Fabrication of a Dihedral Corner Reflector Array for a Floating Image Manufactured by X-ray Lithography Using Synchrotron Radiation

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Abstract
The development of a new imaging optic which can produce a floating image has attracted much attention. One candidate for such an optic is the dihedral corner reflector array (DCRA). A DCRA consists of numerous micro–mirrors placed perpendicular to the surface of a substrate. The micro–mirror array is implemented by the inner walls of minute square holes or by the side of a minute square pillar. The primordial is based on two reflections by a pair of adjacent mutually perpendicular mirrors, i.e. a dihedral corner reflector. Although the principle of operation is based on reflection by mirrors, the device is also transmissive and deflects light. Thus, the primordial of DCRA is not particularly complicated. However, it is too difficult to fabricate the DCRA by typical machining processes, because high aspect ratio micromachining and high mirror accuracy are required. Therefore, in this study, we fabricate the device by deep X–ray lithography using synchrotron radiation. We demonstrate floating image projection using the fabricated DCRA.

Keywords: Micro–mirror, Floating image device, Dihedral Corner Reflector Array, X-ray lithography, Synchrotron radiation

1. Introduction
Displays that can render three–dimensional (3D) images have attracted much attention for use in devices or methods which directly appeal to the human eye. In the near future, 3D displays are likely to become a promising next–generation visual interface. The development of these devices and systems has been actively pursued.[1, 2]

An easily operable device or system for floating 3D or 2D images has applications in the areas of medical imaging, mechanical computer–aided design, movie theatres and military visualization. One of the earliest and simplest systems for achieving two–view 3D images is the color anaglyph wherein a user views a color print or display using a pair of colored filter glasses which encode left and right views in two different color channels. Similarly, some form of eyewear is required in most 3D display techniques in televisions and movie theatres. On the other hand, holographic techniques suffer from difficulties in producing a dynamic 3D image. Several techniques for forming 3D images have recently been developed. Studies and developments of such techniques give us many important knowledge for successfully fabricating 3D displays. However, none of these techniques achieves the dynamic formation of a floating image.

Here, we consider another approach to realize 3D or floating images. There are some basic imaging optical systems that can form a real image, such as convex lenses, concave mirrors, and diffraction optics (Fresnel lens).[1, 2] For example, there are systems based on the lens array of the graded index lens,[3] roof mirror lens array (RMLA)[4], and the stacking of various micro-lens arrays.[5, 6] These lens–based systems have an optical axis and a specific focal length. Moving an object closer to the optic, leads to the formation of the real image farther from the optic and caused its magnification. In contrast, there are several imaging optical systems that can form 3D–images without...
distortion. One of such system is a plane mirror, however, this can only form virtual images.

In this study, we propose a new imaging optic which forms a real mirror image with the use of micro–mirrors. We called this an imaging optics dihedral corner reflector array (DCRA).[7–11] There are both transmission and reflection type DCRA systems. Here, we fabricated a transmission type DCRA by deep X–ray lithography using synchrotron radiation. We demonstrated the formation of a floating image using the fabricated DCRA.

2. Primordial of the DCRA

A DCRA comprises arrays of dihedral corner reflectors (DCRs).[7, 8] To clarify the primordial, let us consider a DCR. Figure 1(a) shows the overhead view of the optical ray trajectories of the DCR. An incident light from a light source ‘A’ is reflected at two mirrors and the trajectory of the light returns to the direction ‘B’, parallel to the light source ‘A’. Next, let us consider the case of Fig. 1(b). Here, the incident light from light source ‘A’ into the DCR reflects at two side mirrors when passing through the DCR. Then, this light deflects toward the point ‘B’ in the 3D structure, as shown in Fig. 1(b). This denotes the primordial of the transmission type DCR, as schematically illustrated in Fig. 1(c). Thus, the refractile body of the DCR refracts the ray trajectory at positions of incidence and output. Another type of DCR, the square–hole–type DCR which is made up of four mirrors, is also proposed, as shown in Fig. 1(d). In the hole-type DCR, the same primordial is implemented. Then, if the micro-mirrors are extremely small, the incident light passes through the substrate plane towards the symmetric point for the light source. When we prepare many DCRs on the substrate, all the light from the light source converges onto the reflection-symmetric point of the source. As a result, the array of numerous dihedral corner reflectors, namely the DCRA, can realize the floating image, as schematically shown in Fig. 2.

3. Design of the DCRA

To design the DCRA, we calculate the optical ray trace and evaluate the declination derived from the processing accuracy. The perpendicularity of the DCR reflector plays the most important role in the resolution of the floating image, and it causes distortion of the image. With optical simulation, it is possible to estimate the dependence of the resolution of the floating image on the perpendicularity of the DCRA wall. In the simulation, we calculate the optical ray trace through the position of light reflected by a line of plane mirrors from a point light. Then, we can choose the number of plane mirrors, the distance of the point light from the head mirror and the taper of the mirrors. If the planes of the mirrors in the DCRA are exactly perpendicular, all light reflected by each mirror passes through the same point on the head mirror. Figure 3(a) shows the schematic cross section of the DCRA and optical ray trace. Here, we assume the distance from the light, the pitch of pillar, the number of mirrors and the taper angle of the pillar to be \( d = 50 \, \text{mm} \), \( a = 24.2 \, \mu\text{m} \), \( n = 164 \) and \( \phi = 1/60 \), respectively. Figure 3(b) shows the focal point distances reflected from the respective mirrors. The mirror position at \( k = 0 \) corresponds to the center of the DCRA. Under the assumption that the pillar size and width between pillars are 150 and 25 \( \mu\text{m} \), respectively, the mirror position at \( k = 160 \) corresponds to 2.8 cm from the center position of the DCRA. The calculation result shown in Fig. 3(b) indicates
a declination of about 5 μm is estimated when the mirror is at \( k = 160 \). As a result, the distortion of the floating image produced by the DCRA can be estimated to be approximately 10 μm when the plane mirrors have a taper of less than 1/60 degree.

Next, we postulate that the transmittance of the DCRA is the percentage of incident light through the reflection-symmetric point. The transmittance is calculated as follows:

\[
\text{Transmittance} = I \times R^2 \times T, \quad (1)
\]

where \( I \) is the ideal transmittance, \( R \) is the reflectance of the micro-mirror and \( T \) represents the losses (defined as the factor consisting of aperture ratio and attenuation of intensity of the incident light after passing through the DCRA). Reflectance \( R \) of the micro-mirrors is the most important factor in imaging by DCRA. In this study, we expect that it is as close as possible to 100%. However, in the actual device, the micro-mirrors are placed perpendicular to the surface of the substrate. Consequently, the micro-mirrors cannot be polished after manufacturing, because of the micro-scale, perpendicularly precipitous pillar-structure array. Accordingly, the reflectance of micro-mirrors is determined during the creation of the DCRA.

Imaging resolution is dependent on the dimensions of the DCR. As described above, a mirror can form a dot which constitutes a floating image. If we prepare a tiny mirror which is less than, or comparable to, the wavelength of the light, the tiny structure will not be a mirror and the array device will become a photonic crystal or metamaterial device, rather than a DCRA. To achieve the DCRA, all mirrors constituting the DCRA are required to exhibit high reflection with respect to visible light. As a result, a mirror must be adequately larger than the wavelength of visible light and is required to sustain its properties as a mirror. The pitch of the mirrors is also required to be adequately large and independent of the wavelength of light, so as to prevent the interference of light. The distance between the imaging plane and DCRA is proportional to the aperture ratio, which is determined by the pitch of the mirrors. Identifying suitable dimensions of the DCRA structure and selecting appropriate materials are important design consideration. The limit of resolution which can be recognized by the human eye is comparable to 250 dots per inch (dpi). This indicates that a dot constituting a floating image is suitable when in the range 30 to 100 μm. For obtaining a higher resolution image, the smaller DCRs in the DCRA have to be fabricated in the range described above. However, the image produced by a DCRA consisting of smaller DCRs will be dark, because the diffractive component of the light increases. Therefore, deep micro-fabrication processes with high precision are required for manufacturing the DCRA. Deep X-ray lithography using synchrotron radiation[12, 13] is one of approach for fabricating a DCRA that can produce a floating image of high quality and adequate brightness.

An ideal transmittance, i.e. the brightness of an object, of 64.9% can be expected by the pillar-type DCRA when the pillar width and the gap between pillars are 150 and 25 μm, respectively. In a DCRA of similar dimensions, the transmittance of a pillar-type DCRA is larger than that of a hole-type DCRA. In this study, we focus on the pillar-type DCRA because it can provide a higher brightness and can be easily fabricated by single X-ray exposure and development.[12, 13]

4. Fabrication of the DCRA Using Deep X-ray Lithography

Polishing the micro-mirrors is a simple tack if they are parallel to the device surface. However, because the micro-mirrors are perpendicular to the device surface in the DCRA, it is impossible to polish them in pre- or post-processes. High precision micro-fabrication is required for the fabrication of DCRA. In this study, we fabricated a pillar-patterned DCRA made of Poly-methyl methacrylate (PMMA) using beam line BL-2 at the NewSUBARU synchrotron radiation facility of the University of Hyogo.[12]

The X-ray lithography system at the BL-2 utilizes two different energy regions; one is a high-energy region from 2 to 12 keV, and the other is a low-energy region from 1 to 2 keV. Each energy region can be selected in accordance with the size and shape of the desired microstructures. In
this study, we used the high-energy region because a high-aspect and deep lithography are required. The fabrication process using synchrotron radiation enables us to fabricate the DCRA structure to an accuracy of about 1 nm.[12] Figure 2 shows a schematic of the dimensions of our DCRA device. The dimensions and desired values of the DCRA are summarized in Table 1. Here, the pillar dimension is the dimension of the DCR.

In the following, we consider the twice reflection of incident light through the inside of pillars made by PMMA in pillar patterned DCRA. Considering the refractive index of PMMA, we designed our device with an aspect ratio (height/width) of two in order to achieve a theoretical light transmittance of 100% under the assumption of total reflection condition. The aperture ratio is determined by the pitch between the reflectors. Considering the contribution of the aperture ratio in our device, we estimate that the effective fraction transmitted is 64.9%. In other words, the brightness of the floating image is expected to be 64.9% that of an object.

5. Results and Discussion

Until now, the criteria and evaluation method for properties such as the resolution and brightness of an image produced by a DCRA have not been established. In this study, we measure the dimensions of a DCRA and demonstrate the formation of a floating image using the DCRA.

Figure 4 shows an optical microscope image of the micro–pillars, and the dimensions of the fabricated DCRA are summarized in Table 2. These are very similar to our proposed design described in Table 1. However, the perpendicularity of the pillars has approximately 6 minutes of taper. According to our simulation, this seems to cause distortion of about 65 μm for the distance of the light source to the device. This distortion is expected to be serious with respect to the quality of the floating image rendered by DCRA.

The attenuation of brightness is evaluated by the transmission–reflection ratio measuring instrument, as schematically illustrated in Fig. 5(a). The measurement system enables us to provide the transmission and reflection properties of the sample in the visible range. First, we show the absorption of the fabricated DCRA device as a function of wavelength. The measurement of absorption was performed when the visible light incident was injected into the DCRA substrate. As shown in Fig. 5(b), the absorption property has an anomaly at a wavelength of 370 nm, while the absorption ratio is broadly independent of wavelength in the visible light range. The anomaly is attributed to the PMMA becoming stained by synchrotron radiation.

Next, to evaluate the reflection properties of the fabricated DCRA, we immobilised the DCRA device at θ = 25° and measured the one-time reflection light from the DCRA by rotating the measurement component between φ = 0° and φ = 90°, as shown in Fig. 5(a). Figure 5(c) shows the reflection ratio as a function of angle φ, at a fixed wavelength of 700 nm. In the angle range between φ = 0° and φ = 20°, we should not estimate the reflection ratio because of the transmitted light injected into the detector. For the sake of excluding the data below φ = 20°, the reflection data is removed by shadow. As shown in Fig. 5(c), we determined the peak structure in the reflection properties.

Table 1. Dimensions of the designed DCRA.

| Dimension                | Value |
|--------------------------|-------|
| Pillar dimension [μm]    | 150   |
| Pillar height [μm]       | 300   |
| Pitch [μm]               | 25    |
| Ideal transmittance [%]  | 100   |
| Aperture ratio [%]       | 64.9  |
| Perpendicularity [°]     | 90    |
| Roughness [nm]           | 10    |

Table 2. Dimension of the DCRA fabricated by the X-ray lithography process.

| Dimension                | Value       |
|--------------------------|-------------|
| Pillar dimension [μm]    | (A) 150.92  |
|                          | (B) 151.42  |
| Pitch [μm]               | (C) 25.87   |
| Pillar height [μm]       | (D) 326.78  |
| Pitch of top [μm]        | (E) 27.34   |
| Pitch of bottom [μm]     | (F) 26.92   |
| Perpendicularity [°]     | Calculated by (E)&(F) 5.8 |

Fig. 4 Optical micrographs: (a) top view and (b) cross-sectional view of the DCRA fabricated by the X-ray lithography process. The indexes (A)–(F) correspond to the measured lengths described in Table 2, respectively.
of the fabricated DCRA. The peak corresponds to the reflection derived from one-time reflection. This reflection peak is in good agreement with the expected peak position, as anticipated by the reflection law ($\phi = 50^\circ$). [14] The broad reflection peak property extends between $\phi = 40^\circ$ and $\phi = 70^\circ$, indicating that the reflection light is spread by diffuse reflection and distortion from the taper structure. Consequently, the real transmittance is estimated by Equation (1) to be 5.4%. This result indicates that the formation of a dark floating image is expected using the fabricated DCRA.

We demonstrate the formation of a floating image using the fabricated DCRA. As shown in Fig. 6, we can produce the floating image, however, it is clear that some Katakana and Kanji characters are blurred. This is attributable to a sharp or uneven edge on a pillar, which is cut from the PMMA substrate using X-ray lithography, and to the taper structure of the pillar (about 6 minutes), as shown in Fig. 4.

To improve the processing accuracy, we are planning to replace the polyimide X-ray mask with the one based on a carbon substrate. This novel approach will shed light on the improving the brightness and the reduction of the taper structure. Figure 7 shows a typical result for this developing novel process. Thus, X-ray lithography enables us to easily adjust the process and perform the micro-fabrication process with high precision.

6. Summary

In this study, we proposed novel imaging optics with a micro–dihedral corner reflector array, which can produce a reflection-symmetric image as a real image in the air. The DCRA was manufactured by synchrotron radiation, and is used to render a floating image.

To improve imaging, our future work aims to increase transmittance and establish a quantitative measurement method for the resolution and reflection ratio.

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