Thin-type integral imaging method with an organic light emitting diode panel

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A thin and lensless two-dimensional (2D) to three-dimensional (3D) convertible display based on integral imaging using an organic light emitting diode (OLED) panel as a direct emissive light source is proposed with improved optical efficiency. A point light source array for 2D–3D convertible display is formed on the surface light source, i.e., the OLED panel. However, a blurring effect and color separation result from the finite (nonzero) size of point light sources since each point light source is generated by a pixel of the OLED panel. Simulation results for a blurring effect and color separation in terms of rays from a light source with finite size is presented. The proposed system has a thin structure and simple convertibility because it does not need any additional optical element to provide 2D–3D convertibility. © 2008 Optical Society of America

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1. Introduction

Display industries have rapidly changed with the trend of thin structure, human interactive technology, and natural color expression. The progress from cathode ray tubes to flat panel displays reflects the public desire for thin high-quality display. The appetite of natural color reproduction influenced the development of an organic light emitting diode (OLED). An OLED is a kind of light emitting diode (LED) whose emissive electroluminescent layer is formed by a film of organic compounds. Since an OLED can be printed onto any suitable substrate, it can have a significantly lower price than a liquid crystal display (LCD). And it enables a greater range of colors, brightness, and viewing angle than a LCD because OLED pixels directly emit light. Additionally, an OLED does not require a backlight and has a faster response time (0.01 ms) than a standard LCD (8–12 ms). These attractive properties of an OLED enable it to be a good candidate for the next generation of display techniques. A problem that is encountered for OLEDs is the limited lifetime of the organic materials due to the degradation of organic compounds caused by the absorption of water in the air [1–3].

The need for a three-dimensional (3D) display, which could be considered the next generation display, has grown in importance, as has the number of applications for it, such as advertisements, medical systems, scientific visualizations, military applications, as well as movies and television. Many approaches for 3D display have been investigated over the past few decades; none of these have occupied the mass market of display industries yet. Holography is an effective approach to express a natural 3D display, but the calculative information of 3D content is excessive, which has imposed difficulty in realizing a practical 3D display [4]. A lenticular or parallax barrier method, which is a kind of autostereoscopic technique providing different images to the user's two eyes, was commercialized earlier. However the constraints on the limited number of views and the insufficiencies of proper content have been obstructions to capturing the display market. Integral imaging, which was primarily called integral

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photography, could be considered an alternative because of both horizontal and vertical parallax, color images, quasi-continuous viewpoints within a viewing angle, and no use of special glasses or head gear. On the other hand, a limited viewing angle, limited depth perception, and a limited image resolution are problems that have been researched in depth [5–7] to mitigate these limitations. Recently, most of the reported investigations concerned with integral imaging focused on improving the viewing parameters [8–11].

In addition, two-dimensional (2D) to 3D convertible techniques adopting integral imaging or other autostereoscopic methods are being researched intensively as a bridge between the maturity stage of the 2D display industry and unripe 3D display industry [12–16]. Samsung SDI has developed a 3D display that they call a field sequential method based on a modified parallax barrier method [12], and LG Electronics has demonstrated the 42 in. 2D/3D switchable high definition LCD television based on the lenticular method [13]. The Ocuity announced switchable 2D/3D monitors, notebooks, personal digital assistants (PDAs), and cellular phones based on polarization-activated microlens technology [14]. A depth-enhanced 2D–3D convertible display that uses a polymer-dispersed liquid crystal (PDLC) based on the integral imaging technique was proposed also [15]. These 2D–3D convertible techniques need additional optical element volumes to invalidate the lens effect. A method that adopts polarization sheets for generation of a pinhole array has also been proposed in integral imaging; however, the optical efficiency is inevitably deteriorated [16].

Here we propose a lensless 2D–3D convertible display technique using directly emissive light sources. In the proposed method, point light sources with a finite size are generated by pixels of an OLED panel. Although a lensless technique was also proposed by the use of a set of polarization films [16], the optical efficiency was degraded because the light passed through two polarization films. In the proposed method, we use OLED pixels which are comprised of self-emission light sources. Hence the optical efficiency can be improved. Moreover, it does not require additional optical elements such as PDLC films [15] to provide a 2D–3D convertible technique. Therefore total structure of the proposed method shrinks effectively, and it can be a thin and simple structure with enhanced optical efficiency compared with the case of polarization films [16]. It can be operated with low voltage, and the heat dissipation can be much reduced compared with the case of using typical small LED chips.

2. Principle of the Proposed Method

Integral imaging employs a lens array in which many small convex lenses are arranged in a matrix. Image information consisting of many pixels is placed behind each elemental lens of the lens array for reproducing a 3D image. In integral imaging, a conversion from 3D to 2D usually works by invalidation of the lens to function. When the lens array is functioning appropriately, a 3D image can be reconstructed through the elemental images and lens array. If the lens array is invalidated because of additional optical elements such as PDLC films or polarization-activated microlenses, a 2D image can be observed just like on a normal flat-panel display. Recently our group has proposed several 2D–3D convertible methods based on integral imaging. Figure 1(a) shows a 2D–3D convertible display that uses a PDLC film based on integral imaging [15]. This method can change between the 2D and the 3D display modes without any mechanical movement and support high quality 2D images. However it is inevitable to use a large lens, huge space, and high voltage that operates the PDLC film. Also, we should adjust the gap between the lens array and the display panel elaborately. Using a pinhole array on a polarization sheet was also proposed [16]. This method provides a simple structure; however, the optical efficiency is very low because the light should pass through two polarization films as shown in Fig. 1(b).

Figure 2 shows the configuration of the proposed method. The concept of the proposed method is motivated by the early work shown in Fig. 1. In the proposed method, an OLED panel substituted backlight unit and lens array. The proposed method does not require additional optical elements for the 2D–3D convertible technique; therefore the proposed method is a favorable proposal having a thin thickness.

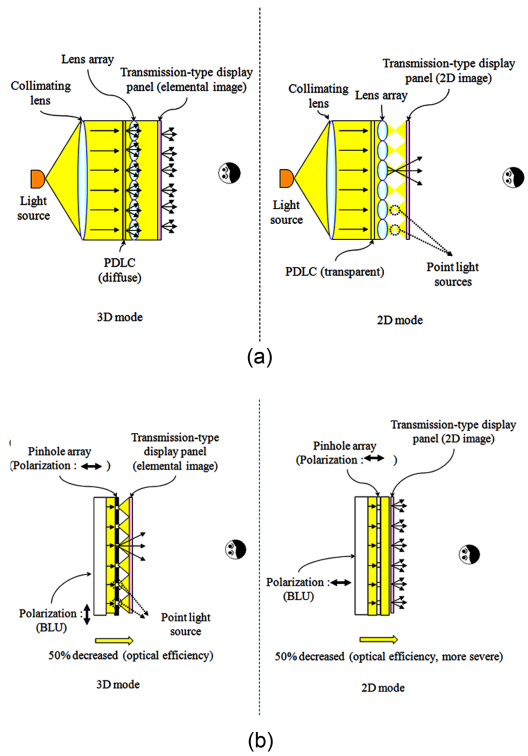


Fig. 1. (Color online) Previous methods of 2D–3D convertible display in integral imaging using (a) polymer-dispersed liquid crystal (PDLC) films and (b) pinhole on a polarizer.

The light source array with finite size that is made up of OLED pixels is generated to serve as the point light source array. Because each pixel has a nonzero size, the point light source is not ideal. We will also discuss the effect of the light source size in the following. The OLED panel is connected with a driver module; hence we can manifest 2D and 3D images with time multiplexing as shown in Fig. 2. That is, we can implement a backlight source for 2D mode or a point finite-size light source array for 3D mode by controlling OLED pixels with the driver module.

This method provides improved optical efficiency compared with the technique of Fig. 1(b) because an OLED can directly emit the light. When the light passes through a piece of polarization film in Fig. 1(b), the optical efficiency will decrease by half. In addition, to generate a point light source array, the pinhole on a polarizer is fabricated by using a drilling machine. In contrast, the proposed method does not cause a loss of light because it merely turns the unit pixel of the OLED panel on. The OLED panel is suitable for the proposed method because it is a self-emissive display. Hence it can form a point light source array without any mechanical process. This method may also be realized by a small LED chip array. However in this case, a serious heat dissipation problem would be induced by the dense structure of small LED chips, while the optical efficiency could be superior. Therefore, it is not easy to construct a 2D–3D convertible display employing a small LED chip array, although a trial was done using rather large LEDs [17].

In this kind of 3D display, viewing condition and parameters are considered crucial issues: the gap between light source and transmission-type display panel, resolution, and modulation problems. In the case of using a lens array, the transmission-type display panel is in front of the lens array at a distance of $2f$ (where f is the focal length of the lens). In the proposed method, the light source array with a finite size is used instead of a point light source array. Consequently the gap between the light source and the transmission-type display panel is adjusted so that each elemental image region on a transmission-type display panel is covered with each light source precisely. As shown in Fig. 3(a), for the integration of a 3D image, only the elemental images that are within their corresponding elemental image regions are displayed on the transmission-type display panel, i.e., spatial light modulator (SLM). However if diverged light rays from an OLED pixel overlap because gap g_o is larger than gap g, the elemental image regions are modulated by more than two light sources as shown in Fig. 3(b). Likewise if gap g_s is smaller than gap g in Fig. 3(c), the light rays from the OLED pixel are not totally covered with corresponding elemental image regions. With the calculation of ray optics and approximation, the size of the elemental image region S_{ele} in Fig. 3(a) is derived to become $S_{\mathrm{ele}} = S_{\mathrm{ls}} + 2g\tan\frac{\psi}{2}$, where S_{ls} is the size of the elemental light source, and ψ is the diverging angle of the OLED pixel. The elemental image region is determined by the diverging angle of the OLED pixel, the size of the elemental light source, and gap g. From the

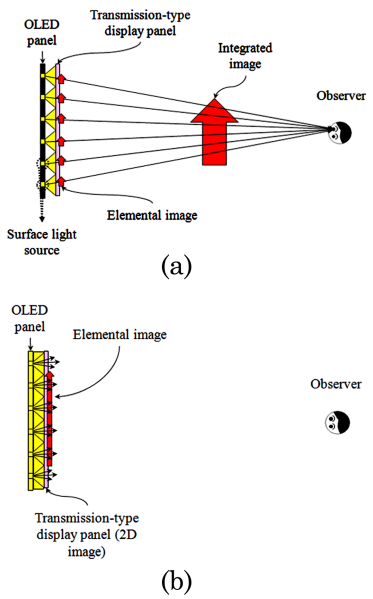


Fig. 2. (Color online) Illustration of the proposed method consisting of a SLM and an OLED panel: the case of (a) 3D mode and (b) 2D mode.

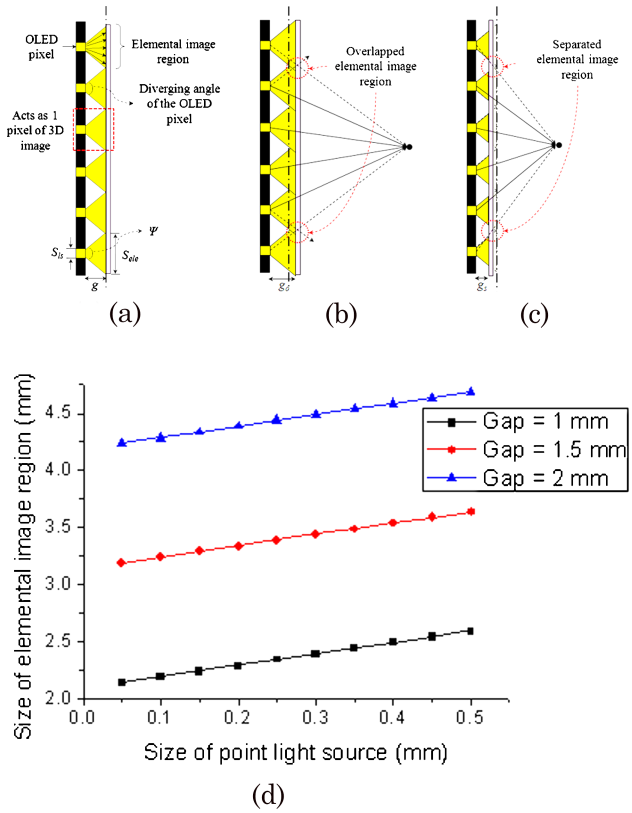


Fig. 3. (Color online) Gap adjustment between the light source array and the transmission-type display panel: (a) when point light source is covered with each elemental image region on the plane of the SLM, (b) gap g_o is larger than g, (c) gap g_s is smaller than g, and (d) comparison of the size of elemental image regions for the diverging angle of 60°.

above calculation, if the emission of the light source is appropriately matched, as shown in Fig. 3(a), reconstructed 3D images are integrated without undesirable modulation.

The resolution in the proposed method is limited by the number of point light sources. Because the transmission-type display panel, i.e., SLM, functions as a modulator of light rays, the resolution is limited by the number of point light sources in integral imaging [18,19]. As shown in Fig. 3(a), a unit comprised of one OLED pixel and corresponding elemental image region acts as one pixel of integrated 3D image. The pixel pitch of an SLM is also a matter of consequence. When the pixel pitch of an SLM is small, the resolution of the 3D image is improved because the light rays are modulated more finely. When the size of the light source and the pixel pitch of an SLM are ideally small, the resolution of the integrated 3D image depends on the number of point light sources. In our experiments to be discussed in the following, the size of the light source is bigger than the pixel pitch of an SLM. Therefore the obtainable resolution with this approach
depends on how many light sources in an array form can be made. The figure of merit for the 3D image is expressed as a function of the number of point light sources and the pixel pitch of an SLM: $\Omega \approx N_{\mathrm{PLS}} \times S_{\mathrm{ele}}/\rho_{\mathrm{SLM}}$,where Ω is the figure of merit for the 3D image, N_{PLS} is the number of point light sources, and ρ_{SLM} is the pixel pitch of an SLM.

Modulation problems which are induced by the nonzero size of the point light source can be caused in the proposed method. Because light rays from the light source are modulated by an SLM, there are four modulation cases according to composition of backlight unit (BLU) and an SLM: (1) white light BLU and an SLM which functions just as a modulator, (2) white light BLU and an SLM with RGB (red/green/blue) pixels, (3) BLU comprised of RGB pixels and an SLM which functions just as a modulator, and (4) BLU comprised of RGB pixels and an SLM with RGB pixels also. Here we use an OLED panel comprised of RGB pixels as a BLU and an SLM that functions as a modulator; therefore we discuss cases (1) and (3). In the point light source integral imaging method, light rays from one OLED pixel might be modulated by the neighboring elemental image region on an SLM with different information because the size of the point light source is even bigger than the pixel pitch of an SLM. That brings a blurring effect [19], which is a distortion characterized by reduced sharpness of edges to observers, and this blurring effect can occur in the above four cases. Another modulation problem called color separation originates from RGB pixels of BLU. When the BLU is comprised of RGB pixels instead of a white light source, color separation can be induced because each light ray from the RGB pixels could be separately modulated by an SLM.

Figure 4 shows an illustration of the blurring effect. The cause of the blurring effect lies in the finite size of the point light source and the distance of the observed 3D image. When the size of the point light source is negligibly small, the light rays are modulated by the SLM and the 3D images are observed as shown in Fig. 4(a). However, if the size of the point light source is bigger than the pixel pitch of the SLM,

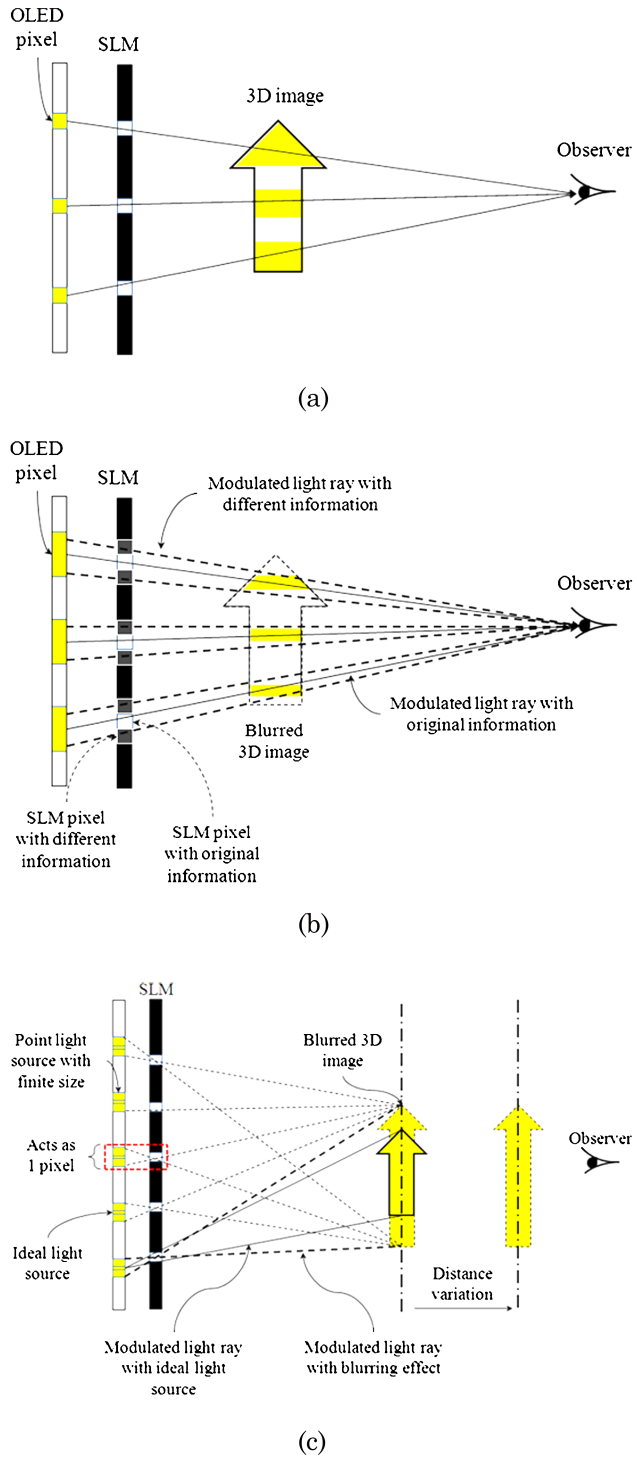


Fig. 4. (Color online) Illustration of the blurring effect: (a) for ideally small OLED pixel and pixel pitch of SLM, (b) for larger light source than pixel pitch of SLM, and (c) for distance variance of observed 3D image.

the light rays from the extended light source might be modulated with different information by the SLM. Consequently, the observed 3D image contains not only original information but different information from the other pixel of the SLM, as shown in Fig. 4 (b). This effect is caused by arbitrary angular emission of the nonzero size OLED pixels. The real lines in Fig. 4 connect the centers of OLED pixels and the observer's eye. The dotted lines represent modulated light rays from one OLED pixel with different information. The pixels of the SLM on real and dotted lines are modulated to represent a 3D image with a blurring effect. The blurring effect shows different patterns according to the distance of the observed 3D images. The farther the observed 3D images are from the plane of the SLM, as shown in Fig. 4(c), the more likely it is that the blurring effect by a neighboring region will arise. Because the size of the elemental image is limited, the key of the blurring effect is determined by the size of the light source and the distance of the observed 3D image.

An OLED cell which is used for the experiment is comprised of a metal cathode, an anode, an electron transport layer, organic emitters, a hole injection layer, and a glass substrate. Figure 5 shows the physical structure of an RGB OLED cell. A conductive, transparent anode material, such as indium-tin-oxide, is first deposited on a transparent substrate, and the organic layers are added. Since the OLED directly emits the individual light output, it does not require a BLU. Because the light source array for 3D display is comprised of RGB pixels in the proposed method, this constitution of RGB pixels will have an effect on the color separation. Figure 6 shows the color separation effect. Light rays from the RGB pixel are modulated by the SLM. At the center region of the SLM, all the light rays from the OLED pixel are well modulated by the SLM and a 3D image will be generated without color separation. However, at the outer region, one of the RGB pixels cannot be modulated. As a result of this effect, the results of the integration of 3D image show the color separation, and this becomes more severe at the outer region of integration points. The real lines and the

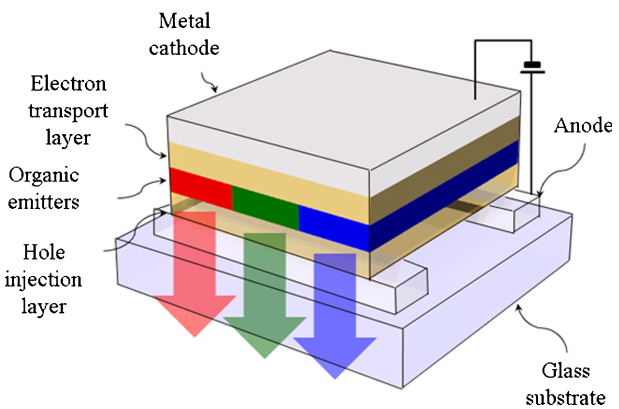


Fig. 5. (Color online) Diagram of the physical structure of an RGB OLED cell.

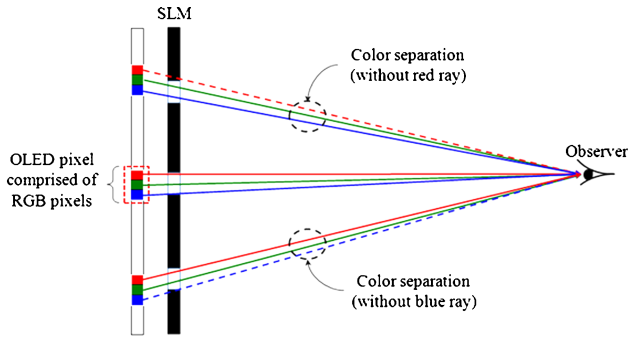


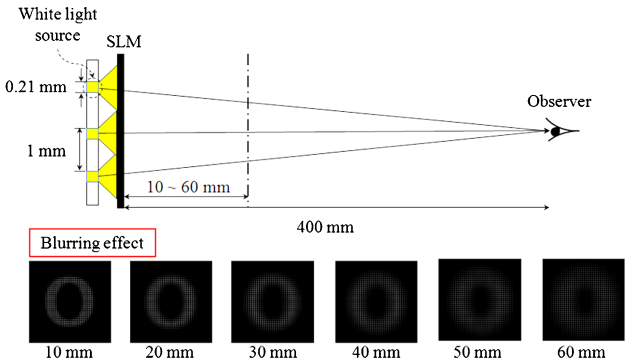
Fig. 6. (Color online) Color separation when the point light source with finite size comprised of RGB pixels is used.

dotted lines in Fig. 6 represent modulated and unmodulated (blocked) light rays, respectively.

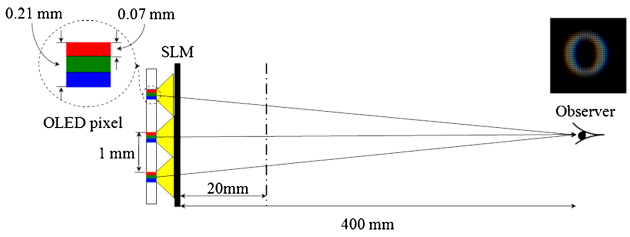
The simulation condition and results for the blurring effect and color separation are presented. Figure 7 shows the modulation problem related to the blurring effect and color separation. To confirm our hypothesis, the light rays coming out of each RGB pixel can be modeled as a superposition of rays emitted from a small area of the light source. Each ray diverges in an arbitrary direction within a specific emission angle. As mentioned in Fig. 4, the blurring effect might be generated by both a point light source array with finite size and the integration distance of 3D image. Because the size of the light source (OLED pixel) is larger than the pixel pitch of the SLM, the blurred image is generated by adjacent light rays from the OLED pixel. The simulation results for the blurring effect related to the size of the point light source are presented in Ref. [19]; therefore, the results for distance of the observed 3D images are merely considered in this paper. Figure 7(a) shows the blurring effects when the assumed value of the size of the point light source is 0.21 mm. The point light source is located 3 mm behind, and the letter "O" is formed at 20 mm in front of the plane of the SLM. The distance varies from 10 to 60 mm, and the blurring effect becomes severe when the observed 3D images are far from the plane of the SLM. The simulation result for color separation is also presented. In the proposed method, color separation, which is provoked by adjacent rays emerging from neighboring pixels, can be generated. Figure 7(b) shows the color separation results when the assumed value of the size of the pixel is 0.21 mm and each RGB pixel has 0.07 mm size. The results indicate that color separation gets worse at the outer region of the integration points.

3. Experimental Results and Discussions

We performed experiments to verify the feasibility of the proposed method. The experimental setup is shown in Fig. 8. As a transmission-type display panel, we used an SLM that had a 0.036 mm pixel pitch in the horizontal and vertical directions with a 37 mm × 28 mm active area. Our preliminary work was presented at a conference [20]. In our system, the OLED panel provided by Neoview Kolon is a full color PM-OLED type (LEADIS Technology) with a 0.95 in.



(a)

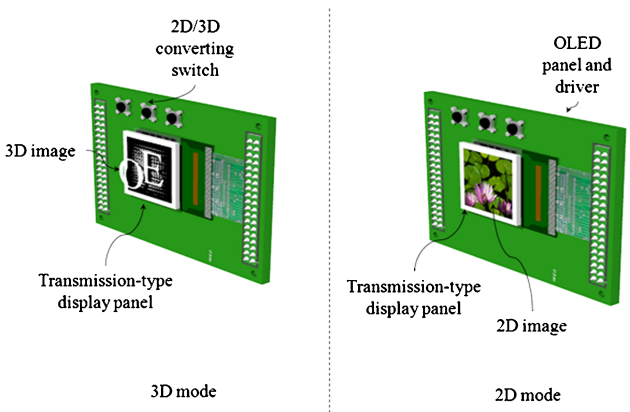


(b)

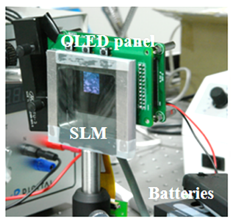
Fig. 7. (Color online) Simulation results: the illustration of simulation condition and results for (a) blurring effect and (b) color separation.

(2.4 cm) size, 96 × 64 resolution, and 0.210 mm × 0.210 mm pixel pitch, and is operated by 9 V batteries. For 3D images, the pitch of the point light source on the OLED panel is 0.840 mm and the light rays from the small area of the surface light source array will be modulated by the SLM and integrate 3D images. There is no noticeable heat problem, and the proposed system has only 3 cm thickness because it consists of only two components (OLED panel and SLM) and the SLM is placed closely on the front of OLED panel. The LDS514 chip is used for the operating circuits and is commercially available. This module is a 65 K full color passive matrix drive OLED module. The LDS514 chip in the OLED module is composed of 288 column and 64 row dot drivers and a controller with RAM for the full color OLED panel. That is, this module consists of an OLED panel and driver integrated circuit part mounted on a film using a tape carrier package.

Figure 9(a) shows the experimental result observed from different viewing directions. In the 3D mode, the image of two letters 'O' and 'E' are formed, respectively, at 20 mm in front of and behind the point light source array which was implemented by controlling the OLED panel pixels. We can see different perspectives from different viewing directions. Figure 9(b) shows the observed image when the system acts in the 2D mode. In the 2D mode, a landscape image

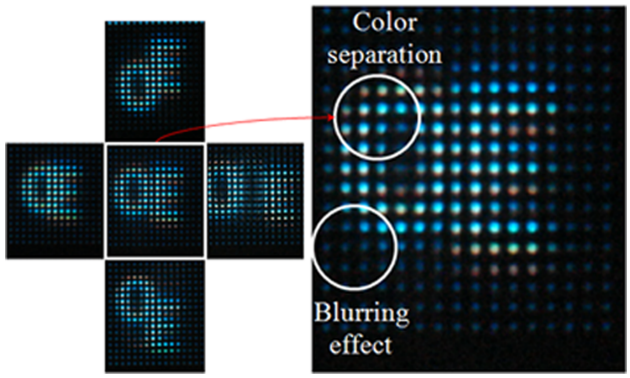


(a)



(b)

Fig. 8. (Color online) Experimental setup: (a) diagram of the experimental setup and (b) photograph of the experimental setup.



(a)

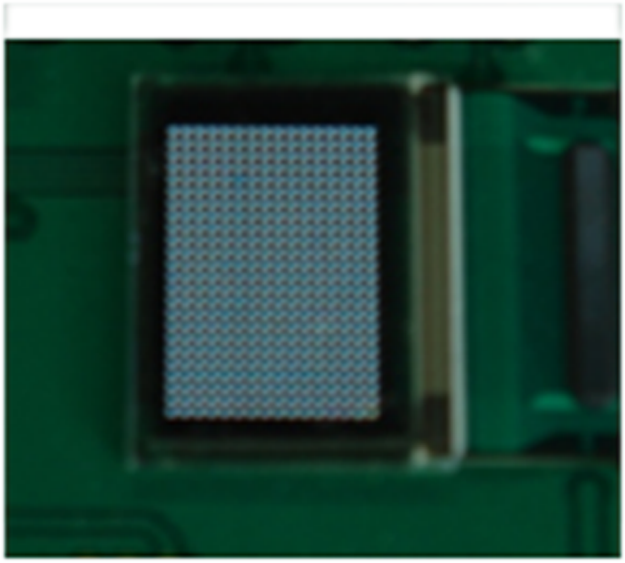
(b)

Fig. 9. (Color online) Experimental results: (a) 3D images observed from different viewing directions, (b) two sets of a 2D image.

and a lotus flower are displayed on the SLM, respectively. At this time, the OLED panel plays the role of a backlight unit [15]. Conversion between the 2D mode and the 3D mode is performed easily by a switch at the top of the OLED panel. The color separation which is caused by incomplete modulation of adjacent rays from RGB pixels arises. If the white OLED panel instead of the mixed RGB panel is used, the color separation will be solved.

Figure 10 shows the OLED panel in the 2D mode and the 3D mode, respectively. In the experimental setup, the white luminance with SLM is 98.01 cd/m^2 in the 2D mode and it is 10.28 cd/m^2 in the 3D mode. The optical efficiency of the 3D mode is 10.48% of the 2D mode, and this result shows the improved optical efficiency compared with the previous method [16].

(a)



(b)

Fig. 10. (Color online) OLED panel in the (a) 2D mode and (b) 3D mode.

4. Conclusion

We have proposed a lensless 2D–3D convertible integral imaging method using an OLED panel. The OLED panel which is connected to the driver module can be controlled easily, and we can form a backlight source or point light sources with a finite size for the 2D or 3D mode, respectively. The blurring effect arises because of the finite size of the point light sources, and color separation is caused because the OLED pixels are comprised of RGB pixels. The proposed method does not require any additional optical element for the 2D–3D convertible technique; the total system of the proposed method is thin. In addition, it is operated at low voltage (9 V) and no heating problem is induced. The experimental results support the feasibility of the proposed method. Because the OLED panel needs just low voltage operation and is compact, we can expect that many applications with the proposed method will be found, especially in the areas of mobile displays, cellular phones, car navigation systems, and hand-carried personal computers.

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