A Polymer Lens Embedded 2D/3D Switchable Display with Dramatically Reduced Crosstalk

Ruidong Zhu[1], Su Xu[1], Qi Hong[1], Shin-Tson Wu[1], Chiayu Lee[2], Chih-Ming Yang[2], Chang-Cheng Luo[2] and Alan Lien[3]
[1]College of Optics and Photonics, University of Central Florida, Orlando, Florida
[2]China Star Optoelectronics Technology, Guangdong, China
[3]TCL Corporate Research, Guangdong, China

Abstract
We demonstrate a twist-nematic liquid crystal cell integrated with a polymeric micro lens array. The device has the advantage of fast response time and low operating voltage. The lens is inserted into a Ultra High Definition (UHD) 2D/3D switchable display, after analyzing the crosstalk of the system, the double lens structure is proposed, which is proved to be highly efficient in reducing the crosstalk.

Author Keywords
Polymer lens; adaptive optics; 3D display; crosstalk analysis.

1. Introduction
Two-dimensional/three-dimensional (2D/3D) switchable autostereoscopic display has great potential in both home entertainment and scientific imaging. Typical methods to achieve autostereoscopic display are parallax barrier, liquid crystal (LC) lens and integral imaging [1]. Among all the feasible methods to achieve 2D/3D switchable autostereoscopic display, the LC lens approach is most promising as it has high optical efficiency and is suitable for both mobile displays and large display panels. Conventional LC lens used in 2D/3D switchable autostereoscopic display usually suffers from sluggish response time and high operating voltage [2] because of the thick cell gap. As for the display system, the bottleneck of the lens based 2D/3D display is crosstalk [3] and severe resolution loss in 3D mode [4], which will greatly degrade the image quality.

Recently, with the emerging of Ultra High Definition (UHD) display, the resolution loss of the display can be greatly reduced. But the problem of response time, operating voltage and crosstalk remains. In this paper, firstly a twist-nematic (TN) cell integrated polymeric lens is presented and the experimental results indicate the lens can be switched between focusing (f=3.73mm) and non-focusing state at a response time of ~10ms, which is at least 10X faster than that of a conventional LC lens. The operating voltage of the lens is ~5V. Then lens is embedded into a 55'' Ultra High Definition (UHD) display system and its crosstalk is analyzed. The crosstalk of the system is dramatically reduced by our proposed double lens structure.

2. The polymeric lens structure
The proposed structure is depicted in Figure 1, when no voltage is applied on the TN cell (Fig. 1(a)), the linearly polarized incident light is rotated by 90º, because of the orientation of the polymeric lens, the light works as o-ray and will not be focused. When a relatively high voltage (~5V) is applied on the TN cell, the polarization rotation effect vanishes, as the LC directors are reoriented along the electrical field. The beam acts as e-ray and is thus focused (Fig. 1(b)).

Instead of tuning the LC lens directly, our polymeric lens is actuated indirectly by the TN cell. This approach helps us to overcome the problems of sluggish response time and high driving voltage.

The fabrication process of the polymeric lens is explained in detail in Ref. 5. For the polymeric lens, the LC/monomer mixture used here is 20wt% BL003 (Δn=0.261, n_o=1.531, $\Delta\varepsilon$=17) and 80wt% RM257 (n_o=1.508, n_e=1.687, $\Delta\varepsilon$=-1.5). At room temperature, this mixture has a $\Delta\varepsilon$ of ~2.2. The cell gap of the polymer lens is 71μm. The TN cell is filled with E7 LC mixture (Δn=0.225, viscosity=39 cP, $\Delta\varepsilon$=13.8) and the cell gap is 5μm. Under 5-V driving voltage the non-focusing to focusing time is measured to be 3.7 ms while the focusing to non-focusing time (the relaxation time) is 13 ms. These results are at least 10X faster than that of a conventional LC lens.

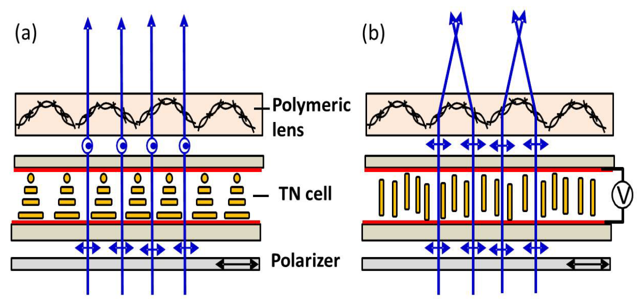

Figure 1. (a) The non-focusing state and (b) focusing state of the proposed TN cell integrated polymer lens.

Figure 2 shows the experimental results of the polymeric lens we fabricated. To measure the focal length of the polymeric lens, we observe the interference pattern under polarized optical microscope at 55Vrms, as is shown in Figure 2(a). The rubbing direction is set at 45° with respect to the optical axis of the polarizer. The measured focal length is ~3.73mm [2] and we can fine-tune it to 4-mm by reducing the applied voltage during UV curing. The cell is then rotated by another 45˚ so that its rubbing direction was parallel to the optical axis of the polarizer. A very dark state is obtained [Fig. 2(b)], and the only light leakage comes from the spacers. Parallel focused lines are clearly observed [Fig. 2(c)] with the analyzer removed. When the cell is rotated by 90˚, i.e., its rubbing direction is perpendicular to the optical axis of polarizer, a bright uniform texture is observed [Fig. 2(d)]. As explained before, the polymeric film presents uniform refractive index to the o-ray. These experimental results demonstrate that our lens structure can be switched between focusing and non-focusing states, namely 3D and 2D mode.

ISSN 0097-966X/14/4503-11363-$1.00 © 2014 SID

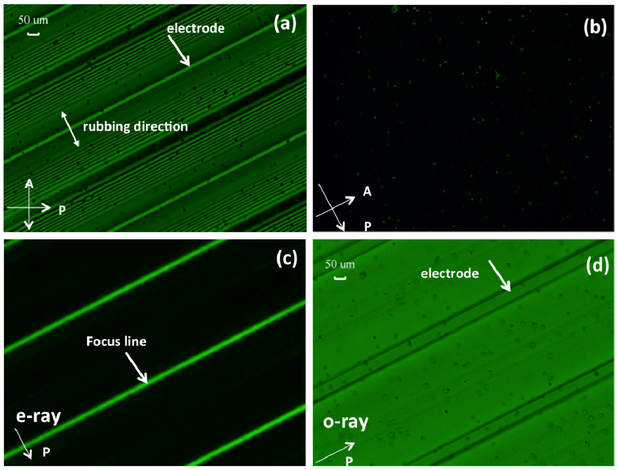

Figure 2. (a) Interference patterns observed under POM after UV curing (b) dark state observed under POM (c) parallel focus lines observed with no analyzer, and (d) uniform bright state observed with no analyzer.

3. Crosstalk reduction of the display system

The polymer lens array can be translated into an equivalent solid lens array according to the equal phase retardation assumption [4], the polymer lens array integrated into a 9-view 55'' 2D/3D switchable UHD display, the parameter of the display panel is listed in Table 1 [6]. As is mentioned in Section 1, even though the resolution in 3D mode is degraded to 1280×720 (720P), such resolution is still acceptable in most cases.

Table 1. Parameters of the autostereoscopic display

Setup	Specification	Characteristic
Display Panel	Resolution	3840×2160 (UHD)
	Size	55''
	Pixel Dimension	315μm×315μm
	Pixel density	80PPI
Lenticular Lens	Lens Pitch	466μm
	Focal Length (*f*)	3.99mm
	Lens Thickness	80 μm
	Slanted Angle	9.46°
Autostereoscopic Display	Viewing Distance	2.48m
	Number of Views	9
	Interval of Viewpoints	32.5mm

The crosstalk of the system is defined as the light illuminance penetrated from the adjacent view into contemporary viewing zone at the sweet spot (best viewing position) [7], as is illustrated in Fig. 3(a). Figure 3(b) is the alignment of the display panel and the polymer lens array, the slanted lines is the boundary of the polymer lens whereas the numbers indicate View numbers. It is obvious that for view 5, the majority of the light leakage comes from view 4 and view 6, while the minority of the light leakage comes from view 3 and view 7. Figure 3(c) proves this concept and we can also deduce an average view-to-view crosstalk of 34% from the normalized illuminance distribution, such severe crosstalk indicates degraded image quality and it is very likely for viewers to feel dizzy.

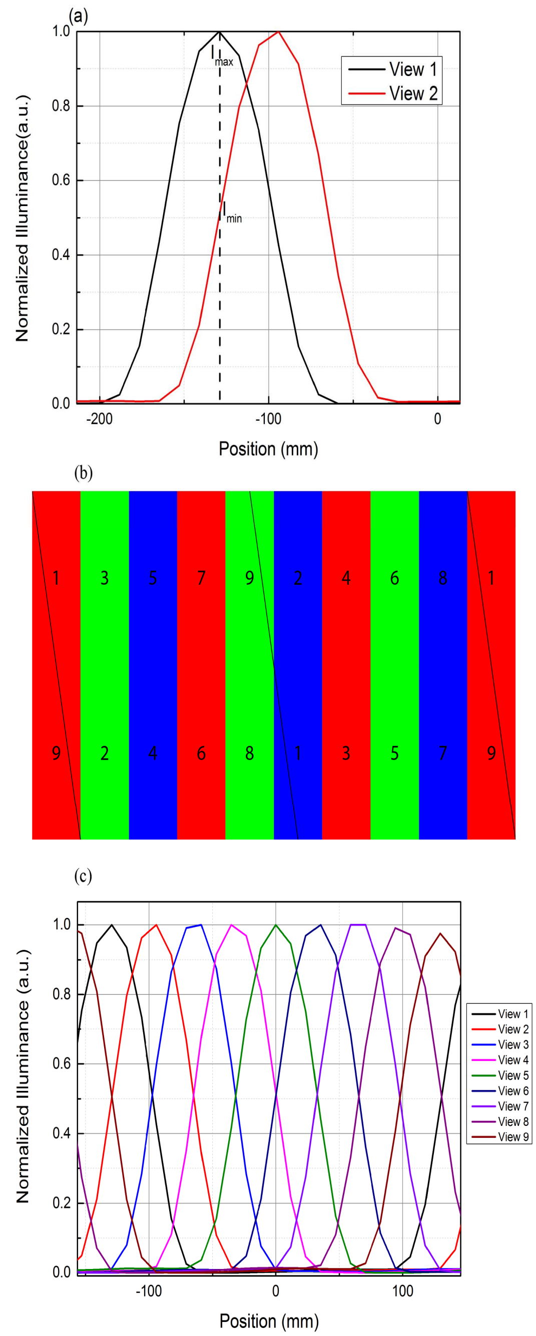

Figure 3. (a) Definition of crosstalk, (b) the alignment between the display panel and the slanted polymeric lens array, and (c) normalized illuminance distribution of the display.

To reduce the crosstalk of the system, unique pixel design is a most straightforward method. Considering the pixel design of the display panel depicted in Fig. 4(a), the aperture ratio of the system is 48.7%, which is already optimized to eliminate crosstalk. However, as can be seen from the normalized illuminance distribution in Fig. 4(b), the average view-to-view crosstalk is 16.7%, which is still too high for commercial products.

Besides pixel design, many other approaches have been proposed to reduce the crosstalk of the system, such as light-blocking photomask and fine-tuning of the lens profile. However, the former suffers from large optical efficiency loss while the latter is quite delicate and usally requires complicate structures [4].

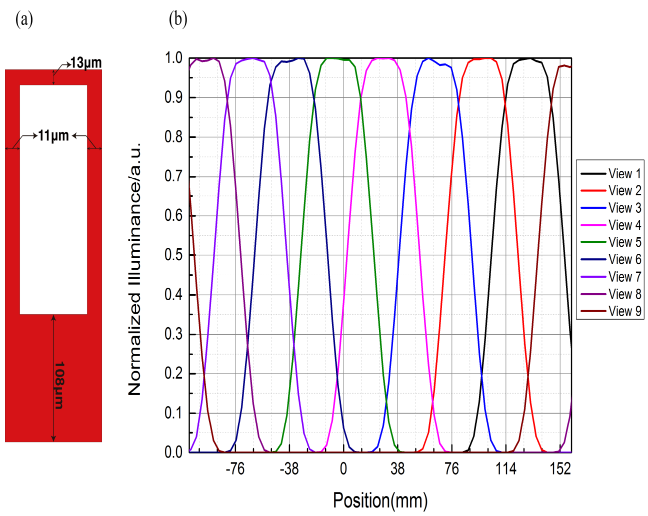

Figure 4. (a) Pixel dimension (AR=48.7%) and (b) normalized illuminance distribution.

In this paper, we propose the double lens structure to reduce the crosstalk of the system, as is shown Fig. 5(a). the concept is quite straightforward, the first lens array (focal length of 1mm) is placed 3mm in front of the display panel, and the second lens array of 4mm focal length is located at 5.5mm away from the first lens array. Again, the viewing plane is 2480mm away from the display panel. The first lens array works as a “shrinking” lens to reduce the effective pixel dimension of the display, while the second lens array acts as a focusing lens array to achieve 3D effect. The normalized illuminance distribution is shown in Fig. 5(b). At the sweet spot, the light leakage from adajacent views is dramatically reduced, and the average viewing zone width is 32mm. The trade-off of the approach is that at the sweet spot the illuminance distribution is not as flat as that shown in Fig. 4(b). A steeper illuminance distribution indicates that the moving freedom is limited, but at the sweet spot the image quality is greatly enhanced.

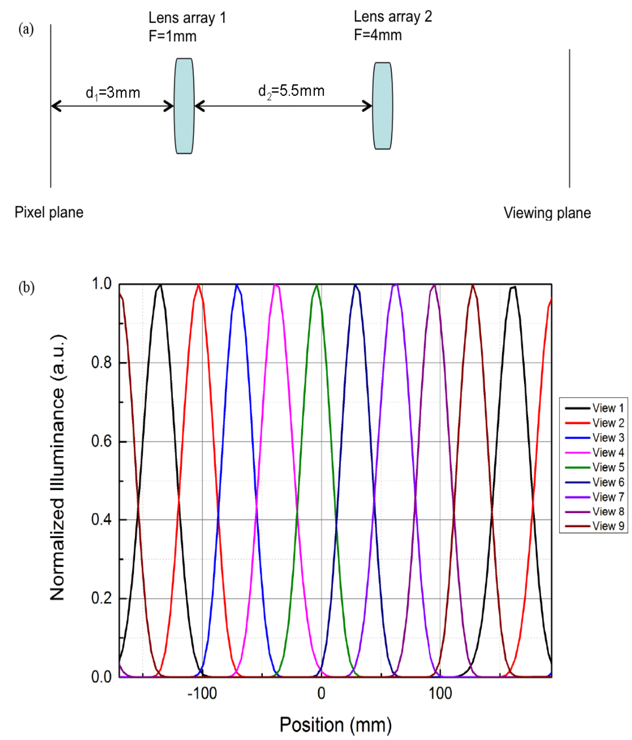

Figure 5. (a) Schematic setup of the double lens structure and (b) normalized illuminance distribution of the double lens structure.

The main concern of the double lens approach is that the optical path of the system (8.5mm) is a little bit too long for practical application. However, in a real system many other components are implanted in the system, such as glass substrates and polarizers, which can reduce the real path length because of the relatively large refractive index. Moreover, the required optical path length of the display modules can be reduced further by using a smaller F# lens array. For example, if the focal length of the first lens array can be reduced to 0.5 mm (F# 4.76), then the total optical path length can be reduced from 8.5 to 6.25 mm (d1=1.5 mm and d2=4.75 mm). This is a 26% improvement in system compactness over what we demonstrate in Fig. 5. Better double lens structure can be designed if we follow the principles below: the first lens array is employed to decrease the effective pixel size of the display panel, and the second lens array is utilized to achieve 3D effect.

4. Impact

We examine contemporary LC lens based 2D/3D switchable display at both the component level and the system level. At the component level, we propose a TN cell actuated polymeric lens, whose focal length can be switched from infinity to ~4mm with a response time is about 10ms, which is at least 10X faster than a conventional LC lens. The driving voltage is kept low at 5V. And if the thin cell approach is utilized, the cell gap of the TN cell can be reduced, which enables an even faster response time (~1ms). At the system level, the polymeric lens array is then integrated into a 55’’ UHD display system and the system crosstalk is analyzed in detailed. The double lenses structure is proposed to reduce the crosstalk of the system from 16.7% to 3%, which is promising for commercial products.

5. Acknowledgments
The authors are indebted to Y. Liu and Z. Luo of UCF for thoughtful discussion and China Star Optoelectronics Technology for financial support.

6. References
[1] G. J. Woodgate and J. Harrold, "Key design issue for autostereoscopic 2-D/3-D displays," Journal of the Society for Information Display **14(5)**, 421–426 (2006).

[2] H. Ren and S. -T. Wu, "Adaptive liquid crystal lens with large focal length tunability," Optics Express **14**, 11292-11298 (2006).

[3] W. X. Zhao, Q. H. Wang, A. H. Wang, and D. H. Li, "Autostereoscopic display based on two-layer lenticular lenses," Optics Letter **35**, 4127-4129 (2010).

[4] R. Zhu, S. Xu, Q. Hong, S. –T. Wu, C. Lee, C. –M. Yang, C. –C. Lo, and A. Lien, "Polymeric-lens-embedded 2D/3D switchable display with dramatically reduced crosstalk," Appl. Opt. **53**, 1388-1395 (2014).

[5] H. Ren, S. Xu, Y. Liu and S. –T. Wu, "Switchable focus using a polymeric lenticular microlens array and a polarization rotator," Opt. Express **21**, 7916-7925 (2013).

[6] J. H. Jung, J. Yeom, J. Hong, K. Hong, S. W. Min, and B. Lee, "Effect of fundamental depth resolution and cardboard effect to perceived depth resolution on multi-view display," Opt. Express **19**, 20468-20482 (2011).

[7] C. –H. Chen, Y. –P. Huang, S. –C. Chuang, C. –L. Wu, H. –P. D. Shieh, W. Mphepö, C. –T. Hsieh, and S. –C. Hsu, "Liquid crystal panel for high efficiency barrier type autostereoscopic three-dimensional displays," Appl. Opt. **48**, 3446-3454 (2009).