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Nature engineered metasurfaces: spin-to-orbital angular momentum conversion in diatom frustules

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Abstract. Evolution provided, through eras, several animal, vegetal, and protist species with sub-micrometric constituent structures able to manipulate light at the nanoscale in non trivial ways. In particular, diatoms are single-celled microalgae enclosed in a porous silica shell, the frustule, perforated by regular patterns of micro- and nano-pores and whose functionalities comprise mechanical stability, sorting of nutrients from harmful agents and optimization of sunlight harvesting. Photonic properties of frustules include focusing, photoluminescence, and optical activity, among others. In the present work we show preliminary results concerning the ability of single valves of *Arachnoidiscus ehrenbergii* diatom frustules to manipulate incoming, circularly polarized radiation in such a way to generate light beams provided with orbital angular momentum (optical vortices). The combination of cross-polarization imaging in different spectral ranges, polarization sensitive digital holographic imaging (PSDHI), and interferometry allowed characterizing the valves and detecting the presence of spin-orbit coupling induced by their ultrastructure.

1 Introduction

Several technological fields such as optical trapping, super-resolution imaging, multiplexed optical communication, and quantum computing can take great advantage by the use of optical vortices (OVs), i.e. light beams provided with a helical phase $\exp(-il\phi)$ and carrying an orbital angular momentum (OAM) equal to $l\hbar$ per photon, with l any integer [1]. OVs can be obtained exploiting phase discontinuities (e.g. by means of spiral phase plates [2], fork holograms [3] or spatial light modulators [4]), inducing spin-to-orbital angular momentum conversion by inhomogeneous birefringent elements (q-plates) [5] or by complex metallic or dielectric metasurfaces [6], or even by photonic crystal slabs supporting bound states in the continuum [7]. Surprisingly, we observed spin-orbit coupling induced by a nanostructured biomaterial. Several organisms and biological systems indeed (viruses, insects, bird plumage, flora, plants) are provided with structures at the micro- and nano-scale able to manipulate light in complex, non trivial ways. Some of the photonic nanostructures found in nature can cause coherent or incoherent scattering, others act as one-dimensional multilayer reflectors, polarization-selective reflectors, two-dimensional diffraction gratings, two- and three-dimensional photonic crystals or even hyperuniform photonic networks [8]. In particular, diatoms are ubiquitous microalgae enclosed in a porous hydrogenated silica shell, the frustule, characterized by regular patterns of pores whose dimensions range between some tens of nanometers up to about one micron, according to the species and the location within the frustule itself [9]. Several optical effects induced by the interaction of light with frustules have been observed, such as focusing, mode guiding, photoluminescence, and optical activity and applications in super-lensing, plasmonics, and optical sensing and biosensing have been successfully performed [10].

We studied the optical activity of single valves of *Arachnoidiscus ehrenbergii* diatom frustules, characterized by inner radiating *costae* connecting an inner flange to the mantle edge. Crossed-polarization imaging, polarization sensitive digital holography, and interferometry measurements revealed the ability of the valve to generate OVs due to spin-to-orbital angular momentum conversion of light at different wavelengths with different efficiencies.

2 Results and discussion

Single valves of *A. ehrenbergii* diatom frustules are characterized by a porous ultrastructure with pore dimensions ranging from some microns down to tens of nanometers, according to their position within the plate. The internal side of the valve hosts a system of ribs (*costae*) radiating from a flange around a central ring (see Fig.1a), giving rise to a birefringence characterized by an inhomogeneously oriented fast axis. Manipulation of polarization (optical activity) induced by the valve can be deduced from crossed-polarization imaging (see Fig.1b for incoherent, wide-spectrum incident radiation), where distinct intensity lobes associated to rotation of incident polarization and characteristic of a q-plate are clearly distinguishable. The lobes are visible also for coherent irradiation at single

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wavelengths (λ = 406, 532 and 633 nm), the effect resulting more efficient for green incoming radiation.

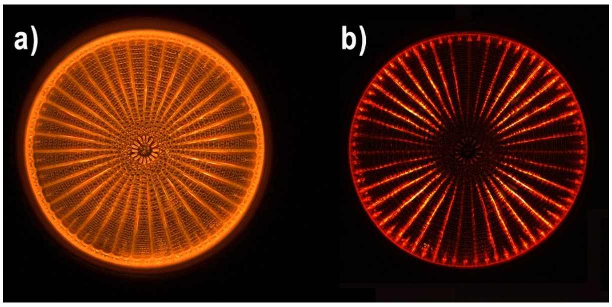

Figure 1. Dark field (**a**) and crossed-polarization dark field (**b**) images of a single valve of *A. ehrenbergii* diatom frustule. Diameter of the valve $\simeq$ 270 μm.

The state of polarization (SoP) of the valve when irradiated by a He-Ne laser beam has been fully characterized by a polarization sensitive digital holographic imaging (PSDHI) technique, which allows retrieving the degree of polarization of the outcoming wave in terms of the Stokes parameters [11]. The results confirm, for red irradiation, a partial depolarization of the incoming light induced by the valve ultrastructure, confirming the lower efficiency in optical activity in this spectral window.

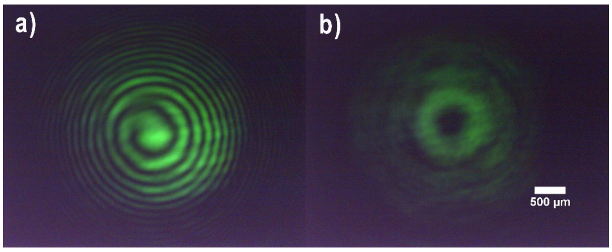

Figure 2. Interference pattern of the helical mode emerging from the diatom valve when illuminated by a LCP beam at λ = 532 nm, (**a**). Intensity distribution of the vortex obtained by blocking the reference beam (**b**).

In order to detect the presence of an OV generated by the interaction of light with the valve, the sample was first shined by a left-handed circularly polarized (LCP) laser beam at λ = 532 nm (where optical activity resulted more efficient), while the outcoming radiation (signal beam) was collected and superimposed to a reference beam after being properly filtered in order to allow the transmission of the sole light which undergoes spin-orbit coupling. The detected interference pattern shows a spiral shape which is associated to the presence of an OAM carried out by the signal beam (see Fig. 2a). Blocking the reference beam allows the detection of the intensity distribution of the vortex, with its peculiar doughnut-like shape (Fig. 2b).

3 Conclusions

Nanostructured, naturally occuring biomaterials can represent a low-cost, alternative way to obtain complex optical devices on a wide scale. We made recent observations on optical activity of single valves of *A. ehrenbergii*, which present an internal system of *costae* radiating from a central flange towards the mantle edge. As in the case of an artificially designed, inhomogenous birefringent waveplate with radial orientation of the fast axis, also *A. ehrenbergii* valves show the ability to induce spin-to-orbital angular momentum conversion of incoming, circularly polarized light with generation of an OV. The effect is more efficient around λ = 532 nm. While the biological significance of this phenomenon is far to be understood, being nevertheless probably related to light-plastid coupling, the ability of natural nanostructures to manipulate light in non trivial ways can stimulate the development of novel solutions for a new generation of bioinspired optical devices.

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