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Separation of multiple images via directional guidance using structured prism and pyramid arrays

HYEMIN LEE, HYEIN SEO, SUNGHWAN KANG, AND HYUNSIK YOON*

Department of Chemical and Biomolecular Engineering, Seoul National University of Science & Technology, Seoul, 139-743, South Korea

*hsyoon@seoultech.ac.kr

Abstract: We propose a new concept of separating images through a directional guide of multi-visuals by using structured prism or pyramid arrays. By placing prism arrays onto two different image arrays, the two collective images below the facets are guided to different directions. Using optical calculations, we identify a condition for successful image separation. Transparent pyramid arrays are used to separate four images into four directions. The direction of refracted rays can be controlled by the refractive index of prisms and liquid filled into the voids. In addition, the images can be switched by stretching and releasing an elastomeric prism array.

OCIS codes: (130.3990) Micro-optical devices; (080.0080) Geometric optics.

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1. Introduction

Optical elements such as lenses and prisms have been developed to enlarge images or refract incident light to desired directions and are used in glasses, microscopes, beam splitters, etc [1]. Due to the intensive development of microfabrication, micro-optical elements, such as microlenses and prism and pyramid arrays, have been utilized to enhance the brightness in liquid crystal display (LCD) devices by collimating light from backlight units or improving the efficiencies of energy harvesting devices by trapping incident light [2–4]. Recently, nanofabrication technologies have received attention to realize structures that mimic moth eyes to fabricate anti-reflection films, and the combination of micro- and nano- fabrication has been used for producing hierarchical structures to mimic the structural colors of morpho-butterfly wings [5–8]. The common aspects of these examples are the special optical functions generated from the innate structures of the materials, without the need for any other additional materials. Previously, we reported an asymmetric prism array partially coated with metal films (Lucius prism arrays) [9]. To provide these arrays with directionality, we coated one face of each prism array with a metal film. The metal-coated faces blocked the incident rays, and the uncoated faces remained transparent. By periodically changing the direction of the faces covered by the metal films, we were able to split a mixed image into two separate images by simply placing the film on the mixed image. The approach was highlighted because the new type of prism array was expected to replace parallax barriers or lenticular lenses which are used for three dimensional (3D) displays without glasses [10–14]. However, the Lucius prism array is still limited by its brightness loss and the fabrication complexity due to the coating process of the metal films. To address these issues, we propose a new concept of using asymmetric ratchet arrays for directional transmission and separate images with structured prism and pyramid arrays. By placing prism arrays onto two different image arrays, the two collective images below the facets are guided to different directions. Using optical calculations, we identify a condition for successful image separation. Transparent pyramid arrays are used to separate four images into four directions. The direction of refracted rays can be controlled by the refractive index of prisms and liquid filled into the voids. In addition, the images can be switched by stretching and releasing an elastomeric prism array.

2. Experimental

The masters used in this study were fabricated by mechanical machining or stereo-lithography. To prepare the metal masters, a blank plate of stainless steel electroplated by nickel was machined mechanically using diamond cutting tools at the desired angle (45 degrees). The period and prism angle of the carved structures depend on those of the diamond tools. The height of the carved patterns corresponds to the cutting depth of the diamond tool. To prepare the polymeric masters, we used a commercial machine for stereo-lithography (LITHO, Illuminade Co., Ltd). After designing the prism and pyramid structures using computer-aided design (CAD) software (3ds Max), we fabricated the three-dimensional structures sequentially exposing a commercial UV curable polymeric resin (Illuminade Co., Ltd) to programmed ultraviolet (UV) light using a digital micro-mirror device (DMD). For easy detachment of the transparent replica films from the masters, we treated the surfaces of the masters with fluorinated self-assembled monolayers (SAMs) (Trichloro(1H, 1H, 2H, 2H, perfluoro octyl) silane, Sigma-Aldrich). Next, we cast a mixture of polydimethylsiloxane (PDMS) prepolymers and curing agents with a ratio of 10:1 and then cured them at 60 °C for 10 hr. The PDMS films detached from the masters were transparent and shaped like a prism or pyramid array. The detail procedure for the preparation of PDMS structures can be found elsewhere [15]. To demonstrate the separation of multiple images, we prepared two images

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for four different images and eliminated half of each image with a period of 1 mm. Next, the multiple images were mixed alternately. Prism and pyramid arrays with the same period as that of the mixed image were placed onto the mixed images. The protruding parts of the prism or pyramid array faced the mixed image (Fig.1).

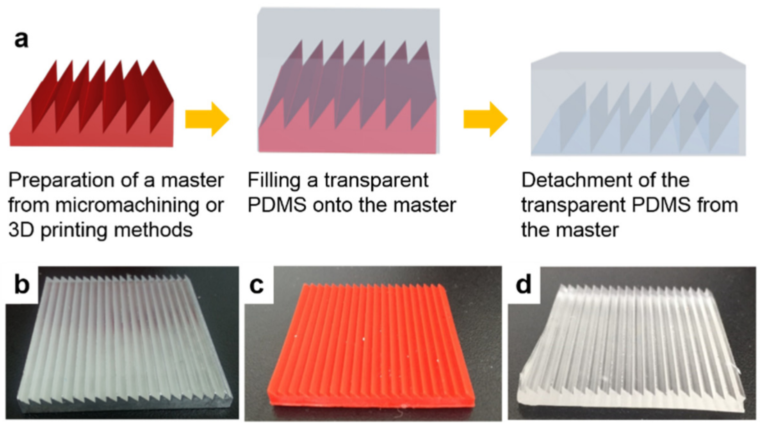

Fig. 1. (a) A schematic of a replica molding for the preparation of a transparent ratchet array. (b) A picture of a metallic master prepared by micromachining and (c) by stereo-lithography. (d) A picture of an obtained transparent ratchet array fabricated by the method.

3. Results and discussion

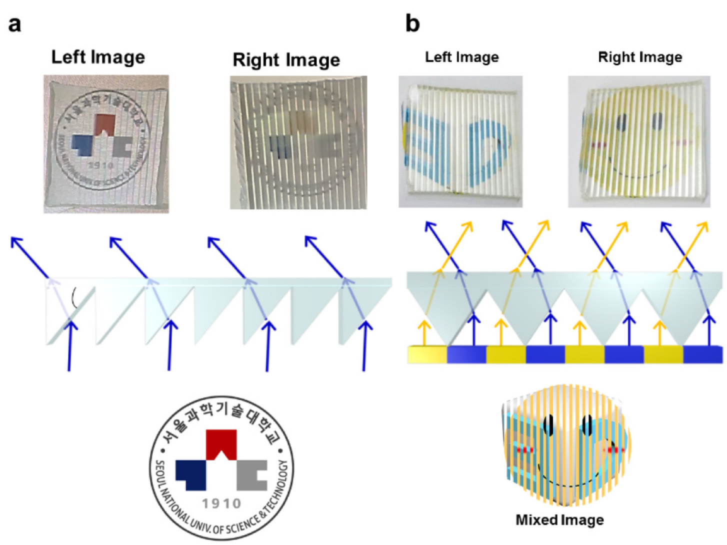

Fig. 2. (a) A schematic of the asymmetric ratchets used to refract the incident beam. The top images acquired from the left and right sides. From the left, the image under the ratchet array can be seen. From the right, the image is blurred because of refraction and total internal reflection. (b) The demonstration of image separation with the symmetric prism array. When we placed the innate prism array on a mixed image of two different images (the yellow smiley face and the blue 3D image), we could see only the blue 3D logo on the left and the yellow smiley face on the right.

Figure 2(a) illustrates the principle of the directional guidance through asymmetric prism (ratchet) arrays. The ratchet arrays guide the incident light to the left at an angle and can be predicted by Snell's law [1, 9]. To demonstrate the optical directionality, we prepared a ratchet array by the mechanical machining of a metal block or by 3D printing using a stereolithographic method. The designed pitch was 2 mm, and the ratchet angle was 45°. We then replicated the design with transparent poly (dimethyl siloxane) (PDMS) from the metal master. We placed the transparent PDMS ratchet array on a display panel and demonstrated the image contrast by changing the viewing position. The left side of Fig. 2a shows the view along the deviation angle. We can easily see the image on the display panel through the ratchet structures. However, when we look at the screen from the right side, the image becomes opaque, as shown in Fig. 2(a). To harness the optical directionality of the ratchet arrays for separating multi-images, we mixed two images (a smiley face and a 3D logo). Then, we aligned the ratchet arrays so that they would guide the blue image (the 3D logo) to the left and the yellow image (the smiley face) to the right. Interestingly, we found that the ratchet arrays were transformed into a symmetric prism array when we aligned the ratchets to guide the two images in different directions, as shown in Fig. 2(b). Thus, we fabricated a transparent symmetric prism array with a pitch of 2 mm and a prism angle of 45° and placed it on a mixed image with a period of 2 mm. The two images of the top part of Fig. 2b are the images acquired from the left and right. We can only see the smiley face from the left, whereas the 3D logo can only be seen from the right (see Visualization 1). When we place the prism array on a mixed image or video, the optical directionality can help two users see two different images.

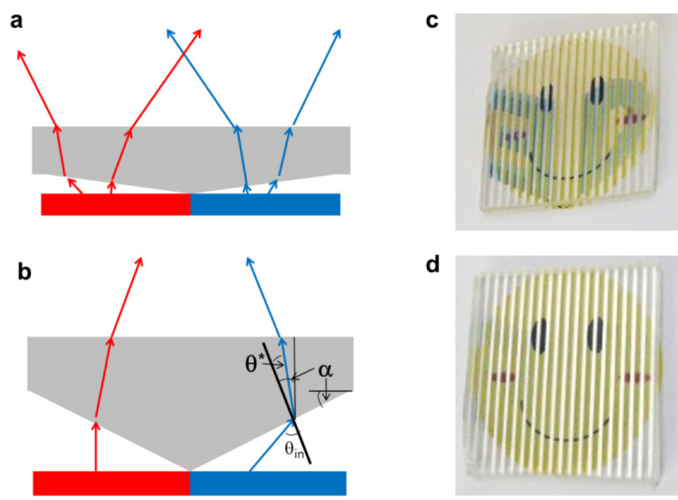

Fig. 3. (a) A schematic illustration of non-directional image guidance with a prism array of a small prism angle. (b) A scheme of image separation by refraction on facets of a prism array. (c) An overlapped image of two images taken from the right with a prism array in 30 degree prism angle. (d) A picture taken from the right side with a prism array in 45 degrees. Only the smiley face can be seen.

To successfully separate two images, the respective refracted rays from the images should go into different directions. When we assume an extreme case, in which the prism angle is close to zero degree, we can see both images (blue and red ones) in the left and right, respectively, as shown in Fig. 3(a). When the directions of all refracted rays from the two images were different from each other, the blue and red ones could be separated, as shown in Fig. 3(b). To analyze the condition of image separation when using the prism array, we obtained the refraction angle θ* from Snell's law [1].

$$\sin\theta^* = \sin\theta_{in} / n_{prism} \quad (1)$$

where n_{prism} is the refractive index of the prism material, and θ_{in} is the incident angle from the image below the prism. Figure 3(b) shows that two images could be separated when the

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refraction angle θ* is less than prism angle α. Because the ranges of θ_{in}, θ*, α are between zero to 90 degrees, the condition for the image separation is as follows:

$$\sin\theta^* = \sin\theta_{in} / n_{prism} < \sin\alpha \qquad (2)$$

In addition, we conclude that the maximum value of sin θ_{in}/n_{prism} is $1/n_{prism}$ (when the incident angle θ_{in} is 90 degrees). From Eqs. (1) and (2), we obtain the following condition for the image separation.

$$\frac{1}{n_{prism}} < \sin\alpha, \quad \alpha > \sin^{-1}(\frac{1}{n_{prism}}) \qquad (3)$$

To certify the criteria, we prepare transparent PDMS prism arrays with two prism angles (30° & 45°). Because the refractive index of PDMS is 1.4176 [16], $\sin^{-1}(1/n_{prism})$ is 44.86°. From Eq. (3), two images can be separated only when the prism angle is greater than 44.86°. When the prism angle (α) is 30°, which is smaller than $\sin^{-1}(1/n_{prism})$, overlapped images are seen from the left side (Fig. 3(c)). Through a prism array of 45°, as shown in Fig. 3(d), the images are separated (only a smiley face is observed from the left).

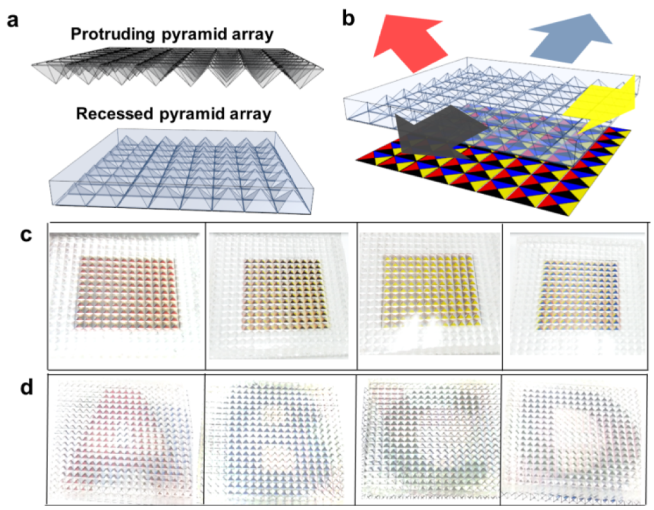

Fig. 4. (a) A schematic of protruding and recessed pyramid arrays. (b) The concept of separating four different colors and guiding them in different directions. (c) Images of four mixed colors obtained from four different directions and observed through a pyramid array. (d) Images of four letters viewed from four different directions.

Figure 4 presents a scheme for the separation of 4 images using a four-directional front guide with a pyramid array. As shown in Fig. 4(a), there are two approaches to create the four-directional front guide film: a protruding or a recessed pyramid array. Both structures show the same effects because the image separation is resulted from the refraction on the slanted facets. With the same principle of the inverted prism array, the four faces of the pyramid can guide light in four different directions. We prepared the metallic pyramid array and a mixed image, shown in Fig. 4(b), with 4 different colors (red, black, yellow, and blue) in 2 mm × 2 mm squares repeated over a 4 cm × 4 cm area. When we placed a PDMS pyramid array on the result, we could see different colors from the different directions. Figure 4(c) shows the images obtained from the four different directions. From the front, we could only see red color because of the way the light was refracted through the pyramid array. When we rotated the viewing angle, the color changed successively from red to black to yellow to blue (see Visualization 2). When we mixed the images of the letters A, B, C, and D

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into a new image and placed it under a pyramid array, we could see the four different letters, A, B, C, and D, as shown in Fig. 4(d) and Visualization 3. We note that the image separation could be generalized to 6-directional guidance with a triangular pyramid array because the images are refracted on the six-different facets of the structures. The multi-directional separation can be applicable to a tabletop for a board game in which several players should see different information.

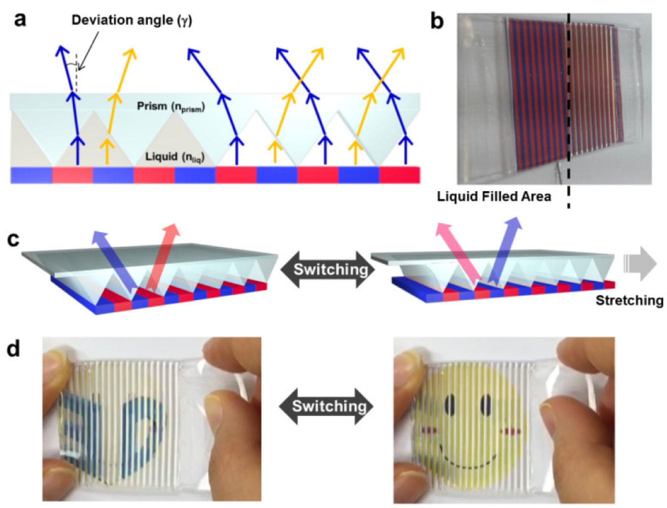

Fig. 5. (a) A scheme of controlling the deviation angle using liquid filler. (b) A mixed image under a prism array. The left half is filled with refractive-index-matching liquid and therefore there is no effect of image separation, whereas only red can be seen in the unfilled region. (c) The concept of switching from the university logo to the smiley face by mechanically stretching an elastomeric prism film. (d) Images taken with the film in its original position and after laterally stretching the elastomeric prism array.

To control the deviation angle through the prism array, we can use a method to control the refractive index of liquid filled into the voids between the prisms on a mixed image, as shown in Fig. 5(a). For example, we can negate the image separation effect by controlling the refractive index of the liquid in the void. To eliminate the separation effect, we simply match the refractive index of the liquid to that of the prism. Then, the deviation angle becomes zero. We prepared a refractive index-matching liquid by mixing polyethylene glycol (PEG) and ethanol to obtain a refractive index of 1.4176, which is the same as that of the transparent elastomer PDMS. Figure 5(b) shows the image separation and the effect-eliminated regions. The left side is filled with a refractive index matching liquid, and we can see a mixture of colors (see Visualization 4). On the right side, only red appears because blue is refracted through the prism array when it is empty. As another method to manipulate the image separation, we used mechanical stretching and releasing to switch images visible from one direction. When we used an elastomer for the prism array, we could change the image seen by one eye by stretching the elastomer. Figure 5c presents a schematic illustrating how the image is switched by mechanical stretching. In its original position, the left faces of the prisms in the array matched the blue image (the smiley face), as shown in Fig. 5(d). When we laterally stretched the transparent elastomer, the left faces matched the red image (the university logo). A demonstration of this approach is in Visualization 5. This approach allowed us to switch a university logo (Fig. 5(d)) and a smiley face simply by mechanical stretching and releasing. In this paper, we propose a use of prism and pyramid shape structures to separate images. When we compare with traditional parallax barriers and the lenticular lenses (Table 1), we can see that the prism array has only two viewpoints. In the case of using barriers or lenses, we can see left and right images periodically when we move the viewpoint only to the left. On

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the other hand, we can see only the left image from the left with the prism array because the left image is refracted on one facet of the prism array in principle. Although this characteristic could be a demerit for multi-view displays, the function of image separation can be enhanced. Compared with our previous Lucius prism array, the innate prism array is advantageous in its affordable manufacturing costs as well as in transmission efficiency because we have removed the procedure of coating metal films. Also, the fabrication of the prism or pyramid type structures is relatively easier compared with lenticular lenses because curved structures could be an obstacle [14] to be fabricated especially when the pixel size is decreased. The mechanical machining process for the prism arrays is relatively established even in smaller pitches (for example, 10 μm). Moreover, the optical film is robust because the protruding parts face the display panel. The top surface of the prism array can be processed for other applications, such as protection, antireflection, and super-hydrophobicity. Furthermore, the directional guidance in front of the display panel is more useful compared with the directional backlighting method [17–19] because the scheme can be exploited for display devices without backlights, such as organic light-emitting diodes (OLED).

Table 1. Comparison of Various Methods to Separate Images

	Number of view points	Transmittance Efficiency	Blocking Efficiency	Manufacturing Cost
Parallax Barrier	Multi-view	Δ	O	O
Lenticular Lenses	Multi-view	O	Δ	Δ
Lucius Prism array	Two-view	Δ	O	Δ
Prism Array	Two-view	O	Δ	O

O: Advantage, Δ: Disadvantage

We demonstrated a simple proof of concept to change the deviation angle by manipulating refractive index of liquid filled in the void of the structures. If combined with optical elements such as collimating films, the concept could be used for autostereoscopic 3D display which has a deviation angle of less than 10 degrees. Also, we note that the refraction of RGB colors could be different respectively due to the dispersion effect of the prism. In this experiment, we used a PDMS which has a small variation of refractive index (1.41~1.42) in RGB region [20], then the deviation angle difference was small (21.3 ~21.8°) enough to obtain clear multi-color images as shown in all Visualizations

4. Conclusion

We proposed a novel concept of image separation based on refraction on the facets of prism and pyramid arrays. The prism array aligned with the mixed image can produce different images in different directions. In addition we derived the condition of prism angles and the refractive index of the prism array for the successful separation of the images. For multiple views, we demonstrated four directional guides with pyramid arrays placed in front of four mixed images. To change the images viewed from one direction, filling refractive index-matching liquid and mechanical stretching can be applied.

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