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Design of Transparent Ratchet Arrays for Directional Transmission

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Abstract: Directional properties originated from asymmetric structures have known as useful tools for optical devices, adhesives, and microfluidic devices. Recently, asymmetric transparent ratchet structures have proposed to be an optical film for directional transmittance, which is transparent in one direction and opaque in the other direction. Here, we study the ratchet design such as ratchet angles and tilted angles to optimize the directionality. From the 3D printing methods, we fabricated asymmetric structures with different ratchet angles, tilted angles, and replicated to transparent polymeric materials to be useful as an optical component. In addition, we compared the results with optical simulation and they show a good agreement.

Keywords: ratchets, PDMS, 3D printing, optical simulation, directional transmission

I. INTRODUCTION

Recently, many researchers have reported bioinspired asymmetric structures, which show special functions such as directional adhesion forces by slanted hairs in gecko's feet and water harvesting abilities by asymmetric needles in Horduem vulgare, and the possibility of manipulation of flow speed in microfluidic devices [1-3]. In addition, structures are related with optical properties, for example, antireflection films are inspired by moth eye and the structural colours are generated from hierarchical structures found in morpho-butterfly [2-3]. In this knowledge, we studied several reports on the optical properties in asymmetric features including prism arrays partially covered by metallic films.[4-6] From the asymmetrically designed optical films, we demonstrated a directional transmittance, which is transparent in the desired direction and opaque in the other direction.[4-5] To avoid the experimental complexity, we designed a ratchet arrays for the directional transmittance in a previous report.[6] In this paper, we design the ratchet array with different ratchet angles and tilted angles to optimize the directional properties. To demonstrate the directional transmittance in various designed structures, we exploited the 3D printing method. 3D printing methods can be utilized to fabricate complex structures for testing the optical properties of designed structures. Especially, tilted structures cannot be obtained by conventional photolithography. Second, we replicated with transparent Polydimethylsiloxane (PDMS) structures from the 3D printed masters. PDMS is a rubber-like material and it is applicable to verify the directional optical properties. Furthermore, we conducted optical simulation to analyse the experimental results and investigated the reason of the directionality through the various ratchet designs.

II. RESULTS & DISCUSSION

Figure 1 shows the scheme of the parameter studies of ratchet arrays. As shown in Figure 1a, the incident light is refracted to one direction (left in Figure 1a) and the transmittance to the left is higher than that in the other direction (right in Figure 1a.) To design the ratchet structures for optimizing directional optical properties through the asymmetric ratchet arrays, we define the ratchet angle as a smaller angle of a ratchet and tilting angle as a deviation from the right angle as shown in Figure 1b. After the design of the ratchet arrays, we fabricated a master pattern with a stereolithographic 3D printer. We used a commercialized UV-curable resin and it is crosslinked by UV light from the printer. After constructing ratchet structures from a 3D printer, we cure the UV cured resin for several hours to crosslink all the prepolymers within the ratchet structures. Then, we poured prepolymers of PDMS mixed with a curing agent (10:1 ratio) onto the master and then detached the PDMS structures from the master after curing at 60°C for 6 hours. We note that the PDMS is a transparent rubber and it can be detached from the trapezoidal structures. It is essential to this study because only elastomeric materials can be released from tilted ratchet arrays fabricated by 3D printing. As shown in Figure 1c, we prepared ratchet arrays with prism angles of 30°, 45°, 60° and tilting angle of 0°, 15°, 30°.

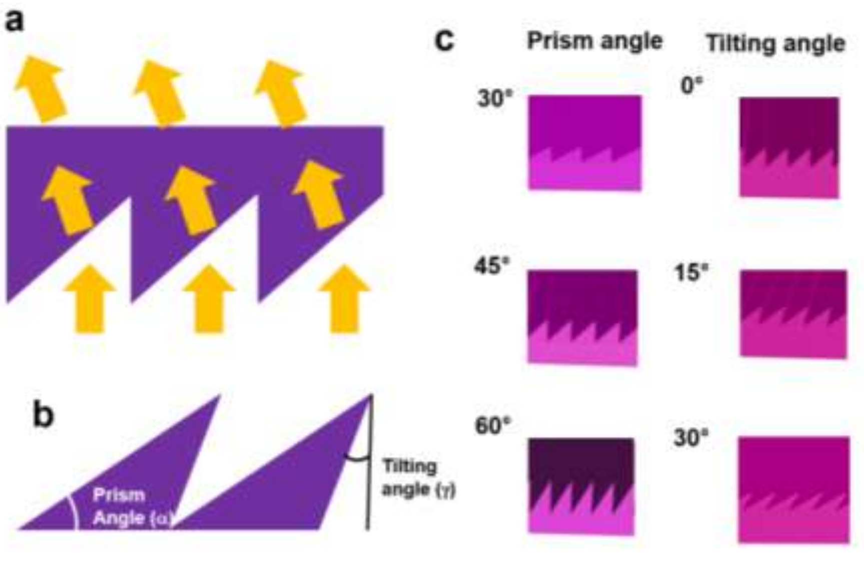

Fig. 1. a) A schematic of the directional transmission through asymmetric ratchets. b) Definition of prism angle and tilting angle. c) Designs for the experiment.

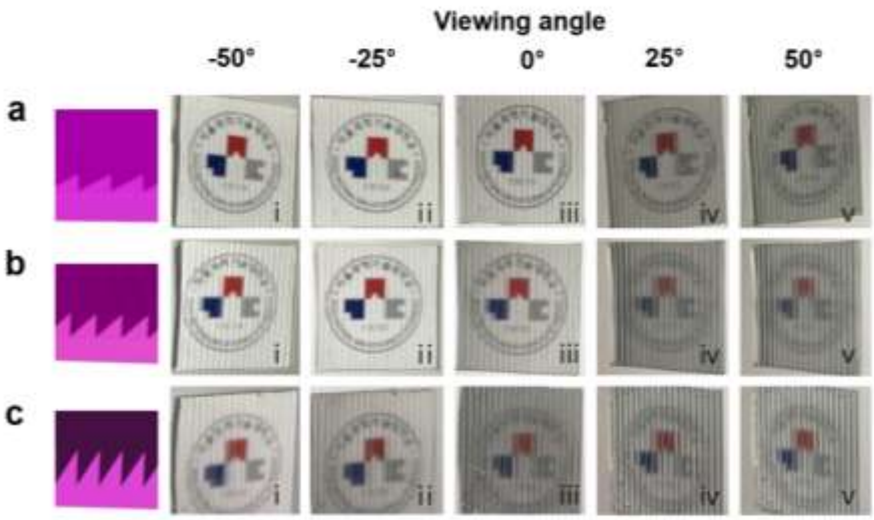

Fig. 2. Images of university logos through the transparent ratchet arrays with different viewing angle of -50°, -25°, 0°, 25°, and 50° when the prism angle is (a) 30°, (b) 45° and (c) 60°.

Figure 2 shows the experimental results of the directional transmission with different prism angles of 30°, 45° and 60°. We placed the transparent PDMS ratchet arrays onto a screen showing a university logo and took pictures by changing viewing angles of -50°, -25°, 0°, 25° and 50°. As shown in Figure 2a, the university logo can be seen clearly in the left side (-50°, -25°) compared with the right side (25° and 50°) when the prism angle is 30°. In the case of 45° prism angle (Figure 2b), the contrast between the left image and the right image is better than the results of 30° prism angle. When we increase the prism angle to 60° as shown in Figure 2c, the opaqueness in the right direction is obvious. However, the logo in the left side is not clear through the ratchet array.

Then, we investigate the directional optical property with different tilting angles. Figure 3 shows the experimental data when we place the PDMS ratchet arrays onto the university logo. In this comparison, we fixed the prism angle to 45°. Figure 3a is the same result with the Figure 2b because the tilting angle is zero from the right angle. When we tilt the ratchets to 15°, the contrast between images in the left and the right became weak because the opaqueness in the right side is not obvious. After increasing the tilting angle to 30°, the contrast became weaker than zero or 15° tilting angles.

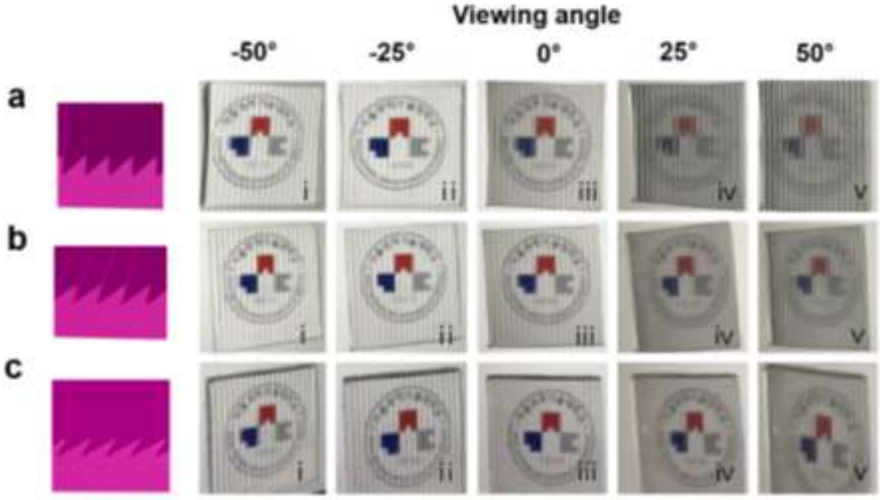

Fig. 3. Images of university logos through the transparent ratchet arrays with different viewing angle of -50°, -25°, 0°, 25°, and 50° when the tilting angle is (a) 0°, (b) 15° and (c) 30°.

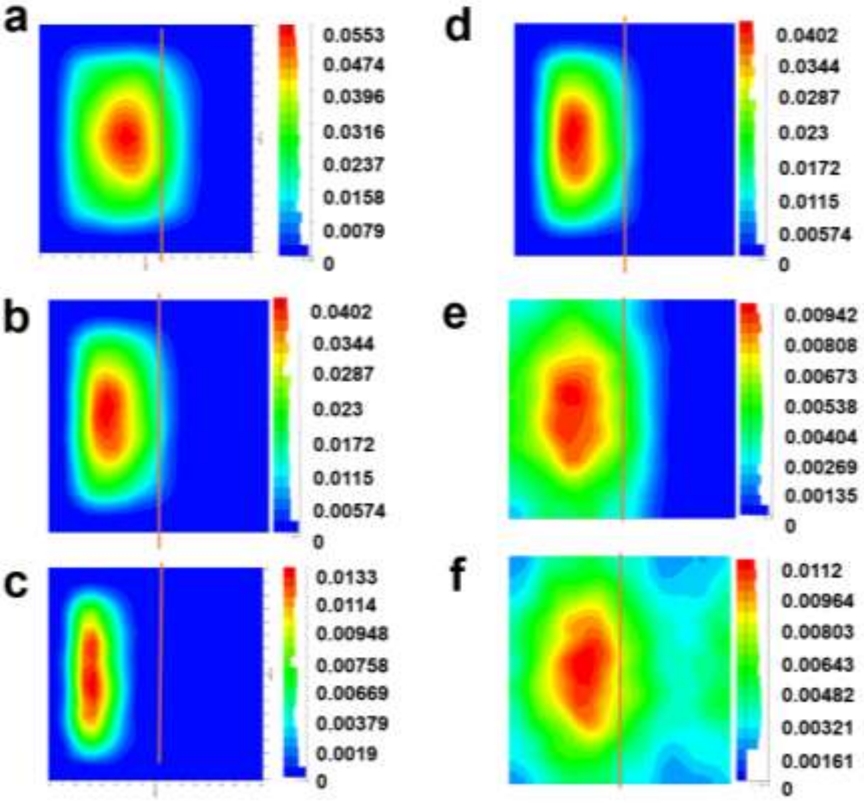

Fig. 4. Optical simulation results with prism angles of (a) 30°, (b) 45° and (c) 60° in zero tilting angle. And the results with tilting angles of (d) 0°, (e) 15° and (f) 30° when the prism angle is fixed to 45°.

To analyse the contrast of the directional transmission, we conducted optical simulation with commercial software (Lighttools). Figure 4 shows the ray tracing results with different prism angles and tilting angles. Figure 4a is the simulation result when the prism angle is 30° with zero tilting angle. The brightest region is focused in the left direction, which is well matched to the experimental results. However, there are rays moving to the right side with the prism angle of 30° as shown in Figure 4a, the contrast could not weakened. Figure 4b is the result with the prism angle of 45°. In this case, there is no leakage to the right direction compared with the previous results of Figure 4a. When we increase the prism angle to 60°, the leakage is small to the right direction. However, the luminance to the left (0.04) is smaller than the results of 45° of the prism angle (0.01). Figures 4d-f are the optical simulation results with different tilting angles when we fix the prism angle to 45°. Figure 4d is the simulation data when the tilting angle is zero. We note it is the same with the result of the Figure 4b. When we tilted the ratchet to 15°, there are a few leakage to light to the right direction as shown in Figure 4e. In addition, the leakage became higher when the tilting angle is increased to 30°. From the experimental results and the optical simulation, the optimum condition is the 45° of prism angle and the zero tilting angle. An easy way to comply with the paper formatting requirements is to use this document as a template and simply type your text into it.

III. CONCLUSION

In conclusion, we design ratchet arrays with different prism angles and tilting angles to optimize directional transmission through the structures. We fabricate masters of ratchet arrays from 3D printing and replicate with elastomeric PDMS materials from the master. From the experimental results and the optical simulation, we can conclude the 45□ of prism angle and the zero tilting angle is the best condition for obtaining the highest contrast.

IV. EXPERIMENTAL

The masters used in this work were fabricated by commercial equipment (LITHO, Illuminade Co., Ltd). The ratchet structures are designed using the 3D Studio Max (3DS MAX) software. Then we fabricated the three-dimensional structures sequentially exposing a UV curable polymeric resin to programmed ultraviolet (UV) light using a digital micro-mirror device (DMD). For the easy releasement of the transparent replica structures 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-9Aldrich). Then, we pour a mixed polydimethylsiloxane (PDMS) prepolymer with crosslinker (wight ratio is 10:1) onto the master and cured them at 60 °C for 10 hr. The PDMS structures detached from the masters were transparent and had a shape of ratchet arrays. We used a commercial software package (LightTools) for the optical simulations. Simulations were performed for 5 prism arrays (500 μm in period, 50 mm in length) with a constant refractive index of 1.41 for the PDMS film.

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