ARTIFICIAL COMPOUND EYE INSPIRED BY IMAGING PRINCIPLE OF XENOS PECKII

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ABSTRACT

This work reports an artificial compound eye inspired by the imaging principle of Xenos peckii, which is an endoparasite of paper wasps. The unique eye design exhibits higher spatial resolution and better sensitivity than conventional compound eyes. The biomimetic compound eye comprises three layers, a microprism arrays, a microlens arrays and an aperture arrays. All of the layers were formed on a planar substrate, the device can be directly integrated with a commercial image sensor. Each channel detects a different part of the whole scene, and the partial images are stitched in the following image processing step. The proposed artificial compound eye can create great opportunities for applications in medical, industrial and military fields.

KEYWORDS

Compound eye camera, Xenos peckii, Wide field of view, Microprism

INTRODUCTION

Nature provides versatile designs of compound eyes; each has their own optical schemes and operating principles to adapt their surroundings. Ommatidium, i.e. individual optical unit of compound eyes, has unique features in receiving light within a small field of view (FOV). Spherical arrangement of ommatidia facilitates wide angle imaging and detection. High sensitivity of motion, low aberration, polarization sensitivity and extremely small volume are another fascinating properties of compound eyes [1].

These physiological features have attracted great research interests in micro-optics. A number of previous works have been implemented on a planar substrate due to the fabrication technology limitations. 2D compound eyes were typically realized with microlens arrays, and light blocking structures such as aperture arrays, signal separator [2-6]. Curved artificial compound eyes have more similar shape with the natural ones. These configurations can have large field of view. However, they are not compatible with a commercialized image sensor because microlens arrays on a spherical surface result in a curved image plane [7,8]. Recently, curved photodetectors were developed and integrated with the artificial compound eyes, but the fabrication procedures are complex [9,10].

This work presents the Xenos peckii vision inspired artificial compound eye. The optical design of the eye of Xenos peckii is quite different from typical compound eyes. A single imaging unit called an eyelet comprises relative large facet lens and multiple photoreceptor cells (Figure 1 (a)). Each eyelet captures different portion of the visual field and the entire image is achieved by assembling the captured images from the eyelets [11-13]. Figure 1 (b) shows the schematic diagram of the artificial compound eye. A single channel consists of a microprism to tilt the incoming light, a microlens to focus the light from the microprism, and an aperture to block the light from neighboring channels. Each channel can be defined by the artificial eyelet, and the channels detect different parts of the whole FOV like that of the eye of Xenos peckii. The flat image plane of the device enables direct integration with a commercially available image sensor. Moreover, the proposed optical scheme has reduced off-axis aberration, since the optical axis of the eyelet is perpendicular to the image sensor.

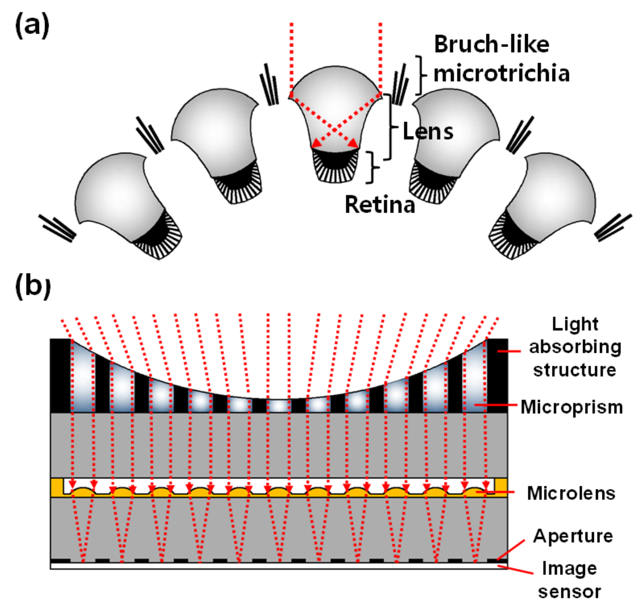

Figure 1: (a) Schematic diagram of the eye of Xenos peckii. Each optical unit (an eyelet) consists of a facet lens and multiple photoreceptor cells. The eyelet captures different portion of the entire field of view. (b) Artificial compound eye inspired by imaging principle of Xenos peckii. A single artificial eyelet consists of a microprism, a microlens and an aperture. Each eyelet detects different part of the whole scene like that of the eye of Xenos peckii.

DESIGN OF THE ARTIFICIAL COMPOUND EYE

The viewing direction of each eyelet in the artificial compound eye can be characterized by a light steering angle. Steering angle is the angle between the vertical center axis of the artificial eyelet and the direction of the incident light. And the intereyelet angle can be defined by the difference of the steering angle of adjacent eyelets (Figure 2 (a)). FOV of a single artificial eyelet should be larger than the intereyelet angle to prevent spatial lacunarity. The single artificial eyelet's FOV is 19.1 degrees, and the designed intereyelet angles vary from 2.5 degrees to 8.4 degrees when the radius of curvature (ROC) of the curved surface is 2.5mm. The amount of image overlap between eyelets can be obtained by difference of the single eyelet's FOV and the intereyelet angle, and it ranges from 10.7 degrees to 16.6 degrees in 2.5mm ROC (Figure 2 (b)).

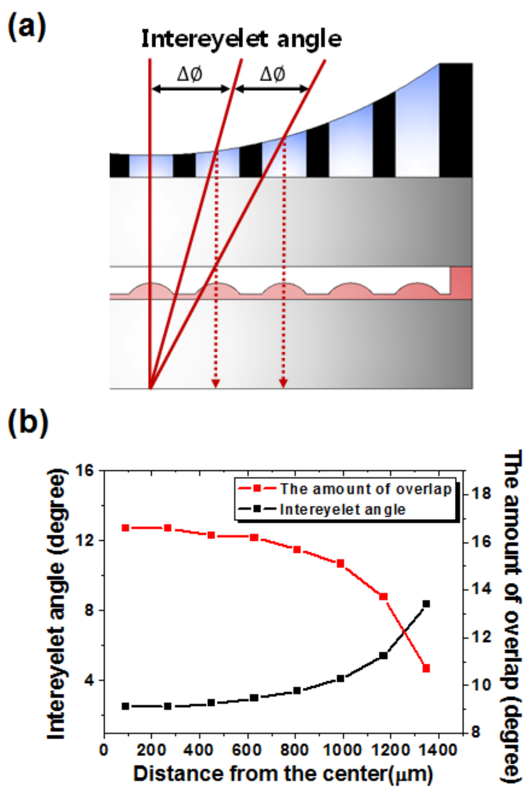

Figure 2: (a) Schematic illustration of an intereyelet angle. (b) The relation between the intereyelet angle and the amount of image overlap in the case of 2.5mm ROC.

FABRICATION PROCEDURES

Figure 3 shows the microfabrication procedures of the artificial compound eye. The microprism arrays were fabricated by lift-off and backside exposure process. First, chrome mask was patterned on a glass substrate using lift-off process. Lift-off resist (LOR) and AZ 1512 were coated on the substrate, and patterned using photolithography. After deposition of chrome layer, LOR and AZ 1512 were removed from the substrate, and finally metal mask was fabricated. Subsequently, adhesion layer was coated on the metal mask, and then tens of microns in thickness post arrays were structured on the adhesion layer using backside exposure process with the pre-patterned metal mask. Both layers were formed with SU-8. SU-8 2150 was spin coated on the post arrays, and a ball lens was put on the photoresist during the soft baking. Downward movement of the ball lens produces a concave curved shape of the photoresist. After finishing soft baking, polydimethylsiloxane (PDMS) was coated and cured on the photoresist to maintain the curved shape during the post exposure baking (PEB), and UV light was illuminated from the bottom side of the substrate once again. PDMS membrane was removed after PEB, and finally microprism arrays were defined after development. Black SU-8 (Gersteltec, GMC 1040) was filled between the microprism arrays using microtip and custom-made pumping system to block the stray light from side wall of the microprism. Microlens arrays were fabricated using resist reflow process with the mixture of AZ 9260 and thinner after patterning of polymer spacers. The polymer spacers are required to prevent direct contact between the microlens and the above substrate. The microlens template was molded onto a PDMS membrane, and the mold was imprinted into the UV curable resin. Two optical component layers were aligned and integrated at the last step.

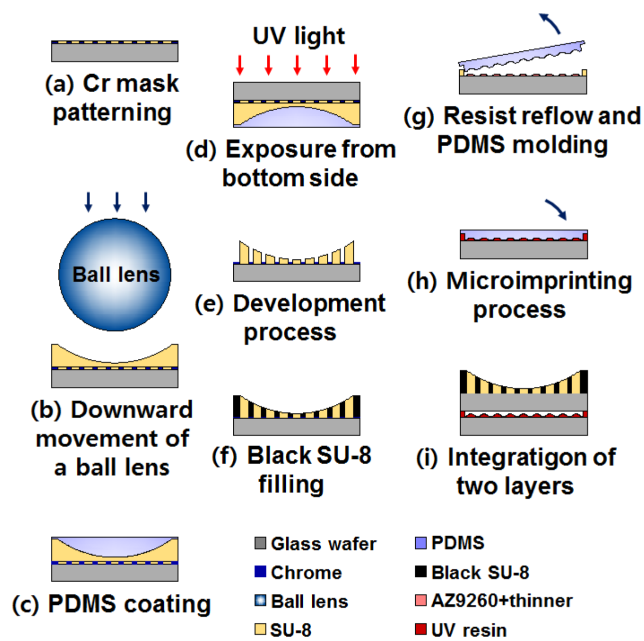

Figure 3: Fabrication procedures of the artificial compound eye inspired by imaging principle of Xenos pexkii. The microprism arrays and the microlens arrays were fabricated separately, and combined together.

FABRICATION RESULTS

The scanning electron microscopic (SEM) images of the artificial compound eye are shown in Fig. 4 (a), (b) and (c). Figure 4 (a) and (b) show the microprism arrays before and after filling the gap with the black polymer. Each microprism has different viewing angle along the curvature of the ball lens. The effects of a curved top surface of the microprism are negligible, because each microprism occupies small portion of the large ball lens. The hexagonal microprism arrays in a polymer boundary structure are shown in Fig. 4 (c). The assembled artificial compound eye was mounted on a commercial CMOS image sensor as shown in Fig. 4 (d).

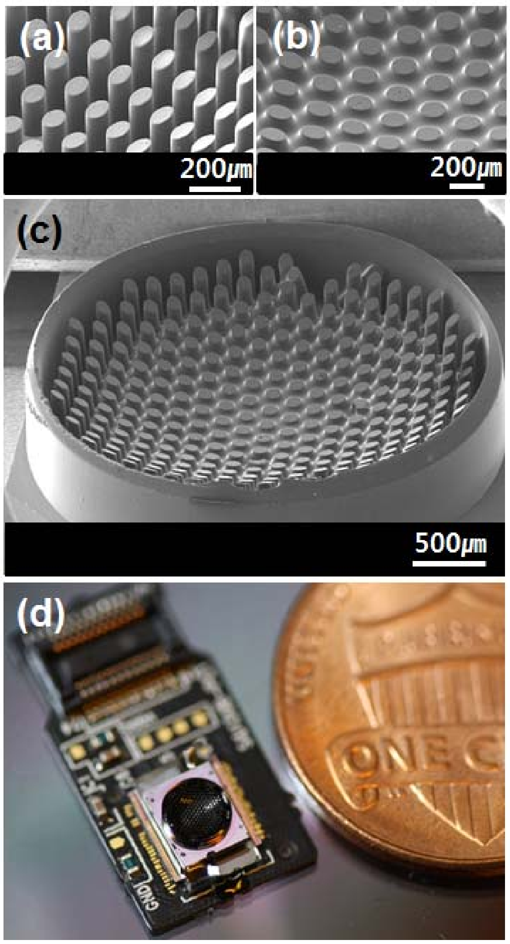

Figure 4: (a), (b) SEM images of microprism arrays before and after filling the gap with the black polymer. (c) SEM image of the microprism arrays within the polymer boundary. (d) Optical image of the fully assembled artificial compound eye.

OPTICAL CHARACTERIZATIONS

Figure 5 shows the optical characterization and imaging performance of the device. Figure 5 (a) shows the measured and designed steering angles when the curved surface is formed by a ball lens diameter of 4mm, 5mm, and 6mm, respectively. The curvature formed by a ball lens with a small diameter has large increment of a steering angle. The measured results agree with the designed values.

Figure 5 (b), (c) show measured images of a test target from the total active area of the image sensor, and the magnified captured image of several artificial eyelets. The transducers 2015 logo (Alaska) was used as a test target (inset of Figure 4 (b)). It is observed that each artificial eyelet receives visual signals from a slightly different direction, while sharing some portion of the FOV with adjacent eyelets. Super-resolution method and stitching algorithm can be combined in the following image processing step.

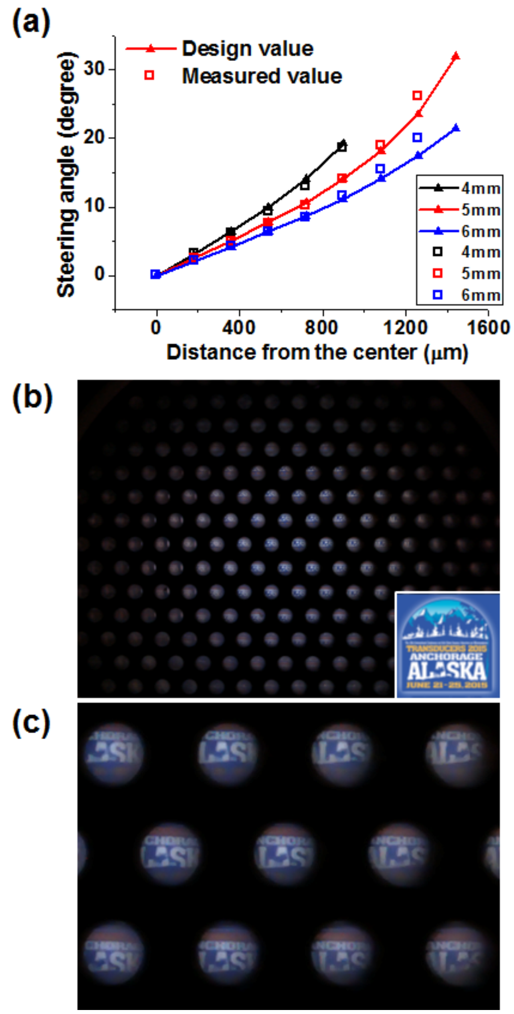

Figure 5: (a) Design and measured steering angles of the microprism. (b) Measured image from the total active area of the image sensor. The transducers 2015 logo (Alaska) was used as a test target (Inset). (c) The magnified captured image of several artificial eyelets.

CONCLUSION

In summary, the artificial compound eye inspired by the vision mechanism of Xenos peckii was designed, assembled and integrated with an image sensor. Each artificial eyelet consists of a microprism, a microlens, and an aperture. The individual eyelet detects a slightly different portion of the total field of view, and the captured images can contribute to form the final image. The assembled optical module was directly integrated with a commercialized flat image sensor, and the imaging performance was successfully demonstrated. We strongly believe this method can open up huge potential for miniaturized imaging system with a large FOV and a high resolution.

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