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Designing efficient microlens arrays: lessons from Nature

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Nature provides a whole host of superior multifunctional structures that can be used as inspirational systems for the design and synthesis of new, technologically important materials and devices. We review here the exceptional optical performance of microlens arrays formed by light-sensitive brittlestars, their structural and compositional features, and advantageous properties. We show that brittlestars form a nearly perfect optical device with micron-scale, lightweight, mechanically strong, aberration-free, birefringence-free, individually-addressed lenses, which offer a unique focusing effect, signal enhancement, intensity adjustment, angular selectivity, and photochromic activity. We discuss first materials fabrication strategies that were inspired by the principles involved in the formation of echinoderm calcitic structures. The biomimetic synthetic microlens arrays could be potentially used as highly tunable optical elements for a wide variety of applications.

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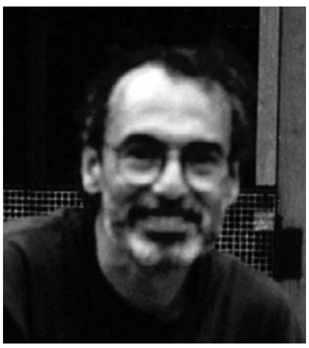

Gordon Hendler

1. Introduction

The increasing technological requirement for a new generation of optical devices with novel architectures, tunability and tailored properties, provides a potent stimulus to the academic study of optical systems in living organisms. Mimicking Nature's methods of biological manufacture is proving to be a major step forward in modern technology.[1–7] In general, a successful bio-inspired engineering effort includes three key objectives: (i) to search for smart biological solutions in the design, synthesis, and integration of complex materials and systems; (ii) to learn about their composition, structure, properties, tunability and mechanisms of formation; and (iii) to identify new bio-inspired synthetic strategies and to apply this knowledge to the fabrication of novel, superior materials and devices.

We are interested in discovering natural optical systems, whose hierarchical architecture and hybrid character offer outstanding optical properties and enable multi-faceted roles for these units. Biology provides a multitude of varied, new paradigms for the development of adaptive optical networks. Recently, we have shown that biologically formed optical systems are often unique in their ability to perform multiple functions – optical and structural. For example, the study of light-sensitive ophiuroids showed that the skeletal dorsal arm plates of some species not only afford protection,[8,9] but also form highly efficient microlens arrays.[10] Other research has concentrated on the exceptional fiber-optical properties of siliceous spicules of certain hexactinellid sponges, whose primary function is structural (either skeletal or anchoring).[11–13]

This feature article describes the composition, design and optics of the natural ophiuroid microlenses, summarizes their advantageous materials properties, and shows our first, bio-inspired synthetic efforts in the fabrication of new optical structures.

2. Structural and optical characterization of biologically formed microlenses

Echinodermata, the group of animals including sea stars and sea urchins, show various levels of photosensitivity. An especially interesting example is presented by brittlestars (Ophiuroidea) in the genus *Ophiocoma*, which exhibit strong light responses. It has been generally believed that many echinoderms have an extraocular sensitivity to light that is supported by unspecialized, 'diffuse', dermal receptors.[14–16] The absence of specialized 'eyes' is not, however, readily reconciled with such reactions as the color-change and negative phototactic behavior observed in certain species. The variations in color and escape mechanisms are most striking in a brittlestar *Ophiocoma wendtii* (Fig. 1).[17,18] The individuals are a dark brown color during the day, and are strikingly banded with gray and black during the night. It has been documented

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Fig. 1 The same individual of the brittlestar *O. wendtii*, photographed during the day (top) and during the night (bottom).

that *O. wendtii* is able to escape from predatory fish by hiding in coral crevices, and that it may be able to sense shelter at a distance.[18,19] Recently, we suggested that these strong responses to light might be related to the presence of a characteristic lensar extension of the brittlestar skeleton, which may constitute an advanced photoreception system.[10,17,18]

Echinoderms use calcium carbonate for their skeleton construction. Each skeletal element (ossicle) is a single crystal of calcite.[8,9,20,21] Unlike biogenic calcite of other phyla or abiologically formed calcite crystals, echinoderm skeletons are composed of a unique, intricately shaped, three-dimensional, single-crystalline meshwork with smooth and curved surfaces lacking crystal faces (so-called, stereom) (Fig. 2). In the living animal, the calcite meshwork is filled with soft tissue (so-called, stroma), and the ossicles are attached to one another by connective tissue and muscle. Every joint of a brittlestar arm is composed of five major ossicles, including two lateral arm plates that support several spines and tentacle scales, one dorsal and one ventral arm plate. These surround the arm and enclose a large internal skeletal ossicle (vertebra) that is adapted for articulation. The analysis of the ultrastructure of these skeletal units showed that while the stereom in the vertebrae, spines, tentacle scales, and ventral arm plates generally share a typical design (Fig. 2), the dorsal arm plates (DAPs) and portions of the lateral arm plates in certain species of *Ophiocoma* exhibit an unusual extension of the stereom – a thick, transparent, layer (*ca.* 40 μm thick) that covers the external surface of the plate.[10,17] It is composed of a close-set array of hemispherical calcitic structures (reaching 40–50 μm in diameter) with a characteristic double-lens design (Fig. 3).[10] The lenses are uniform in shape and appear as the scaled replicas of each other. The ratio between the lens thickness (t) and the lens diameter (L) estimated for a statistically significant set of microlenses was:

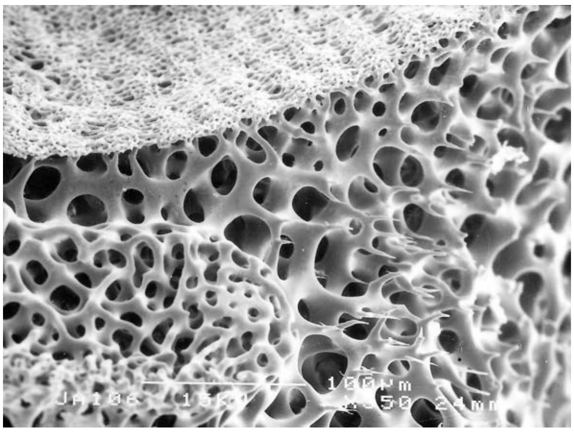

Fig. 2 Scanning electron micrograph (SEM) of a typical stereom structure in echinoderm skeletons. The entire elaborate mesh is a single calcite crystal.

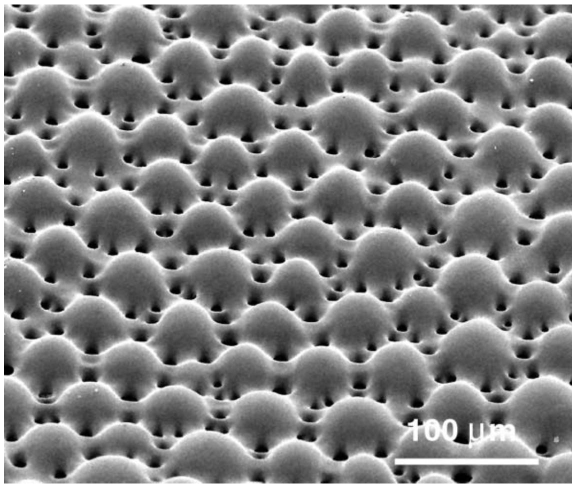

Fig. 3 SEM of an array of microlenses on the surface of the dorsal arm plate in *O. wendtii*.

$$t/L = 0.9 \pm 0.05$$

The degree of development of the lensar layer seems to correlate with the photosensitivity among several ophiocomid brittlestars that were studied. The layer is particularly pronounced in a highly photosensitive species, *Ophiocoma wendtii*, and it is absent in the light-indifferent species, *Ophiocoma pumila*.[10,17]

The optical properties of the microlens array were tested using photolithography.[10] In these experiments, a film of a photosensitive material (positive photoresist) was illuminated through the isolated lensar layer (Fig. 4). The illumination dose (I) was fixed slightly below the sensitivity level of the photoresist (I_0). As a result, the developed photoresist film was only affected precisely where the illumination dose increased due to the focusing activity of the lenses. The photoresist was placed at different distances h from the array. The photoresist films appeared to be selectively exposed under each microlens. Thus, the lensing effect was confirmed and mapped, and its quantitative characteristics (such as the position of the focal plane, d; the coefficient of the intensity enhancement by the microlenses, E; the angular selectivity, ϕ; the size of the focused beam at the focal plane, a_0; *etc.*) were experimentally determined from the values of h, L and the sizes of the spots in the photoresist, a, using basic equations of the geometric optics for a thick lens.[22]

Our analysis showed that the average position of the focal plane is located at the distance d = 4–7 μm below the microlenses. The size of the spot in the focal plane a_0 is approximately 3 μm. The intensity of the incoming light is enhanced at the focal point by a factor of $E \approx 50$. The angular selectivity ϕ is about 10°. These results presented the first experimental evidence that the microlens arrays are effective optical elements capable of significantly enhancing and guiding the light inside the tissue.[10] Calcitic microlenses of analogous structure were also reported in trilobite eyes.[23–25]

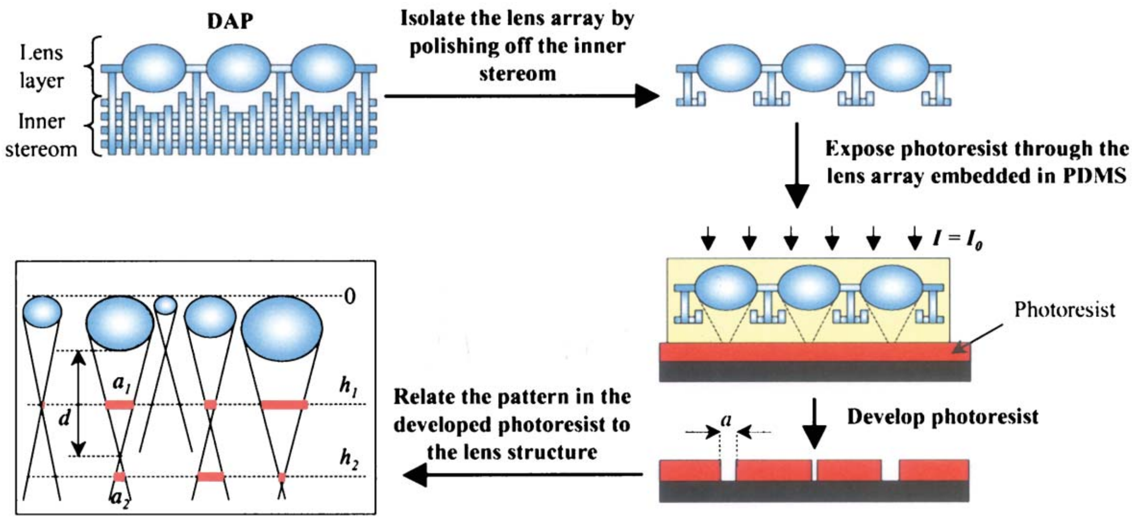

Fig. 4 Schematic presentation of the lithographic experiment, in which the focusing capabilities of the lens array were studied.

3. Advantages of the natural microlens design

The optical characteristics of the external DAP layer obtained in the imaging experiments showed that brittlestar microlenses are in many aspects superior to their man-made analogs. This bio-optical system presents a spectacular example of Nature's ability to evolve sophisticated solutions even to complex technological problems.

We have identified a number of unique, advantageous properties and design strategies found in the brittlestar microlenses, which could be emulated in synthetic microlens arrays:

(a) high fill factor lens array with characteristic micron-scale porous structure;

(b) individually-addressed crystalline lenses;

(c) wide-range transmission adjustment using pigment rearrangement;

(d) characteristic lens geometry that minimizes spherical aberration;

(e) fracture toughness due to the formation of an inorganic–organic composite;

(f) crystallographic orientation along the optical axis of the lens crystal to eliminate birefringence;

(g) angular selectivity;

(h) cross-talk suppression by pigment distribution in pores;

(i) potential wavelength selectivity due to the pigment involvement;

(j) potential refractive index modification by gradient of specialized intracrystalline biomolecules.

The importance of these properties in the improvement of the optical performance of microlenses is detailed below.

3.1 Signal reception

It has been shown that the remarkable focusing properties of the bio-microlenses are used by the brittlestars in their natural habitat for survival purposes.[18] In a series of transmission electron microscopy (TEM) studies, Hendler and Byrne have identified neural bundles under the lenses, and suggested these to act as primary photoreceptors in the light signal detection.[17] This hypothesis was further confirmed in our lithographic experiments.[10] The nerve bundles are positioned in the pores of the stereom at a distance of about 5 μm from the lens, which corresponds well to the location of the experimentally identified focal point *d*. Moreover, the diameter of the nerve fibers correlates with the size a_0 of the focused beam in the focal plane.

Therefore, the arrays of lenses appear to form a sophisticated optical device, in which each component (a single microlens) is individually-addressed by the detector positioned at the focal point of the lens. Owing to the observed angular selectivity of these lenses and their different orientation, such a device could act as a compound eye[26] that provides a wide field of view due to the non-planar arrangement of the lenses, which can be tuned on demand when the arm moves. The ways in which the signals detected by each receptor are processed and integrated remains unknown, and are worthy of further investigation.

3.2 Transmission tunability

One of the most noticeable reactions to light in certain species of ophiocomid brittlestars is diurnal color change (Fig. 1).[18] The change from a dark color during the day to a light color at night cannot be explained by camouflage, as has been shown experimentally.[18] Hendler and Byrne have shown that the channels in the stereom contain chromatophore cells filled with pigment granules.[17] They proved that the diurnal color change is caused by the migration of these cells. The light microscopic sections of DAPs prepared from night and day samples showed that during the day, pigment-filled processes of the chromatophore beneath the epidermis cover the lenses. During the night the chromatophores withdraw into the stereom channels surrounding the lenses, deeper within the DAP. As a result, the intensity of the light reaching the receptors is regulated by chromatophores depending on the illumination conditions; a function performed by an iris in a human eye. A similar process is utilized in so-called 'transition' sunglasses. The behavior of *O. wendtii* suggests that the transmitted light signal is tuned to match the sensitivity level of the neural bundle and to optimize the reception.[18]

The intensity-adjustment function of the chromatophore cells as well as the involvement of the sub-lens nerve bundles in photoreception (as opposed to a 'diffuse' dermal reception) were corroborated by neurophysiological[27–29] data. Cobb and Hendler studied the reaction of *O. wendtii* to light stimuli by direct recording from the nerve cord in brittlestar arms.[27] Nervous response of light-adapted, dark brown pigmented brittlestars has been monitored after the chemical disruption (by bleaching) of successive layers of the tissue (Fig. 5). The removal of the epidermal layer only (bleaching for less than 10 s) did not result in any change in the response compared to untreated, control specimens (Fig. 5a). Thus, 'diffuse' photoreception by epithelial cells was ruled out. The removal of the pigment layer (bleaching for *ca.* 30 s) caused an approximately ten-fold increase in the response to light 'ON', confirming the involvement of pigment in photoreception and its 'sunglasses' function (Fig. 5b). The disruption of the sub-lens layer

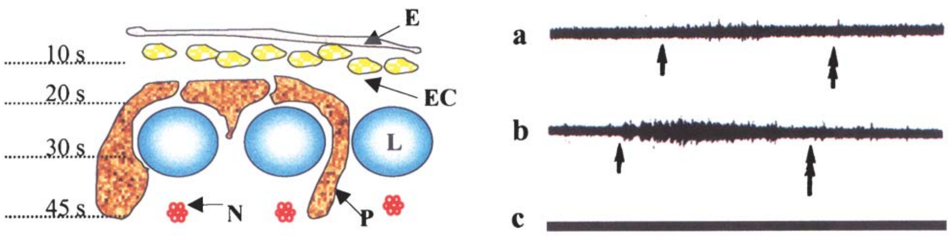

Fig. 5 Left: schematic presentation of the structure of the epidermis and dermis in the DAP. Lenses (L), pigment (P), cuticle of the epidermis (E), epithelial cells (EC) and nerve bundles (N) are indicated. Right: recordings of the nervous response. Single arrows represent ''Light 'ON'''. Double arrows represent ''Light 'OFF'''. a) Response to light in a control, untreated specimen or specimen treated for <10 s. b) Response to light when the arm was bleached for 30 s. c) Response to light when the arm was bleached for >45 s. Adapted from ref. 27.

(bleaching for >45 s) resulted in no photic responses, consistent with the suggestion that the sub-lens neural bundles are the primary photoreceptors (Fig. 5c).

In technical terms, the brittlestar microlenses is a tunable optical device that exhibits a wide-range transmission tunability achieved by controlled transport of radiation-absorbing intracellular particles. Other functions of the chromatocyte pigment may include the diaphragm action, and therefore, numerical aperture tunability; wavelength selectivity; minimization of the 'cross-talk' between the lenses, and therefore, the improved angular selectivity.

3.3 Aberrations

In an ideal lens, all rays of light would converge to the same point in the focal plane, forming a clear image. The influences that cause different rays to focus to different points in real optical systems are called aberrations.[22] For a most common lens type, *i.e.* for lenses made with spherical surfaces, rays that are parallel to the optical axis but at different distances from the lens center do not converge to the same point. Rays that strike the outer edges of the lens are focused closer to the lens than rays that strike the inner portions of the lens (Fig. 6). This effect, called spherical aberration, results in a considerable image blurring and presents a serious technological problem in lens fabrication.

For a thick calcitic lens that has the size of the brittlestar microlenses and is formed by two spherical surfaces, the expected value of the light enhancement factor at the distance d from the lens would be $E_0 = 3$–4. The experimental value of E determined in the lithographic experiments was 15 times higher than the latter.[10] Therefore, the brittlestar microlenses must be significantly compensated for spherical aberration. Indeed, a close examination of the design of the brittlestar microlenses showed that they have a very peculiar shape. Only the top surface is spherical. The bottom surface has a characteristic aspherical form. The calculated shape of the ideal calcitic lens that is totally compensated for spherical aberration appeared to completely coincide with the shape of the bio-lens (Fig. 7).[10] Moreover, the presence of pigment-filled chromatophores in the pores around the lenses would presumably block the light striking the outer portion of the lens, thus improving the operational size of the lens (L_0).

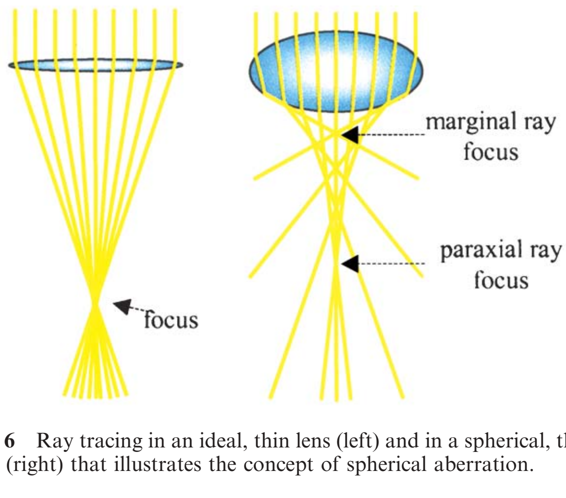

Fig. 6 Ray tracing in an ideal, thin lens (left) and in a spherical, thick lens (right) that illustrates the concept of spherical aberration.

Technological ways to minimize spherical aberration include: (i) the use of lens doublets instead of the single lens; (ii) bending one lens of the doublet into its best, aspherical (usually parabolic) form; (iii) the use of screens that disable the most problematic, exterior portions of the lens; and (iv) the use of high-index materials. Brittlestars seem to employ all of the above four approaches in their lens design. As a result, a remarkable level of compensation for spherical aberration is achieved and significantly enhanced light converges into one point where the photoreceptor is positioned.

3.4 Birefringence

Birefringence is the division of light into two components, which is found in materials that have two different indices of refraction in different crystallographic directions.[22] It is observed in crystals that have a crystallographic axis of higher symmetry, so-called uniaxial crystals. The direction of the axis of higher symmetry is optically unique, in that the propagation of light in this direction is independent of its polarization. This direction is called the optical axis of the material. Light propagating in any other direction will split into two beams that travel at different speeds.

Calcite is the classical example of a doubly refracting

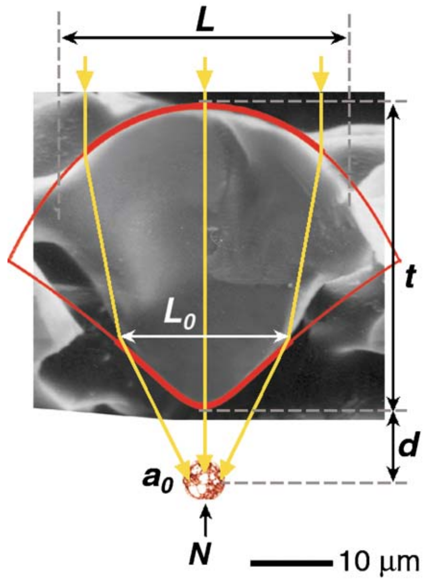

Fig. 7 SEM of a cross-section of the brittlestar lens, showing its doublet structure delineated by one spherical and one aspherical surface. The nerve bundle (N) is shown under the lens. The bio-lens is superimposed with the calculated profile of an ideal lens that is compensated for spherical aberration (red contour). The match is striking.

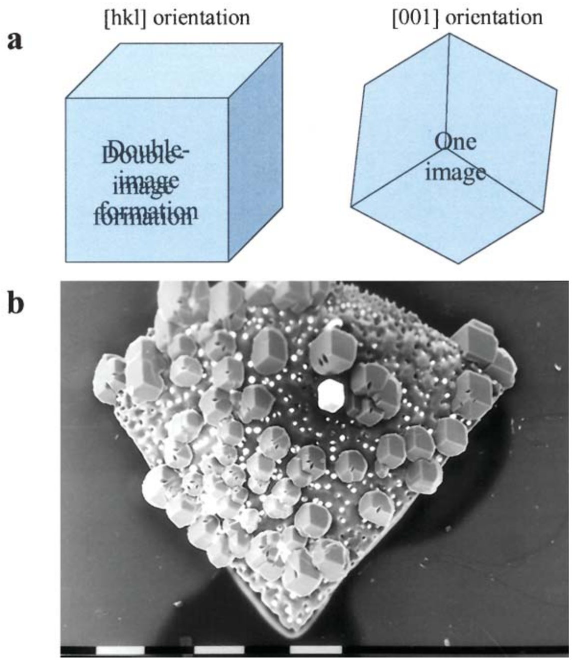

Fig. 8 a) Schematic illustration of birefringence in calcite crystals. A double image is formed when the crystal is oriented in the general {*h k l*} crystallographic direction. One image is formed when the crystal is oriented in the [001] direction, *i.e.* along the optical axis. b) SEM of the DAP decorated with synthetic calcite crystals that grew epitaxially on the surface. The experiment visualizes the crystallographic orientation of the biogenic substrate. The overgrown calcite crystals and therefore the lenses are oriented in the optical axis direction.

material. Its birefringence is extremely large, with indices of refraction of 1.66 and 1.48 along the optical axis and in the perpendicular direction, respectively. The use of calcite in the construction of optical lenses is, therefore, disadvantageous as it will result in the formation of two images unless the crystal is precisely oriented in the direction of the optical axis (Fig. 8a). Amazingly, in the brittlestar dorsal arm plate it is indeed the case: the optical axis of the constituent calcite is oriented parallel to the lens axis and perpendicular to the plate surface (Fig. 8b). Since only the light striking the array perpendicular to the plate surface is effectively detected (rays striking the surface at an angle are stopped by pigment), the negative effect of birefringence is corrected and the receptor receives one clear signal.

3.5 Mechanical properties

Calcite is typically used in echinoderms for structural purposes.[6,8,9] This material is, however, highly brittle: cracks propagate easily along the {104} cleavage planes (Fig. 9, left). Organisms have evolved several sophisticated means to reinforce this intrinsically brittle material for skeleton construction. To that end, living organisms commonly employ organic–inorganic composite structures.[8,9] Addadi and Weiner and co-workers suggested that specialized, intracrystalline macromolecules found inside biogenic calcite crystals of different origin are involved in the control of their mechanical properties.[6,8,30,31] These macromolecules are often adsorbed onto selective crystallographic planes in the crystal. It has been shown that in echinoderm calcite, the intracrystalline macromolecules interact specifically with crystallographic planes approximately parallel to the optical axis.[6,8,30–32] Positioned oblique to the cleavage planes (the optical axis forms an angle of about 45° with the cleavage planes), these macromolecules provide an effective crack-stopping mechanism by absorbing and deflecting the advancing cracks (Fig. 9, right). Such a reverse fiber-reinforced composite exhibits reduced brittleness, increased plasticity, and fracture toughness.[6,31]

As a result, the ossicles and associated microlenses formed by brittlestars are mechanically strong. It is also conceivable that intracrystalline macromolecules are involved in the regulation of the refractive index of calcite, thus further reducing the aberrations in the lens.

In summary, photosensitive brittlestars are impressively armed for light sensing. They form an array of nearly perfect optical lenses that are micron scale, lightweight, mechanically strong, aberration-free, birefringence-free, and individually-addressed; they show a unique focusing effect, signal enhancement, intensity adjustment, angular selectivity, and photochromic activity. Together with neural receptors and intraskeletal chromatophores, these microlenses form an effective optical device that may function as a compound eye. Given appropriate neural integration, each DAP would have an effective visual field of *ca.* 10°, surveying a different part of the object space.[26] Since *O. wendtii* has a large number of differently oriented DAPs, it could potentially extract a considerable amount of visual information about its environment.

4. Bio-inspired engineering

For the purpose of advancing the state-of-the-art optical technology and striving towards the construction of a new generation of open space devices with a variable field of view, tunable transmission, wavelength selectivity, *etc.*, the brittlestar microlens arrays represent an inspirational example. We believe that the above biological principles, if understood correctly and creatively applied in technology, could well

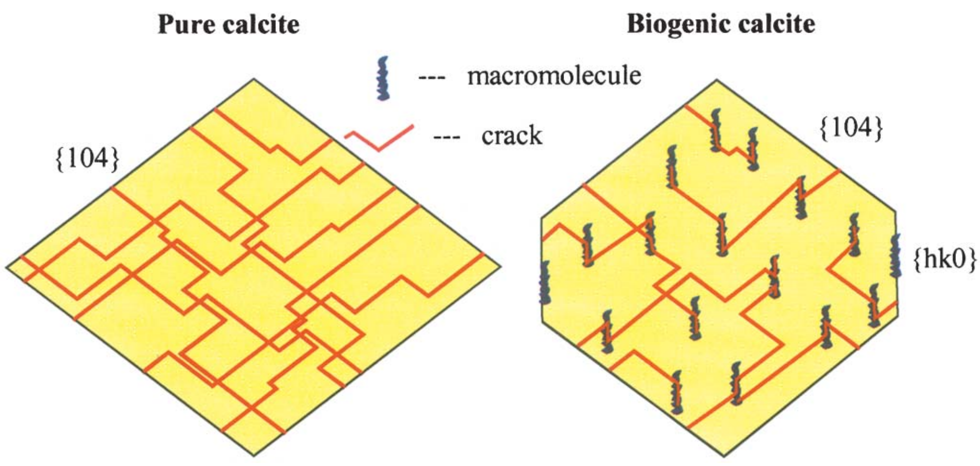

Fig. 9 Schematic presentation of the crack-arresting function of specific intracrystalline macromolecules in biogenic calcites. See text for details.

revolutionize our ability to make tunable, lightweight, porous microlens arrays for a wide variety of applications.

The following fabrication strategies were inspired by the principles involved in the formation of echinoderm calcitic structures.

An interesting feature of the brittlestar microlens arrays is the presence of pores surrounding the lenses. We discussed in Section 3.2 that these pores are important functional elements of the biological optical device, since they are used for the transport of pigment that regulates the illumination dose reaching the lens. Microporous single crystals are widely used in technology as components of various electronic, optical and sensory devices. Their fabrication is, however, a complex, multi-step process that could be potentially improved by learning from Nature and introducing biological crystal growth techniques. In our approach to the fabrication of micropatterned single crystals, we applied the following biomineralization principles: (i) the use of controlled amorphous-to-crystalline transition initiated at a well-defined nucleation site and (ii) the use of an ornate reaction volume that determines the shape of the deposited structure.[6–8,33–35] This new bio-inspired crystal engineering strategy made it possible, for the first time, to directly fabricate millimeter-size perforated single crystals with a predetermined sub-10-micron pores and controlled crystallographic orientation.[36]

We have also developed a novel, simple approach that uses multi-beam interference lithography to create porous hexagonal microlens (1–8 μm in diameter) arrays from photoresist materials.[37] In our experiments, we used a continuous wave diode-pumped solid-state laser to photopolymerize a negative-tone resist. The physical basis for the process is detailed below. When the interference light is transferred into a negative-tone photoresist during exposure, a periodic pattern of strongly and weakly exposed regions is generated. The highly exposed regions are then polymerized and the unexposed regions are dissolved away to reveal the holes. When the difference between the adjacent strongly and weakly exposed regions is close to a certain threshold value, the gradual change in the intensity between the regions produces the lens-like topography in the photoresist film combined with holes.

The appearance of thus synthesized microlens arrays (Fig. 10) is strikingly similar to their biological prototype shown in Fig. 3. The lens size, shape, symmetry and connectivity are controlled by beam wave vectors and their polarizations, while the pore size is adjusted by laser intensity, exposure time and the concentration of a photosynthesizer in the resist. These synthetic microlenses are capable of focusing light. The incorporation of holes in the lens array provides means for the transport of photoradiation-absorbing liquids and, therefore, for transmission and numerical aperture tunability and wavelength selectivity. These exciting preliminary results show that synthetic microlens arrays, inspired by the design of their nearly perfect biological prototypes, could be potentially used as highly tunable optical elements for a wide variety of applications.

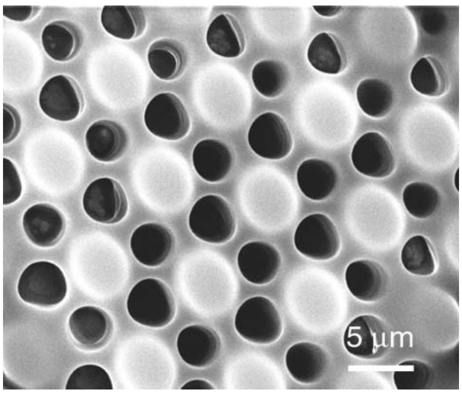

Fig. 10 SEM of a synthetic biomimetic microlens array with integrated channelled pores fabricated by multi-beam lithography.

5. Conclusion

Multidisciplinary groups involving materials scientists, chemists, physicists, biologists work together trying to understand the mechanisms controlling the formation of elaborate structures of biological minerals. We believe that further studies of biological systems will increase our understanding of how organisms evolved their sophisticated optical structures for survival and adaptation and will provide additional materials concepts and design solutions. Ultimately, these biological principles will improve our current capabilities to fabricate optical elements and contribute to the construction of novel, adaptive, micro-scale optical devices.

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