Status and prospect of 3D/2D convertible displays

Byoungho Lee*, Heejin Choi and Yunhee Kim
School of Electrical Engineering, Seoul National University
Kwanak-Gu Shinlim-Dong, Seoul 151-744, Korea

ABSTRACT

The three-dimension (3D) to two-dimension (2D) convertibility of display hardware described in this paper is an essential factor in the commercialization of a 3D display. The liquid crystal (LC), which is a suitable material with its optical anisotropy and electric properties, is widely used for various 3D/2D convertible display techniques. There are three kinds of autostreoscopic 3D/2D convertible techniques – the LC lenticular lens, the LC parallax barrier, and integral imaging. The techniques are on their ways for continuing development and improvement. In this keynote paper we summarize the principle and status of the techniques.

Keywords: Three-dimensional display, convertible display, autostreoscopy, lenticular lens, parallax barrier, integral imaging

1. INTRODUCTION

In recent years, the two-dimensional (2D) display technology has been rapidly developed and 2D display system is now widespread among the general public. With this success of 2D flat panel display systems, people now became to expect the emergence of other display systems like three-dimensional (3D) display systems, interactive display systems or other functional display systems. Many researches are now on-going for the purpose, especially for 3D display systems.

For 3D display systems, especially, for 3D television systems, it is essential for them to have convertibility between 3D mode and 2D mode. There are several reasons why the convertibility is important. The most important reason is that if a 3D television system is not convertible with a 2D television, it cannot penetrate into the current display market and so, cannot be commercialized. Another reason is that, in general, if we want to display 3D images, we need to sacrifice some quality of 2D images like image resolution. Hence observers should be provided with the option of switching between 2D and 3D modes of display. The third reason is that there exist more 2D contents than 3D contents. Therefore 3D/2D convertibility is an essential for commercializing the 3D television systems or 3D cellular phones.

From the technical viewpoint for realization of a 3D/2D convertible display, the material for implementing 3D/2D convertible display systems is expected to have the following properties: (1) The material should have some optical anisotropy for 3D/2D conversion. (2) The material of the devices stacked or added for 3D/2D conversion functionality should be transparent (low light loss) for visible light. (3) The material should be controlled electrically. For the above requirements, liquid crystal (LC) is a useful material which can satisfy all of these properties. Regarding properties (1) and (3), the LC is an appropriate birefringence material that can be controlled with bias voltage. As a result, most of the 3D/2D convertible techniques adopt an LD display (LCD) technology for their realization. In this paper, three kinds of 3D/2D convertible techniques using the LCD technique will be explained and summarized.

2. THE LC LENTICULAR LENS TECHNIQUE

LC lenticular lenses use the optical birefringence of the LC. Two kinds of LC lenticular lens methods are introduced in this section. One method uses fixed-state LC lenses and the other changes the state of the LC.

2.1 The solid phase LC lenticular lens method

In the solid phase method developed by Ocuity Ltd., the state of the LC lenticular lens does not change and the different polarization of light is chosen so that the light feels or does not feel the existence of the lens. The structure of the solid

* Correspondence: E-mail: byoungho@snu.ac.kr ; www: http://oeqelab.snu.ac.kr ; Tel: +82-2-880-7245; Fax: +82-2-873-9953

Three-Dimensional TV, Video, and Display VI, edited by Bahram Javidi, Fumio Okano, Jung-Young Son,
Proc. of SPIE Vol. 6778, 677803, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.741649

phase method and its principle in 2D and 3D modes are shown in Fig. 1[1, 2]. It is composed of a display panel, LC lenses, a refractive medium, an electrical polarization switch, and a polarizer. The polarization switching is needed to change the polarization. In the 3D mode, the horizontal polarized light component is used. It feels the refractive index of the LC lens, which is higher than the refractive index of the outside medium. In this situation, light rays are refracted as shown in Fig. 1. The images are displayed by the principle of a lenticular 3D display. On the contrary, in the 2D mode, the vertical polarization component of the backlight is selected. This makes the light through the lens feel the same refractive index as that of the outside medium. Hence no refraction occurs. In this situation, the polarization of the output light is not matched with the axis of the polarizer. The polarization rotator (polarization switch) rotates the polarization direction of the light by 90 degrees.

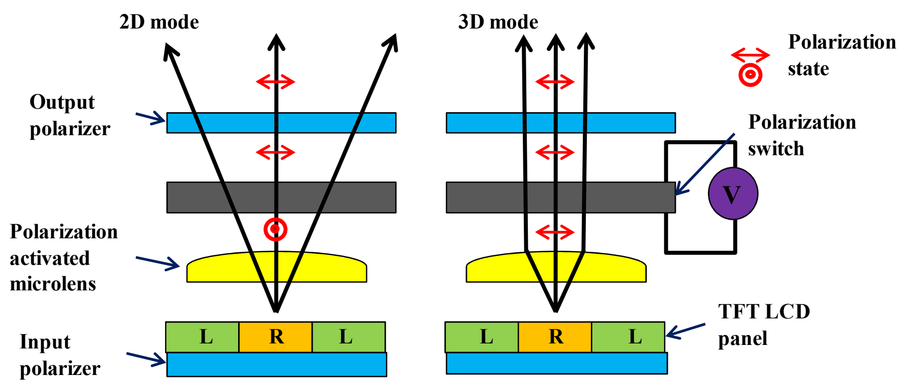


Fig. 1. The principle and structure of the solid phase LC lenticular lens

2.2 The LC active lenticular lens method

The LC active lenticular lens, developed by Philips, is an active device which can function as a lens or not[3]. The principle uses the optical property of the LC of having different refractive indexes depending on its state. The structure and principle of the LC active lenticular lens method is shown in Fig. 2. Each lenticular lens is filled with LC. Outside of the lens, there is a replica which has the same refractive index as that of the LC when the bias voltage is applied. The indium tin oxide (ITO) electrodes are positioned around it to provide the control voltage. In the 3D mode, no voltage is applied to the electrode and there is an index difference between the LC and the replica. In this case, polarized light is used that feels the extraordinary refractive index of the LC in the lens. As a result, the 3D image can be formed through the LC active lenticular lens as shown in Fig. 2(a). In the 2D mode, with appropriate voltage, the index difference between the LC and the replica is vanished and the LC active lenticular lens cannot perform any role of a lens. Therefore, the observer can see the 2D images on the display panel without any distortion.

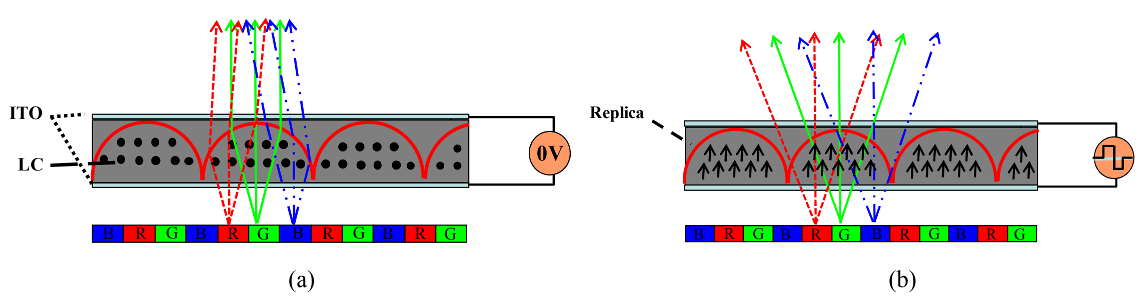
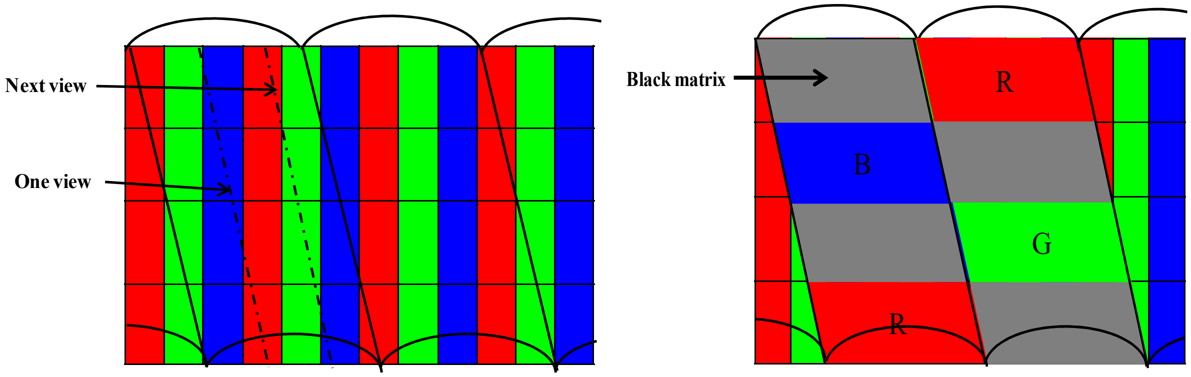


Fig . 2. The principle and the structure of the LC active lenticular lens: (a) 3D mode and (b) 2D mode

In conventional 3D systems with parallax barriers or normal lenticular lenses, only the horizontal parallax is provided to satisfy the binocular disparity of 3D images. As a result, only the horizontal resolution of the 3D display system is decreased, whereas the vertical resolution remains unchanged. Moreover, the periodical structure of the parallax barrier and normal lenticular lens is only in the horizontal direction. This structure results in a black stripe pattern and color separation which comes from the sub-pixel structure of the display panel. The pattern and color separation degrade the quality of the 3D image. The slanted lenticular lens technique, developed by Philips, is the most advanced method which can mitigate some of the disadvantages of the current parallax barrier/normal lenticular lens method by tilting the lenticular lens[3-5]. The structure and principle of the slanted lenticular lens are shown in Fig. 3. With the slanted structure of the lenticular lens, the 3D pixel is composed of R/G/B sub-pixels which are located in different columns and rows as shown in Fig. 3(a). As a result, the resolution degradation in the 3D mode is divided into both horizontal and vertical directions. Moreover, with the slanted structure, there is no black stripe, as shown in Fig. 3(b), since the R/G/B sub-pixels are observed between the black matrices. Therefore, the quality of the 3D image can be enhanced. Philips has adopted this technique and demonstrated a 42-inch 3D display system. It recently extended this technique and demonstrated a 3D/2D convertible 42-inch display system [5].



(a) (b)

Fig. 3. The principle of the slanted lenticular lens: (a) the structure and (b) the observed color sub-pixels

3. LC PARALLAX BARRIER TECHNIQUES

3.1 The LC parallax barrier method

The LC parallax barrier uses the basic principle of the parallax barrier method. The parallax barrier is one of the simplest autostreoscopic methods, widely used for many applications. The parallax barrier is composed of black and white patterns. The LC parallax barrier is realized by using a simple LCD panel which can display only white and black stripe patterns. Since the white stripe is transparent in the LCD, the light can be transmitted through the white stripe. On the other hand, the black stripe blocks the light and acts like an optical barrier which can be generated or eliminated by the applied voltage. With this principle, 3D/2D convertible display systems have been developed that consist of LCD panels and parallax LC barriers[6-8]. The location of the LC barrier can be in front of or behind the LCD panel. The structure of the LC parallax barrier system is shown in Fig. 4. Through the open windows, eyes at specific positions observe different images displayed on interleaved different areas of pixels of the display panel. Hence the stereo images for these eyes are displayed in the interleaved format.

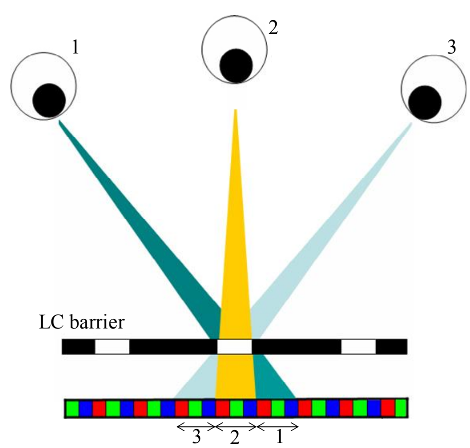


Fig. 4. The structure of an LC parallax barrier system (3-view example)

The LC parallax barrier method has advantages in cost and productivity, but it also has disadvantages in display quality when in 3D mode. As a result, this method is commonly used in mobile applications which require low cost and medium 3D image qualities. For example, Sharp and Samsung SDI have introduced 3D/2D convertible cellular phones based on the parallax barrier technique[6, 8]. In this year Samsung Electronics introduced the 3D/2D convertible cellular phone into the market adopting the Samsung SDI technique. Some developers of large sized displays are also adopting this technique. The most advanced example is that of the LG Electronics/LG.Philips LCD system, 42-inches size with a 1920x1080 pixel panel[7]. The luminance for the 3D display is 450 cd/m^2 and is 200 cd/m^2 for 2D. The optimum observation position for the 3D image is 4 m from the panel.

3.2 The time multiplexing method

The time multiplexing method is a type of application of the latest and most improved version of the LC parallax barrier. It is composed of two phases as shown in Fig. 5.

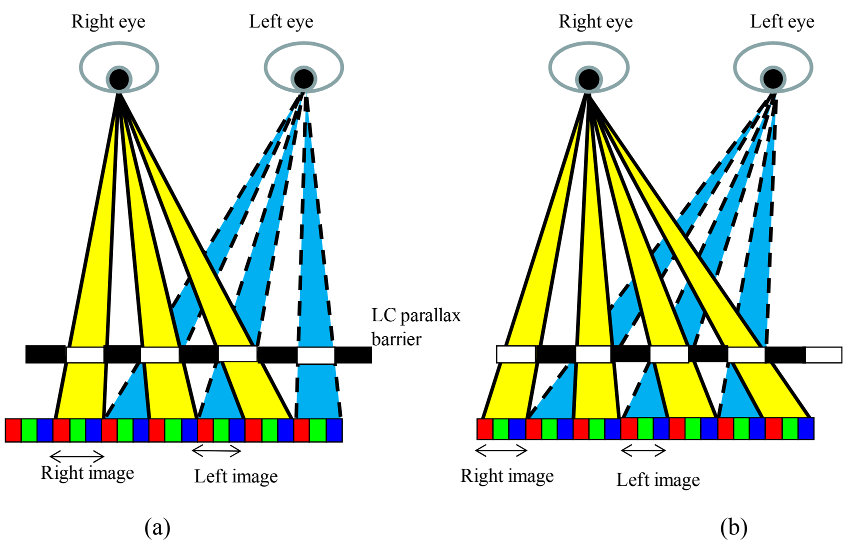


Fig. 5. Two phases of the time multiplexing method: (a) mode 1 (b) mode 2

Figure 5(a) shows the same principle as the conventional LC parallax barrier. The left/right eye observes the odd/even set of R/G/B pixels, respectively. Since only half of the total pixels are shown to each eye, the resolution of the observed 3D image is decreased by a factor of 1/2. In Fig. 5(b), we show a configuration similar to Fig. 5(a) except the black/white patterns have been exchanged. The left/right eye observes the opposite (even/odd) set of R/G/B pixels, respectively. As a result, by switching the system with twice the driving speed of the conventional driving method (mostly 60 Hz) between the two modes of Figs. 5(a) and (b) to induce the afterimage effect, each eye can observe all of the pixels of the display panel. There is a method called the field sequential method which is similar to this technique except that at each phase all light rays are directed to a single (left or right) eye only.

Samsung SDI and the Samsung Electronics are pursuing this technique[8, 9]. Samsung SDI is using an optically compensated birefringence mode of LC barriers [8].

4. PARTIAL 2D/3D DISPLAY TECHNIQUES

The time-multiplexing method using LC parallax barrier mentioned above has also proposed partial 2D/3D display technique [9]. It is developed by Samsung Electronics. In its structure, it is possible to display 2D and 3D at the same time only by image processing of display device behind the LC parallax barrier. For local 2D display, the same 2D images are displayed in the region of both the left eye and the right eye. In the region for 3D, the left eye image and the right eye image are processed and displayed in the corresponding regions. This enables to display the 2D/3D simultaneously, which is important for commercialization of the 3D display in market.

Another method has been proposed by NEC LCD Technology Ltd. They developed a novel pixel arrangement, called horizontally double-density pixels (HDDP)[10]. In this structure, two pictures (one for the left and one for the right eye) on two adjacent pixels form one square 3D pixel. This doubles the 3D resolution, making it as high as the 2D display and shows 3D images anywhere in 2D images with the same resolution. The display is lenticular lens based, is 2.5 diagonal inches in size, and has a 320×2 (RL) × 480×3 (RGB) resolution. As a 3D display, the horizontal and vertical resolutions are equal. The arrangement of the HDDP method is shown in Fig. 6.

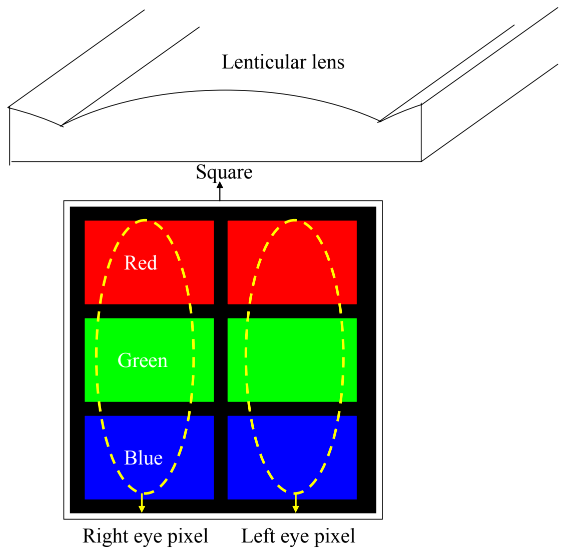


Fig. 6. The arrangement of the HDDP: right-eye pixel and left-eye pixel combine to form a square and a lenticular lens is over the HDDP.

In conventional LCD, each pixel is a square and one pixel is assigned to the left eye and another to the right eye in a two-view 3D display. Each set will form a rectangle in which the length in the horizontal direction is twice of that in the vertical direction. The horizontal resolution is half of that of the vertical in 3D display. Further, when 2D characters are displayed, this arrangement causes certain characters to be eliminated, causing the characters to be illegible. However, in the HDDP method, the horizontal pixel density is twice of that in the vertical direction. Each set of pixels forms a square, and horizontal resolution is equal to vertical resolution. In addition, 2D characters can be displayed with legibility without the need for 2D/3D conversion structure. That is, left and right pixels can simply be made to display the same content, in which case full proportioned characters will be perceived. With this method, both 3D and 2D images can be displayed simultaneously in the same picture with no need of 2D/3D conversion. The configuration of the system is thin and compact.

5. 3D/2D CONVERTIBLE INTEGRAL IMAGING

5.1 3D/2D convertible integral imaging with point light sources

In a common integral imaging system, the 3D image is formed from elemental images through a lens array[11]. However, the lens array is a fixed device and is an obstacle for 3D/2D conversion. Therefore, various 3D/2D convertible methods which do not use a lens array have been developed. In an integral imaging system, a lens array can be replaced with a point light source array or pinhole array[12-14]. The principle to display a 3D image, using a point light source array[15] and elemental images, is illustrated in Fig. 7[12]. The lens array has better optical properties than the point light source array or pinhole array. However, the point light source array is easier to generate/eliminate and is suitable for 3D/2D convertible integral imaging.

The earliest 3D/2D convertible integral imaging method used a point light source array and a polymer-dispersed liquid crystal (PDLC) as shown in Fig 8[12]. The PDLC is a kind of active diffuser that can be both diffusive and transparent according to the voltage application. In the PDLC, the liquid crystal droplets are randomly arranged in the polymer. With no voltage applied, the directions of liquid crystal droplets do not have uniformity. The light through the PDLC is scattered by those droplets. If voltage is applied, the liquid crystal droplets are arranged into a uniform direction and the PDLC becomes transparent. This method used a collimated light[12]. A two-dimensional lens array is used to form a point light source array in Fig. 8(b). If the PDLC plane, attached to the lens array, scatters light, then no point light source array is formed. This case can be used for the 2D display mode. Therefore, electrical 3D/2D conversion is possible by controlling the PDLC. The point light source array is formed by the lens array which has a transparent structure and can provide high optical efficiency. However, to collimate the light rays, the thickness of the proposed system should be more than 10 cm for a 1.8-inch screen size. Therefore, the system has use in only limited applications and the system is not suitable for mobile devices.

Recently the improved methods of the point light source array method – using a light emitting diode array, using pinholes on polarizer, and using a fiber array – have also been proposed[13, 14]. Figure 9 shows the experimental results of the point light sources method using pinholes on polarizer. In 3D mode, '3' and 'D' characters are integrated at different depths. The different perspectives of the images are observed as the observation location is changed. In 2D mode, the 2D images are displayed successfully with the resolution of 2D transmission type display panel as shown in Fig. 9.

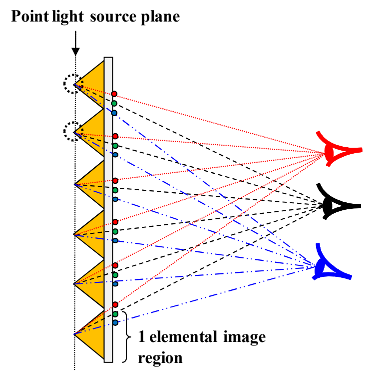


Fig. 7. The principle of the 3D display with a point light source array

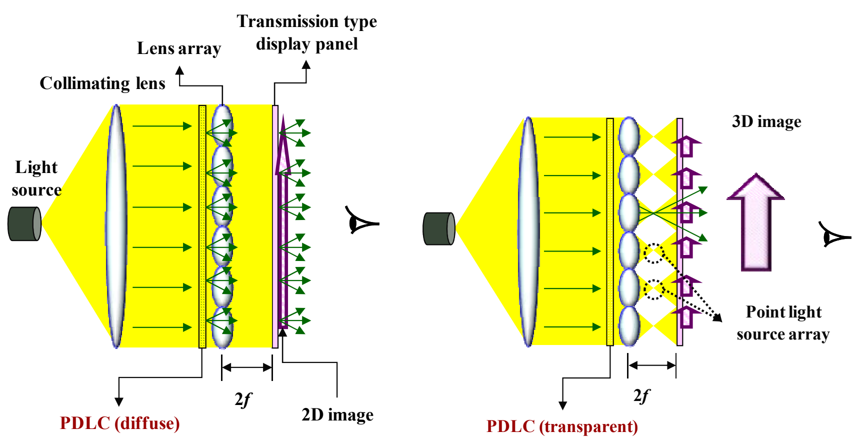


Fig. 8. The structure of point light source array method using PDLC

5.2 3D/2D convertible integral imaging with a lens array – a multilayer display system

Another method for a 2D/3D convertible integral imaging system has been proposed[16]. Figure 10(a) shows the scheme of the proposed system. The basic principle of the multilayer display system is preparing independent devices for the 2D and the 3D modes. Since the LCD panel is a transmission type display which displays the image by controlling the transmittance of the light, it is possible to stack multiple LCD panels and drive them independently.

◈ **3D mode** ◈ **2D mode**

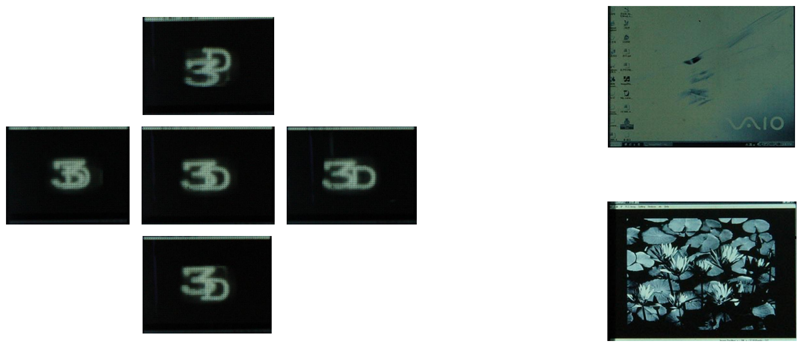
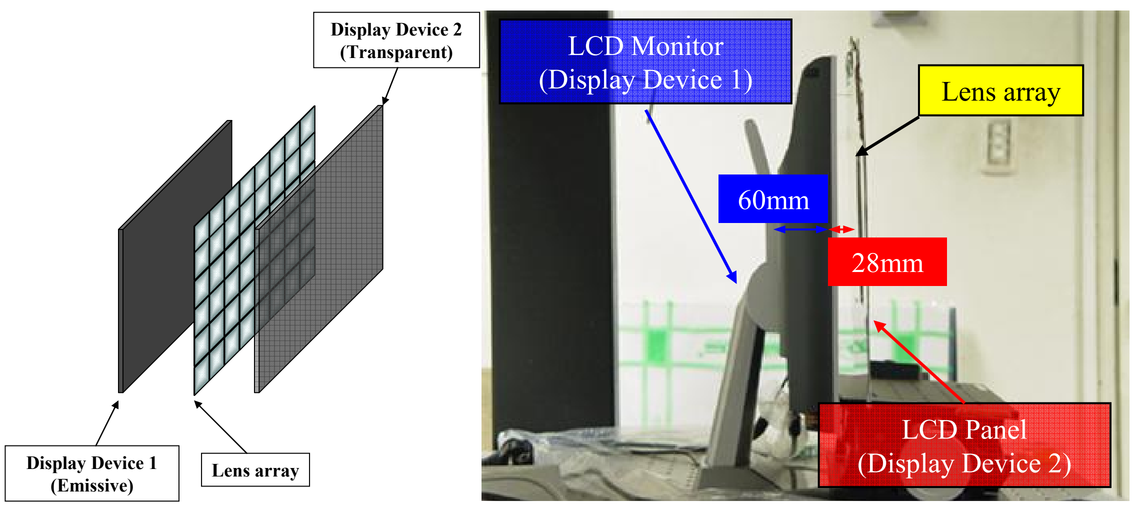


Fig. 9. The experimental results for the method of pinholes on polarizer

In the proposed structure, a display device 2 is added in front of the lens array in the conventional integral imaging system as shown in Fig. 10(a). In the 3D mode, display device 2 is set to be transparent by displaying a white screen; whereas, the elemental images are displayed on display device 1 and 3D images are formed through the lens array. In the 2D mode, on the other hand, display device 1 displays a white screen to become a light source for display device 2 and the 2D image on the display device 2 is shown to the observer. Figure 10(b) shows the experimental setup. Two LCD panels are used. Display device 1 is a commercially available LCD monitor, which is an emissive display whose thickness is 60 mm. Display device 2 is the LCD panel, transparent type display, and the lens array is attached behind the panel. The gap between the two display devices is 28 mm.



(a) (b)

Fig. 10. (a) The structure of the two-layer 3D/2D convertible integral imaging (b) experimental setup

Figure 11 shows an experimental result. A virtual shopping mall is implemented by using multilayer 3D/2D convertible display system shown in Fig. 10(b). A 3D image is displayed in the center, and at the same time 2D images are displayed on both sides of the display. The multilayer system is not only 3D/2D convertible, but also able to display partial 3D/2D images simultaneously.

Fig. 11. The experimental result: virtual shopping mall

Table 1. Status of 3D/2D convertible techniques with LC

	LC lenticular lens		LC parallax barrier		Integral imaging	
Research Group	Ocuity Ltd.	Philips	LG Electronics / LG.Philips LCD	Samsung SDI	Seoul National University	Seoul National University
Detail classification	Solid phase LC lenticular method	Slanted LC active lenticular method	LC parallax barrier method	Time multiplexing method	Point light source	Multilayer
Size	2.2”	42”	42”	2.2”	1.8”	17”
Purpose	Mobile	TV	TV	Mobile	Mobile	Monitor

6. CONCLUSION

The 3D/2D convertibility described in this paper is an essential factor in the commercialization of a 3D display. The LC is a suitable material with its optical anisotropy and electric properties. It is widely used for various 3D/2D convertible techniques. There are three kinds of autostreoscopic 3D/2D convertible techniques – the LC parallax barrier, the LC lenticular lens, and integral imaging. The first two have been commercialized. The third technique has been developed to a certain level of technology and is close to commercialization. Each of these techniques has its own advantages and disadvantages. The LC parallax barrier technique is easier to implement and so, has a merit in cost. However its brightness is low. More power is needed in 3D mode to increase the luminance of the backlight. As the number of view points is increased, the brightness falls in proportion. The LC lenticular method has a strong merit in brightness, especially for multi-view system. However it is not easy to obtain large size uniform lenticular lenses. This method shows the best 3D image quality among the three techniques. The integral imaging technique is good in brightness and has the advantage of both horizontal and vertical parallaxes. However its 3D image is inferior to the other technologies, and to fabricate a large size uniform 2D lens array is a challenging task. The status of the techniques is shown in Table 1. It is important to adopt an appropriate technique for a specific application with consideration of the techniques' characteristics. The first applications of 3D/2D convertible displays would be digital signage for advertisement and cellular phones.

ACKNOWLEDGMENT

This research was supported by a grant (F0004190-2007-23) from the Information Display R&D Center, one of the 21st Century Frontier R&D Programs funded by the Ministry of Commerce, Industry and Energy of the Korean Government.

REFERENCES

1. G. J. Woodgate and J. Harrold, "A new architecture for high resolution autostereoscopic 2D/3D displays using free-standing liquid crystal microlenses," Society for Information Display 2005 International Symposium, vol. 36, 2005, pp. 378-381.
2. J. Harrold and G. J. Woodgate, "Autostereoscopic display technology for mobile 3DTV applications," Proc. SPIE, vol. 6490, paper 64900K, 2007.
3. S. T. de Zwart, W. L. IJzerman, T. Dekker, and W. A. M. Wolter, "A 20-in. switchable auto-stereoscopic 2D/3D display," Proc. of International Display Workshops, Niigata, Japan, Dec. 2004, pp. 1459-1460.
4. O. H. Willemsen, S. T. de Zwart, M. G. H. Hiddink, and O. Willemsen, "2-D/3-D switchable displays," Journal of the Society for Information Display, vol. 14, no. 8, pp. 715-722, 2006.
5. M. G. H. Hiddink, S. T. de Zwart, and O. H. Willemsen, "Locally switchable 3D displays," Society for Information Display 2006 International Symposium, San Francisco, CA, USA, June 2006, vol. 37, book 2, pp. 1142-1145.
6. http://www.sharp-world.com/corporate/info/rd/tj4/4-2-3.html
7. H. Kang, M. K. Jang, K.J. Kim, B.C. Ahn, S. D. Yeo, T. S. Park, J. W. Jang, K. I. Lee, and S. T. Kim, "The development of 42" 2D/3D switchable display," Proc. of The 6th International Meeting on Information Display and The 5th International Display Manufacturing Conference (IMID/IDMC 2006), Daegu, Korea, Aug. 2006, pp. 1311-1313.
8. H. J. Lee, H. Nam, J. D. Lee, H. W. Jang, M. S. Song, B. S. Kim, J.S. Gu, C. Y. Park, and K. H. Choi, "A high resolution autostereoscopic display employing a time division parallax barrier," Society for Information Display 2006 International Symposium, San Francisco, CA, USA, June 2006, vol. 37, book 1, pp. 81-84.
9. D.-S. Kim, S. D. Se, K. H. Cha, and J. P. Ku, "2D/3D compatible display by autostereoscopy," Proc. of the K-IDS Three-Dimensional Display Workshop, Seoul, Korea, Aug. 2006, pp. 17-22.
10. N. Takanashi, S.-I. Uehara, and H. Asada, "A 470 x 235 ppi LCD for high-resolution 2D and 3D autostereoscopic display and user aptitude investigation results for mobile phone applications," Proc. SPIE, vol. 6490, paper 64900L, 2007.
11. B. Lee, J.-H. Park, and S.-W. Min, "Three-dimensional display and information processing based on integral imaging," in Digital Holography and Three-Dimensional Display (edited by T.-C. Poon), Springer, New York, USA, 2006, Chapter 12, pp. 333-378.
12. J.-H. Park, H.-R. Kim, Y. Kim, J. Kim, J. Hong, S.-D. Lee, and B. Lee, "Depth-enhanced three-dimensional-two-dimensional convertible display based on modified integral imaging," Optics Letters, vol. 29, no. 23, pp. 2734-2736, 2004.
13. S.-W. Cho, J.-H. Park, Y. Kim, H. Choi, J. Kim, and B. Lee, "Convertible two-dimensional-three-dimensional display using an LED array based on modified integral imaging," Optics Letters, vol. 31, no. 19, pp. 2852-2854, 2006.
14. H. Choi, S.-W. Cho, J. Kim, and B. Lee, "A thin 3D-2D convertible integral imaging system using a pinhole array on a polarizer," Optics Express, vol. 14, no. 12, pp. 5183-5190, 2006.
15. S.-S. Kim, K. Sohn, V. Savaljev, E. F. Pen, J.-Y. Son, and J. Chun, "Optical design and analysis for super multiview three-dimensional imaging system," Proc. SPIE, vol. 4297, pp. 222-226, 2001.
16. H. Choi, J.-H. Park, J. Kim, S.-W. Cho, and B. Lee, "Wide-viewing-angle 3D/2D convertible display system using two display devices and a lens array," Optics Express, vol. 13, no. 21, pp. 8424-8432, 2005.