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Two-Dimensional/Three-Dimensional Convertible Integral Imaging Using Dual Depth Configuration

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We propose a novel scheme to provide a two-dimensional/three-dimensional convertible feature for integral imaging operation under real/virtual mode. With a new fabrication method for a concave (or convex) half mirror array, a prototype system was implemented to verify the feasibility of our proposed scheme. Experimental results show that the proposed scheme also provides a wider viewing angle of an integrated image than the conventional integral imaging system. It is expected that the proposed two-dimensional/three-dimensional convertible integral imaging scheme will be useful for providing an integrated image with high resolution and a wide viewing angle.

Three-dimensional (3D) display has recently appeared as a commercial product in the display market with a success of products based on stereoscopy. However, considering autostereoscopic displays, there still remain some issues that should be resolved before commercialization. One of such issues is that the industry requires 2D/3D convertible feature for a new 3D television (TV) product to make it compatible to a number of 2D contents accumulated so far. To meet such a demand, a lot of investigations have been conducted to make existing 3D display systems 2D/3D convertible. A long time already has passed since 2D/3D convertible feature had been developed for multiview displays, such as parallax barrier and lenticular lens display, with a liquid crystal (LC) panel or LC lens.[1–3] Recently, investigations have been conducted to make integral imaging (InIm), provide a 2D/3D convertible feature.[4,5] Most of them implement 2D/3D convertible feature by generating an array of point light sources with active devices.[4] However the implementation of an InIm system based on an array of point light sources cannot retrieve full functionality of the InIm scheme. InIm has two options, real/virtual mode and focused mode in displaying a 3D image. Real/virtual mode shows better quality in resolution of the reconstructed 3D image, while the 3D image in focused mode shows a better depth expression.[6] Hence, which display mode will be enabled should be determined considering a usage scenario. Although a 2D/3D convertible InIm scheme that can utilize the real/virtual mode is also necessary, with an array of point light sources, only the focused mode can be utilized. To date, only one method has been reported to implement a 2D/3D convertible InIm that can operate as a real/virtual mode. Hence, further study on this issue is still needed.[7]

In this letter, we propose a novel scheme that can realize a 2D/3D convertible InIm system utilizing a real/virtual mode based on a dual depth configuration. The feasibility of our scheme is verified by experimental results obtained from an implemented prototype. For the implementation of the prototype, we also propose a viable fabrication method of a concave (or convex) half mirror array (CHMA). Our proposed system implements an InIm scheme with a 2D array of concave mirrors instead of convex lenses. In general, the focal length of a concave mirror is shorter than that of the convex lens if the radius of curvature is the same. It will be discussed that such a short focal length can provide advantageous features for integrated images.

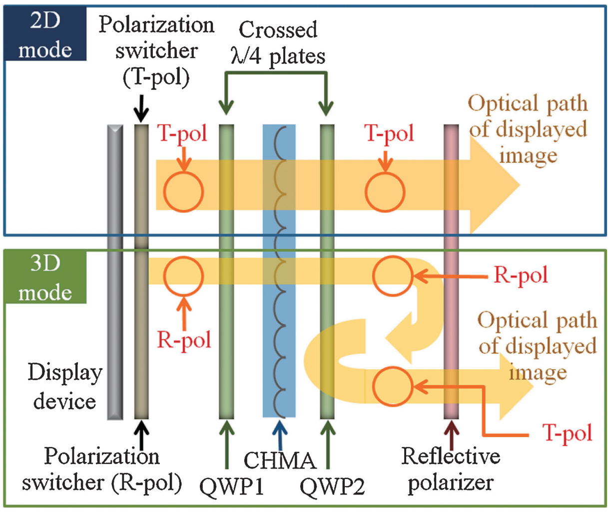

Fig. 1. System configuration of the proposed scheme.

Figure 1 shows the configuration of the proposed 2D/3D convertible InIm system using a combination of dual depth configuration and CHMA. CHMA is an optical component which is a transparent plate to transmitted rays, whereas the optical paths of reflected rays are modulated by the embedded half mirror structure, i.e., a 2D array of concave mirrors.[8] Because a concave mirror is a direct alternative to a convex lens, if a properly generated elemental image is provided, the reflected image can be used to generate 3D images based on the InIm scheme.[9,10] A transmitted light can provide a clear 2D image, which is not altered by the embedded half mirror structure of CHMA. However, CHMA cannot provide a 2D/3D convertible feature solely as the reflected and transmitted rays come out together. By adopting a dual depth configuration, CHMA can provide a 2D/3D convertible feature without such a problem. A dual depth configuration is a display scheme that changes the optical path length from observer to display by a polarization-based multiplexing method.[11] As shown in Fig. 1, CHMA replaces a half mirror of the conventional dual depth configuration. A polarization state of the polarization shutter in Fig. 1 determines whether the final image shown to the observer will be a 2D or 3D image by changing the optical path of the displayed image. The optical path

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of each mode is described in Fig. 1. In 2D mode, the polarization state of the polarization shutter is the same as the transmission polarization of the reflective polarizer, and this polarization will be named T-pol. After passing through two crossed $\lambda/4$ plates, QWP1 and QWP2, the polarization state of the 2D image is maintained as T-pol. Hence, in 2D mode of the proposed system, a 2D image is directly delivered to an observer through the reflective polarizer. In 3D mode, the polarization state of the polarization shutter is the same as the reflection polarization of the reflective polarizer, which will be named R-pol. In this case, as the polarization state of the displayed image is R-pol after passing through QWP1 and QWP2, it is reflected back by a reflective polarizer. The reflected image reaches the CHMA again passing through QWP2. Among the reflection and transmission of CHMA, reflection has a valid direction for delivering an image to an observer. By reflection of CHMA, the displayed image is integrated by a 2D array of a concave mirror structure following the InIm principle. During this round-trip between the reflective polarizer and CHMA, the displayed image meets QWP2, CHMA, and QWP2 in sequence. As a result of the round-trip, the polarization state of the displayed image is changed to T-pol. Hence, the displayed image is transmitted through the reflective polarizer and the 3D integrated image is delivered to the observer.

Besides achieving a 2D/3D convertible feature, our proposed system can also take advantage of using a concave mirror instead of a convex lens to implement the InIm scheme. Under the same radius of curvature, a concave mirror has shorter focal length than a convex lens. If the focal length of the convex lens is f_0, the focal length of the concave mirror of the same shape is approximately $f = (n-1)f_0/2 = f_0/s$, where n is the refractive index of the reference convex lens and s is a scaling factor. The refractive index of a convex lens is usually around 1.5; hence, the focal length can be reduced to nearly a quarter with the concave mirror. A shorter focal length brings a wider viewing angle of an integrated 3D image. The viewing angle θ of the InIm system implemented by a concave mirror is

$$\theta = 2\tan^{-1}\left[\frac{\phi}{2}\left(\frac{s}{f_0}-\frac{1}{l}\right)\right], \tag{1}$$

where ϕ is the pitch of the convex lens or concave mirror and l is the distance from the convex lens or concave mirror array to the central depth plane where image planes of the convex lenses or concave mirrors are superposed. Hence, the viewing angle becomes wider as s increases. Another advantage of adopting a concave mirror is that its short focal length can also be helpful in overcoming a severe limitation in depth expression of the InIm system utilizing a real/virtual display mode. To enhance the expressible depth range of the InIm system with a real/virtual display mode, a number of methods have been developed to make multiple central depth planes by changing the gap between the lens array and the display panel mechanically or electronically.[4] However, as the varied gap distance becomes larger, it becomes problematic because it can induce a vibration or time delay in mechanical implementation. It also gives a limitation in designing a system for electronic implementation, as various system parameters are closely related to the gap value. A shorter focal length enables the generation of multiple central depth planes at the same locations with a smaller change in the gap value. A change in the gap affects the change in the location of the central depth plane by the relationship

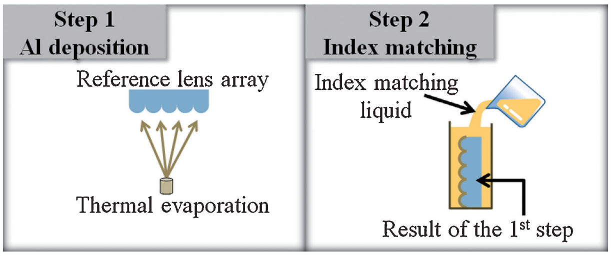


Fig. 2. Fabrication process for CHMA.

$$\Delta l \simeq \left|\frac{\partial l}{\partial g}\right|\Delta g = \left(\frac{sl}{f_0}-1\right)^2\Delta g. \tag{2}$$

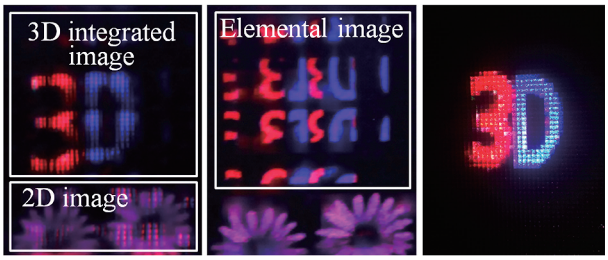
Hence, a change in the gap can move the location of the central depth plane more with s larger than one. Moreover, our system configuration enforces rays to have round-trips between CHMA and the reflective polarizer when the 3D mode is enabled. By changing the distance between CHMA and the reflective polarizer, the varied distance of the effective gap value is amplified to be three times larger. As a result, the required distance in moving some part of the system is reduced by a ratio of

$$\frac{(1-f_0/l)^2}{3(s-f_0/l)^2}. \tag{3}$$

Figure 2 briefly shows the fabrication process we used to construct the CHMA structure. Unlike the fabrication method demonstrated in ref. 8, our new fabrication method can achieve nearly perfect index matching between reference and cover layers. A convex lens array should be prepared as a reference layer to determine the shape of the target concave mirror array. As the first step, a thin metallic layer is deposited on the reference layer and this layer becomes the embedded concave mirror array of the CHMA. The ratio between the reflectance and transmittance of the CHMA can be controlled by the thickness of the metallic layer. We deposited Al by thermal evaporation and the thickness was determined to make the reflectance 50% for the highest brightness in the 3D mode. With this value of reflectance, the brightness of the 2D mode is ideally two times larger than that of the 3D mode considering the leakage caused by CHMA. Hence, the brightness of the image on the display panel should be adjusted to balance the brightness of the image between the 2D and 3D modes. Moreover a leakage occurred by CHMA incurs a reduction in contrast ratio and it is required to use a brighter light source to enhance the contrast ratio. As the second step, the result of the first step is immersed into an index matching liquid that has ideally the same index as the reference lens array. Using the proper index matching liquid as a cover layer, the refraction at the surface of the reference lens array nearly vanishes. We adopted a commercial twisted nematic (TN) LC panel for the polarization switcher. The type of LC panel should be carefully determined because it can affect

Table I. Specifications of the implemented prototype system.

Display device	Resolution	800 × 600
	Pixel pitch	$200 \times 200\,\mu m^2$
Reference lens array	Lens pitch	5.4 mm (H) × 7 mm (V)
	Focal length	41.9 mm
	Material	Glass



(a) (b) (c)

Fig. 3. Images displayed by prototype system operating on (a) 3D and 2D display mode and (b) 2D display mode. (c) 3D image displayed by a focused mode for the comparison of image resolution. Lens pitch of the lens array was determined to be 1 mm to guarantee enough viewing angle and depth expression.

the performance of polarization switching. For the usage as a polarization switcher, polarizers attached to the LC panel were removed. Detailed system specifications are listed in Table I.

Figure 3 shows the camera-captured images of experimental results. As we implemented the polarization switcher using an LC panel in the prototype system, the polarization state of the switcher is addressable pixel by pixel. Hence, it is possible to display 2D and 3D images in one scene simultaneously, as shown in Fig. 3(a). A conversion to 2D mode can be done by simply changing the polarization state of the polarization switcher to T-pol. The InIm principle does not work in the 2D mode of the proposed system; hence, the elemental image used to show an integrated image in 3D mode is explicitly shown in Fig. 3(b). In the real implementation, the characteristics of LC panel and reflective polarizer are not ideal. Hence the ghost images can appear as observed in Fig. 3. The performance of each component in the implemented system should be improved to reduce such artifacts. Figure 3(c) shows the 3D image reconstructed by the focal mode of the InIm scheme. As shown in Fig. 3, image resolution is much higher in real/virtual mode.

Figure 4 shows the experimental result, comparing the viewing angle between the conventional and proposed InIm systems. The central depth plane of the prototype system was located 31 mm in front of the system. Referring to Table I, the theoretical viewing angle of the prototype system is around 19.5°. As shown in Fig. 4, an integrated image is well displayed inside the viewing angle nearly up to the theoretical value. In this large viewing angle, lens grid of the lens array becomes noticeable as vertical dark lines. However, a conventional InIm system, which is implemented using a 2D convex lens array that has the same radius of curvature, cannot support such a viewing angle, as shown in Fig. 4. Though we can enhance a viewing angle by reducing the f number of lens array, it is difficult to make a diffraction-limited (or aberration-free) structure compared with concave mirror.$^{10)}$

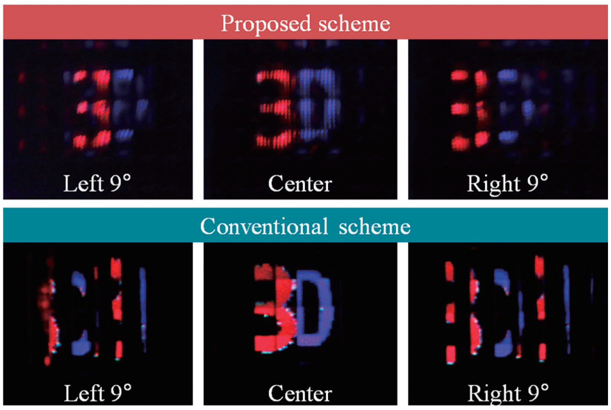


Fig. 4. Integrated images to compare a viewing angle between systems implemented by proposed and conventional schemes. For both cases, "3" is located 5 mm in front of the central depth plane and "D" is located 5 mm behind the central depth plane. A flipping problem is apparent in the integrated image displayed by the conventional scheme.

In conclusion, we provided a new method to implement a 2D/3D convertible InIm system operating as a real/virtual display mode. Our method can be used for an application where the resolution of the reconstructed 3D image is highly important. As discussed, our proposed scheme shows a wide viewing angle characteristic. However, the viewing angle is in a tradeoff relationship with the depth expression of the integrated image,$^{12)}$ and it means that our scheme is disadvantageous in the depth expression. Compared with the scheme in ref. 7, which is based on a convex lens, our proposed scheme is expected to be used for cases where a wide viewing angle is required.

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1) P. Benzie, J. Watson, P. Surman, I. Rakkolainen, K. Hopf, H. Urey, V. Sainov, and C. von Kopylow: IEEE Trans. Circuits Syst. Video Technol. **17** (2007) 1647.
2) G. J. Woodgate, J. Harrold, A. M. S. Jacobs, R. R. Moseley, and D. Ezra: Proc. SPIE **3957** (2000) 153.
3) J.-G. Lu, X.-F. Sun, Y. Song, and H.-P. D. Shieh: J. Disp. Technol. **7** (2011) 215.
4) J.-H. Park, K. Hong, and B. Lee: Appl. Opt. **48** (2009) H77.
5) J. Arai, M. Okui, T. Yamashita, and F. Okano: Appl. Opt. **45** (2006) 1704.
6) Y. Kim, S. Park, S.-W. Min, and B. Lee: Appl. Opt. **48** (2009) H71.
7) H. Choi, J.-H. Park, J. Kim, S.-W. Cho, and B. Lee: Opt. Express **13** (2005) 8424.
8) J. Hong, Y. Kim, S.-G. Park, J.-H. Hong, S.-W. Min, S.-D. Lee, and B. Lee: Opt. Express **18** (2010) 20628.
9) Y. Jeong, S. Jung, J.-H. Park, and B. Lee: Opt. Lett. **27** (2002) 704.
10) J.-S. Jang and B. Javidi: Opt. Express **12** (2004) 1077.
11) E. Walton, A. Evans, G. Gay, A. Jacobs, T. Wynne-Powell, G. Bourhill, P. Gass, and H. Walton: SID Int. Symp. Dig. Tech. Pap. **40** (2009) 1395.
12) S.-W. Min, J. Kim, and B. Lee: Jpn. J. Appl. Phys. **44** (2005) L71.