Multifunctional Biomimetic Microlens Arrays with Integrated Pores

Shu Yang; Department of Materials Science & Engineering, University of Pennsylvania, Philadelphia, PA Joanna Aizenberg, Bell Laboratories, Lucent Technologies, Murray Hill, New Jersey, USA

Abstract

Biology provides a multitude of varied, new paradigms for the development of adaptive optical networks. We discuss a first example of synthetic, biomimetic microlens arrays with integrated pores, whose appearance and function are strikingly similar to their biological prototype – a highly efficient optical element formed by brittlestars. The complex microstructure is created directly by three-beam interference lithography in a single exposure from a negative-tone photoresist, SU8. We show that (i) these synthetic polymeric microlenses have strong focusing ability and the structure can be, therefore, (ii) used as an adjustable lithographic mask, and that (iii) light-absorbing liquids can be transported in and out of the pores between the lenses, which provides a wide range of tunability of the lens optical properties.

Introduction

In the course of evolution, nature has developed strategies that endow biological processes and structures with exquisite selectivity and performance. We are interested in learning from natural optical systems, whose hierarchical architecture and hybrid character offer outstanding optical properties and enable multi-faceted roles.[1-5] Recently, we have characterized a spectacular example of a biologically produced adaptive optical system – a close-set, nearly hexagonal array of uniform microlenses formed by a light-sensitive brittlestar, *Ophiocoma wendtii* (Figure 1a).[3] The lenses were shown to be involved in photoreception as optical elements that guide and concentrate light onto photosensitive tissue and offer remarkable focusing ability, angular selectivity and signal enhancement. An interesting design feature of this bio-optical structure is the presence of a pore network surrounding the lenses, which is essential to the diurnal migration of pigment-filled chromatophore cells.[6] Because of the presence of pore network, the brittlestar microlenses can be considered as an adaptive optical device that exhibits a wide-range transmission tunability achieved by controlled transport of radiation-absorbing intracellular particles. Other functions of the chromatocyte pigment include diaphragm action, numerical aperture tunability, wavelength selectivity, minimization of the "cross-talk" between the lenses, and improved angular selectivity.

It will be highly desirable to have complex, small photonic devices that can mimic the unusual design of the brittlestar optical elements and their consequent outstanding optical properties, by creating a structure that combines microlens arrays with the porous surrounding microfluidic system. The fabrication of such structure using existing techniques – inkjet printing,[7] melting of patterned photoresists,[8] reactive ion etching of silica and silicon,[9] soft-lithography,[10] or self-assembly of monodispersed polymer beads[11] – is, however, not straightforward. Most of these techniques only create lenses without pore structures and their optical properties are not tunable.

Here we present a first example of synthetic, biomimetic microlens arrays with integrated pores (Figure 1b), whose appearance and function are strikingly similar to their biological prototype – a highly efficient optical element formed by brittlestars.[3] The complex microstructure is created directly by three-beam interference lithography in a single exposure. We show that (i) these synthetic polymeric microlenses have strong focusing ability and the structure can be, therefore, (ii) used as an adjustable lithographic mask,[12] and that (iii) light-absorbing liquids can be transported in and out of the pores between the lenses, which provides a wide range of tunability of the lens optical properties.[13]

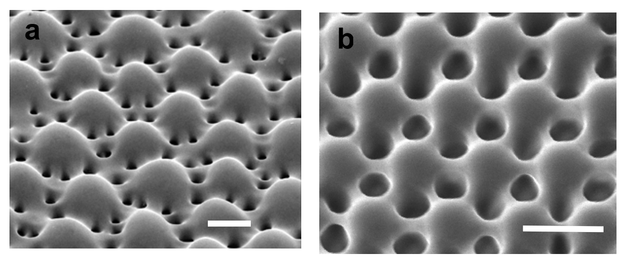

*Figure 1. **a**) Scanning electron micrograph (SEM) of a brittlestar lens design. Scale bar, 50 μm. **b**) Corresponding SEM of a synthetic, biomimetic microlens array with integrated pores. Scale bar, 5 μm.*

Materials and Method

In interference experiment, we used a continuous wave (CW) diode-pumped solid-state laser (wavelength λ = 532 nm), to photopolymerize SU8. The primary laser beam was split into three beams and overlapped into a spot with diameter of 4-5 mm. For the lens structure demonstrated in Figure 1, the wave vectors were arranged as:

$k1 = 2\pi/a\,[0.035,0,0.999]$, $k2 = 2\pi/a\,[-0.017,0.03,0.999]$,
$k3 = 2\pi/a\,[-0.017,-0.030,0.999]$.

The polarization of each wave was parallel to each other. The resist was formulated by dissolving 2 wt% of Irgacure 261, which acts as a photoacid generator that is sensitive to the green laser, and SU8 in cyclopentanone (~30-50 wt%). The solution was then spun coated on a pre-cleaned glass substrate, followed by soft bake at 90°C to completely remove solvent. The film thickness was in the range of 5-15 μm depending on the spin speed and resist concentration. When exposed to laser beam (output of 2W) for 1-6 s, photoacids were generated in the regions corresponding to the interference pattern. The ring-opening reactions of epoxy groups were initiated at post-exposure bake and the acids were regenerated, resulting in a highly crosslinked film. Finally the film was developed in propylene glycol methyl ether acetate (PGMEA) to remove unexposed or weakly exposed film to form pores.

In the lithographic experiment, a 1μm-thick film of AZ5209 was spun on a glass substrate, followed by casting a polydimethylsiloxane (PDMS) film with different thickness on top of the resist as a transparent spacer. The lenses attached to glass substrate were then placed directly on the PDMS spacer for conformal contact (Figure 2a). We set the illumination dose just below or above the lithographic threshold to create a variety of different microscale patterns using the porous microlens arrays as a multipattern photomask. For the microfluidics assembly, we sandwiched a film (3-4 mm diameter) with lens arrays between two copper grids (3.05 mm diameter, 50 mesh) and sealed it with instant epoxy. We then carefully glued two micropipette tips on both sides of the copper grids and pumped dye-containing solution using syringe.

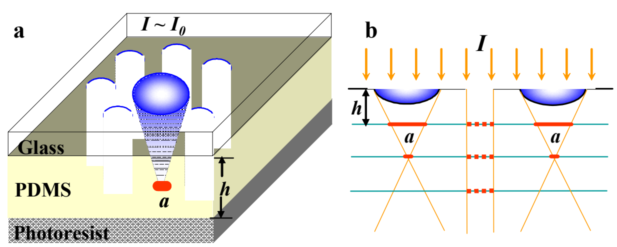

*Figure 2. Biomimetic porous microlens array as a multipattern lithographic photomask. (**a**) Schematic presentation of the experiment. (**b**) Illustration of the photomask action at different distances from photoresist,* h*, and different light intensities,* I*. For* $I < I_{th}$*, only features under the lenses are expected (shown as the bold red lines). Their size,* a*, will depend on the distance from the focal point,* f*. For* $I > I_{th}$*, the features under the lenses will be surrounded by the features originating from the pores (shown as the dotted red lines).*

Results and Discussion

Multi-beam interference lithography has been shown as a fast, simple, and versatile approach to create two-dimensional (2D) and three-dimensional (3D) periodic porous microstructures defect free over a large area.[14-17] The symmetry and the porosity of the resulting structures can be conveniently controlled by the wavevectors and polarizations of the interfering beams.[18] None of the studies, however, has paid attention to integrate the two different structures, lenses and pores, together into a more complex photonic device, nor has shown the resulting tunability of lens optical properties.

In our approach, we use three-beam interference lithography to create a synthetic, biomimetic analog of the brittlestar microlens array, which is the first example that combines both functional elements, *lenses* and *pores*, in one structure.[13] When the wave vectors are kept the same and the polarizations of the waves are parallel to each other, a periodic variation of light intensity is generated with hexagonal symmetry, and the simulated intensity profile resembles the shape of the biological lens array. We then subject the interference light to a negative-tone photoresist, SU8. During exposure, the highly exposed regions of the photoresist crosslink and become insoluble in an organic developer solution, while the unexposed or weakly exposed regions are dissolved away to reveal holes in the film. When the intensity difference between strongly exposed and adjacent weakly exposed regions is above the threshold, formation of a contour of a lens is introduced. We can control the lens size (diameter of 1.5 to 4.5 μm, height of ~ 200 nm to 1.0 μm), shape, symmetry and connectivity by adjusting the beam wave vectors and their polarizations, while the pore size and porosity are determined by the laser intensity and exposure time (porosity of about 10% to 80%).

The synthesized biomimetic microlens arrays have unique optical structures: that is they combine two imaging elements – microlens arrays and clear windows – in one structure. Photolithographic masks are key components in the fabrication process of patterned substrates for various applications. Different patterns generally require different photomasks, whose total cost is high for the multilevel fabrication. Here, we demonstrate their application as multipattern photomasks (Fig. 2 and 3); that is, by using the same photomask and simply adjusting (i) the illumination dose, (ii) the distance between the mask and the photoresist film, and (iii) the tone of photoresist, we are able to create a variety of different microscale patterns with controlled sizes, geometries and symmetries that originate from the lenses, clear windows or their combination.

When the illumination dose is fixed slightly below the sensitivity threshold of the photoresist (I_{th}), no pattern is expected to originate from the light passing through the clear windows, while the focusing activity of the lenses enhances the light field near focus to surpass the resist threshold intensity. Indeed, for $I < I_{th}$, features in photoresist were selectively generated under the lenses, showing hexagonally packed holes (Fig. 3 a, b) that closely matched the microlens array in the mask (see Fig.1b). The size of the features in the resist layer, *a*, can be effectively controlled by placing transparent PDMS spacers with different thickness, *h*, between the lens and the resist film. The diameter of the generated holes in the photoresist gradually changed from ~3 μm to a minimum value of ~700 nm when *h* was increased from 1 to 8 μm. The minimum dose to realize patterns under the lenses (i.e. holes near the focal point at a distance of ~8 μm) was ~2 mJ/cm^2, while normally the dose of > 40 mJ/cm^2 is needed to produce a good feature in the photoresist using a conventional chrome mask.

For the illumination dose set above the lithographic threshold intensity of photoresist ($I > I_{th}$), we generated patterns originated from both the lenses and the windows (Fig. 3 c, d). The relative sizes of the features formed from the lenses and pores are controlled by the distance between the lens structure and the resist film. When $I > I_{th}$ and $h > 2f$, we observed a honeycomb structure originated from the light coming through the pores only (Fig. 3e). The microscale honeycomb structures are of interest as 2D photonic crystals with a large bandgap. When $I < I_{th}$, and using a negative tone resist (e.g. SU8), we observed hexagonally packed dots that corresponded to the hexagonal lens array in the mask, while their size was reduced (Fig. 3f).

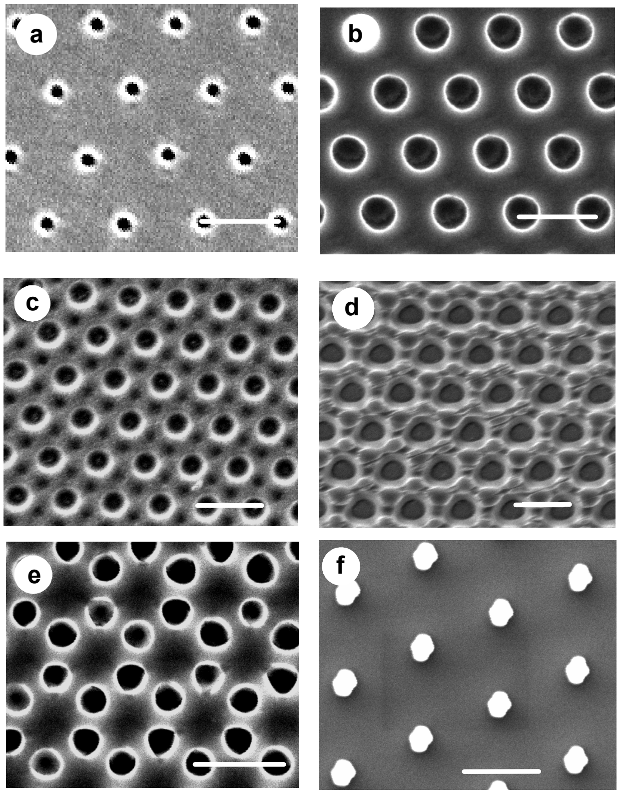

*Figure 3. Examples of photoresist patterns generated using the porous lens arrays as photolithographic masks. (**a-e**) from positive tone resists and **f**) from a negative tone resist. (**a**) $I < I_{th}$, $h \sim f$; (**b**) $I < I_{th}$, $h < f$; (**c**) $I > I_{th}$, $h \sim f$; (**d**) $I > I_{th}$, $h < f$; (**e**) $I > I_{th}$, $h > 2f$; **f**) $I < I_{th}$, $h \sim f$.*

Another application of the biomimetic microlens array is based on using the porous network as a microfluidic system that mimics the pigment movement in the brittlestar stereom. We studied the possibility of actuating photoactive liquids within the microlens array. The thin film with porous microlens arrays was assembled between two copper grids and light-absorbing liquid was introduced from one side. When a dye-containing liquid was pumped through the pores (to mimic the migration of pigment-filled chromatophore cells in photosensitive brittlestars), the reduction in light transmission was detected under optical microscope (Figure 4). We observed the change of transmission intensity depending on the dye concentration and/or thickness of the dye layer covering the lens. This result clearly demonstrates that the presence of pore networks will allow the dynamic tuning of the lens optical properties. One potential application will be an optical shutter that turns light on and off in an optical interconnect. By using different liquids (e.g. with selective refractive index and/or including dyes that can absorb a certain wavelength) as surrounding medium between lenses, we can introduce further control over the lens focal length, numerical aperture and wavelength selectivity.

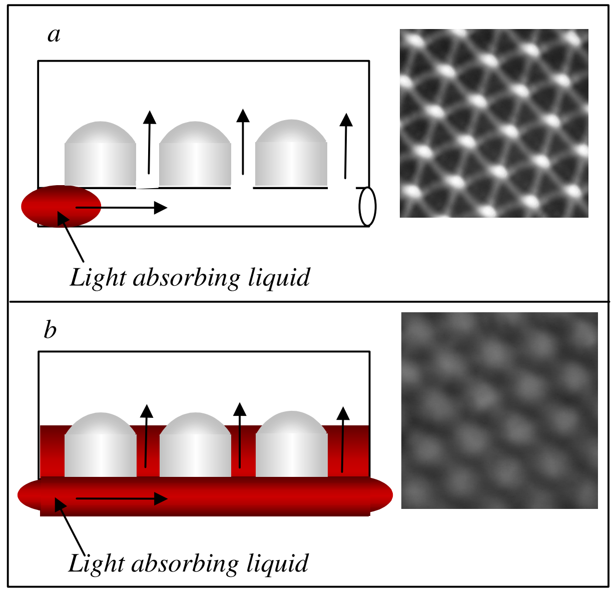

*Figure 4. Illustration of the transmission tunability through the lens array, using controlled transport of light-absorbing liquid in the channels between the lenses. Light micrographs were recorded in a transmission mode near the focal point: **a**) without the light-absorbing liquid, **b**) with the light-absorbing liquid between the lenses.*

Conclusion

Fabrication of microlens arrays with the integrated pores reported here is a first step toward creating and mimicking complex optical devices that are prominent in biology. The presented application as a multipattern photomask and their tunable optical properties clearly demonstrate that the lessons learned from sophisticated microlens arrays evolved by brittlestars for successful survival and adaptation may improve our current capabilities to construct new, adaptive, micro-scale optical devices potentially useful for a wide variety of technological applications. The knowledge we gain from fabricating these complex structures will provide important insights to create novel hybrid structures with multi-functionalities.

References

1. A. R. Parker, et al. "Structural colour - Opal analogue discovered in a weevil". Nature 426, 786 (2003).
2. M. F. Land and D.-E. Nilsson. Animal Eyes Oxford University Press, New York, 2002).
3. J. Aizenberg, et al. "Calcitic microlenses as part of the photoreceptor system in brittlestars". Nature 412, 819 (2001).
4. P. Vukusic, et al. "Structural colour - Colour mixing in wing scales of a butterfly". Nature 404, 457 (2000).
5. P. Vukusic, et al. "Remarkable iridescence in the hindwings of the damselfly Neurobasis chinensis chinensis (Linnaeus) (Zygoptera : Calopterygidae)". Royal Soc. Lond. Ser. B-Bio. Sci. 271, 595 (2004).
6. G. Hendler and M. Byrne. "Fine-Structure of the Dorsal Arm Plate of Ophiocoma-Wendti - Evidence for a Photoreceptor System (Echinodermata, Ophiuroidea)". Zoomorphology 107, 261 (1987).
7. S. Biehl, et al. "Refractive microlens fabrication by ink-jet process". J. Sol-Gel Sci. Technol. 13, 177 (1998).
8. S. Haselbeck, et al. "Microlenses Fabricated By Melting a Photoresist On a Base Layer". Opt. Eng. 32, 1322 (1993).

9. P. Savander. "Microlens Arrays Etched Into Glass and Silicon". Opt. Lasers Eng. 20, 97 (1994).
10. M. H. Wu, et al. "Fabrication of arrays of microlenses with controlled profiles using gray-scale microlens projection photolithography". Langmuir 18, 9312 (2002).
11. Y. Lu, et al. "A self-assembly approach to the fabrication of patterned, two- dimensional arrays of microlenses of organic polymers". Adv. Mater. 13, 34 (2001).
12. S. Yang, et al. "Microlens Arrays with Integrated Pores as a Multipattern Photomask". Appl. Phys. Lett. in press (2005).
13. S. Yang, et al. "Functional biomimetic microlens arrays with integrated pores". Adv. Mater. 17, 435 (2005).
14. V. Berger, et al. "Photonic band gaps and holography". J. Appl. Phys. 82, 60 (1997).
15. M. Campbell, et al. "Fabrication of photonic crystals for the visible spectrum by holographic lithography". Nature 404, 53 (2000).
16. S. Yang, et al. "Creating periodic three-dimensional structures by multibeam interference of visible laser". Chem. Mat. 14, 2831 (2002).
17. Y. V. Miklyaev, et al. "Three-dimensional face-centered-cubic photonic crystal templates by laser holography: fabrication, optical characterization, and band-structure calculations". Appl. Phys. Lett. 82, 1284 (2003).
18. C. K. Ullal, et al. "Triply periodic bicontinuous structures through interference lithography: a level-set approach". J. Opt. Soc. Am. A 20, 948 (2003).

Author Biographies

Shu Yang received the B.S. degree from Fudan University, China in 1992, and Ph.D. degree from Chemistry and Chemical Biology at Cornell University in 1999. She then joined Bell Laboratories, Lucent Technologies as a Member of Technical Staff. She is now Skirkanich Assistant Professor in Materials Science & Engineering at University of Pennsylvania. Her research includes synthesis and fabrication of functional polymers; novel micropatterning techniques for complex 3D structures; surface/interface and dynamic tuning.

Joanna Aizenberg received the B.S. degree in 1981, the M.S. degree with honors in physical chemistry in 1984 from Moscow State University, and the Ph.D. degree in Structural Biology from the Weizmann Institute of Science in 1996. As a postdoctoral fellow at Harvard University, she focused on near-field photolithography and new nano- and microfabrication techniques. She joined Bell Laboratories in 1998, where she is working on bio-inspired optics and methods for controlling various aspects of crystal formation at the nanoscale.