Applications of multidirectional asymmetrical microlens-array light-control films on reflective liquid-crystal displays for image quality enhancement

Yi-Pai Huang, Han-Ping David Shieh, and Shin-Tson Wu

The multidirectional asymmetrical microlens-array light-control film (MAMA-LCF) is developed for enhancing the image brightness and contrast ratio of various reflective liquid-crystal displays. By use of index-matching material, the interface reflection is greatly reduced. Through optimized designs, the surface-scattering effect is also suppressed; thus the contrast ratio is much enhanced. From experimental results, the MAMA-LCF leads to a ~1.5× gain in brightness over the MgO standard white and a 15:1 contrast ratio for the reflective color super-twist nematic liquid-crystal display, 2.8× MgO and a 23:1 contrast ratio for the polymer-dispersed liquid-crystal, and 2.8× MgO and a 13:1 contrast ratio for the cholesteric liquid-crystal display. Potential applications of this low-cost plastic thin film for reflective liquid-crystal displays are foreseeable. © 2004 Optical Society of America

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1. Introduction

Reflective liquid-crystal displays[1] (LCDs) are widely used in portable personal digital assistants and mobile communications. Varieties of new applications, such as super-twist nematic LCDs[2] (STN-LCDs) for mobile phones, polymer-dispersed liquid crystals[3] (PDLCs) for smart cards, and cholesteric LCDs[4,5] (Ch-LCDs) for electronic books, have been considered. In these applications, low power consumption, high brightness, high contrast ratios, and low cost are critical. However, most reflective LCDs still suffer from inadequate brightness and contrast ratio (CR).

Many methods, for example, laminating front-scattering film[6] on color STN-LCDs, building rough-surface reflectors (bump reflectors)[7] on the bottom substrates of PDLCs, and using single-surface rubbed cells for Ch-LCDs, have been proposed for improving the brightness and the CR. Our group has developed an asymmetrical microlens-array light-control film[8] (AMA-LCF) to enhance the brightness of reflective LCDs. Figure 1(a) depicts the device structure and working principle of the AMA-LCF. Later the concept of the AMA-LCF was extended to multidirectional asymmetrical microlens-array light-control film[9] (MAMA-LCF) to widen the display viewing angle and brightness. As illustrated in Fig. 1(b), by arrangement of microlenses into various orientations, multiple ambient illuminations can be effectively collected and redirected. As a result, the viewing angle is widened; brightness and the CR are enhanced. Additionally, simple fabrication and low cost are the other advantages of the MAMA-LCF. In this paper the performances of MAMA-LCF on three kinds of reflective LCD, color STN-LCD, PDLC, and Ch-LCD, are demonstrated. Through optimized designs, the image quality of these displays can be significantly improved.

2. Reflective Liquid-Crystal Displays with MAMA-LCF

MAMA-LCF with a 100% fill factor was designed for a typical ambient environment to significantly improve the image quality of reflective LCDs. For avoiding color dispersion, the MAMA-LCF structure was modeled as multiple slit gratings[9] and was considered in terms of diffraction angle and intensity. By comparing the intensity of different diffraction orders, we can determine which order is relevant and derive the dispersion angle. Accordingly, the human pupil and the viewing distance determine the

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Y.-P. Huang and H.-P. D. Shieh (hpshieh@mail.nctu.edu.tw) are with Institute of Electro-Optical Engineering, National Chiao Tung University, Hsinchu 30010, Taiwan. S.-T. Wu is with the School of Optics and the Center for Research and Education in Optics and Lasers, University of Central Florida, Orlando, Florida 32816.

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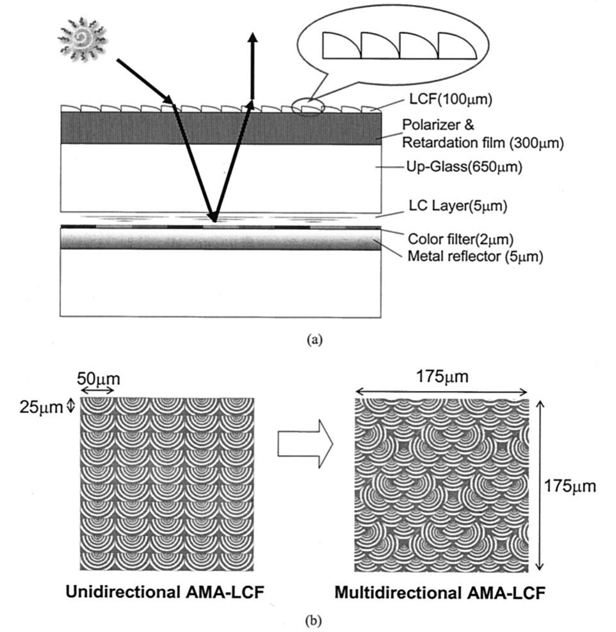


Fig. 1. (a) Panel configuration of a reflective display laminating a light-control film and (b) unidirectional AMA-LCF modified as a multidirectional AMA-LCF for collecting and redirecting multiple ambient illuminations. LC, liquid crystal; LCF, light-control film.

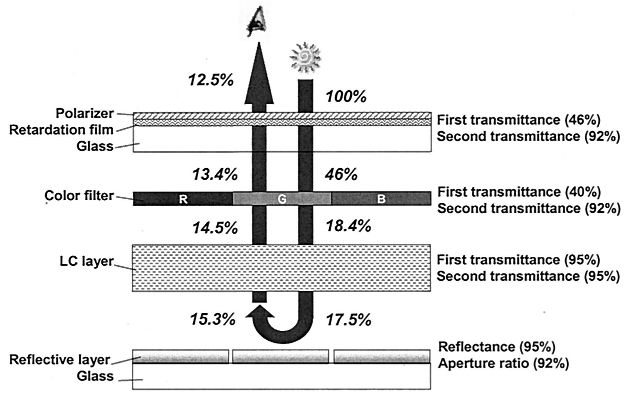


Fig. 2. Estimated reflective light efficiency of a reflective LCD.

minimum grating period of indistinguishable color dispersion that is taken into account in the design of MAMA-LCF.

Furthermore, in this design, the moiré pattern,[9] which might occur when periodic light-control film (LCF) structures and periodic pixels of a color filter are superimposed, was also considered. The moiré pattern can be prevented by one's adopting a specific ratio of the periods of those two structures with a fixed angular difference. Then MAMA-LCF can be designed to have microlenses with multiple orientations, in which each microlens has a different pitch and orientation. From the above calculations, an optimal size and arrangement of microlenses can be determined, so that the MAMA-LCF laminated onto a color STN-LCD can yield high brightness and good contrast without visible color dispersion or the moiré pattern.

Additionally, index matching and surface scattering should also be considered while the LCF is laminated onto a reflective LCD. From Fresnel's equation and Snell's law, the surface reflective ratio[10] between two layers with different refractive indices for the S wave (TE) and P wave (TM) can be respectively shown as Eqs. (1) and (2):

$$R_s = |r_s|^2 = |(\cos\theta - \sqrt{n^2 - \sin^2\theta})/(\cos\theta + \sqrt{n^2 - \sin^2\theta})|^2, \tag{1}$$

$$R_p = |r_p|^2 = -|(n^2\cos\theta + \sqrt{n^2 - \sin^2\theta})/(n^2\cos\theta + \sqrt{n^2 - \sin^2\theta})|^2. \tag{2}$$

Here $n = n_t/n_i$ is the relative refractive index of refraction of the refractive indices of the incident (n_i) and the transmitted (n_t) media and θ is the light incident angle. Therefore the total surface reflective ratio R_{total} is

$$R_{\text{total}} = \sqrt{(I_{is}R_s)^2 + (I_{ip}R_p)^2}/\sqrt{(I_{is})^2 + (I_{ip})^2}, \tag{3}$$

where I_{is} and I_{ip} are the intensities of the incident S and P waves, respectively. Assuming the incident light is unpolarized, then $I_{is} = I_{ip}$. Consequently, R_{total} can be simplified to

$$R_{\text{total}} = \sqrt{(R_s)^2 + (R_p)^2}/\sqrt{2}. \tag{4}$$

For example, with the light illuminated from 30° on a plastic film of refractive index $n = 1.55$, the total surface reflection is 5.15%. Compared with the 12.5% reflective light efficiency of a reflective LCD, as signified in Fig. 2, the surface reflection results in serious degradation to the CR. Additionally, the microlens on MAMA-LCF was approximated by use of a four-step Fresnel lens instead of a traditional curvature lens. Therefore the edge of each step may scatter the incident light, which results in increased dark-state light leakage and a degraded CR. Thus several methods were proposed for laminating the LCF on three kinds of LCD, reflective color STN, PDLC, and cholesteric, to overcome the abovementioned issues.

A. Reflective Color Super-Twist Nematic

The designed patterns and system configuration of the MAMA-LCF on reflective color STN-LCDs are shown schematically in Figs. 1(b) and 3(a), respectively. In a reflective color STN-LCD, the 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, coating an index-matching material on LCF and laminating it below the polarizer, as depicted in Fig. 3(a), is found to greatly reduce the intensity of interface reflection and front-scattering light. As a result, MAMA-LCF that is laminated below the polarizer should be made of a low-birefringence material to avoid the color shift caused by the retardation effect.

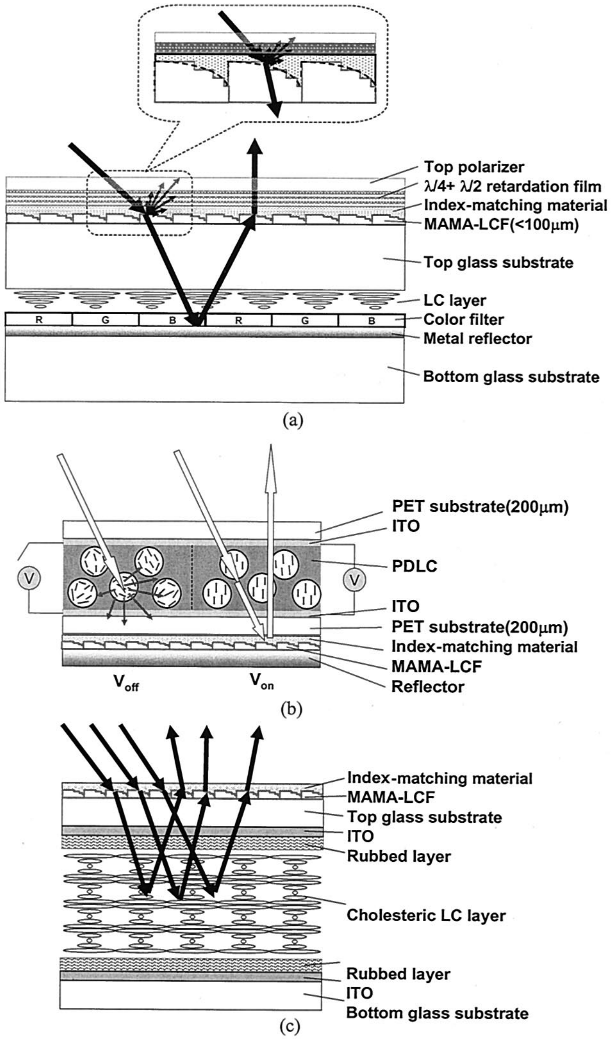


Fig. 3. Schematic plot of the system configuration of the MAMA-LCF on the (a) reflective color STN-LCD, (b) PDLC display, and (c) two-surface rubbed Ch-LCD. PET, polyethylene terephthalate; ITO, indium tin oxide.

B. Reflective Polymer-Dispersed Liquid Crystal

MAMA-LCF is also applicable to the reflective PDLC developed for plastic smart cards. Usually, the MAMA-LCF is laminated on the top surface of the PDLC. Under such circumstances, the film modulates the reflected light from the interface of each layer and deteriorates the blackness of the dark state. Thus the MAMA-LCF coated with an index-matching material is preferably laminated between the bottom substrate of the plastic PDLC panel and the aluminum reflector with an index-matching material coated, as depicted in Fig. 3(b). Moreover, the plastic LCF is flexible and can be easily combined with the plastic PDLC displays.

C. Reflective Cholesteric Liquid-Crystal Display

The Ch-LCD is a candidate for electronic books because of its low power consumption. For a conventional Ch-LCD to achieve a wide viewing angle, only the bottom substrate is rubbed, and the top plate has no rubbing. The liquid-crystal (LC) directors tilt to different angles. These slightly disordered cholesteric layers help to diffuse the reflected light to a wider viewing zone. The trade-off 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. Integrating a MAMA-LCF on the two-surface rubbed cell to widen the viewing angle while preserving high reflectivity will be more appealing for applications. As shown in Fig. 3(c), the MAMA-LCF helps to diffuse light to a larger angle. Moreover, coating an index-matching material on MAMA-LCF can reduce the interface reflections. Benefitting from the LCF, the two-surface rubbed Ch-LCD is expected to exhibit a wide viewing angle and high reflectivity.

3. Experiments

A. Fabrication of MAMA-LCF

The asymmetrical microlens array is implemented with a binary Fresnel microlens structure because of its 100% fill factor and the simple fabrication of the asymmetrical microlens pattern. Furthermore, the binary Fresnel microlens is easily fabricated with standard semiconductor processes of photolithography and reactive ion etching on a Si wafer utilized as a substrate for making a father mold. Then the Si substrate is electroplated with a nickel layer to serve as a mother mold. Next, this Si-based structure is duplicated from the mother mold to a transparent plastic film, such as polyvinyl chloride and arton cyclic olefin copolymers (arton-COCs), by stamp molding. The arton-COC film is used for color STN to avoid the color shift because of its low birefringence.

Table 1. Configuration of Test Panels

Code Name	Type of Test Panel	Index-Matching-Material Coating	Laminated Position of LCF
Bare STN	Color STN	No	Without LCF
STN-A	Color STN	No	Above top polarizer
STN-B	Color STN	Yes	Between top polarizer and top glass substrate
Bare PDLC	PDLC	No	Without LCF
PDLC-A	PDLC	Yes	Between bottom substrate and bottom reflector
Bare Ch-LCD	Ch-LCD	No	Without LCF
Ch-LCD-A	Ch-LCD	Yes	Above top glass substrate

Table 2. Parameters of the Reflective Color STN, PDLC, and Ch-LCD Used

LC Mode	Color STN	PDLC	Cholesteric
LCF	100 μm	100 μm	100 μm
Index-matching material	EGC1700 (3 μm)	EGC1700 (3 μm)	EGC1700 (3 μm)
Polarizer	200 μm	None	None
Retardation film	100 μm	None	None
Substrate	Glass (0.6 mm)	Plastic PET (0.1 μm)[a]	Glass (0.7 mm)
Indium tin oxide (μm)	0.1	0.1	0.1
LC cell gap (μm)	5	6	5
Color filter (μm)	2	None	None
Rubbed layer	Both sides (0.15 μm)	None	Both sides (0.15 μm)
Reflector	Metal reflector	Metal reflector	Cholesteric reflector

[a] Polyethylene terephthalate.

An index-matching material, EGC1700 ($n = 1.38$), is then spin coated on the surface of the plastic film to protect the microlens structure and reduce the surface scattering. From Eq. (4), the surface reflection of the MAMA-LCF ($n = 1.55$) coated with EGC1700 ($n = 1.38$) can be diminished to only 0.41%. Finally, the multidirectional LCF is laminated onto the reflective LCD to realize control of the distribution of the reflected light. By use of these well-developed fabrication processes, a precise micro-optical structure can be produced economically and reproducibly in large volume.

B. Liquid-Crystal-Display Parameters

The configurations and the parameters of the different LCDs laminated with MAMA-LCF are listed in Tables 1 and 2, respectively. Different focal lengths and the lens configuration of the microlens array can be designed with the optical software ASAP. The light-control effect of MAMA-LCF can be optimized for each LCD depending on its specific needs.

C. Evaluation of Morphological and Optical Properties

We evaluated the light-control effect and the contrast improvement of MAMA-LCF by laminating MAMA-LCF on the reflective color STN-LCD, reflective PDLC, and reflective Ch-LCD. To measure the reflective brightness and CR, we fixed a single incident light at −30° as an ambient light and detected the reflected light by using Otsuka LCD evaluator 5100 at effective viewing angles from 0° to 40°. For evaluating the effect of surface reflection, a conoscopic system, ELDIM EZContrast 160R, which can measure a ±80° viewing cone, was used with a −30° illumination.

4. Experimental Results

A. Surface Reflection of MAMA-LCF

To observe the surface reflection induced by MAMA-LCF, we measured test panels of the reflective color STN laminated with MAMA-LCF. The test panels were in a dark state with a collimated light illuminated from −30°; thus the specular reflection occurred at 30°, as the white spots shown in Fig. 4. The reflectivity of the panels were measured and plotted in polar coordinates to reveal the effect of surface reflection. The measured results of the bare STN, STN-A, and STN-B are shown in the left part of Figs. 4(a)–4(c), respectively, and the right part displays photographs of the dark-state images of the three test panels taken from normal viewing angles.

Obviously, both the measured result and the photograph of the bare STN reveal that the panel can

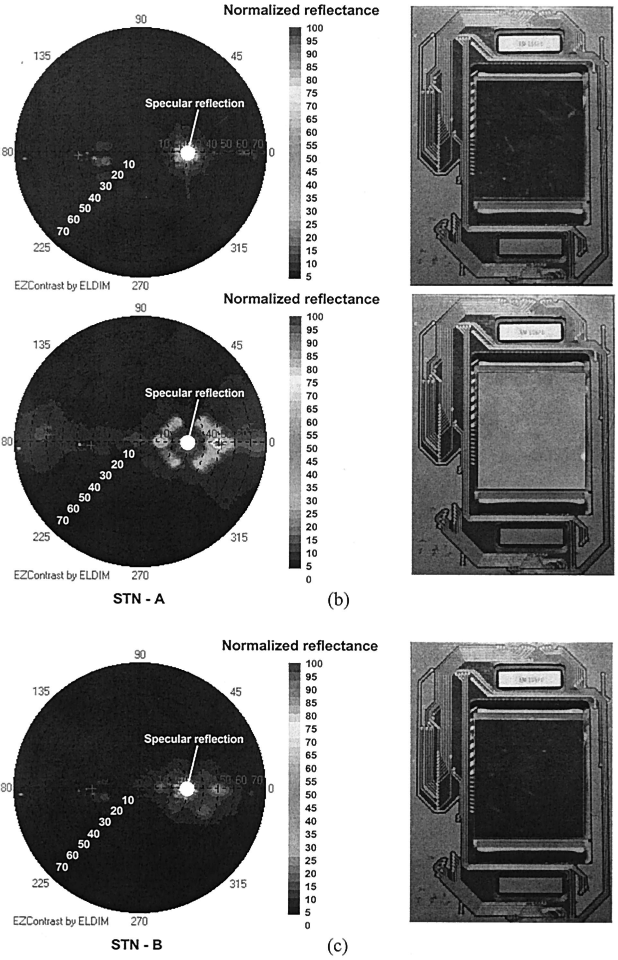


Fig. 4. Measured reflectivity (left part) and photographs (right part) of the dark-state images of the (a) bare STN, (b) STN-A, and (c) STN-B.

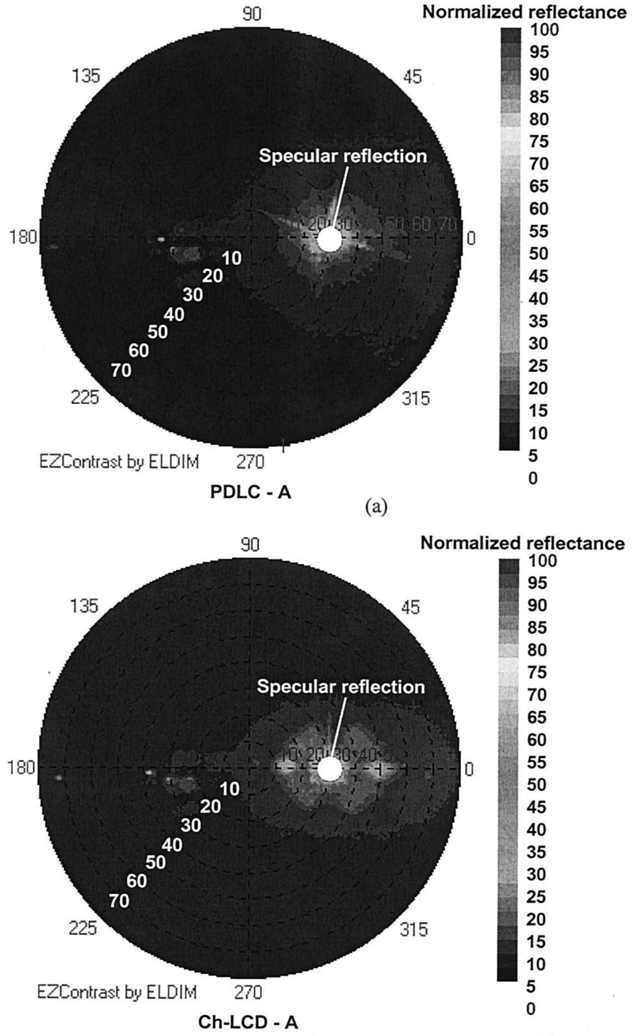
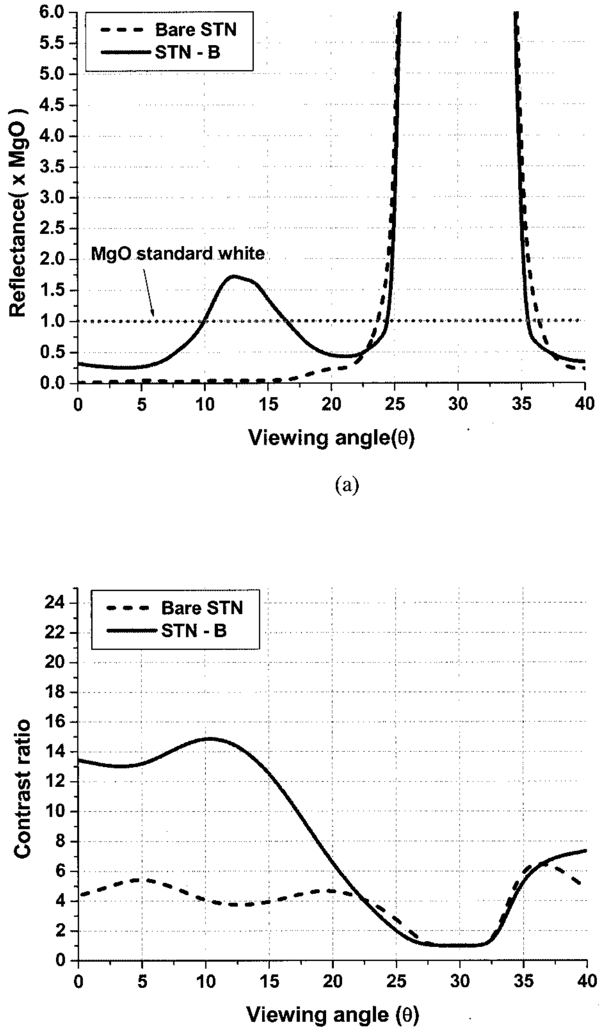


Fig. 5. Measured results of the dark-state reflectance of the (a) PDLC-A and (b) Ch-LCD-A.

display a very dark image in the viewing region. However, from Fig. 4(b), the reflective light of the dark state of the STN-A has a noticeably crescent distribution because the LCF was not coated with an index-matching material; thus the interface reflection efficiency was higher, to 5.15%. The interface reflective light was modified by the Fresnel lenses of the LCF and directed into the viewing region as the crescent distribution to increase the brightness in the dark state of the STN-A, as shown in the photograph in Fig. 4(b). Additionally, the edge of each step of the four-step Fresnel lenses causes surface scattering, as the dark gray area shown in the polar plot of Fig. 4(b), which also degrades the image quality at a large viewing angle. By use of the configuration of the STN-B, in which MAMA-LCF was coated with an index-matching material (EGC1700, $n = 1.38$) to reduce the interface reflection and laminated below the polarizer to decrease the surface scattering, the darkness of the panel was greatly improved, as shown in the photograph in Fig. 4(c).



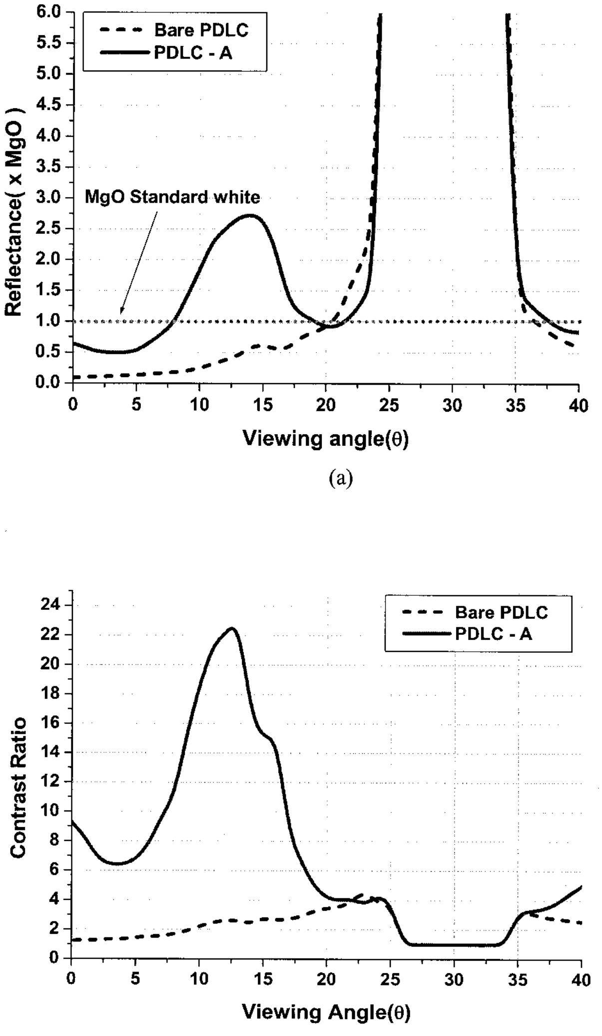
(b)

Fig. 6. Measured (a) reflectivity and (b) CR of the reflective color STN-LCD as a function of viewing angle under illumination from −30°.

MAMA-LCF coated with an index-matching material was also used for the PDLC and Ch-LCD; the measured dark-state reflectance polar plots of the two LCDs are shown in Figs. 5(a) and 5(b), respectively. These two devices are nonpolarized displays; thus the LCF for the PDLC was laminated between the bottom substrate and the reflector to decrease the surface scattering. The reflector of the Ch-LCD, however, is the LC cell itself. Therefore LCF can be added only to the top surface of the Ch-LCD; the interface reflection can be reduced by one's coating the LCF with an index-matching material, yet the surface scattering is slightly visible while the dark-state image is displayed.

B. Image Improvement by MAMA-LCF

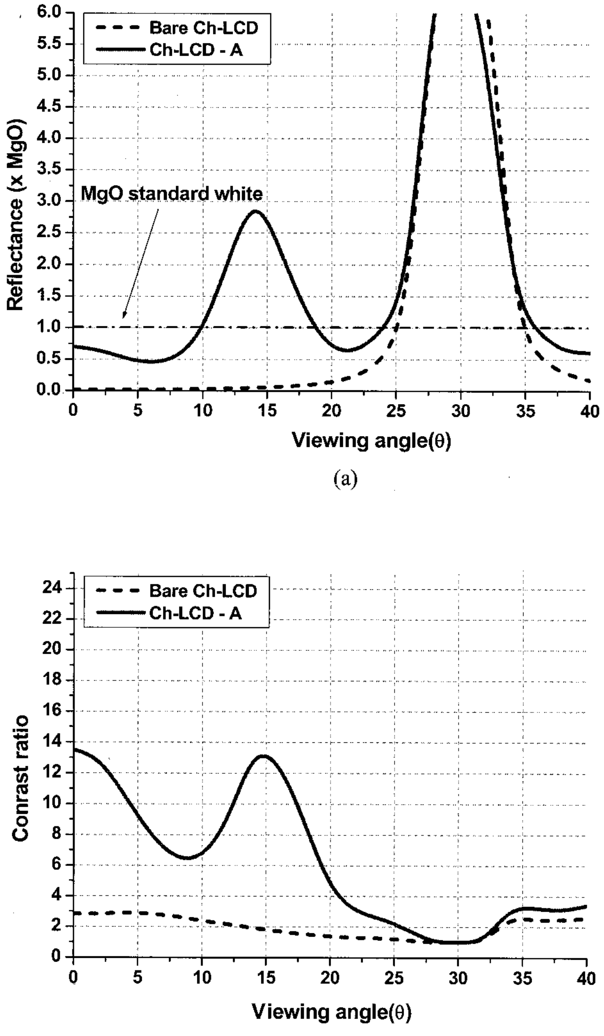
By one's coating an index-matching material on the MAMA-LCF, the intensity of the surface reflection can be much reduced to improve the display quality of



(a)

(b)

Fig. 7. Measured (a) reflectivity and (b) CR of the reflective PDLC as a function of viewing angle under illumination from −30°.



(a)

(b)

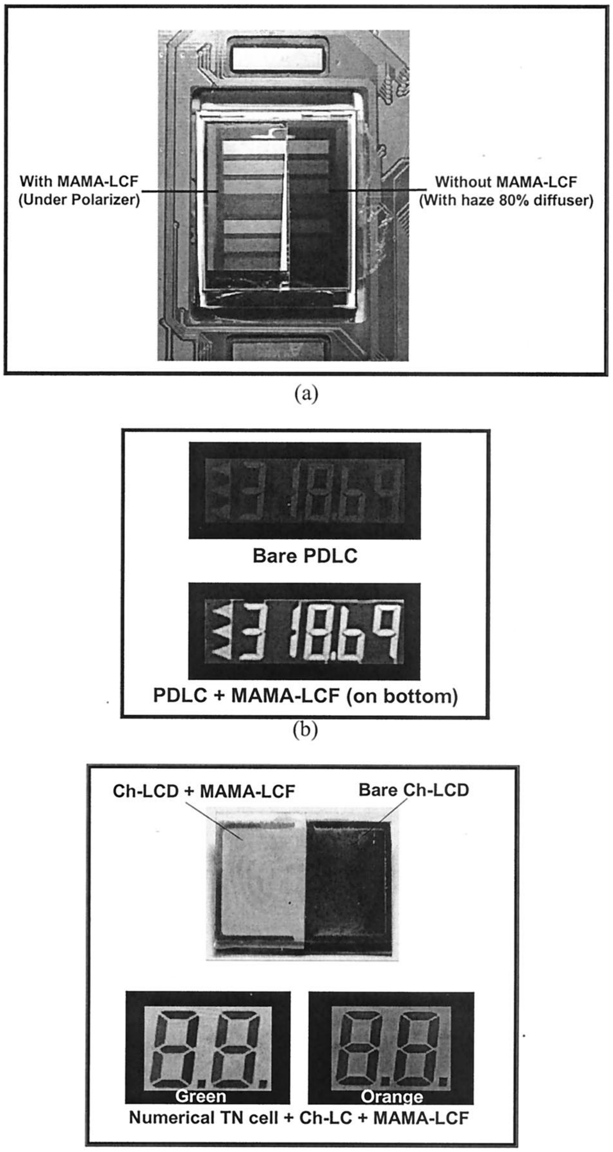
Fig. 8. Measured (a) reflectivity and (b) CR of the reflective Ch-LCD as a function of viewing angle under illumination from −30°.

a dark-state image. Thus the new configurations of the three display panels, STN-B, PDLC-A, and Ch-LCD-A, were measured and compared with the bare test panels. The measured angular-dependent reflectivity and CRs of the reflective color STN, PDLC, and cholesteric panels are shown in Figs. 6–8, respectively. For a collimated illumination from −30°, the specular reflection occurs at 30°. At this angle, although the reflectivity is high, the CR is poor. Adding a MAMA-LCF not only shifts the peak reflectance of the color STN panel from 30° to 15° but also enhances reflectivity by ~1.5× over the MgO standard white [solid curve, Fig. 6(a)]. Because the LCF was coated with an index-matching material, EGC1700 ($n = 1.38$), and laminated below the top polarizer, the surface reflection is reduced and the CR is increased, as shown by the solid curve in Fig. 6(b), where the CR is higher than 10 within viewing angles of 0° to 18° with a peak value of 15. Therefore MAMA-LCF, covered by EGC1700 and adhesive below the top polarizer, can provide an image with a good CR and high brightness in the viewing region.

Similarly, the reflectance profile of a PDLC sample also reveals that laminating the LCF on the bottom side of the reflective PDLC (PDLC-A) yields a very high brightness (2.8× of MgO) with a maximum CR ~23:1 in the viewing angle of 14°, as shown in Figs. 7(a) and 7(b). In the Ch-LCD experiments, two cells using E48 LCs doped with ZLI-811 chiral agent, which has a peak wavelength at green, were used. The back side of each cell was painted black for improving the CR. The MAMA-LCF was coated with EGC1700 and laminated on the top surface of the Ch-LCD cell. Figure 8 plots the measured reflectance and CRs of the two-surface buffed Ch-LCDs with and without MAMA-LCF. The Ch-LCD with LCF (solid curve) shows a higher reflectance in the 0°–20° viewing zone. At 14°, the LCF enhances the display brightness by a factor of 2.8 to that of MgO standard white. Additionally, the CR of the Ch-

LCD with MAMA-LCF, depicted as the solid curve in Fig. 8(b), is increased to 13 at 14°.

Photographs of displayed images in which MAMA-LCF was used on a color STN-LCD, PDLC, and Ch-LCD, taken under ambient conditions, are shown in Figs. 9(a)–9(c), respectively. In a comparison, Fig. 9(a) is the photograph of the STN-LCD with MAMA-LCF (left) and an 80% haze diffuser (right), which is commonly used to enhance the brightness of mobile displays. The photographs of a PDLC with MAMA-LCF and a bare PDLC are shown in Fig. 9(b). Additionally, Fig. 9(c) displays the two-surface buffed Ch-LCD with and without MAMA-LCF and the photographs of MAMA-LCF used on conventional numerical twist nematic panels with injected Ch-LC material, which reflected green and orange colors. The high image quality by the MAMA-LCF on the three different LCDs is clearly demonstrated.



(a)

(b)

(c)

Fig. 9. Sample photographs of the (a) color STN-LCD, (b) PDLC, and (c) Ch-LCD. The displays with MAMA-LCF clearly show much better image quality. TN, twist nematic.

5. Discussion and Expectation

Many image-enhanced components for reflective displays have been proposed and used. These components are generally divided into two categories: diffusive (bump reflector[7] and diffuser[6]) and collective (MAMA-LCF,[9] microslant reflector,[11] and holographic film[12]). The comparison of their respective performances among MAMA-LCF and other components is listed in Table 3. The bump reflector can provide the best image quality with high brightness, a good CR, and a wide viewing angle, yet it requires a complex fabrication process that results in a high cost. A diffuser has the lowest price; nevertheless, its image quality is not as good as other approaches. MAMA-LCF, the slant reflector, and holographic film can display almost the same image quality. MAMA-LCF, however, utilizes a well-developed semiconductor process and stamp molding to reduce the fabrication cycle. Plastic film is used as the substrate; thus the material cost is low. Furthermore, the filmlike component can be laminated on most kinds of reflective display, which extends the competitiveness of MAMA-LCF.

The modified MAMA-LCFs have been demonstrated to increase the image quality of reflection-type display. The lens structure of MAMA-LCF can collect and redirect the reflected light into a lower

Table 3. Comparison of Conventional Image-Enhanced Components Used for Reflective Displays

	Diffusive Type		Collective Type		
Compared Items	Bump	Diffuser	MAMA-LCF	Slant Reflector	Holographic Film
Brightness	High	Low	Very high	Very high	Very high
Contrast ratio	Very good	Poor	Good	Very good	Good
Viewing angle	Very wide	Narrow	Wide	Wide	Wide
Fabrication process	Very complex	Very easy	Easy	Complex	Complex
Fabrication time	Very long	Short	Short	Long	Short
Cost	Very high	Very low	Low	High	High
Applicable displays	TFT,[a] STN, PDLC	STN, PDLC, Ch-LCD	TFT, STN, PDLC, Ch-LCD	TFT, STN, PDLC	TFT, STN, PDLC, Ch-LCD

[a] TFT, thin-film transistor.

viewing region, resulting in a high-brightness image. Nevertheless, such a lens structure also focuses the reflected light to a limited viewing angle, as shown experimentally. To further extend the application for different kinds of reflective LCD, one can also design the LCF by using grating structures that widen the viewing angle, improve the brightness uniformity, and keep the reflectance to approximately 1× MgO.

6. Conclusions

Conventional reflective LCDs are of low brightness and poor contrast ratio. The use of MAMA-LCF effectively enhances the display brightness and contrast of reflective color STN (1.5× MgO, CR ~15), PDLC (2.8× MgO, CR ~23), and Ch-LCD (2.8× MgO, CR ~13) under ambient light conditions. By use of an optimized design, the dispersion, moiré patterns, and parallax, which may be caused by the microcomponents, are all invisible. The surface scattering of MAMA-LCF can also be reduced by coating an index-matching material (EGC1700, $n = 1.38$). The MAMA-LCF can be easily fabricated by semiconductor processes and injection–stamp molding. By use of these well-developed fabrication processes, the designed microlens structure on a thin transparent plastic substrate can be produced economically and reproducibly in large volume.

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