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Artificial eye for scotopic vision with bioinspired all-optical photosensitivity enhancer

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Edited by John A. Rogers, University of Illinois, Urbana, IL, and approved February 5, 2016 (received for review September 9, 2015)

The ability to acquire images under low-light conditions is critical for many applications. However, to date, strategies toward improving low-light imaging primarily focus on developing electronic image sensors. Inspired by natural scotopic visual systems, we adopt an alloptical method to significantly improve the overall photosensitivity of imaging systems. Such optical approach is independent of, and can effectively circumvent the physical and material limitations of, the electronics imagers used. We demonstrate an artificial eye inspired by superposition compound eyes and the retinal structure of elephantnose fish. The bioinspired photosensitivity enhancer (BPE) that we have developed enhances the image intensity without consuming power, which is achieved by three-dimensional, omnidirectionally aligned microphotocollectors with parabolic reflective sidewalls. Our work opens up a previously unidentified direction toward achieving high photosensitivity in imaging systems.

bioinspired optical devices | low-light imaging | microopto-electromechanical systems | femtosecond laser micromachining | low aberrations

mproving the photosensitivity level for low-light imaging is important for visual information acquisition and is critical to many applications in medicine, military, security, and astronomy (1–5). Current methods for this purpose predominantly rely on electronics, including the use of external image intensifiers or on-chip multiplication gain technology, or highly photosensitive imaging sensors with emerging photoactive materials (6–9). These electronic devices, although able to increase the overall photosensitivity of imagers by several orders of magnitude, have inevitable physical and material limitations (10). Another direction to improve the photosensitivity of imaging systems could be seeking a breakthrough in the optics for the imaging, which is largely unexplored.

In pursuit of a groundbreaking optical approach to photosensitivity enhancement, we look to nature for inspiration. Some biological eyes have adopted exquisite, purely optical scheme for scotopic vision (11-13). For example, superposition eyes possess much better scotopic vision than equivalent apposition eyes because light received by a single rhabdom is collected from multiple lenses or reflectors (14) (SI Appendix, Fig. S1 A and B). However, mimicking superposition eyes in artificial devices poses tremendous technical challenges in both manufacturing and maintaining the optical performance (SI Appendix, Fig. S1C). In the retina of the elephantnose fish (Gnathonemus petersii), collecting light (wavelength $\lambda \sim 615$ nm) to reach the photoreceptors is achieved by crystalline microcups with reflecting photonic crystal sidewalls (15) (Fig. 1A). This focusing mechanism of guiding light rays through an enclosed structure is much less prone to imperfection in optical elements, and thus provides a viable solution to realizing superposition in man-made imagers.

In this paper, we introduce an all-optical strategy to improve the low-light imaging through a biologically inspired photosensitivity enhancer (BPE) consisting of thousands of microphotocollectors (μ -PCs). The miniaturized, low-cost, and zero-power-consumption device presented here can be implemented independently in

imaging systems, or combined with other image enhancement technologies. As an example, we present an artificial eye (Fig. 1 B and C) for scotopic vision using our all-optical photosensitivity enhancer (Fig. 1D). Experimental results show the key aspects of optics and fabrication of the functional device.

Fig. 1E shows a 3D layout of the artificial eye and the structure of the bioinspired µ-PCs (Fig. 1E, Inset and SI Appendix, Fig. S2). Our artificial eye (diameter R = 12.5 mm) consists of a ball lens (BK-7 glass, R = 6 mm) mounted in a central iris (R = 4 mm), a 48 \times 48 array of μ -PCs supported by a hemispherical polydimethylsiloxane (PDMS) membrane (R = 12.5 mm, thickness $t = 300 \ \mu\text{m}$), and a protective shell ($R = 12.5 \ \text{mm}$, thickness t =1 mm), which are packaged in a 3D-printed protective casing of matching radii (Fig. 1B). The ball lens generates a hemispherical image plane on the PDMS membrane, analogous to a natural camera-type eye (Fig. 1A). The close-packed μ -PCs are omnidirectionally arranged on the PDMS membrane, with orientations directed toward the geometric center of the ball lens, anatomically equivalent to the crystalline microcups in the eyes of the elephantnose fish. Each µ-PC is a glass microstructure with two opposite facets enclosed by four parabolic sidewalls coated with reflecting aluminum (Al; Fig. 1E, Inset). The incoming light from the large facet (input port, diameter D_{in} = 77 μ m) is collected to the small facet (output port, diameter D_{out} = 20 µm) by the parabolic sidewalls, consequently increasing the light intensity (see SI Appendix, Fig. S3 for ray-tracing demonstration). In this manner, µ-PCs function as superposition of incoming light to pixels on the imager. The resultant image can then be acquired by a matching image sensor (16-18).

Significance

Although biological eyes ingeniously adopt diverse optical approaches to improve their scotopic vision, enhancement of the photosensitivity in artificial imaging systems still clings to electronic methods. Here we present an all-optical strategy to significantly improve the low-light imaging capability of manmade sensors, which is inspired by the optical concept of superposition eyes and elephantnose fish eye. Besides showing an artificial eye whose scotopic vision is largely improved by a bioinspired photosensitivity enhancer, we also demonstrate a complete solution to acquire high-resolution images under low-light conditions with our device. More importantly, our purely optical approach can be used on top of other electronic technologies, which can boost the most state-of-the-art imaging sensor whose photosensitivity is gaining on the physical limitations.

Author contributions: H.L., Y.H., and H.J. designed research, performed research, analyzed data, and wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Freely available online through the PNAS open access option.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10. 1073/pnas.1517953113/-/DCSupplemental.



Fig. 1. Schematic illustrations and images of a natural eye of elephantnose fish and an artificial eye. (*A*) Illustrations of the anatomical structure of the elephantnose fish eye and a crystalline cup in the retina (*Inset*). (*B*–*D*) Images of the artificial eye, its front view, and the BPE on the rear side, respectively. (*E*) Exploded illustration of the artificial eye. (*Inset, Right*) The structure of μ -PCs is shown.

The main steps of fabrication of the artificial eye are illustrated in Fig. 2 A-F (see SI Appendix, Figs. S4-S7 for details). The process begins with a femtosecond laser layer-by-layer micromachining (Fig. 2A) to form a 48×48 array (height h =120 μ m, space $\Lambda = 77 \mu$ m), each unit with precisely controlled parabolic sidewalls on glass. To reduce the scattering loss on the laser-ablated surface (19), the sidewalls are smoothened by reflowing a thin layer (a few micrometers in thickness) of sprayed-on Su-8 photoresist (Fig. 2B). Our smoothing process will not damage the parabolic profile of the sidewalls, as demonstrated by the scanning electron microscope (SEM) images in Fig. 2 G and H. An Al layer (t = 150 nm) is sputtered onto the smooth Su-8 photoresist (Fig. 2C), generating highly reflecting sidewalls (see SI Appendix, Fig. S8 for details). Al covering the output ports of the µ-PCs, which blocks the output light, is then removed by laser ablation.

To transfer the obtained flat µ-PCs onto the hemispherical PDMS membrane, the underlying residual glass ($t \sim 80 \ \mu m$) is removed by chemical etching with diluted hydrofluoric acid (5%). The released μ -PCs are thereafter bonded to the PDMS membrane that is radically stretched into a flat shape (20) (Fig. 2D). After removal of the protecting wax by acetone, the PDMS membrane with the µ-PCs is released to restore the hemispherical shape, forming the BPE (Fig. 2E). Finally, the curved BPE is integrated with the rest of the artificial eye (Fig. 2F). Our transfer process does not deform individual µ-PCs because they are fabricated using hard materials; hence, the strain generated in the transfer process is predominantly on the soft PDMS membrane. In addition, the hemispherical PDMS membrane is uniformly and radially stretched. Once the membrane is released, the closely packed µ-PCs are omnidirectionally aligned, maintaining the uniform pitch between each unit. Fig. 2 I and J shows the SEM images highlighting the hemispherical surface

profile and detailed features of the transferred μ -PCs, respectively. The uniform topography of the device and smooth curved sidewalls of the μ -PCs indicate precise 3D processing capability of our fabrication process.

Fig. 3A shows the focal spots of light (collimated He–Ne laser, power intensity $P = 0.26 \ \mu W/cm^2$) acquired with a BPE (containing $48 \times 48 \ \mu$ -PCs on a flat glass substrate) butt-coupled with a monochrome charge-coupled device (CCD) (*SI Appendix*, Fig. S9 and Table S1; see *SI Appendix* for optical setup). Focusing of incoming light is due to the reflective parabolic sidewalls of the μ -PCs. The uniform brightness of the focal spots in Fig. 3A indicates the high homogeneity in the geometric structure of the μ -PCs. To estimate the improvement of light intensity by the BPE, pixel gray-scale values are extracted from the images acquired by the CCD with and without the BPE, respectively (*SI Appendix*). Three-dimensional distributions of the gray scale of a focal spot obtained without (Fig. 3B) and with (Fig. 3C) a μ -PC clearly demonstrate the effect of the BPE.

To maximize the output light intensity of the μ -PC, the parabolic profile of sidewalls is optimized by varying the diameter of the output port ($D_{out} = 10 \sim 35 \ \mu m$) while fixing the height $(h = 120 \,\mu\text{m})$ and the diameter of the input port $(D_{in} = 77 \,\mu\text{m})$. As illustrated in Fig. 3D, the maximum improvement of $3.87 \times$ in light intensity is achieved by the µ-PCs with an output-port diameter of 20 µm (SI Appendix, Fig. S10 and Table S2). The high improvement factor of light intensity by the BPE with $48 \times 48 \mu$ -PCs is steady for a wide illumination range ($P > 0.05 \ \mu W/cm^2$) (see green triangles in Fig. 3*E*). For extremely low luminance ($P \leq$ $0.05 \,\mu\text{W/cm}^2$), without the BPE, the photon-induced electronic signal in a single pixel of the CCD does not exceed the noise level under the extremely low-light condition. As a result, the obtained gray-scale values (red dots in Fig. 3E) are caused by the noise of the CCD (21, 22) (SI Appendix, Fig. S11). By collecting the photons from the source via the μ -PCs, the photoelectronic signal in the CCD pixels is significantly increased, and accordingly, gray-scale values of the focal spots obtained by the image enhancer (blue squares in Fig. 3E) are greatly improved.

One of the most attractive features of our bioinspired image enhancer is its wide-spectrum optical property (Fig. 3F),



Fig. 2. Fabrication process and micrographs of the artificial eye and BPE. (A-F) Schematic illustration of the fabrication procedures. (*G* and *H*) SEM images of a μ -PC. (*I* and *J*) SEM of the BPE transferred onto a hemispherical PDMS membrane. (Scale bars: *G*, 50 μ m; *H*, 1 μ m; *I*, 200 μ m, and *J*, 100 μ m.)



Fig. 3. Optical characterization of the BPE. (*A*) Focal spots of collimated light generated by BPE consisting of $48 \times 48 \mu$ -PCs. The power intensity of the light source *P* is 0.26 μ W/cm². (*B* and *C*) Distribution of gray-scale values obtained without and with a μ -PC, respectively. *P* = 0.26 μ W/cm². (*D*) Enhancement of light intensity (green triangles) by the μ -PCs with the diameter of output ports ranging from 10 to 35 μ m. (*E*) Enhancement of light intensity (green triangles) by the BPE under different illuminating conditions with *P* ranging from 0.01 to 0.26 μ W/cm². Blue squares and red dots in *D* and *E* show the gray-scale values obtained with and without the BPE, respectively. (*F*) Enhancement of light intensity (blue dots) at wavelengths ranging from 380 to 900 nm. The red line is obtained by a cubic polynomial fit.

whereas its natural counterpart only reflects red light (15). An integrating sphere and a spectrometer are used to collect and analyze the white light outputted from the image enhancer (SI Appendix, Fig. S12). The results in Fig. 3F demonstrate the significant improvement of the light intensity (increase $>3\times$) over a wide, entire visible light spectrum ($\lambda = 400-780$ nm), which is compatible with the working spectral range of most imaging sensors (23). The improvement of the light intensity in UV ($\lambda < 400$ nm) and near-infrared ($\lambda > 780$ nm) spectral range is slightly lower than 3. Such wavelength dependency of the improvement factor is attributed to the high absorption of the UV light by the Su-8 photoresist and low reflectivity of the nearinfrared light by the Al film (24, 25). Besides, energy loss is more at the UV wavelength than the visible and near-infrared owing to a stronger light scattering caused by the nanoscale surface roughness on the sidewalls (see SI Appendix, Figs. S13-S15 for simulating demonstration).

To demonstrate the imaging capabilities of our BPE that contains $48 \times 48 \mu$ -PCs on a flat glass substrate, objects with a letter logo (Fig. 4*A*) and a more complex pattern (Fig. 4*D*) are used (see *SI Appendix*, Fig. S16 for optical setup). At the low illumination condition ($P = 0.05 \mu$ W/cm²), the images acquired

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by the CCD without the BPE cannot be recognized (Fig. 4 B and E). Much brighter images are obtained with our BPE and are easily seen (Fig. 4 C and F). The spatial resolution of the eyes in the elephantnose fish is reduced by its unique retina with crystalline microcups (15). For our artificial device, a complete set of hardware and software strategy based on a superresolution image reconstruction method is adopted to increase the resolution of images (26) (SI Appendix, Figs. S17 and S18). In the example in Fig. 4F, the resolution (384×384) has been improved by $4 \times$ (see the low-resolution image in SI Appendix, Fig. S17D for comparison), able to show fine spatial features and sharp boundaries of the complex pattern. Our flexible BPE can be integrated with curved image sensors fabricated onto curved surfaces to reduce the distortions due to planar sensors (17, 18). To characterize the distortions of the artificial eye with the hemispherical BPE, a 3×3 array of a square pattern is extracted from a scanned image produced by the ball lens (SI Appendix, Figs. S19-S21). The ball lens generates a hemispherical image of the squares. The projected image (Fig. 4G) obtained by scanning the imager along the hemispherical BPE shows little distortion, as demonstrated by the blue bars in Fig. 4H (see SI Appendix for detail). In stark contrast, because of the mismatch between the



Fig. 4. Imaging performance of the BPE and analysis of distortion of the artificial eye. (A-C) A scanned University of Wisconsin logo as the object, images obtained without and with the BPE, respectively. (D-F) A scanned University of Wisconsin Bucky Badger head logo, images acquired without and with the BPE, respectively. Without the BPE, images in B and E are too dark to be visually recognized. (G) Square shapes acquired from a curved image plane of the artificial eye. (H) Distortions of square patterns acquired with a flat (red bars) and the hemispherical BPE (blue bars). Images in B, C, E, and F are acquired with a flat BPE, and the image in G is obtained by the hemispherical BPE.

curved image plane and the flat imaging device, the images of the peripheral square patterns obtained with the ball lens and a flat BPE suffer severe distortion (red bars in Fig. 4*H* and *SI Appendix*, Fig. S21 *B* and *D*).

The bioinspired low-light image-enhancing strategy presented here leads to a conceptually advantageous, all-optical route to

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improve scotopic imaging. Our artificial eye will be a powerful compact night-vision camera with low-distortion characteristics. Its working spectrum could potentially be expanded to X-ray and far infrared for a host of applications such as endoscopes, robots, and space exploration. In addition, the manufacturing process demonstrated in this work is applicable to other flexible microsystems and bioinspired devices.

Methods

Fabrication of BPE. To fabricate glass microstructures with parabolic sidewalls, a layer-by-layer ablation process was performed by a femtosecond laser (Uranus2000-1030-1000, PolarOnyx) with a pulse duration of 700 fs, a wavelength of 1,030 nm, and a repetition rate of 120 kHz. The scanning path was precisely controlled by a 3D translation stage (XM ultraprecision linear motor stages, Newport) and the diameter of the laser spot was 1 µm, which was focused by a microscope objective lens (N.A. = 0.5, Nikon). A thin layer of photoresist (SU-8 MicroSpray, MicroChem) was sprayed onto the microstructures, and the photocured photoresist was reflowed in an oven at 210 °C for 90 min. Aluminum reflecting layer was coated on the reflowed Su-8 surface by a sputterer (Denton Discovery 24), and the Al covering the output ports was ablated by a tightly focused femtosecond laser (focused by Nikon objective lens with N.A. = 0.8). To remove the underlying glass substrate by a hydrofluoric acid [5% (vol/vol)], µ-PCs were protected by a layer of acid-resistance wax (Crystalbond 509, SPI Supplies), and the etching process lasted about 4 h at 23 °C. The released $\mu\text{-PCs}$ were then transferred onto a radially stretched PDMS (Sylgard 184, Dow Corning) membrane. After the removal of the protection wax by submerging the device in acetone for 15 min, the stretched membrane was released, forming the curved BPE.

Acquisition and Processing of Images. We used a CCD camera (model KAl-02050, TRUESENSE) to acquire images generated by our device. The cover glass on the CCD was removed to enable the close contact between the devices. To obtain focal spots of light in Fig. 3*A*, a collimated He–Ne laser (model 1108, Edmund Optics) with uniform distribution in light intensity was used as the light source and a flat BPE was butt-coupled with the CCD. The images in Fig. 4 *C* and *F* were generated by a double-convex lens (BK-7, Thorlabs) with a focal length of 100 mm, and were processed by an algorithm based on a superresolution image reconstruction method and coded in MATLAB. The image shown in Fig. 4*G* was acquired by scanning the CCD with a five-axis stage consisting of three linear stages (PT1, Thorlabs) and two rotation stages (PR01 and RBB18A, Thorlabs).

ACKNOWLEDGMENTS. The authors thank X. Wu and Drs. C.-C. Huang, Y.-S. Lu, and G. Lin for technical assistance and discussion. This work was mainly supported by the National Institutes of Health (Grant 1DP2OD008678-01) and the National Science Foundation (Grant 1329481), and partially supported by the University of Wisconsin-Madison College of Engineering.

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Supporting Information

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SI Text

Biological compound eyes

Figure S1 schematically illustrates an apposition compound eye (Fig. S1*A*) and a superposition compound eye (Fig. S1*B*). The apposition compound eyes, which are found in arthropod groups (1), consist of up to thousands of individual ommatidia, each of them having a lens and a rhabdom. The light is gathered by the single lens to the rhabdom, contributing a single point of image. In superposition eyes, the light received by the rhabdom is superimposed from multiple lenses (refractive superposition eyes) or mirrors (reflective superposition eyes) that are precisely aligned on a curved surface (2). Mimicking those superposition eyes in man-made devices, however, presents extreme challenges in both manufacturing technologies and maintenance of the optical performance during use. Any misalignment of the optics (Fig. S1*C*) would cause a failure in light collecting and imaging.

Optical simulation on light propagation and focusing in a µ-PC

The optical simulation and modeling was performed in Zemax (Radiant Zemax, LLC, Raymond, WA), a ray-tracing software. The μ -PCs in the model and in the experiment had the same size, with the dimension of the input/output ports and the height of 77 μ m, 20 μ m and 120 μ m, respectively. The sidewall of the μ -PC model was determined by a parabolic equation: $y = 101.28x^2$ (mm). The model contains a BK7 glass core, Su-8 coating (5 μ m) and Al reflective sidewalls (300 nm), and the parameters of these materials, including refractive index and transmission, were obtained from references [3,4]. The device was modeled in the non-sequential ray-tracing mode

so that multiple reflections within the optical structure can be fully represented and simulated. As for the incident source, a collimated light (632.8 nm) were modeled with 10^9 analysis rays and any rays with reflection over 100 times were ignored during the simulation (in experiments, light with multiple reflections could be absorbed by the materials).

Figure S3 presents the schematic illustration of the modeled μ -PC and results of the ray-tracing simulation. The 2D layout shows the light propagation and focusing process in the μ -PC, and the light intensity distribution detected by the detector 1 and 2 demonstrates the improvement of the light intensity by the μ -PC. The improvement factor in the simulation is 8.46, which is higher than the experimental result of 3.84, because the model in the simulation has ideal parabolic sidewalls without any surface roughness that causes scattering and energy loss of the light.

Fabrication of the artificial eye

Figure S4 shows the fabrication detail of the artificial eye, including:

Femtosecond laser layer-by-layer micromachining (Fig. S4A)

Fabricate 48-by-48 microstructures on a glass wafer by the laser ablation.

Treat with diluted hydrofluoric acid (HF, 1%) for 1 min.

Clean the ablated wafer (acetone 10 min, ethanol 10 min, DI water 10 min).

Smoothing process (Fig. S4B)

Spray on Su-8 photoresist.

Post bake for 10 min (105 °C).

UV curing (45 s).

Thermal reflow of the Su-8 (210 °C for 90 min).

Fabricate flat μ -PCs (Fig. S4C and D)

Sputter 150-nm aluminum (Al).

Remove Al on output ports by laser ablation.

Release μ -*PCs* (*Fig. S4E-G*)

Protect upper surface by acid-resistance wax.

Etch the underlying glass with HF (5%) for 4 hours.

Obtain the 48-by-48 μ -PC array with a dicing saw.

Transfer process (Fig. S4H-J)

Mold casting PDMS hemispherical membrane.

Radially stretch the PDMS membrane to a flat surface.

Bond the 48-by-48 μ -PCs on the flat PDMS membrane.

Remove the protecting wax (acetone 15 min).

Generate curved μ -PCs (Fig. S4K and L)

Release the membrane.

Clean the μ -PCs in piranha for 3 min.

Package the artificial eye (Fig. S4M)

Integrate optics to form a working artificial eye.

Femtosecond laser layer-by-layer micromachining

Figure S5 illustrates the optical setup of the femtosecond laser micromachining system for the fabrication of the 3D glass microstructures. The laser source (*URANUS-1000-1030-0700*, PolarOnyx Inc. USA) delivered 700-fs laser pulses with a wavelength of 1030 nm at a repetition rate of 120 kHz. The laser was focused by an objective lens (N.A. = 0.5, Nikon) vertically onto the glass surface. The pulse energy of laser used to fabricate the microstructures was 3 μ J. The glass wafer was mounted on an *x*-*y*-*z* translation stage with an accuracy higher than 0.1 μ m.

The scanning path of the layer-by-layer laser ablation is shown in Fig. S6A. The material (in gray shade) is removed by layer-by-layer ablation with the depth of each layer, $\Delta d = 3 \mu m$, leaving behind rectangularly-packed microstructures with parabolic sidewalls (Fig. S6*B*). The profile of the sidewalls of a microstructure was extracted in MATLAB software, and plotted against the designed parabolic curve in Fig. S6*C*.

Smoothing process

To generate a uniform layer of Su-8 photoresist on the sidewalls of the microstructures, the liquid photoresist (SU-8 MicroSprayTM, MicroChem) was sprayed during the spinning of the glass microstructures. The spraying process lasted 8 seconds at an initial spinning speed of 500 rpm, and thereafter at an increased speed to 2000 rpm to remove the extra liquid on the wafer. The solvent was then evaporated by post-baking for 10 min. The resist was photo-cured under an UV-exposure for 45 s. The smooth surface was obtained after reflowing the cured Su-8 photoresist in an oven at 210°C for 90 min. Figure S7*C* and *E* shows the surface morphology of the microstructure before and after the smoothing process, respectively. The micrometer-scale roughness of sidewalls ablated by the laser was improved to nanometer-scale, and the profile was not damaged.

The reduction of scattering loss on the rough laser-ablated surface is schematically demonstrated in Fig. S7A. Because the refractive index of the reflowed Su-8 photoresist (n=1.58) is close to that of the glass (n=1.52), the majority of light would transmit into the photoresist layer and be reflected by the smooth Al surface. Figure S8 shows an experimental demonstration of the increase in the reflection rate by the smoothing process. The samples included a flat glass wafer coated with Al (Fig. S8A), Al on a wafer with laser ablated surface which was coated by the thermal-reflowed Su-8 photoresist (Fig. S8B) and Al on the laser ablated surface (Fig. S8C). A laser (He-Ne laser, 45° incidence angle) was reflected by the samples and collected with an integrating sphere (Fig. S8D). The intensity of the reflected light is illustrated in Fig. S8*E*, indicating that the reflection rate was improved from 9.78% to 72.42% by our smoothing process (Fig. S8*F*).

Fabrication of flat µ-PCs

A 150-nm Al thin film was sputtered (Denton Discovery 24 sputter) onto the smooth Su-8 photoresist to generate the reflecting sidewalls of the μ -PCs. To remove the Al covering the output ports, we linearly scanned a tightly focused femtosecond laser (focused by a Nikon objective lens with N.A. = 0.8); the whole process was monitored by a CCD camera equipped in the laser micromachining system. The laser pulse energy was 50 nJ, which could ablate the thin Al layer without burning the Su-8 photoresist and glass beneath. Subsequently, we dipped the wafer in a metal etchant for 3 s to remove the debris of the Al.

Release µ-PCs from rigid glass wafer

To transfer the μ -PCs on the rigid glass to the hemispherical surface, the underlying substrate was removed by chemical etching with diluted HF (5%). Melted and re-cured acid-resistance wax (Crystalbond 509, SPI Supplies) was used to protect the devices during this etching process and to support the isolated μ -PCs. The etching was conducted in a Teflon container at a fixed temperature of 23°C, and monitored under a microscope. The thickness of the underlying substrate was 80 μ m, and the entire process lasted about 4 hours.

Transfer µ-PCs onto hemispherical PDMS membrane

The device that contains the 48-by-48 μ -PCs was extracted by removing the other parts of the wafer with a dicing saw. A PDMS membrane was made by casting the PDMS pre-polymer (mass ratio between the base and curing agent = 10:1) onto a hemispherical plastic dome (diameter R = 12.5) and curing at 70°C for 60 min. The hemispherical PDMS membrane was radially stretched on a platform with a larger diameter (R = 15 mm) to form a flat surface (5). The transfer element

was spin-coated with a layer of PDMS pre-polymer and bonded to the stretched PDMS membrane, and the bonding PDMS was cured at 70°C for 60 min. The protection wax was removed by submerging the device in acetone for 15 min.

Package the artificial eye

The μ -PCs on the hemispherical PDMS membrane were integrated with a ball lens, a mounting plate with an iris and a plastic protecting shell to form the artificial eye, which was subsequently packaged in a 3D-printed plastic casing of a matching diameter. Packaging was applied to block the stray light and to offer protection for the device during implementation.

Optical characterizations of the bioinspired photosensitivity enhancer (BPE)

Acquisition of focal spots with the BPE

Figure S9 shows images of the optical setup utilized to acquire the spots of incoming light focused by the BPE. Helium-Neon laser (Model 1108, Edmund Optics) was used as light source. The laser was expanded by a beam expander (1:10) and collimated to form a light beam with a diameter of 10 mm. To obtain the light source with uniform distribution, a condenser lens with diffuser surface (ACL2520U-DG15-A, Thorlabs Inc., Aspheric Condenser lens w/diffuser, f = 20.1 mm, 1500 Grit) was applied in the light expander to homogenize the Gaussian-distributed laser beam, and the central part of the homogenized laser was selected by an iris with a diameter of 5 mm. The power of the light was controlled by reflective neutral density filters and measured by a laser power meter (Model 1936-R, Newport). The cover glass of a monochrome image sensor (Model KAI-02050, TRUESENSE, see Table S1 for parameters) was removed to be closely coupled with the BPE. To match the flat surface of the image sensor, the 48-by-48 μ -PCs were transferred onto a flat glass wafer ($t = 100 \mu$ m), and butt-coupled with the sensor surface by optical adhesive resin (Fig. S9). The laser beam irradiated vertically into the input ports of the μ -PCs, and was reflected by the parabolic sidewalls. The concentrated light spots were captured by the CCD.

<u>Calculation of the improvement in the light intensity</u>

To calculate the light intensity improvement resulting from the BPE, we extracted the gray-scale values (ranging from 0 to 255 with 0 = totally dark) of the images acquired by the CCD and plotted them into 3D distribution images (Fig. 3*B* and *C*). In every 14 × 14 pixel area (corresponding to a μ -PC which covers an 77 μ m × 77 μ m area), maximum gray-scale values, *G*_{without} (without μ -PC) and *G*_{with} (with μ -PC), were selected to calculate the multiplication of the light intensity:

$$M = \frac{G_{with} - G_{without}}{G_{without}}$$
Equation S1

Optimization of the parabolic sidewall of the µ-PCs

Six 10-by-10 arrays of μ -PCs with different diameter of output ports ($D_{out} = 10 \sim 35 \ \mu$ m) and the same size of input port and height ($D_{in} = 77 \ \mu$ m, $h = 120 \ \mu$ m) were fabricated on a single wafer (10 mm × 10 mm × 0.2 mm). The improvement of the light intensity by those μ -PCs was measured by the aforementioned method. The focal spots of light obtained by μ -PCs with different output port diameters and their corresponding incoming light acquired without μ -PCs are shown in Fig. S10. All the results shown in Table S2 and Fig. 3*E* are average values obtained from the 10-by-10 μ -PCs. The maximum improvement of light intensity was achieved by μ -PCs with $D_{out} = 20 \ \mu$ m. *Optical response of the CCD under low-light illuminating condition*

Figure S11 *A-E* shows the gray-scale distribution of the images acquired by the CCD without μ -PCs at low light conditions ($P = 0 \sim 0.056 \ \mu\text{W/cm}^2$). To test the response of the CCD in totally dark environment ($P = 0 \ \mu\text{W/cm}^2$), the setup was enclosed by black curtains and no light source was applied. The obtained gray-scale value was 3.02, which was caused by the noises in the sensor.

When the illumination was extremely low ($P < 0.05 \,\mu\text{W/cm}^2$), the gray-scale values of the obtained images slightly vacillated around 3, indicating that the photon-induced signals were overwhelmed by the noises in the CCD. When the light power was 0.056 μ W/cm², the readout signal exceeded the noises, which is demonstrated by a sharp growth in the gray-scale value as shown in Fig. S11*F*. The results prove that the CCD used in this work was unable to capture any recognizable images without μ -PCs with a light power lower than 0.05 μ W/cm².

Wide-spectrum characterization of the BPE

Figure S12*A* shows a schematic illustration of measuring the improvement of light intensity by the BPE at wavelengths ranging from 380 to 900 nm. The BPE was mounted on a thread sample holder (Fig. S12*C*), and screwed into the integrating sphere (Fig. S12*D*). A collimated broad-spectrum white light source (Xenon Arc lamp, Oriel) illuminated the BPE from the input ports, and focused light was collected by the integrating sphere and measured by a spectrometer (Fig. S12*E*). An Alon-glass mask with a transparent area equivalent to the area of output ports of the BPE was used as a comparison. Figure S12*B* shows the light intensity at different wavelengths with the BPE (blue line) and the metal mask (red line). Because the parabolic sidewalls of the μ -PCs in the BPE reflected more light into the integrating sphere, the light intensity at any wavelength was much higher than the result obtained by the metal mask. The intensity values on the curves were extracted to calculate the intensity improvement using equation S1. The results were plotted in Fig. 3*F*.

Optical simulation on the wavelength dependency of the light intensity improvement factor

The Zemax ray-tracing model was applied to simulate the wavelength-dependency of the enhancement in the light intensity because of the μ -PCs. The model used for this simulation has been described in Fig. S3. The parameters of the materials, including the refractive index and transmission of Su-8 photoresist, and complex refractive index of Al are obtained from Refs. [3]

and [4] and plotted in Fig. S13. Higher values of scattering factor were set for the light source with shorter wavelengths, which simulates the higher scattering loss at shorter wavelengths (0.6 for 340 nm, 0.4 for 436 nm, 0.2 for 563 nm, 0.1 for 632.8 nm, 800 nm and 1000 nm. For light at red and near-infrared spectral range, the roughness of less than $\lambda/10$ would induce much lower scattering loss and can be considered as a constant value). The intensity of output light was detected at different wavelengths of 340 nm, 436 nm, 563 nm, 632.8 nm, 800 nm and 1000 nm, respectively. Figure S14 shows the intensity distribution of light at wavelengths of 340 nm, 632.8 nm and 1000 nm, which demonstrates the decline of the intensity at ultraviolet (340 nm) and near-infrared (1000nm) spectral range compared to the visible light (632.8 nm). The plot in Figure S15 shows the power of light detected at the output port with different wavelengths of the light source (the power of the input light was set to be 1 W). The wavelength dependency shown in the simulation is in agreement with that from the experimental results.

Image acquisition with the BPE

Figure S16 schematically illustrates the main steps to acquire high-resolution images with the BPE. The power intensity of the laser source was 0.05 μ W/cm², and transparent masks with University of Wisconsin and Bucky Badger head logos were used as objects. A single double-convex lens was used to generate real images on the BPE-coupled CCD which was mounted on a computer-controlled *x*-*y* translational stage.

Figure S17A and *B* demonstrates the images of the logos acquired by scanning our 48-by-48 BPE in a $7.392 \times 7.392 \text{ mm}^2$ area with increments of 3.696 mm. To process the raw images with discrete light spots, the pixels with highest gray-scale values in each light spot were selected and combined to form low-resolution images (96 × 96 pixels), as shown in Fig. S17*C* and *D*.

In order to increase the resolution of the images, a complete set of hardware and software process based on super-resolution image reconstruction algorithm (6,7) was developed. Figure S18 illustrates the flow chart of the process. Initially, 16 low-resolution images (Fig. S17*C* and *D*) were obtained when shifting the BPE-coupled CCD both horizontally and vertically with increments of 18 μ m. Because the displacement between the adjacent low-resolution images was smaller than the pixel size of BPE (77 μ m), the 16 images contained different sub-pixel information.

Subsequently, the super-resolution algorithm was applied without considering noise and blurring (7; the flow chart of the super-resolution algorithm is illustrated in Fig. S18). The underlying algorithm is iterative. An initial guess for the high-resolution image $x^{(0)}$ must be provided that matches the desirable resolution; the superscript 0 indicates the initial guess and 1 would indicate the next guess, and so on. In our implementation, the average of all low-resolution image was used as the initial guess. Then the difference between the obtained low-resolution images and the computed low-resolution images obtained from the guess { $Y_k - Y_k^{(0)}$ } was calculated, which was used to improve the initial guess $x^{(0)}$ by back-projecting values in the difference images onto the guessed high-resolution image. This whole process was repeated until the following error function

$$e^{(n)} = \sqrt{\sum_{k} \sum_{(x,y)} (Y_k(x,y) - Y_k^{(n)}(x,y))^2}$$
 Equation S2

became less than a pre-specified tolerance value or a preset maximum number of iterations was reached, whichever was satisfied first.

To update the value for the high-resolution image iteratively, the following scheme was utilized

$$x^{(n+1)} = x^{(n)} + ch^{BP'} \sum_{k} (Y_k - Y_k^{(n)})$$
 Equation S3

where *c* is a constant normalization factor and $h^{BP} = DM_k$ is the back-projection kernel that incorporates the displacement among low-resolution images and undersampling of the highresolution image. The image undersampling matrix *D* was obtained by placing the high-resolution grid onto the low-resolution image grid in which all values of high-resolution pixels not falling on low-resolution grid were lost. Since 16 (4-by-4) low-resolution images with identical subpixel horizontal or vertical displacement were super-resolved, the initially guessed high-resolution image and the updated high-resolution images on-the-fly were undersampled (*i.e.* decimated) every four pixels horizontally or vertically. The warping matrix M_k which is in fact a purely global translational matrix in our application, was obtained via a linear kernel that processed the subpixel displacement among low-resolution images. The kernel primarily consisted of a sparse asymmetric Toeplitz matrix whose first row and first column were determined by a simple linear interpretation of the sub-pixel displacement value for each image respectively. Equation S3 was used to iteratively update the guessed high-resolution images $x^{(n)}$, until the pre-specified tolerance value or the preset maximum number of the iterations was reached. The resolved high-resolution images (384 × 384 pixels) are demonstrated in Fig. S17*E* and *F*. Compared to the low-resolution images (Fig. S17*C* and *D*), the super-resolution images offer fine features and sharp boundaries of complex patterns.

Analysis of image distortion in the artificial-eye-produced image

To acquire images from the curved BPE, a CCD sensor was scanned along the hemispherical surface of the μ -PCs with increments of 16° by a 5-D stage consisting of three linear stages and two rotation stages. The schematic illustration and photos of the optical setup are shown in Fig. S19. A mask with a transparent square array was used as the imaging object. The ball lens generated a 3-by-3 array of square images onto the hemispherical BPE. Each square pattern at the center of the image covered about 7-by-7 μ -PCs, and in such a small area, the output ports of the μ -PCs were in close contact with the CCD; therefore the focused light spots could be acquired. The peripheral patterns of the image were out of focus because of the hemispherical configuration

of the BPE, as demonstrated in Fig. S20. The central parts of the nine individual images were selected and combined to an image with 3-by-3 square patterns composed of discrete light spots (Fig. S21*A*). To demonstrate the uniformity of these patterns, we extracted the square shapes from Fig. S21*A* by a MATLAB software and projected them onto a hemispherical surface with a curvature equal to that of the BPE (Fig. 4*G*).

Figure S21*B* shows the image of the same object acquired with the ball lens and a flat BPE. Because of the mismatch between the curved focal plane and the flat imager plane, peripheral patterns were severely distorted. In order to quantitatively estimate the distortion, the contours of the patterns in Fig. S21*A* and *B* were extracted in MATLAB software, and the diameter of them was measured (Fig. S21*C* and *D*). The shape distortion can be calculated with the diameter of the peripheral patterns, R_n , and the central patterns, R_o , by an equation $\frac{R_n - R_0}{R_0} \times 100\%$, and the results are plotted in Fig. 4*H*.

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Fig. S1. Schematic illustrations of an apposition compound eye (A), a superposition compound eye (B) and a superposition eye with misaligned optics (C).



Fig. S2. Schematic of the design of the artificial eye. (A and B) 3D layout of the artificial eye and a μ -PC, respectively. (C) Cross-section view of the artificial eye. (D) Illustration of the image acquisition system. The ball lens generates an image plane on a hemispherical surface which is coincident with input ports of the μ -PCs. The image from the output ports is captured by a matching imager.



Fig. S3 Ray tracing simulation on the light propagation and focusing process inside a μ -PC.



Fig. S4. Schematic illustration of the fabrication process of the artificial eye.



Fig. S5. Schematic illustration of the optical setup of the femtosecond laser micromachining system.



Fig. S6. Schematic illustration and results of the femtosecond laser layer-by-layer ablation. (A) Schematic illustration of the laser ablation process. (B) SEM of the cross-section of the laser ablated microstructures. The scale bar is 50 μ m. (C) The extracted profile (red circle) of the microstructure shown in (B). The blue solid lines show the designed parabolic shape.



Fig. S7. Schematic illustration and results of the smoothing process. (A) Schematic illustration of reducing the scattering loss after the smoothing process. (B and C) Surface morphology of the microstructures. (D and E) Surface morphology of the microstructures after the smoothing process.



Fig. S8. Measurement of the reflection rate on different Al surfaces. Reflection rates of Al on flat glass (*A*), Al on Su-8 photoresist coated surface (*B*), and Al on rough laser ablated surface (*C*) are tested by an integrating sphere and a He-Ne laser (*D*). (*E*) Intensity of the reflected and the directly incident laser beam. (*F*) Plot of the reflection rate.



Fig. S9. The experimental setup for optical characterization.



Fig. S10. Images obtained without and with μ -PCs with different output port diameters.



Fig. S11. Response of the CCD under totally dark (*A*) and low-light illuminating conditions (*B*-*E*). Notable variation of the obtained gray-scale distribution can be observed when laser power $P > 0.05 \,\mu\text{W/cm}^2$. The values of the gray-scale are illustrated in (*F*).



Fig. S12. Schematic illustration and images of the experimental setup for characterizing the widespectrum property of the BPE. (A) Schematic illustration of the experimental method. (B) The optical spectrum obtained with and without BPE. (C) Photo of a BPE mounted on the sample holder. (D) The BPE screwed into the integrating sphere. (F) Optical setup of the experiment.



Fig. S13. The parameter of materials applied in the ray tracing process. (*A*) and (*B*), refractive index and transmission of the Su-8 photoresist. (*C*) Complex refractive index of the Al thin film. The data of Su-8 photoresist and Al are obtained from Ref. [3] and Ref. [4], respectively.



Fig. S14. Intensity distribution of light at the output port of a μ -PC. The results are obtained by a ray-tracing modeling using the Zemax software, with wavelengths (from left to right) of 340 nm, 632.8 nm and 1000 nm, respectively.



Fig. S15. Simulation results of the light power detected at the output port of μ -PC with different wavelengths. The input power is set to be 1W across the whole spectral range.



Fig. S16. Schematic illustration of the image acquisition process.



Fig. S17. The results of imaging characterization. (A and B) Raw images of a University of Wisconsin-Madison logo and a Bucky Badger head logo acquired with the BPE. (C and D) The processed low-resolution images. (E and F) High-resolution images obtained using a super-resolution reconstruction method.



Fig. S18. Flow chart of the super-resolution reconstruction algorithm.



Fig. S19. Schematic illustration and images of the optical setup for acquiring images from the curved BPE.



Fig. S20. Images acquired by scanning the CCD along the hemispherical surface. The central parts of the images (shown in boxes) are extracted and combined to a single image shown in Fig. S17.



Fig. S21. Comparison of the images acquired with a curved and a flat BPE. (*A*) The raw image acquired from the ball lens and a curved BPE. (*B*) The raw image acquired by the ball lens and a flat BPE. (*C*) and (*D*) shows the extracted contours of the patterns in (*A*) and (*B*), respectively. The diameters of the peripheral patterns, R_n, and that of the central square, R₀, are measured, and the distortion was calculated by $\frac{R_n - R_0}{R_0} \times 100\%$.

Parameter	Typical Value		
Architecture	Interline CCD; Progressive Scan		
Number of pixels	1640 (H) × 1240 (V)		
Number of effective pixels	1600 (H) × 1200 (V)		
Active image size	8.8 mm (H) \times 6.6 mm (V)		
Pixel size	5.5μm (H) × 5.5μm (V)		
Number of outputs	4		
Output sensitivity	34 μV/e*		
Quantum efficiency	50 % (500 nm)		
Read noise (f = 40 MHz)	12 electrons rms		
Dark current			
Photodiode	7 electrons/s		
VCCD	100 electrons/s		
Dynamic range	64 dB		
Frame rate	68 fps		

Table S1. Parameters of the image sensor. All parameters are specified at $T = 40^{\circ}$ C. More detail at <u>http://www.ccd.com/pdf/ccd_2050.pdf</u>.

Table S2. Values of gray scale obtained by μ -PCs with different output port diameters.

Dout (µm)	10	15	20	25	30	35
Gray scale	1.49	3.32	3.87	2.81	1.38	0.81