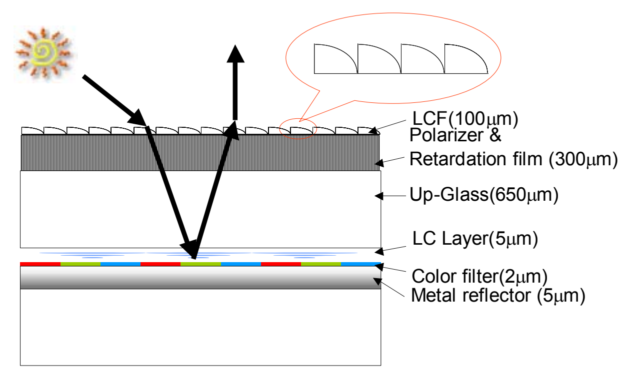
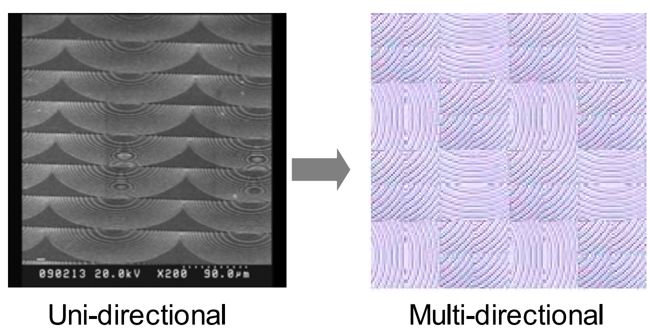


Fig. 1. The panel configuration of a reflective LCD using a AMA-LCF.



(a) (b)

Fig. 2. Plane view of (a) unidirectional and (b) multidirectional AMA-LCFs for a reflective LCD.

REFLECTIVE LCDS WITH MAMA-LCF

1. PDLC and Cholesteric LCD

MAMA-LCF is also applicable to the reflective PDLC which has been developed for plastic smart cards. Usually,

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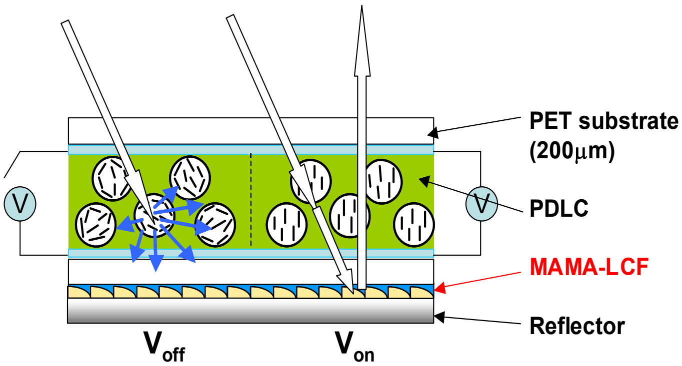
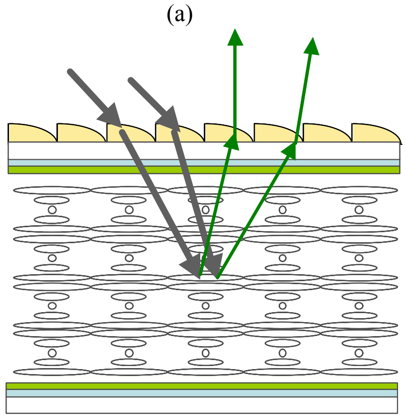
the MAMA-LCF is laminated on the top surface of PDLC. Under such circumstance, the film would modulate the reflected light from the interface of each layer, and deteriorate the blackness of the dark state. Thus, the MAMA-LCF is preferred to be laminated between the bottom substrate of the plastic PDLC panel and the aluminum reflector, as shown in Fig. 3(a). The bottom-laminated MAMA light control film shows a much darker state than that on the top. Moreover, the plastic LCF is flexible and can be easily combined with the plastic displays.



(a)



(b)

Fig. 3. Schematic drawings of Aligned structure of (a) PDLC displays and (b) two-surface rubbed Ch-LCD with MAMA-LCF.

Cholesteric liquid crystal display (Ch-LCD)[9,10] is a strong contender for electronic-books because of its low power consumption. In a conventional Ch-LCD, in order to achieve wide viewing angle, only the top substrate is rubbed and the bottom plate has no rubbing. Thus, the LC directors tilt to different angles. These slightly disordered cholesteric layers help diffuse the reflected light to a wider viewing zone. The tradeoff of this approach is that the maximum reflectivity is reduced to 35%. On the other hand, the two-surface rubbed cell exhibits a higher (~50%) reflectivity except that its viewing angle is much narrower. Our motivation is to integrate a MAMA light control film on the two-surface rubbed cell, such as conventional TN cell, for widening viewing angle while preserving high reflectivity. As shown in Fig. 3(b), the MAMA light control film helps to diffuse light to a larger angle and reduces surface reflections in the viewing zone. Benefiting from the light control film, the two-surface rubbed Ch-LCD is expected to exhibit a bright image and wide viewing angle.

2. Reflective Color STN

The design patterns and system configuration of the MAMA-LCF on reflective color STN-LCDs are shown schematically in Figs. 4. In a reflective color STN-LCD, the color pixel size is 210 μm × 210 μm which covers more than 50 microlenses. Thus, the moiré patterns are not visible because the designed structure and the pitch of the microlenses are much smaller than the pixel size. Moreover, the MAMA-LCF is made of low birefringence material and laminated between the polarizer and top-glass, as shown in Fig. 4. As a result, the surface diffusion is low and parallax remains invisible.

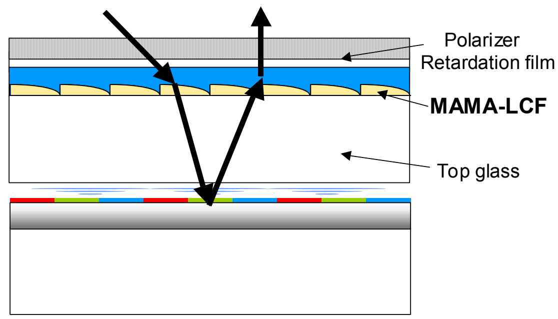
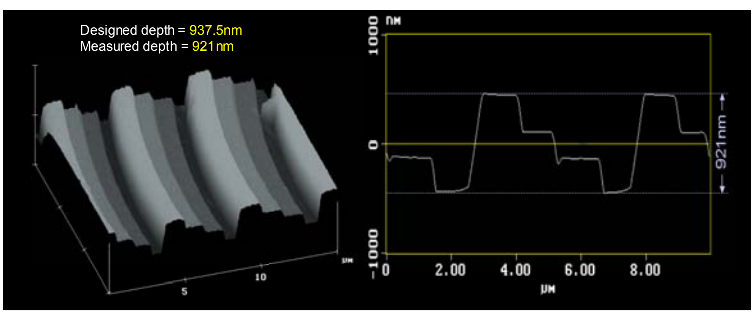


Fig. 4. The panel configuration of a reflective color STN using a MAMA-LCF.

EXPERIMENT RESULTS

Four-level Fresnel microlens with three different orientations was fabricated. Figs. 5(a) and (b) are the top view and the cross-sectional profile of the microlens array structure on a Si substrate, respectively. The depth of the microlens array structure on a Si substrate was 921nm, as shown in Fig. 5(b), and the fabrication tolerance was better than 1.8% for the designed depth of 930 nm.



(a) (b)

Fig. 5. (a) Top view and (b) cross-sectional profile of the asymmetrical microlens array structure on Si wafer.

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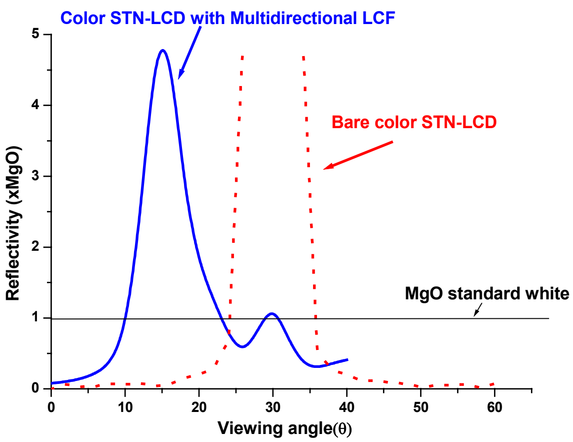
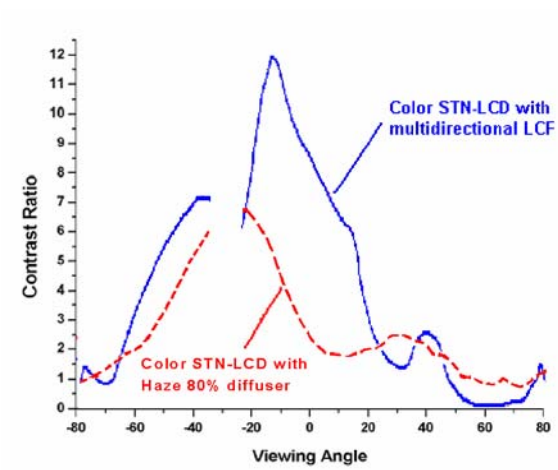
The angular-dependent reflectivity and CR of a color STN and a PDLC cells are measured and results are shown in Figs. 6-7, respectively. For a collimated illumination from -30°, the specular reflection occurs at 30°. At this angle, although the reflectivity is high, the contrast ratio is poor. Adding a MAMA light control film not only shifts the peak reflectance of the STN panel from 30^0 to 14^0 but also enhances reflectivity by ~5x over the MgO standard white, as shown by the solid line in Fig. 6(a). Similarly, the reflectance profile of a PDLC with and without MAMA-LCF shown in Fig. 7(a) also proves that MAMA-LCF yields a much higher brightness (~10x of MgO). The contrast ratios of the color STN and PDLC with MAMA-LCF are shown by the solid lines in Figs. 6(b) and 7(b), respectively. The maximum CR~12:1 is higher than those of the commonly used diffuser and bump reflector.

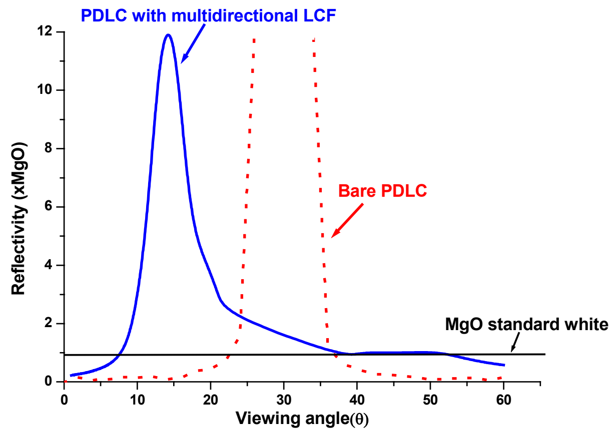


(a)

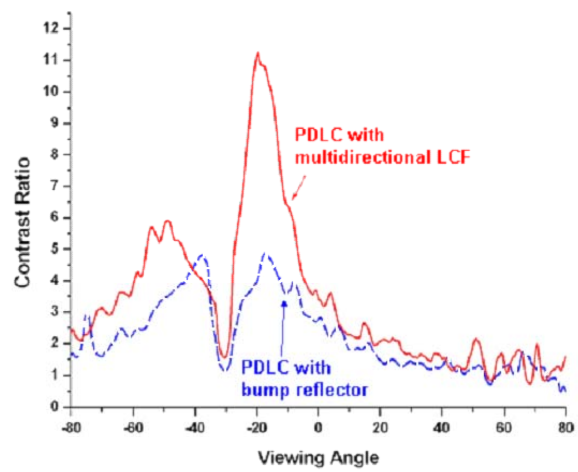


(b)

Fig. 6. The measured (a)reflectivity and (b) contrast ratio of reflective color STN as a function of viewing angle under illumination from -30^0.



(a)



(b)

Fig. 7. The measured (a)reflectivity and (b) contrast ratio of reflective PDLC as a function of viewing angle under illumination from -30^0.

The photographs of displayed images using the MAMA-LCF on a color STN-LCD, PDLC and Ch-LCD, taken under ambient light condition are shown at the top of Figs. 8(a), (b) and (c), respectively. Fig. 8(a) compared STN-LCD with a MAMA-LCF and an 80% haze diffuser, which is commonly used to enhance the brightness of mobile displays, on different viewing angle. The photographs of PDLC with MAMA-LCF are shown in the upper right corner of Fig. 8(b). Additionally, Fig. 8(c) shows the MAMA-LCF used on the conventional numerical TN panel by injected Ch-LC material, which reflected green and orange, respectively. The high image quality with the MAMA light control film on the three different LCDs is demonstrated.

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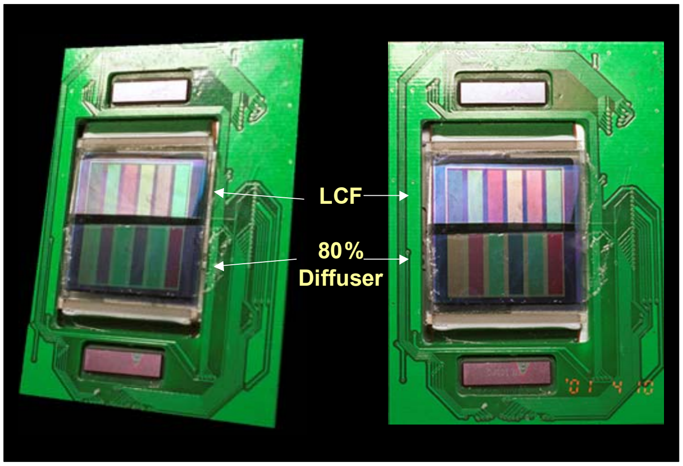
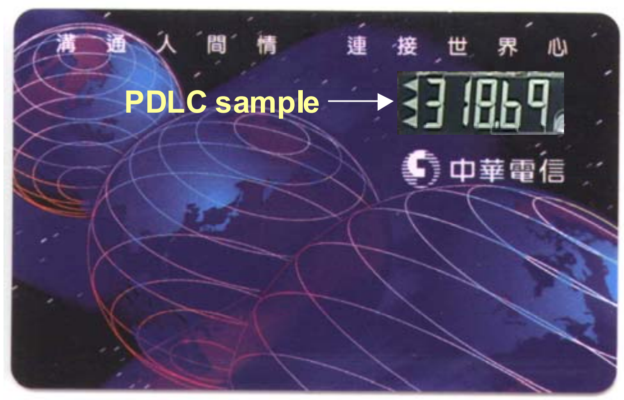


(a)



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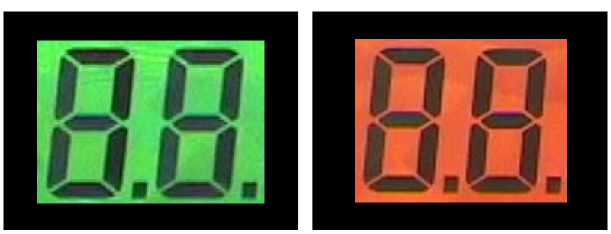

(c)

Fig.8. Sample photographs of (a) color-STN LCD, (b) PDLC, and (c) Ch-LCD. The displays with MAMA-LCF clearly show high image quality.

CONCLUSIONS

The use of MAMA-LCF effectively enhances the display brightness and image quality of the color STN, PDLC and Ch-LCD under ambient light condition. The dispersion, moiré patterns, and parallax are all invisible. The MAMA light control films can be easily fabricated by standard semiconductor processes and injection/stamping molding. By using these well-developed fabrication processes, the designed microlens structure on thin transparent plastic substrate can be produced economically and reproducibly in large volume. The wide spread application of MAMA light control film for reflective LCDs are foreseeable.

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