Pleurosigma strigosum **diatom frustule as a natural, multi-functional photonic platform.**

Edoardo De Tommasi[1,*], *Ilaria* Rea[1], *Maria Antonietta* Ferrara[1], *Luca* De Stefano[1], *Adil. Y.* Al-Handal[2], *Marija* Stamenković[2,3], and *Angela* Wulff[2]

[1]National Research Council, Institute of Applied Sciences and Intelligent Systems "Eduardo Caianiello", Unit of Naples, Via P. Castellino 111, 80131 Naples, Italy.

[2]Department of Biological and Environmental Sciences, University of Gothenburg, Box 463, 405 30 Gteborg, Sweden.

[3]University of Belgrade, Department of Ecology, Institute for Biological Research "Sinisa Stankovic", Bulevar despota Stefana 142, 11060 Belgrade, Serbia

Abstract. Nature provides various organisms with ordered or quasi-ordered dielectric nanostructures that enable several animals, plants, and protists to manipulate light, optimizing inter- and intra-species communication, camouflage, or solar light harvesting. In particular, diatom microalgae possess nanostructured silica cell walls, known as frustules, which efficiently interact with optical radiation through multiple diffractive, refractive, scattering, waveguiding, and frequency down-conversion mechanisms. These properties contribute to diatoms' efficiency in photosynthesis, UV tolerance, and possibly influence the phototaxis mechanisms of motile species. In our study, we utilized several imaging, spectroscopic, and numerical techniques to explore the optical functionalities of individual frustule components in the pennate, motile diatom *Pleurosigma strigosum*. We discuss the implications of frustule photonic properties on the living cell, and envision the exploitation of these properties in multifunctional, bio-derived photonic devices.

1 Introduction

Diatoms, unicellular microalgae responsible for about 20-25% of the global primary production, are characterized by a porous silica shell, the frustule, enclosing their protoplasm [1]. Frustules consist of two overlapped thecae, each formed by a valve and one or more lateral girdles. Valve and girdle surfaces are covered by an ordered pattern of micro- and nano-pores, which allow substance exchanges between the organism and its environment. It has been demonstrated that regular arrangements of micro- and nano-features in several vegetal and animal species can promote or inhibit light propagation in specific spectral ranges, which is advantageous from an ecological point of view (e.g., for intra-species communication, inter-species interaction, camouflage, or to enhance photosynthetic efficiency) [2]. Optical properties observed in several centric (radially symmetric) diatom species include photonic crystal-like behavior of girdles and valve, diffraction-induced optical lensing, manipulation of the polarization state of the incoming radiation, photoluminescence, and ultraviolet radiation (UVR) selective screening [3].

Recently, research on the optical properties of diatoms has expanded to include the evolutionarily younger pennate ones, characterized by bilaterally symmetric frustules and primarily benthic [4]. In particular, raphid (motile) pennate diatoms are able to change their orientation as a response to changing illumination conditions. In the case of raphid *Pleurosigma strigosum* diatom, optical properties of the valve already observed in other species (high efficiency in photosynthetic active radiation (PAR) collection; UVR attenuation and frequency-downconversion [5]) are combined with a specific, striking resemblance with a photonic crystal waveguide (see Fig. 1).

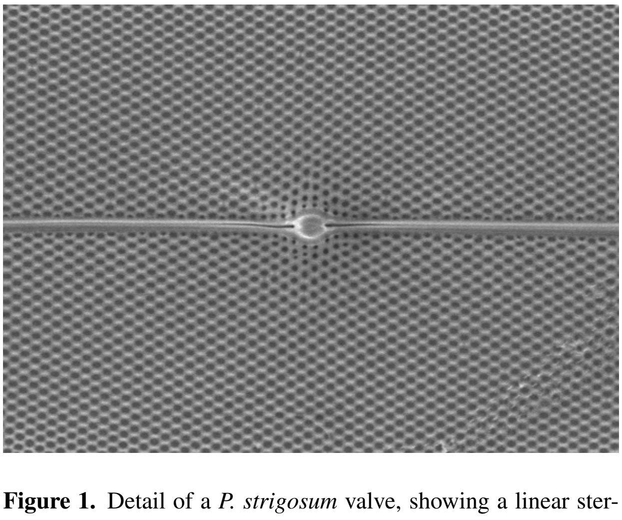

Figure 1. Detail of a *P. strigosum* valve, showing a linear sternum with narrow raphe openings which converge towards an oval, central nodule.

In this work, we summarize the photonic properties we identified so far in *P. strigosum* frustules and ana-

*e-mail: edoardo.detommasi@cnr.it

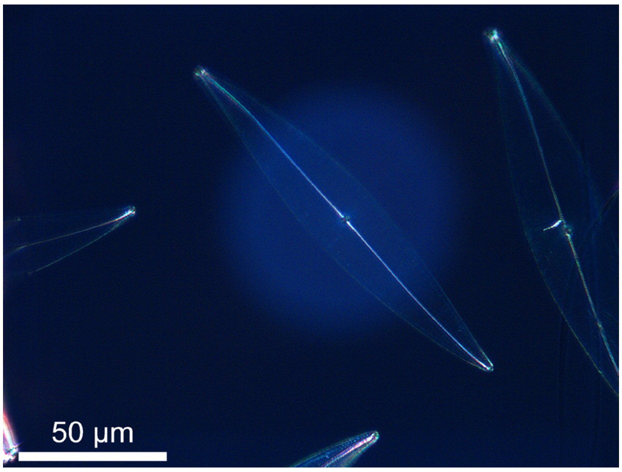

Figure 2. Cross-polarization micrograph of *P. strigosum* valves, showing de-polarized light confined along the sternum.

lyze their potential links to photosynthesis, photoprotection, and phototaxis processes of the living organism. Specifically, we present preliminary results from Finite Difference Time Domain (FDTD) numerical simulations and cross-polarization spectroscopic imaging, suggesting that radiation at specific wavelengths is trapped in the hexagonally-patterned valve of *P. strigosum*, while radiation in complementary spectral ranges is confined and guided along the sternum towards a central nodule.

2 Results and discussion

Bright-field, dark-field, fluorescence, holographic, and cross-polarization microscopies allowed a first identification of the optical properties associated to the different districts of the frustule: the periodic modulation of refractive index allows the valve to behave like a diffraction micro-grating, relocating optical radiation inside the cell with different spatial distributions according to wavelength and favoring PAR collection; flattened areas as the nodule or the valve apices act as micro-lenses, strongly localizing the optical field into intense hot-spots; detrimental UVR is mostly absorbed by frustule biosilica and partially frequency down-converted by photoluminescence processes into PAR; light is guided along the longitudinal sternum (see Fig. 2). In particular, the combined use of FDTD numerical simulations and of spectroscopic, cross-polarization imaging by using a broad-band, fiber-based supercontinuum coherent source allowed identifying in which specific spectral ranges the optical radiation is trapped into the valve or guided along the sternum. The evanescent fields associated with guided optical modes can penetrate only a few hundred nanometers inside the protoplasm and are scarcely related to photosynthesis or photoprotection, and may rather be connected to diatom motility, for example by triggering a signal cascade involved in phototaxis.

3 Conclusions

Nowadays, dielectric and metallic metasurfaces can simultaneously manipulate several optical parameters for diverse functions, but they require high-cost nanofabrication facilities for their production. Conversely, nature offers zero-cost, ordered dielectric nanostructures which various animals, plants and protists exploit for light manipulation. In particular, we showed how the various components of *P. strigosum* frustule are associated with a specific optical effect and possible biological functionality. Thus, a single diatom frustule represents a natural photonic platform unifying the functionalities of multiple optical components (gratings, lenses, waveguides, photonic crystal slabs, spectrally-selective attenuators). Understanding the photonic properties of frustules will enable the exploitation of diatom biosilica in applications where interaction with optical radiation is fundamental, such as solar energy harvesting [6], allowing for a more precise design of bio-derived devices and hybrid materials.

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