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Large-Field-of-View Wide-Spectrum Artificial Reflecting **Superposition Compound Eyes** H. Jiang, and co-workers

Large-Field-of-View Wide-Spectrum Artificial Reflecting Superposition Compound Eyes

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n nature, reflecting superposition compound eves (RSCEs) found in shrimps. lobsters and some other decapods are extraordinary imaging systems with numerous optical features such as minimum chromatic aberration, wide-angle field of view (FOV), high sensitivity to light and superb acuity to motion. Here, we present lifesized, large-FOV, wide-spectrum artificial RSCEs as optical imaging devices inspired by the unique designs of their natural counterparts. Our devices can form real, clear images based on reflection rather than refraction, hence avoiding chromatic aberration due to dispersion by the optical materials. Compared to imaging at visible wavelengths using conventional refractive lenses of comparable size, our artificial RSCEs demonstrate minimum chromatic aberration, exceptional FOV up to 165° without distortion, modest aberrations and comparable imaging quality without any post-image processing. Together with an augmenting cruciform pattern surrounding each focused image, our large-FOV, wide-spectrum artificial RSCEs possess enhanced motion-tracking capability ideal for diverse applications in military, security, medical imaging and astronomy.

1. Introduction

The study of the imaging principles of natural compound eves^[1-3] has fueled the advancement of modern optics with

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many attractive design features beyond those available with conventional technologies.^[4,5] Current artificial compound eyes are mostly refraction based, mimicking the natural refractive compound eyes.^[4-7] However, in addition to the advantages of wide-angle field of view (FOV) and high acuity to motion shared with the refractive compound eyes, reflecting superposition compound eyes (RSCEs) of some decapods (e.g. shrimps, lobsters, and crayfish) are also known to possess superior optical properties such as minimum chromatic aberration and enhanced sensitivity to light,^[8-10] owing to their unique lens-free, reflection-based imaging mechanism first discovered by Vogt.^[11] These fascinating characteristics, once implemented into existing optical imaging devices and systems, can benefit a wide variety of demanding applications in real-time motion tracking, surveillance, medical imaging and astronomy. Previous work has demonstrated incorporating the operating principles of RSCEs into large-scale apparatus such as astronomical telescopes and inspection equipment only within the spectrum of X-ray wavelengths.^[12–14] However, such apparatus generally suffer poor image quality,^[15] thus inevitably requiring additional image de-blurring processing.^[16] For the first time, we applied the optical concepts of RSCEs towards miniaturized optical imaging devices suitable for wide visible spectrum by

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Figure 1. Operating principles of a 3-D, hemispherical artificial RSCE structurally and functionally inspired by its natural counterpart. a) $Schematic illustration of the anatomical microstructures of a natural {\tt RSCE}$ showing an array of closely packed, mirrored ommatidia with square cross-sections omni-directionally arranged on a hemispherical surface. b) An exploded schematic representing the imaging characteristics of an artificial RSCE consisting of an array of mirrored micro-square-tubes radially curved into a hemispherical configuration (radius of curvature r) under collimated illumination. Even number of reflections (i.e. blue rays) on the sidewalls in only one of the X and Y coordinates within the square-micro-tubes form the blue cross on the hemispherical focal plane halfway, namely r/2, to the center of the sphere. Odd number of reflections (i.e. red rays) in both coordinates converge the reflected light towards a central red focused point on the same focal plane. A real image is formed at the hemispherical focal plane with radius of curvature of r/2 on the opposite side of the device from the source, acting like a refractive lens.

realizing 3-D artificial RSCEs mimicking the key operational features of their natural counterparts.

Figure 1a presents a schematic illustration of the anatomical microstructures of a natural RSCE. An array of closely packed, high aspect-ratio ommatidia with square cross-sections is omni-directionally arranged on a hemispherical surface. Each ommatidium is enclosed by four smooth and highly reflective sidewalls. To fully match the unique imaging characteristics found in natural RSCEs, our artificial RSCEs are anatomically and functionally equivalent to their natural counterparts. Figure 1b schematically

illustrates the operating principles of our 3-D, hemispherical artificial RSCE. Here, only a portion of the device is presented to elucidate the mechanism of image formation. Micro-square-tubes with reflecting sidewalls, analogous to the ommatidia of RSCEs in Figure 1a, are radially curved into a hemispherical configuration (radius of curvature: r) to focus the incident light by reflection rather than refraction.^[11] The orientation of each micro-square-tube is parallel to the surface normal and thus aims towards the geometric center of the sphere (see the upper half of the sphere in Figure S1a). The focused image is projected in a superimposed fashion onto a single common imager (i.e. the hemispherical focal plane with the radius of curvature of r/2in Figure 1b) located halfway to the geometric center of the sphere,^[17] thus increasing the light sensitivity of the device. One of the most noticeable features that distinguishes the artificial RSCEs from the rest of the compound eye devices is the cruciform pattern (i.e. the blue cross on the detector surface in Figure 1b) around every focused image, which is attributed to the even number of reflections (i.e. blue rays) on the mirrored sidewalls in only one of the X and Y coordinates within each square-micro-tube. On the other hand, odd number of reflections (i.e. red rays) in both coordinates converge the reflected light towards a central focus (i.e. the red focused point on the detector surface).^[18] Even number of reflections in both coordinates form a uniform background exposure to the image. In general, the focusing behavior of our artificial RSCEs is equivalent to that by a spherical mirror with the same radius of curvature r (see the bottom half of the sphere in Figure S1a). Since the height of each square tube (i.e. 60 μ m) is much smaller than r (i.e. 1.1 cm) of the hemispherical substrate, reflection can be assumed to occur right at the top surface of the hemisphere. Hence, paraxial light is focused in the same way, with a focal length f of r/2 (i.e. 5.5 mm). However, unlike the spherical mirrors, the object and the real image are located on the opposite sides of the device, much like a refractive thin lens. In this case, the imager does not obstruct the incoming light, as would happen in reflective spherical mirrors. Hence, a wide FOV close to 180° can ideally be achieved if a sufficiently large array of reflective micro-square-tubes covers the entire thin, hemispherical substrate.

2. Results and Discussion

2.1. Lens Equation of Artificial RSCEs

To quantitatively characterize the imaging behavior of our artificial RSCEs, the lens equation of our device can be derived theoretically based on the ray-tracing method (see Figure S1c for detail). A non-collimated point source placed at an object distance p from the artificial RSCE was used as the starting point. The rays passing through the micro–square-tubes on the device surface via reflection converged to a point at an image distance q on the opposite side of the device. Here, a 2×2 transfer matrix method was applied to derive the thin lens equation and the corresponding magnification as follows:

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Figure 2. Illustrations representing key steps of fabrication and images of a 3-D, hemispherical artificial RSCE. a) A large-area array of square-micro-tubes fabricated on an SOI wafer by microfabrication. b) Preparation of a transparent, flexible hemispherical elastomeric membrane. c) The hemispherical membrane omni-directionally stretched into a flat configuration by mounting it onto a cylindrical transfer stage of a larger radius of curvature. d) The flattened membrane brought into conformal contact with the SOI wafer and quickly peeled away for the transfer. e) Reverse transformation of the elastomeric membrane from the 2-D layout back into a hemispherical shape by dismounting it from the cylindrical transfer stage. f) The fabrication concludes with the production of an ultra-large-FOV, 3-D artificial RSCE.

$$\begin{bmatrix} x_2 \\ \theta_2 \end{bmatrix} = \begin{bmatrix} A & B \\ C & D \end{bmatrix} \begin{bmatrix} x_1 \\ \theta_1 \end{bmatrix}$$
(1)

$$\begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 - \frac{2q}{r} & P - q - \frac{2pq}{r} \\ \frac{2}{r} & \frac{2p}{r+1} \end{bmatrix}$$
(2)

Here, x_1 and x_2 represent the positions of the object and image, respectively. θ_1 and θ_2 indicate the directions of the paraxial rays from the object and to the image with respect to the optical axis, respectively. When imaging condition is satisfied, B = 0 as shown in Equation (3):

$$p - q - \frac{2pq}{r} = 0 \tag{3}$$

Rewriting Equation (3) and substituting f = r/2 into it, we can obtain the thin lens equation and magnification in Equations (4) and (5), respectively. Equation (4) and (5) can theoretically characterize the relationship between the object distance p, image distance q, focal length f and the corresponding magnification M. It should be noted that since p, q, and f are all positive, the magnification is thus positive, indicating real, erect images,^[10] a feature opposite to imaging from a refractive lens.

$$\frac{1}{p} + \frac{1}{f} = \frac{1}{q} \tag{4}$$

$$M = \frac{q}{p} \tag{5}$$

2.2. Fabrication of a 3-D, Hemispherical Artificial RSCE

Key steps of the fabrication for our artificial RSCEs by a peeling micro-transfer printing method are illustrated in **Figure 2**. The process started with a large-scale array of high aspect-ratio silicon (Si) micro-square-tubes with mirrored

sidewalls on a p-type, (100) silicon-oninsulator (SOI) wafer (60 µm-thick device layer and a 2 µm-thick buried oxide (BOX) laver) mimicking the size and aspect ratio of the ommatidia of the RSCEs via contact-mode lithography and inductively coupled plasma-based (ICP) deep reactive ion etching (DRIE), followed by the preparation of a transparent hemispherical elastomeric membrane via a polymer molding process (Figure 2a and b). The height, opening, sidewall thickness and inter-tube spacing of each micro-square-tube were 60, 20, 24 and 15 µm, respectively. For comparison, the height and opening of the microsquare-tubes found in shrimps are about 63 and 30 µm, respectively.^[8] The hemispherical elastomeric membrane (refractive index n = 1.43 and thickness $t = 400 \ \mu m$) with a peripheral rim was molded by casting and curing the pre-polymers of

polydimethylsiloxane (PDMS) (mass ratio between the base and curing agent = 10:1) and another silicone rubber (Solaris, mass ratio between the base and curing agent = 1:1) mixed at a 5:1 weight ratio with a hemispherical plastic mold at 65 °C in a baking oven for 2 hours with a hemispherical plastic mold (radius of curvature r = 1.1 cm). Prior to the actual transferprinting step (Figure 2d), several process optimizations had to be implemented to ensure (i) sidewalls of each microsquare-tube were smoothened to serve as perfect reflectors to focus light and (ii) large-area surface coverage of the RSCEs on the hemispherical polymeric membrane to maximize the FOV. First, the sidewall scalloping induced by the DRIE process could cause undesirable aberrations and distortions in the images and hence was removed by a 45% potassium hydroxide wet-etching process for 6 minutes. Secondly, the SOI wafer was immersed in a buffered oxide etch (BOE) solution to perform selective undercut etching of the BOX layer to a level that all micro-square-tubes were only loosely attached to the underlying substrate and was ready to be lifted by the elastomeric membrane. A layer of 400 nm-thick aluminum with reflectivity >90% in the wide visible spectrum was then sputtered onto the smoothened facets of the Si micro-tubes. Subsequently, the hemispherical elastomeric membrane was omni-directionally stretched into a flat, 2-D configuration by mounting it onto a cylindrical transfer stage of a larger radius (radius R = 1.55 cm), followed by contact with an SOI wafer (Figure 2c and d). The omni-directional tension provided by the cylindrical transfer stage enabled elastically reversible deformation of the hemispherical membrane into a 2-D, planar geometry, such that conformal contact between the flattened membrane and the micro-square-tube array could be achieved. The Si micro-square-tubes were transfer-printed to the flattened membrane by peeling the membrane away from the SOI (see Figure S2 in SI for more processing details).^[19] Figure 2e and f present the reverse transformation of the elastomeric membrane relaxing back into a 3-D, artificial RSCE from the 2-D, planar layout. The radius of curvature r remained 1.1 cm after it was dismounted from the cylindrical





Figure 3. Representative images of the detailed microstructures of a 3-D, hemispherical artificial RSCE. a) An SEM image of a portion of a 410-by-410 array of high aspect-ratio Si micro-square-tubes fabricated on an SOI wafer. b) Close-up photograph of the smooth hemispherical profile of an artificial RSCE packaged with a 3-D printed plastic casing of matching radii. c) SEM image highlighting the hemispherical profile of the artificial RSCE. d) An exploded view of part of the detailed microstructures of micro-square-tubes in the peripheral region of the RSCE. e) Close-up SEM image of an aluminum-covered, smoothened facet of one micro-square-tube in d) where the reflection takes place.

transfer stage. The theoretical focal length of our lens was 5.5 mm accordingly. The primary advantage of the peeling micro-transfer printing method is that it combines the benefits of standard microfabrication (i.e. high yield and throughput) and elastic deformability of flexible elastomeric materials such that integration of wafer-scale micro-electro-mechanical system and/or optoelectronic devices, initially fabricated in 2-D layouts, onto a flexible membrane with curvilinear shapes is feasible.

Images representing part of the fabricated 410-by-410

(total 168,100) array of high aspect-ratio Si micro-square-tubes fabricated in a planar layout on the SOI substrate, picture of the hemispherical profile of our device packaged with a 3-D printed plastic casing of matching radii, and a scanning electron microscope (SEM) image highlighting the hemispherical surface profile of the artificial RSCE are shown in Figure 3a, b and c, respectively. Packaging was applied to block stray light and offer protection for the device during implementation. Detailed features of the micro-square-tube array located on the peripheral region of a hemispherical membrane and the uniformly aluminum-covered, smoothened facets of the micro-square-tubes where the reflection takes place are presented in Figure 3d and e, respectively. The yields associated with the peeling micro-transfer printing process were high for the system investigated here: more than 90% of the tubes within the 410-by-410 array have been reproducibly transferred from the SOI wafer to the hemispherical substrate. The efficacy and precise control of the fabrication process have been demonstrated with the fact that the robustness of the device structures and uniform topography of our device were achieved.

2.3. Imaging Characterizations of the Artificial RSCEs

To fully characterize the performance of our artificial RSCEs in terms of focusing, imaging capabilities and image quality, real focused images generated by one artificial RSCE using a collimated laser beam (**Figure 4**a) and a non-collimated point source (i.e. a laser beam diffused by a ground glass) illuminating on real objects (Figure 4c, e-g) were captured and compared to those simulated by theoretical modeling (Figure 4b and d). Note that all focused images were acquired without any post-image processing. Cross-shaped patterns surrounding all focused images

produced by our device (Figure 4a, b, d and Figure S3) were clearly observed. The intensity ratio between the focused image and the surrounding cruciform pattern, a key factor associated with the overall image quality, was dictated by the aspect ratio of each square-micro-tube. This ratio in our device was 3, close to that found in natural RSCEs (i.e. 2-3).^[20] The corresponding intensity ratio, which was measured to be 5 in our system, was the highest among all producible aspect ratios of the tubes (**Figure 5**) and hence was able to improve the clarity of the output images. The aspect



Figure 4. Imaging characteristics of the artificial RSCE in comparison with a conventional refractive lens. a) and b) Experimental and theoretical focused images, respectively, produced by our artificial RSCE with a collimated light source. The focal plane was measured to be 5.5 mm. c) and d) Experimental and theoretical focused images, respectively, of different W-shaped objects (insets on the upper right-hand corners show the original objects) with a non-collimated point source. Real, erect, de-magnified focused images of e) a canine paw print, f) a heart and g) an apple with a bite mark on the left side produced by our RSCE with a non-collimated point source. These images were formed without any post-image processing. h) Inverted, focused image of the same logo in c) formed by a commercial conventional refractive lens with a non-collimated point source. All images were displayed on a planar imager. The overall image quality generated by our RSCEs in c) was comparable to that achieved by a regular lens with comparable size in h).

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Figure 5. Relationship between the aspect ratio of the micro-squaretube and the corresponding intensity ratio of the final image. The highest intensity ratio was 5 when the aspect ratios reached 3 and thus can improve the clarity of the images.

ratio of 3 was considered the optimal optical design in terms of image clarity and intensity ratio in the final image based on our theoretical studies. On the other hand, the dimensions of each tube were mainly determined by the working spectrum of our device and its applications. As the size of the ommatidia became closer to the working wavelength, diffraction would deteriorate the image quality more severely. Since our primary goals were to investigate the optical design features of the natural RSCEs and then to implement them into a functional optical imaging device operated in the wide visible light spectrum, the dimensions of each tube anatomically matched those found in its natural counterparts. Each point in Figure 5 was a simulated result produced by an optical simulation software called Zemax by varying the aspect ratio of each micro-square-tube in the artificial RSCE. For simplicity, an 11-by-11 array of reflective Si micro-square-tubes radially arranged on a transparent, hemispherical elastomeric membrane (refractive index n =1.43 and thickness $t = 400 \ \mu m$) was modeled as the optical imaging device (Figure S8). In our optical characterization system (see Figure S4a for the system set-up), the output images were first projected on either a planar photographic screen (Figure 4a, c, e-h and Figure S3, S6, S7) or a thin, painted PDMS hemispherical screen with a radius of curvature of 5.5 mm (Figure S5), and then captured by a camera. The focal length of our device was measured to be approximately 5.5 mm in Figure 4a, equivalent to the r/2 depicted in Figure 1b. The original objects used for producing images in Figure 4c-g were the logo of University of Wisconsin-Madison, a regular "W", a canine paw print, a heart and an apple with a bite mark on the left side, all shown in the upper right inset of respective figures. The object/image distances used in Figure 4c-g were p = 3f and q = 3f/4, respectively, thus producing focused images de-magnified by four times from the original object. Figure 4c, e-g clearly demonstrated the overall image quality without the cross-shaped pattern due to a combined effect of the thin photographic screen attenuating the dimmer cross surrounding each focused image and shorter camera exposure setting (see Figure S3 captured with much longer exposure settings for comparison). The imaging characteristics of our artificial RSCEs in terms of object/image distances and magnification were consistent with Equation (4) and (5) (see Figure S5–7 for more examples). More importantly, the overall image quality generated by our device without the aid of any post-image processing (Figure 4c) was comparable to those acquired by a regular N-BK7 plano-convex lens with comparable size (D = 25.4 mm, f = 25.4 mm, f-number = 1, Thorlabs LA1951) in Figure 4h.

2.4. Quantitative Analysis on the Image Quality of the Artificial RSCEs

For any optical imaging system, its optical performance in terms of image quality and resolving power can be best characterized by the modulation transfer function (MTF), which is a quantitative measure of the ability of a system to transfer contrast from the object to the final image. Figure 6a demonstrates the theoretical characteristic MTF curves of our RSCEs versus different spatial frequencies (cycles per mm) by Zemax. Again, the same 11-by-11 array of reflective Si micro-square-tubes (aspect ratio of 3) on a transparent, hemispherical elastomeric membrane used in Figure 5 was employed as the optical imaging device. The computation of MTF generally involves Fourier transform of the point spread function (PSF). The simulation was performed using Fast Fourier Transform (FFT) technique with the sampling rate of 4096×4096 . Both tangential (T) and sagittal (S) responses for each field point were plotted. Due to the symmetrical intensity distribution of the (PSF) (Figure 6b), the T and S curves overlap well with each other in Figure 6a. Generally, an MTF value of 1 indicates that perfect contrast is maintained in the final image, while an MTF of 0 means the worst contrast preservation and hence no resolving power at all. MTF value of 0.5 has been widely applied to assess the resolution of an optical imaging system. For our artificial RSCE, its MTF-0.5 corresponds to a 20 line pairs/mm line frequency, or equivalently a spatial resolution of 50 µm. The MTF curve of the aberrated RSCE (blue line) compared to the ideal aberration-free, diffraction-limited one (black line) was shown. It should be noted that the resolving power of our RSCEs was dictated by both diffraction and spherical aberration and the curve representing aberrated RSCE only deviated slightly from the diffraction-limited device, indicating modest aberrations in the RSCEs. This argument can be further supported by the fact that the measured aberrations (i.e. coma, tilt, spherical aberration, astigmatism) of our artificial RSCEs were small and equivalent to those measured in the commercial refractive lens with comparable size (i.e. aperture) and curvature (N-BK7 plano-convex lens, D =25.4 mm, f = 25.4 mm, f-number = 1), as shown in Table 1. Here, we intended to select a refraction-based commercial lens with comparable size (i.e. comparable aperture) and curvature with our RSCE device to maintain a fair comparison that highlights the differences in the optical performance and properties between refraction-based and reflection-based optical imaging devices. The measurement was performed by a Shack-Hartmann wavefront sensor (see Figure S4b for the system set-up) and the results are displayed in the unit of waves.





Figure 6. a) The simulated plot of MTF versus spatial frequency (cycles per mm) of the diffraction-limited (black solid line) RSCE and the RSCE device with spherical aberrations (blue solid line). b) Simulated intensity distribution of the PSF in both X and Y axes in space.

2.5. Optical Characterizations of the Wide-Spectrum, Large-FOV Artificial RSCE

One of the most attractive features of RSCEs unmatched by existing refraction-based optical imaging devices is the ability to achieve minimum chromatic aberrations in the focused images, which can be best demonstrated in **Figure 7**a and b with a non-collimated white light source. Focused image produced by our device (Figure 7b) showed no signs of chromatic aberration while that produced by the same regular plano-convex lens (Figure 7a) clearly revealed strong chromatic aberration (i.e. fringes of colors of purple and yellow) along the boundaries separating the bright and dark parts of the image (see exploded views highlighting the distinct difference in focused images with and without chromatic

aberration shown in the lower-right-corner insets of Figure 7a and b, respectively). Identical camera exposure settings were applied to capture and compare both figures. The minimum chromatic aberration thus makes our device ideal for widespectrum imaging applications. Figure 7c demonstrates an exceptional 165° FOV of our artificial RSCEs enabled by the hemispherical configuration. The FOV measurement was performed with a He-Ne laser (wavelength = 630 nm, JDS Uniphase 1107), mounted on a circular rotating breadboard (RBB12, Thorlabs) sequentially illuminating the artificial RSCE placed on a fixed stage at the center of the breadboard from various angles of incidence (see Figure S4c for the system setup). Here, three focused images captured from three distinct angles, -82.5° (left), 0° (center) and 82.5° (right), in one dynamic scan were selected to represent the total 165° viewing angle. Identical camera exposure settings were applied to capture all three figures. Owing to fact that the hemispherical geometry possessed no primary optical axis, all representative focused images showed good clarity, without noticeable off-axis aberration, distortion and blur commonly seen in most wide-angle lenses such as those based on fish-eye optics. Again, all images were generated without any additional post-image processing and captured with the same exposure setting. The pattern of the focused images in terms of size, brightness and position remained almost identical over the entire scanning path corresponding to the 165° FOV. One thing should be noted: as the incident light source mounted on the breadboard traveled from -82.5° (left) to 82.5° (right), the cross pattern on the detector surface produced by our RSCE moved instantly

in the same direction, indicating its real-time motion-tracking capability. Moreover, the cruciform pattern around the focused image augmented the size of the resulting image and

 Table 1. Zernike coefficients of RSCEs and a refractive lens measured by Shack-Hartmann Sensor.

Zernike Polynomial	RSCEs	N-BK7 lens	Physical meaning	_
2ρ cos(θ)	-0.463	-0.451	Tilt in x-axis	
2ρ sin(θ)	0.319	-0.662	Tilt in y-axis	
$\rho^2 \cos(2\theta)$	-0.464	0.363	Primary Astigmatism	
$(3\rho^2 - 2\rho)\cos\theta$	0.005	0.005	Coma in x-axis	
(3ρ² – 2ρ)sinθ	-0.237	0.288	Coma in y-axis	
$6\rho^4 - 6\rho^2 + 1$	0.026	0.021	Spherical aberration	

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Figure 7. Imaging performance of the large-FOV, wide-spectrum artificial RSCE. Focused images produced by a) a commercial regular plano-convex lens revealing strong chromatic aberration (i.e. fringes of colors of purple and yellow) along the boundaries of the image and b) artificial RSCE showing no signs of chromatic aberration. Exploded views of details highlighting the distinctive differences in focused images with and without chromatic aberration are shown in the lower-right-corner insets. Identical camera exposure settings were applied to capture and compare both figures. Upper right corner insets: the logo used as objects. c) Composite pictures corresponding to 165° of FOV by sequential illumination of the artificial RSCE with a He-Ne laser captured at 3 distinct angles of incidence: -82.5° (left), 0° (center) and 82.5° (right). All images were formed without any post-image processing and were captured with the same exposure setting.

thus enhanced its ability to dynamically track motion of tiny objects. This could be advantageous in building real-time, high-speed motion tracking systems due to the magnified overall image size.

to new directions in implementing biological optics into advanced photonic applications in military, security, medical imaging and astronomy. In the future, we will continue to improve the imaging based on more quantatative studies on optimizing the optical designs concerning the dimensions and the aspect ratios of the micro-square-tubes^[21] as we extend the applications to other wavelengths, (e.g. the mid- and far-infrared). In addition, a blocking layer will be added to cover the gaps between the micro-square-tubes to stop the stray light from passing through to improve the image quality.

4. Experimental Section

Fabrication of 3-D artificial RSCEs: A transparent hemispherical membrane surrounded by a peripheral rim was composed of PDMS (Sylgard 184, Dow Corning) and another type of silicone rubber (Solaris, Smooth-On Inc.) mixed at a 5:1 weight ratio (refractive index n = 1.43 and thickness $t = 400 \mu$ m). It was molded with a hemispherical plastic shell (Complex Plastics, Inc.) with a radius of curvature of 1.1 cm at 65 °C in a baking oven. Sidewall polishing of each micro-square-tube was performed by a 45% potassium hydroxide (KOH, Fisher Scientific) at 40 °C for 6 min. Prior to the transfer, the buried oxide (BOX) layer was selectively undercut by a buffered oxide etch (6:1 BOE, Fisher Scientific) and remained loosely attached to the supporting substrate. The smoothened sidewalls were sputtered with aluminum to serve as mirrors with high reflectivity across the wide visible spectrum. A thin layer of partially cured PDMS plus Solaris mixed at the same ratio was pre-coated as adhesives before the contact between the SOI wafer and the flattened elas-

tomeric membrane. Detailed fabrication parameters are provided in the Supporting Information Appendix.

3. Conclusion

In summary, our artificial RSCEs possess optical features such as exceptional FOV, minimum chromatic aberration, fine image quality, modest spherical aberrations, enhanced sensitivity to light, and augmented motion tracking. The same engineering concept, fabrication methods and scheme can be extended to wide-spectrum imaging devices spanning from infrared to X-ray wavelengths due to minimum chromatic aberration. In a general sense, our work points

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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