SPECIAL TOPIC — Physical research in liquid crystal

Liquid crystal Fresnel lens display*

Xiao-Qian Wang(王骁乾)[1,†] Srivastava Abhishek Kumar[2], Ming-Wai Alwin Tam(谈明威)[2], Zhi-Gang Zheng(郑致刚)[1], Dong Shen(沈冬)[1,‡], Chigrinov G Vladimir[2], and Hoi-Sing Kwok(郭海成)[2]

[1] *Physics Department, East China University of Science and Technology, Shanghai* 200237, *China*

[2] *State Key Laboratory on Advanced Displays and Optoelectronics Technologies, HKUST, Hong Kong, China*

(Received 18 May 2016; published online 19 July 2016)

A novel see-through display with a liquid crystal lens array was proposed. A liquid crystal Fresnel lens display (LCFLD) with a holographic screen was demonstrated. The proposed display system has high efficiency, simple fabrication, and low manufacturing cost due to the absence of a polarizer and color filter.

Keywords: see-through display, liquid crystal, Fresnel lens array, holographic screen

PACS: 42.70.Df, 42.79.–e, 42.79.Bh, 42.79.Kr **DOI:** 10.1088/1674-1056/25/9/094215

1. Introduction

A see-through display or a transparent display is an electronic display that allows the user to see what is shown on the glass screen while still being able to see through it. This technology that has been around for a decade or two, but only as of 2012 was it being incorporated by companies such as Samsung and Planar Systems into consumer products such as handheld devices, televisions, and other technologies.[1] These screens could be used for augmented reality, a way of enhancing our view of the world with digital images overlaid onto the real world, and other applications such as shopping displays and more sophisticated computer screens.[2–6] The fundamentals of these screens were mostly based on the transparent self-emissive organic materials integrated into the organic light-emitting diode (OLED). However, under high ambient light conditions, the brightness of the OLED had to be set very high in order to maintain the visual performance, this meant high power consumption. Even so, the visual performance was not that satisfactory. Moreover, the manufacturing cost of such kind of screens was expensive and its fabrication process was complicated. A twisted-nematic (TN) cell placed in between two polarizers could also be a candidate for a see-through display, but the polarizers cut down the transmittance by half, which resulted in a poor visual experience. Recently, attention has been given to the polymer-dispersed liquid crystal (PDLC) display, but its high driving voltage made it not that practical. Hence, a see-through liquid crystal display with low manufacture cost, low power consumption, low operating voltage, and acceptable visual performance is in demand.

In this article, a novel see-through display, which was a liquid crystal Fresnel lens display based on an LC Fresnel lens[7–9] array, was proposed and demonstrated. A modern LC fabrication process (i.e., photoalignment technology) was employed.[10,11] This display could be either transparent or translucent depending on which kind of screen was used. The fabrication of the display was quite simple, thus the manufacturing cost was very low. Because sunlight was optionally used as a backlight, it had much less power consumption as compared with the conventional displays. Therefore, this type of display is very promising.

2. Methodology

The configuration of a liquid crystal Fresnel lens display (LCFLD) is shown in Fig. 1. The LCFLD comprises a liquid crystal Fresnel lens array, a thin film transistor (TFT) array, a specific screen, and a light-emitting diode (LED) array/other quasi-collimated backlighting systems. On a sunny day, sunlight is used as the backlight for the LCFLD, as shown in Fig. 1(a). On a day lacking sufficient sunlight or at night, an LED array with a small aperture ratio is utilized as the backlight for the LCFLD, as shown in Fig. 1(b).

Due to the small aperture ratio, the LED array seems transparent when it is switched off. Other quasi-collimated backlighting systems that uniformly shine on the LC Fresnel lens array can also be used for the LCFLD. The liquid crystal Fresnel lens that is individually controlled by the TFT converges light to a high-intensity tiny spot on the screen. Because of the lens focus effect, the tiny bright spot is surrounded by a round shadow where a very small portion of the light can reach. When the LC Fresnel lens is switched off, low-

*Project supported by Partner State Key Laboratory on Advanced Displays and Optoelectronics Technologies HKUST, China, the National Natural Science Foundation of China (Grant Nos. 61435008 and 61575063), and the Fundamental Research Funds for the Central Universities, China (Grant No. WM1514036).

†Corresponding author. E-mail: xqwang@ecust.edu.cn

‡Corresponding author. E-mail: shen@ecust.edu.cn

© 2016 Chinese Physical Society and IOP Publishing Ltd

intensity light is uniformly projected on the screen. The contrast is caused by the light intensity distribution that is mentioned above, this helps to display the information content on the screen. In the primary design, a holographic screen with a holographic film (i.e. transparent projection film) array is employed.

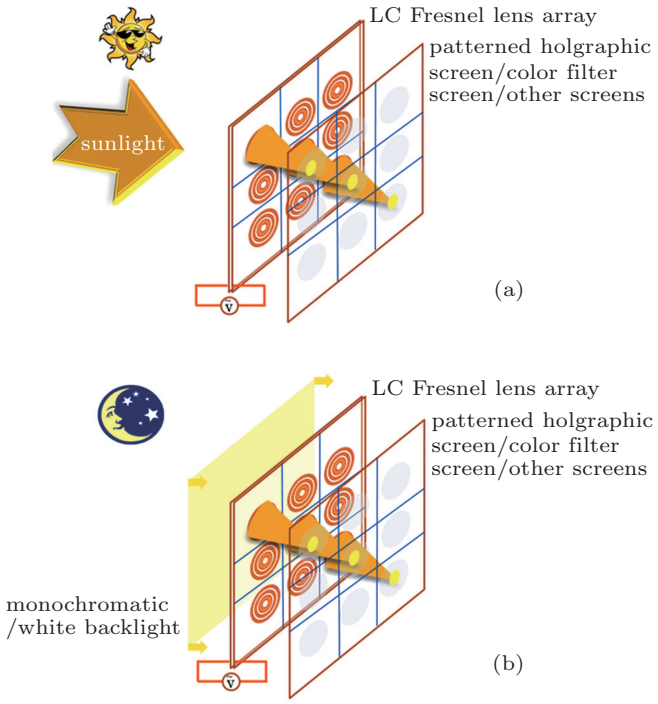


Fig. 1. (color online) Schematics of liquid crystal Fresnel lens display: (a) LCFLD in day mode, (b) LCFLD in night mode.

By using a 10×10 LC Fresnel lens array, the LCFLD can display letters "S", "K", and "L" on the screen as shown in Fig. 2. The bright green area represents the lens-on region and the light green area stands for the lens-off region.

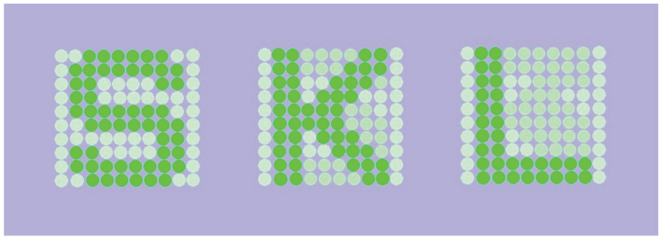


Fig. 2. (color online) Displaying letters "S", "K", and "L" by using three 10×10 LC Fresnel lens arrays.

3. Results

In the experiment, the LC Fresnel lens array was fabricated with the help of photoalignment technology. SD1 (from DIC company, Japan) was utilized as the photoaligning material and coated onto the glass substrates. And the patterned alignment was arranged in the form of specific Fresnel zone lens arrays for displaying letters "S", "K", and "L". Note that SD1 as a photoalignment material in the experiment was optically rewritable, and it could not maintain the alignment under the sunlight or intense LED light for long, therefore it was very important to improve the photostability of SD1 once the patterned alignment was made. The investigation on the SD1 stabilization was in progress and some feasible methods might be worked out soon. The cell gap and the birefringence of the LC cell satisfied the half-wave condition for the green light, and the diffraction efficiency of the polarization-independent LC Fresnel lens approached its theoretical limit $\sim 40\%$. In principle, the Pacharatnam–Berry (PB) phase liquid crystal lens could substitute for the LC Fresnel lens in this design, but the efficiency would be enhanced by $\sim 10\%$ because the PB phase LC lens was a polarization-dependent element. A 532 nm laser with a divergence angle of 15° and a beam expander were employed as the backlight and an LCFLD with a translucent screen was used to display information. The LCFLD was controlled by two uniform indium-tin oxide (ITO) layers on two respective glass substrates, and it displayed the letter "K" without external electric field as shown in Fig. 3(a). The contrast ratio (CR) for each pixel of the LCFLD was measured to be larger than 10:1 according to the definition of $\mathrm{CR} = I_{\mathrm{brightest}}/I_{\mathrm{darkest}}$. Actually any light, object or scene from behind the back of a see-through display would influnce the visual performance and form a dynamic contrast ratio. Due to the non-uniformity of the laser backlight, the contrast ratio in the marginal area was much better than that in the center, but it could be improved by using a collimator. When a small voltage was applied to the LCFLD, all of the liquid crystal molecules tended to be homeotropically aligned, thus the letter "K" disappeared, as shown in Fig. 3(b).

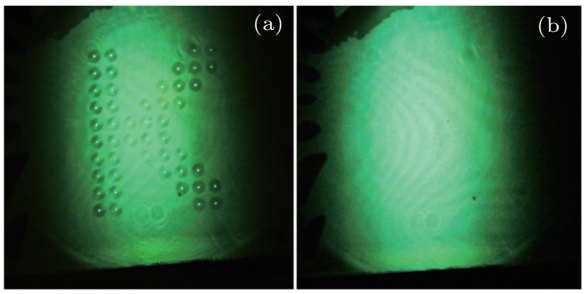


Fig. 3. (color online) LCFLD displaying (a) letter "K" and (b) blank.

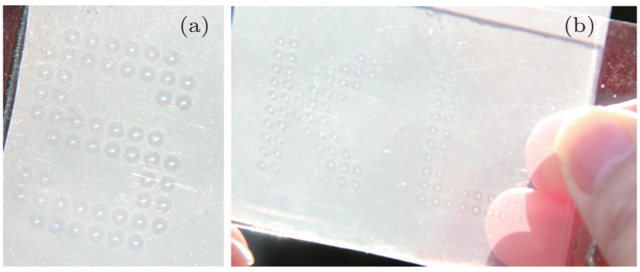


Fig. 4. (color online) LCFLD with holographic screen: (a) letter "S" was displayed with a whitish background, (b) two fingers could be seen from behind the LCFLD.

By using various types of screens and adjusting the distance between the screen and the LC Fresnel lens array panel, a variety of LCFLDs can be formed. Sunlight was used as the backlight and a uniform holographic screen with transparency of 90% was placed at the focal plane of the LC Fresnel lens array, as shown in Fig. 4. A letter "S" was displayed with a whitish background (Fig. 4(a)). The letters "K" and "L" were displayed as shown in Fig. 4(b), meanwhile two fingers could be seen from behind the LCFLD. Because the distance between the sun and the earth is much larger than the size of the earth, sunlight can be treated as the quasi-collimated light which meets the requirement for the LCFLD.

4. Conclusion

To increase the contrast ratio and obtain a better performance from the LCFLD, the specific screen should be further designed and improved. The LCFLD is a novel display that simultaneously gets rid off the polarizer and color filter and it can be used as a smart window. It is also an energy-saving technology because it can optionally make use of the sunlight. The fabrication process of the LCFLD is simple, hence it results in low manufacturing costs. This is the starting line for the LCFLD, even though it has some drawbacks at the current stage. The LCFLD is promising and is worth more investigation.

References

[1] http://www.youtube.com/watch?v=3tsfWRDUM94 2012

[2] Kiyokawa K, Kurata Y and Ohno H 2000 *Augmented Reality 2000 (ISAR 2000). Proceedings IEEE and ACM International Symposium on IEEE* **99** 60

[3] Kuo H P, Hubby L M, Jr. Naberhuis S L and Birecki H 2011US Patent 20110157708 A1

[4] Liu J Q and Sun X D 2006 US Patent 7090355 B2

[5] Liu S, Hua H and Cheng D 2010 *IEEE Transactions on Visualization and Computer Graphics* **16** 381

[6] Kim D, Kim K H, Kim S J, Kim J H, Kim T, Park S, Beon B H, Shin N and Lee S 2013 US Patent 20130107160 A1

[7] Wang X Q, Srivastava A K, Chigrinov G V and Kwok H S 2013 *Opt. Lett.* **38** 1775

[8] Wang X Q, Fan F, Du T, Tam A M W, Ma Y, Srivastava A K, Chigrinov G V and Kwok H S 2014 *Appl. Opt.* **53** 2026

[9] Srivastava A K, Wang X Q, Gong S Q, Shen D, Lu Y Q, Chigrinov G V and Kwok H S 2015 *Opt. Lett.* **40** 1643

[10] Wang X Q, Shen D, Zheng Z G and Kwok H S 2015 *Chin. J. Liq. Cry. Disp.* **30** 737

[11] Hu H C, Wei B Y, Hu W and Lu Y Q 2013 *Chin. J. Liq. Cry. Disp.* **28** 199