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Replication and characterization of the compound eye of a fruit fly for imaging purpose

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In this work, we report the replication and characterization of the compound eye of a fruit fly for imaging purpose. In the replication, soft lithography method was employed to replicate the compound eye of a fruit fly into a UV-curable polymer. The method was demonstrated to be effective and the compound eye is replicated into the polymer (NOA78) where each ommatidium has a diameter of about 30 μm and a sag height of about 7 μm. To characterize its optical property, the point spread function of the compound eye was tested and a NA of 0.386 has been obtained for the replicated polymeric ommatidium. Comparing with the NA of a real fruit fly ommatidium which was measured to be about 0.212, the replicated polymeric ommatidium has a much larger NA due to the refractive index of NOA78 is much higher than that of the material used to form the real fruit fly ommatidium. Furthermore, the replicated compound eye was used to image a photomask patterned with grating structures to test its imaging property. It is shown that the grating with a line width of 20 μm can be clearly imaged. The image of the grating formed by the replicated compound eye was shrunk by about 10 times and therefore a line width of about 2.2 μm in the image plane has been obtained, which is close to the diffraction limited resolution calculated through the measured NA. In summary, the replication method demonstrated is effective and the replicated compound eye has the great potential in optical imaging. *© 2014 AIP Publishing LLC.*

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During the last few decades, the optical performance of natural compound eyes of arthropods have been intensively studied due to their exceptionally wide field of view (FOV), the ability of the fast tracking of moving objects, and the infinite depth of field.[1–3] For small invertebrates, such as flies or moths, the compound eye is a perfect solution to obtain sufficient visual information of the surrounding environment without the need to overload their brains with too much necessary image processing units.[4,5] The compound eye is thus a promising archetype for compact and simple imaging optical sensors for applications, such as machine vision, security, and surveillance, and may even find their way into the applications like smart- or credit-cards, stickers, and mobile phones.[6–8]

Earlier work on insect inspired artificial compound eyes mainly focused on the realization of the compound eye on planar substrates. Tanida *et al*. proposed a compact image-capturing system called TOMBO (an acronym for thin observation module by bound optics), which consists of a multiple-imaging system and a post-digital processing unit to realize a compact hardware configuration with a flexible processing capability.[9–11] One of the notable features of the TOMBO architecture is its simple construction by means of stacking the microlens array, the signal separation layer, and the photodetector array together layer by layer. Duparre and Tudela proposed another type of artificial apposition compound eye, which consists of a microlens array on a thin silica-substrate with a metallic pinhole array fabricated on the backside.[12,13] This system makes a trade off between the large FOV and the low spatial resolution and low sensitivity. To improve the resolution uniformity, a chirped array of ellipsoidal micro-lens was used to realize the ultra-thin artificial apposition compound eye objective.[14–16] Furthermore, the same group demonstrated a multi-channel configuration by integrating multiple light sensitive pixels within the footprint of each microlens to realize the color vision with enhanced sensitivity and reduced volume of the system.[17]

Because the compound eye based on the planar substrate has a far smaller FOV in comparison with the natural compound eye, methods to fabricate the compound eye on curved substrate were explored and developed. Besides the advantage of the large FOV, off-axis aberrations can also be eliminated by the compound eye with a curved geometry.[14] Lee *et al*. reported the fabrication of artificial ommatidia on a hemispherical polymer dome such that a wide FOV close to that of a natural compound eye was obtained.[18] Recently, Radtke *et al*. reported the fabrication of a spherical artificial compound eye by laser lithography, which comprised an imaging microlens array and a pinhole array in the focal plane serving as receptor matrix.[19] The pinhole surface is imaged onto a conventional CCD-camera by a C-mount objective due to the unavailability of curved photoreceptor arrays. Nevertheless, the lack of cross-talk avoiding structures leads to generation of ghost images that can clearly be

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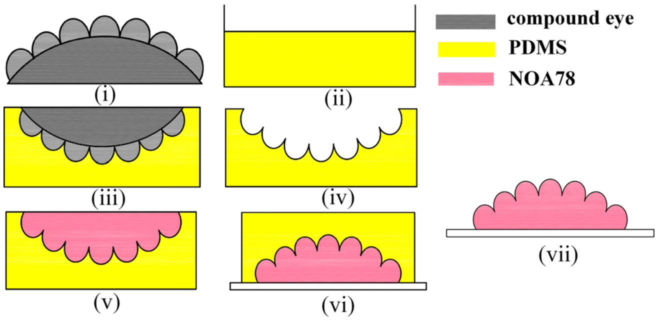


FIG. 1. Schematic illustration of the replication procedure of the nature compound eye into the NOA78 UV-cured polymer.

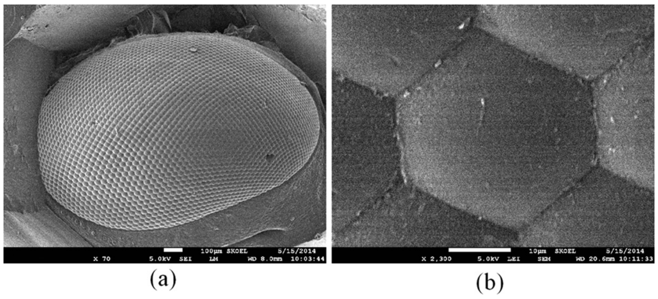


FIG. 3. SEM pictures of the replicated compound eye in a whole form (a) and the details of the replicated ommatidium (b).

seen in the middle section, which results in the limited FOV. Recent development in flexible sensors represents a promising avenue for curved vision sensors. Floreano *et al.* proposed a unique method for the fabrication of biomimetic compound eyes featuring a panoramic, undistorted FOV in a very thin package.[20] They prototyped and characterized an artificial compound eye with a hemispherical FOV with embedded and programmable low-power signal processing, high temporal resolution, and local adaptation to illumination. The prototyped artificial compound eye possesses several characteristics similar to the eye of the fruit fly Drosophila and other arthropod species. The FOV is as large as 180° × 60°. At the same time, an arthropod-inspired digital camera with a near hemispherical shape was reported.[21] This camera consists of an elastomeric compound optical element and a deformable thin silicon photodetector array to realize a FOV of 160° and the elimination of the off-axis aberration.

However, unlike the previous work focusing on the fabrication artificial biomimetic compound eye, we demonstrate the replication of the natural compound eye directly by soft lithography to obtain the compound eye structures with a large FOV.[22,23] In the replication, the compound eye of a fruit fly was used as the biotemplate which was then transferred into the UV-curable epoxy resin (NOA78, Norland Products Incorporated, Cranbury, NJ) by soft lithography method. The replica of the compound eye was then characterized in terms of the point spread function as well as the imaging capability to show its great potential for the imaging application.

The procedure developed to replicate compound eye in polymer NOA78 is schematically outlined in Figure 1. The polydimethylsiloxane (PDMS) was prepared by mixing the prepolymer with crosslink agent (10:1 wt ratio) and cured for 24 h at room temperature. The head of a fruit fly was first cleaned and then dipped into the liquid PDMS. After curing at 65 °C for an hour, the cross-linked and elastomeric PDMS was carefully peeled off from the original fruit fly's head. In this way, the relief structure in the surface of the fruit fly's head has been replicated into the PDMS mold. Next, precured NOA78 polymer in liquid form was filled into the PDMS mold and the excess liquid was removed by scraping with a flat PDMS block. Next, a glass substrate was carefully put onto the mold to make sure it is in intimate contact with the surface of the mold to prevent the leakage of the liquid polymer once the mold is flipped over. Finally, the NOA78 prepolymer was fully cured and solidified by illuminating it with a UV light. After fully cured, the PDMS mold was peeled off from the solidified NOA78 to finish the whole process of replication of the natural compound eye into the polymer.

A fruit fly's eye has thousands of integrated optical units called ommatidia which are arranged in a hexagonal manner on a curvilinear surface. Fig. 2(a) shows the optical microscopic image of the whole shape of a fruit fly's head. As can be seen, there are one pair of compound eyes on the head of the fly. The size of a single compound eye is about 1.3 mm in diameter and the field of view is about 180°. The detail of the compound eye is shown in Fig. 2(b). As is shown, the ommatidia are arranged in a highly ordered hexagonal manner across the entire curved surface. Each ommatidium has a hexagonal shape on the bottom and a spherical shape on the surface. The hexagonal has a minimum diameter of about 30 μm and the sag height of each ommatidium is about 7 μm. Fig. 2(c) shows the negative replica of the PDMS mold of the compound eye. This PDMS mold carries the detailed structure information of the compound eye which will be transferred into the polymer by soft lithography later on.

The negative PDMS mold was then used to transfer the positive compound eye structure into the UV curable polymer NOA78 (Norland Products, Inc.). Fig. 3 shows the SEM

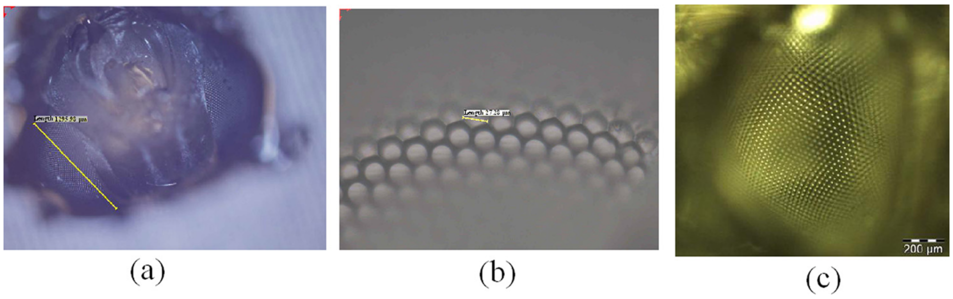


FIG. 2. (a) Low magnification optical microscopic image of a fly's head; (b) detailed optical microscopic image of the hexagonal packed ommatidia; (c) optical microscopic image of the PDMS mold replicated with the structure of the compound eye.

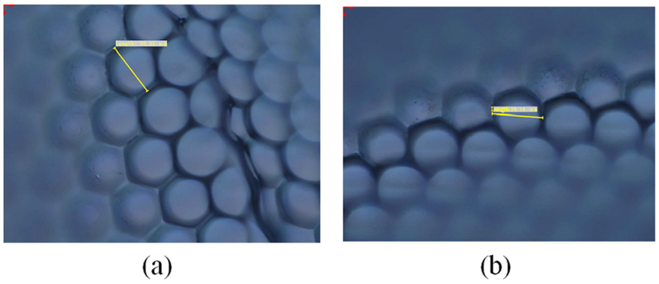

(a) (b)

FIG. 4. Optical microscopic of the ommatidium replicated in NOA78 (a) and the natural fruit fly (b).

pictures of the replicated compound eye in the whole form as well as the details of the replicated ommatidium. As is shown, the fine structure of the fruit fly is reproduced on a micrometer scale and the NOA78 replica exhibits features identical to that of the original natural fly eye. As shown in Fig. 3(a), the replicated compound eye has a size of 1.3 mm in diameter with a hemispherical global shape, which is about the same with that of the natural one. Fig. 3(b) shows the details of the replicated ommatidium, where the hexagonal shape as well as the spherical top surface can be clearly seen. To show the fidelity of the replication process, the minimum diameter of the hexagonal ommatidium of both the natural and the replicated one was measured and is shown in Fig. 4. As can be seen, the minimum diameter of the replica is 30.32 μm and the minimum diameter of the nature one is about 29.14 μm. Therefore, the deviation is about 1.18 μm. Considering the measurement error of the optical microscope is about 1 μm, one can conclude that the replication process has a good fidelity.

To characterize the fabricated compound eye, the point spread function of it was tested. Fig. 5 shows the optical setup used for the characterization of the compound eye. A He–Ne laser with a wavelength of 632.8 nm was used as the light source. In the setup, the laser beam is first collimated and then deflected onto the compound eye by a 45° mirror. A 1000× optical microscope was used to capture the focal points of the compound eye. Fig. 6 shows the measured images of the point spread function of the natural fruit fly ommatidium and the fabricated compound eye. As shown in Fig. 6(a), the airy disc of the real fruit fly ommatidium has a diameter of about 3.61 μm. According to the diffraction theory, the NA of the fabricated ommatidium (assuming the aperture is circular) is calculated to be about 0.386 for the wavelength of 633 nm. However, the airy disc of the ommatidium of the fabricated compound eye has a diameter of about 2 μm, as shown in Fig. 6(b) and the corresponding NA is calculated to be about 0.212 for the same wavelength. This indicates that the resolving power of the replicated polymeric ommatidium is much higher than that of the natural one, which can be explained by the higher refractive index of NOA78 in comparison with that of the material used to form the real fruit fly ommatidium. It should be noted that there are some speckles in the airy pattern, as shown in Fig. 6(b), which should be attributed to the scattering of the contaminated particles incorporated during the replication process.

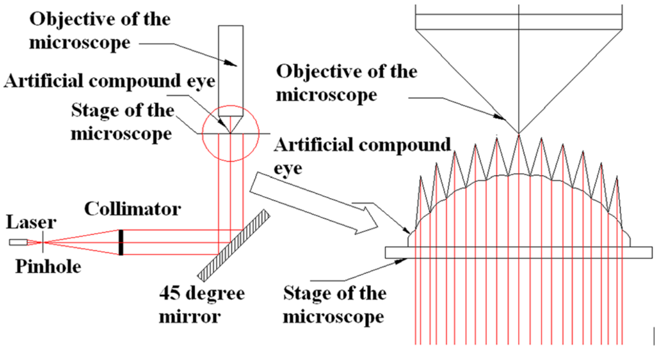
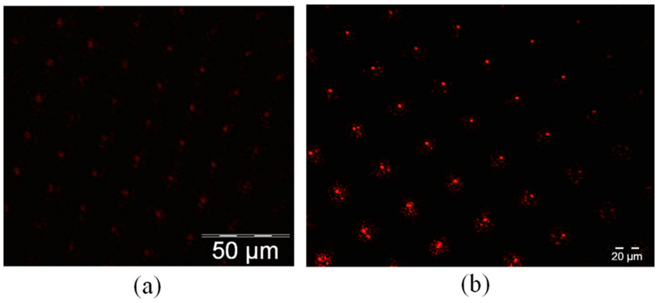


FIG. 5. Optical setup used for the measurement of the point spread function of the compound eye.



(a) (b)

FIG. 6. The images of the measured point spread function of the natural compound eye (a) and the fabricated compound eye (b).

Considering that the compound eye is formed in the Norland UV-cured polymer with a refractive index of 1.56 and the ommatidium has a circular aperture with a diameter of 30.32 μm and a sag height of 7 μm, the NA of the replicated ommatidium is calculated to be 0.398. This value is a little bit larger than that measured by the point spread function. This deviation can be explained from two aspects. On one hand, the actual shape of the ommatidium is hexagonal but not circular. On the other hand, since the bottom of the ommatidium is not circular, its surface is actually is not a spherical one and hence the actual usable sag height with a spherical shape should be less than 7 μm. As a result, the calculated NA based on the sag height is a little bit higher than that obtained by measuring the point spread function.

In order to further characterize the imaging property, the replicated compound eye was used to image a photomask. The photomask has a pattern of grating with a line width of 20 μm. The replicated compound eye was placed on the top

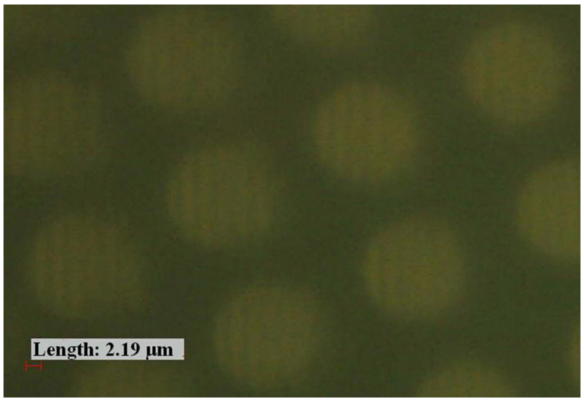


FIG. 7. Photograph of the image of a stripe array with a line width of 20.29 μm for each stripe formed by the replicated compound eye.

of the photomask and an Olympus optical microscope was used to capture the image formed by the compound eye. Fig. 7 shows the photograph of the photomask imaged by the replicated compound eye. As can be seen, the image of the grating has been formed by every ommatidium of the compound eye. The line width of the grating is about 2.19 μm; this means a demagnified image has been formed because the object distance is far greater than twice the focal length of the ommatidium. Since the image just can be resolved and line with of the image of the grating is very close to the diameter of the airy disc, one can conclude that the image formed by the compound eye has nearly reached its diffraction limited resolution. That is to say, the compound eye has a fairly good imaging property, which should have the great potential for the imaging applications in the relatively near field.

In summary, the fine structure of the fly compound eye has been replicated and carefully characterized in terms of the optical properties. It is demonstrated that the soft lithography has a good fidelity to replicate the compound eye from the natural one. The NA of the replicated ommatidium is measured to be around 0.386 for the wavelength of 633 nm. The image of the photomask with a grating pattern has been clearly formed by the compound eye and the resolution of the image is close to that of the diffraction limited. As a conclusion, the compound eye of the fruit fly has a good optical imaging property and can be used for imaging applications in the relatively near field.

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