Multifunctional reflectors in the carapace of scarab beetles

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ABSTRACT

The carapace of insects can generate optical information with vivid structural colors, which may be of paramount importance in the life and the evolution of most day-living animals. A cholesteric liquid crystal organization of chitin fibrils is recurrently at the origin of optical properties. We summarize some recent results on the carapace of scarab beetles with possible functions related to optical information and thermoregulation. In the case of *Chrysina gloriosa*, green bands include wavelength-selective micromirrors and silver stripes play the role of flat metallic reflector operating over the visible spectrum and into the NIR-IR spectrum. Bio-inspired materials might address broadband reflectors for energy savings, stealthiness, cryptography or wavelength-specific light modulators in routing technologies.

Keywords: cholesteric liquid crystals, insect cuticle, structural color, bio-inspiration.

1. INTRODUCTION

The left-handed helix of the cholesteric liquid crystal structure (CLC) is a recurring design in animal and plant kingdoms, as reviewed in 2017 [1]. It may be observed under *in vivo* and *in vitro* conditions, and in fluid, soft or solid materials. The CLC geometry concerns major biopolymers and macromolecules like DNA, collagen, cellulose and chitin. In the world of arthropods (insects, crustaceans, arachnids and myriapods—approximately 80% of the animal species), the CLC structure is present in the exocuticule and the endocuticle, which consist of a hard mineralized fibrous chitin–protein tissue. The twisted CLC structure lends peculiar mechanical [2] and optical properties to the cuticle. Insects use their colors for sexual communication, for camouflage or, inversely, for warning predators [3]. Both narrow and broadband cholesteric reflectors are present [4]. Many insects own a tessellated carapace with iridescent bumps, pits, indentations, pixels, stripes or spots [5]. Little is known on the physical properties of these geometric variations and biological functions are unknown or still debated. The purpose of the present communication is to give a digest of optical properties with a few examples recently found in literature. Peculiar attention is given to the scarab beetle *Chrysina gloriosa* whose cuticle cumulates selective and broadband light reflections, tessellated and non-tessellated parts.

2. INSECT CUTICLES AS ADVANCED OPTICAL MATERIALS

The cholesteric structures in insect cuticles display unique optical signatures with selective light reflection property, vivid hues and strong angle-dependency of reflected colours or polarization-dependent patterns. In nature, the 'tour de force' of cholesteric structures consists in producing a broad set of dramatic lighting effects from biological materials whose refractive indices vary in a narrow range. This behavior is attributed to the helicoidal geometry and not the composition. Beetles from the genus *Chrysina* show very vivid light reflections in a variety of colours, from bright green to metallic silver–gold, including broadband reflections [6] (Fig.1).

For narrow-band reflectors, a diffuse reflection may arise from the irregularities in the cuticle (bumps, pits, etc.) resulting in the matte or dull appearance of the cuticle. In the absence of color changeability with the viewing angle, this optical feature could help green beetles to be hidden in green foliage. For other insects, the angle dependence of the color can slow or hinder the recognition process by predators or make the signal ineffective if predators approach from the

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directions relative to the cuticle surface where there is no apparent reflectance [7]. A high visual contrast may also confuse the predator leading to the escape of the prey [8].

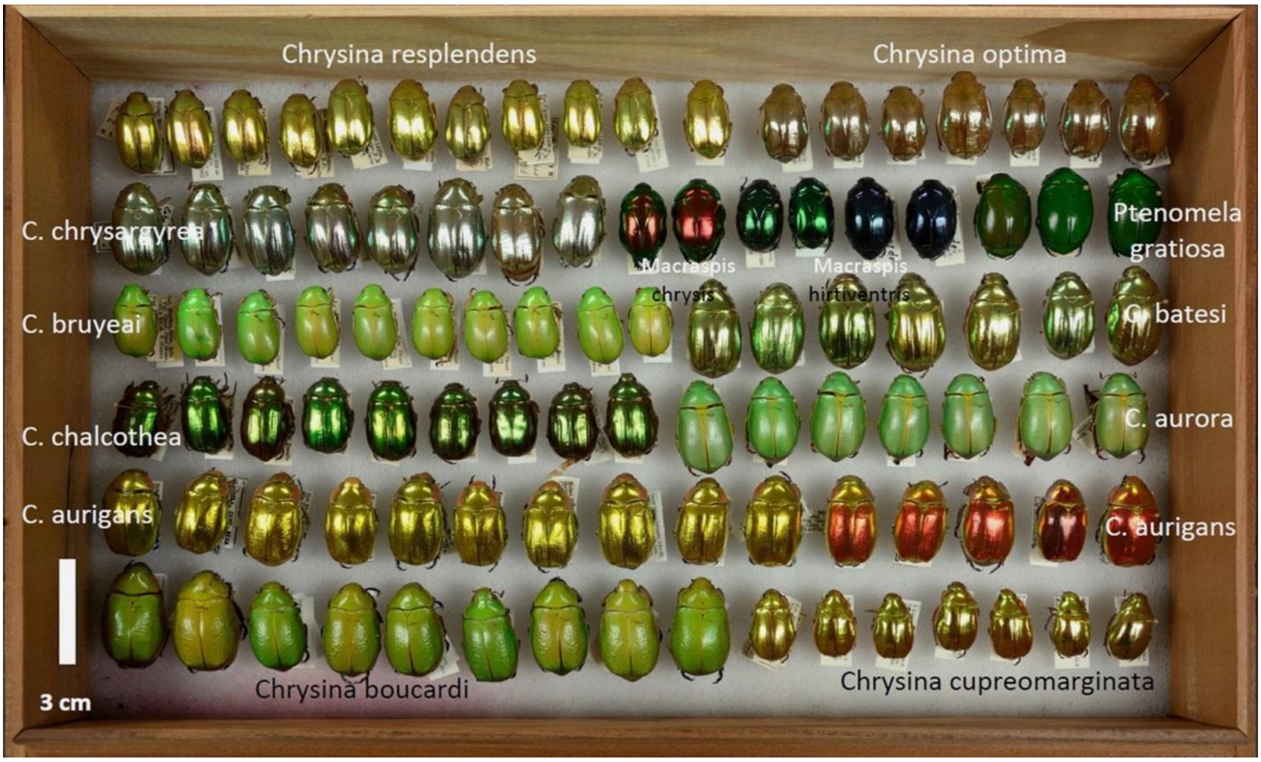

Figure 1. Specimens of *Chrysina* beetles (plus other scarabs) with selective or metallic (broad band) reflections. [9] INBio's collection (INBio: Instituto Nacional de Biodiversidad, Costa Rica. http://www.inbio.ac.cr). © 2015 Elsevier Ltd.

As an example of broadband reflector, the cuticle of *C. chrysargyrea* reflects left-handed polarized light from 340 to 1000 nm [10]. Pitch gradient and effective refractive indices (Fig. 2) are determined through non-linear regression analysis of the experimental Mueller matrix by using a cuticle model based on twisted biaxial dielectric slices.

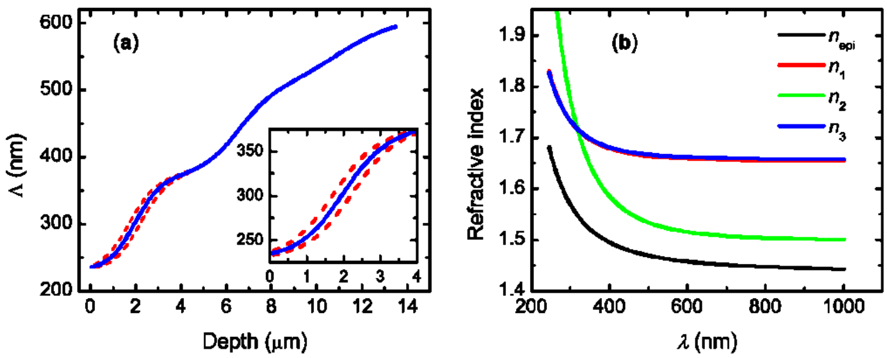

Figure 2. (a) Pitch profile across the exocuticle of *C. chrysargyrea* determined from the regression analysis of Mueller-matrix data. (b) Refractive indices of epicuticle (n_{epi}) and principal components (n_1, n_2, n_3) of the anisotropic slices modelling the exocuticle. The insert in (a) shows the pitch variation near the cuticle surface accounting for depolarization at wavelength shorter than 550 nm. [10]. © The Authors 2018.

For camouflage strategies, the organisms that reflect light similarly to a specular broadband mirror would match their background from any angle of observation (the color of the broadband reflectors is less directionally dependent when a full range of wavelengths is reflected). In addition, the surrounding environment would be reflected from the mirrored surface so that the animal cannot be seen [11]. Camouflage may also be achieved in an environment with diffuse light to prevent a strong, direct reflection from the sun [12]. The bright glare from metallic carapaces might temporarily blind a potential predator, enabling the beetle to escape [13]. Since the carapace mirrors the color of its environment, the beetle might hide among the leaves when they are brown during the dry season.

C. resplendens is remarkable in that it preserves right-handed circularly polarized (RHCP) light upon reflection [14,15]. Two left-handed (LH) cholesteric layers were identified, separated by a unidirectional layer for which the rotation of chitin microfibrils is suppressed (Fig. 3). This nematic-like layer forms a birefringent retarder and acts as a half-wave plate within the Bragg band. RHCP reflection was explained by a switch to LHCP on transmission through the nematic layer, followed by reflection by the second cholesteric layer and a switch back to RHCP on the return pass through the retarder. Reflectance limit is consequently exceeded and the cuticle reflects inside the Bragg band more than 50% of an unpolarized incident beam. In this virtual three-layer material, no strong structural discontinuity is visible from layer to layer. Both cholesteric layers exhibit a pitch gradient, giving rise to broadband reflection and golden color.

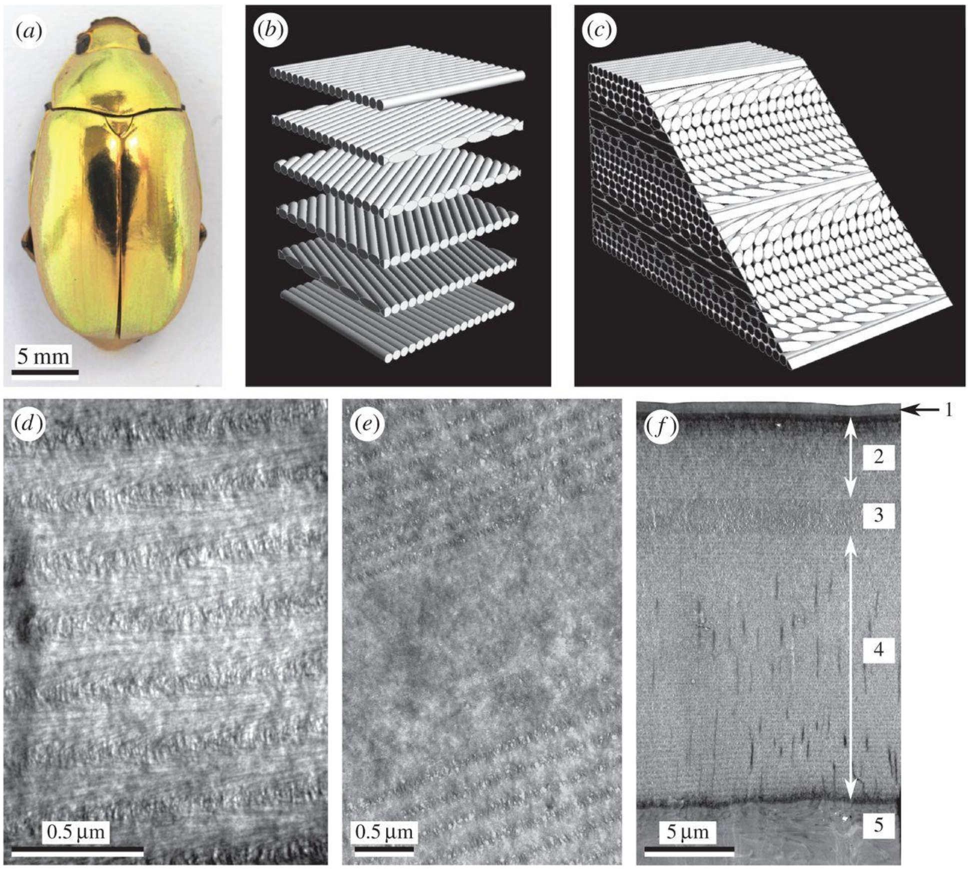

Figure 3. (a) *C. resplendens* photographed under unpolarized illumination. (b) An exploded view of a helicoidal set of fibrils 'planes'. (c) A view of a section of helicoidal stack. The oblique cut reveals Bouligand arc patterns in the arrangement of fibrils. A full helicoidal pitch is shown. (d) TEM image showing details of an oblique section of the elytron. (e) TEM image showing details of a section perpendicular to the cuticle surface. The unidirectional layer or birefringent retarder is shown as the uniform band extending across the center of the image. Cholesteric regions are disposed above and below. (f) TEM of a perpendicular section through the outer part of the cuticle, indicating its component regions: 1: epicuticle; 2: upper cholesteric region; 3: unidirectional (nematic) layer; 4: lower cholesteric region; 5: endocuticle (portion). Regions 2 to 4 form the exocuticule [15]. © The Authors 2017.

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The presence in the endocuticle (lowest part of the chitineous cuticle) of a cholesteric grating with a graded pitch related to the IR spectrum might avoid overheating. Dorsal coloration is associated with thermoregulation in diurnal beetles. Niche differentiation associated with thermoregulation is well documented in tiger beetles ([16] and references therein).

Despite the long history of interest in warning coloration, many questions remain unanswered regarding the tactical design features of warning signals that contribute to their effectiveness.

3. SMART LIGHT MODULATORS IN THE CUTICLE OF *CHRYSINA GLORIOSA*

The cuticle of *C. gloriosa* exhibits green and silver stripes arranged on a curve surface (Fig. 4). The green stripe is a mosaic of contiguous polygonal cells. Each polygonal cell contains a bright yellow core with orange edges surrounded by a dark-green region, with a brighter green rim delimiting the cells.

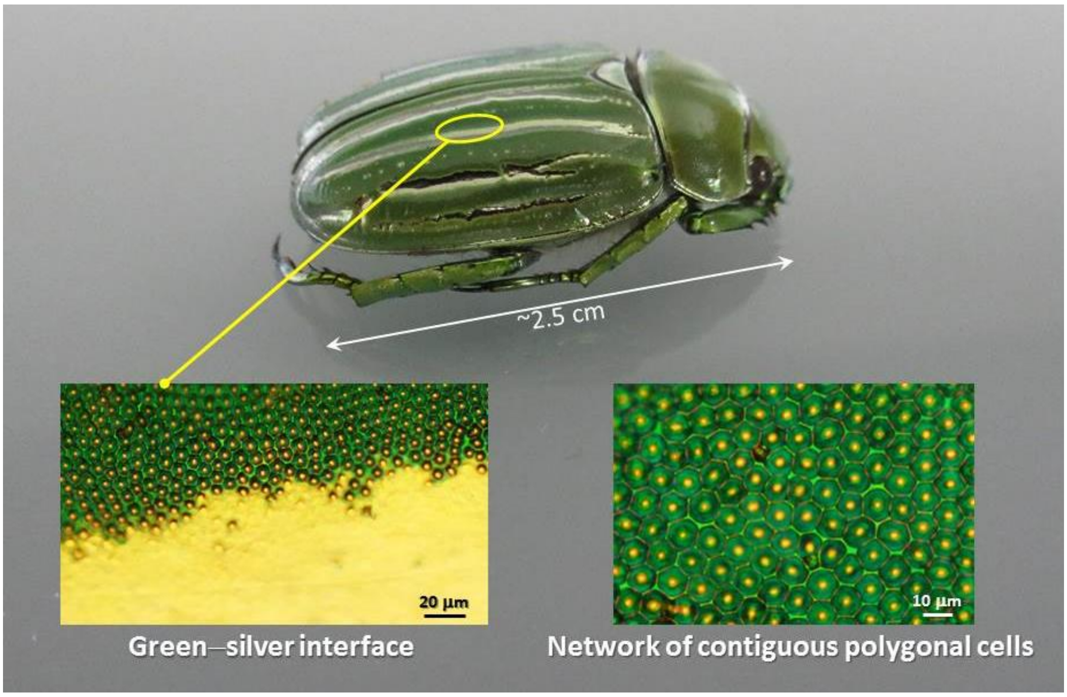

Figure 4. *C. gloriosa*: from macroscopic view to micrographs of green and silver bands (reflection mode, unpolarized light).

Polygonal patterns exhibit concentric rings when observed by TEM [17] or fluorescence confocal microscopy [18]. Mueller-matrix spectroscopic ellipsometry provides a description of reflection properties including polarization changes and changes in degree of polarization [19]. By combining confocal microscopy and spectrophotometry, electron microscopy and numerical simulations, the relationship between the reflectance over the visible and near infrared (NIR) spectra and the structural parameters for both stripes at the micro- and nanoscales is established [20]. The orientation of the helicoidal structure varies in the green stripe (Fig. 5) whereas it is fixed in a silver stripe.

Remarkable optical phenomena are displayed [20]:

- the green stripe serves as a wavelength selective (green) diffuser due to the set of polygons arranged on a curved surface;
- at the mesoscopic scale, the green stripe is an array of wavelength-selective micromirrors;
- the silver stripe plays the role of a flat metallic reflector operating over the visible spectrum and into the NIR spectrum.

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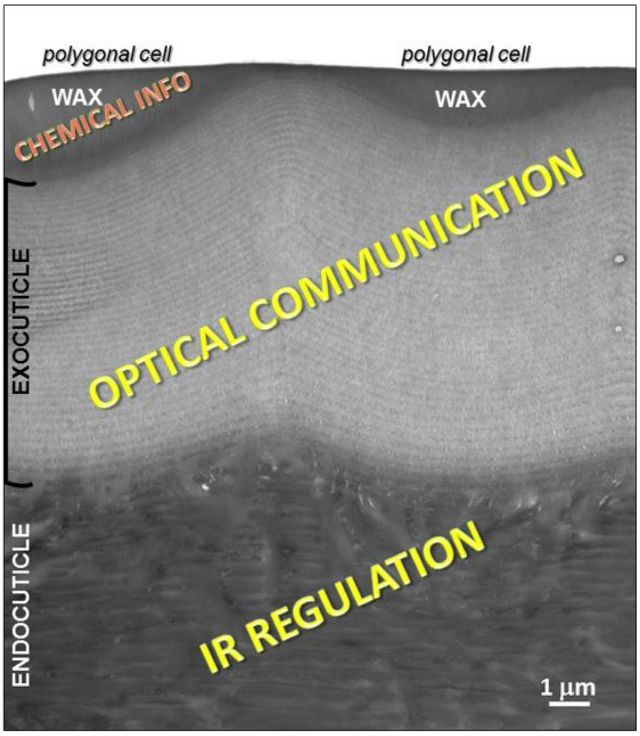

Figure 5. Transverse view of the cuticle of *C. gloriosa* in a green band as seen by TEM. A typical fingerprint texture is displayed in the chitin network of the cuticle. The distance between two lines of equal contrast is related to the pitch of the twisted structure. Helicoidal axis is perpendicular to the lines. Concave nested arcs are visible below each polygonal cell. Fingerprint texture in the endocuticle appears as less regular (stripes are interrupted) and grainy. The same phenomenon may be observed in the *Homarus americanus* exoskeleton [21]. Hypothetical functions are reported: chemical information (wax layer), optical communication in the visible and NIR spectra (exocuticule), IR thermoregulation (endocuticle).

Bragg gratings of both green and silver bands occur in comparable scales [20]. Strikingly, it thus appears that macroscopic green color is the consequence of a periodic network of microcells with a spatially-variable orientation of the helicoidal axis (Fig. 6).

The endocuticular part of both stripes is characterized by a broad reflection in the NIR-IR spectrum due to a graded-pitch cholesteric structure with no tessellated texture.

The cuticle of *C. gloriosa* may be approached as a network of *smart* modulators in the sense that:

- Optical response is adapted to the wavelength of the incident light:
  - ✓ In the green bands, patterned reflection occurs in the visible spectrum with high selectivity, spatially and spectrally; reflected light is focused into spots, donuts and intermediary patterns in strong dependence with the wavelength of the incident light;
  - ✓ non-patterned and non-selective reflection occurs in a broad range of IR spectrum in both green and silver bands.

- Such an adaptive response is reached without adaptive structure. In return, the solution advantageously consists in cumulating several properties inside a single layer without structural discontinuity (Fig. 5). For example, in a green band, thermoregulation is added to optical communication (color, polarization, plus changeability of these parameters with viewing angle) towards conspecifics or predators. Circular polarization sensitivity [22] might allow *C. gloriosa* to communicate with conspecifics while remaining cryptic to predators with eye geometries not capable of CP light detection. The research on the role of polarization in light reflection by insect cuticles is still in its nascent phases. Chemical information may be added to thermoregulation and optical information by taking into account the wax layer (the outermost part of insect cuticles is very often covered with wax). The

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diversity of hydrocarbons in wax composition indicates a significant role in chemical communication where relatively non-volatile signals are required [23]. Hydrocarbons serve as sex pheromones, species and sex recognition cues or nestmate recognition [24].

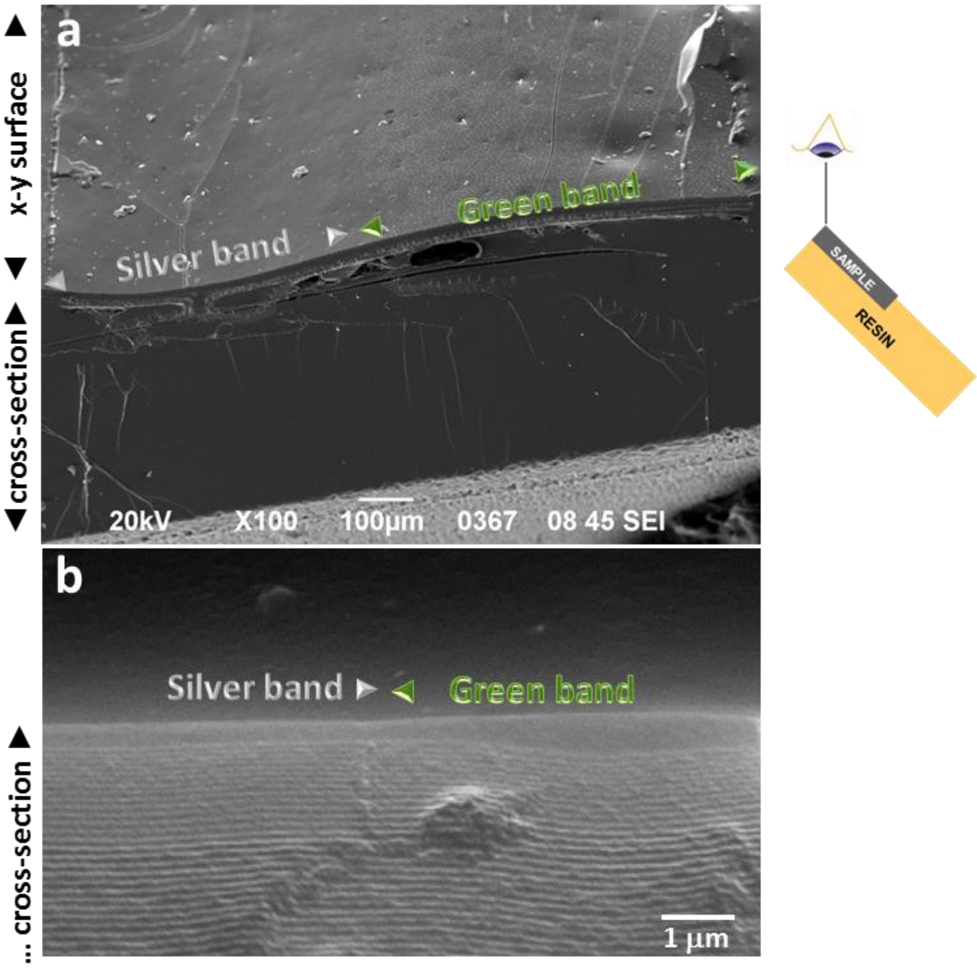

Figure 6. Cross-sectional views of the cuticle of *C. gloriosa* at the interface between silver and green bands by SEM (Scanning Electron Microscopy). (a) View including the surface of the cuticle and the transverse section. (b) Magnified view of the transverse section at the interface with the exterior.

Polygonal texture as found in the cuticle of *C. gloriosa* is not similar to polygonal textures as displayed in synthetic CLCs [25-27]: the patterns are not structurally and optically analogous to the focal conic domains formed spontaneously on the free surface of a synthetic cholesteric film [28]. The cuticle has concave cells whereas the artificial films have convex cells. Minimum intensity is located at the center of synthetic polygons for all ranges in the synthetic film, whereas a bright central spot is allotted to the polygon center in *C. gloriosa* cuticle. Reflection behaviors are thus antagonistic. Concave micromirrors would be targeted under the strategy of fabrication of bio-inspired optical components.

Microtextured cuticles of scarabs may inspire researchers and engineers to make their replicas as optical materials. Potential applications could be in the field of optical routers [20], coatings for cryptography purposes (wavelength-dependent and polarization-dependent micro- or nanoscale patterns), stealthiness (suits with a broad reflection in the IR spectrum identical to the one of the background) or thermoregulation (for buildings).

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