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Holographic and Nonlinear Optical Study of Natural Photonic Structures: Where Biology Meets Physics

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ABSTRACT

Nano-optics exploits linear and nonlinear phenomena at the nanoscale to advance our understanding of materials and their interaction with light in both classical and quantum domains. This not only deepens our fundamental knowledge but also drives new photonics-based technologies, from sensing to communication. Nonlinear optics further offers a way to explore and leverage the complexity of natural structures for technological advancement. The presented research investigates natural photonic structures through holographic and nonlinear optical studies, revealing the correlations among their geometries, optical, and dynamic responses. These findings will inspire novel designs for optical devices and systems.

Keywords: nonlinear analysis, nonlinear optics, holography, natural photonics, biophotonics, optics.

1. INTRODUCTION

It has been known for a long time that colours in nature are not designed for beauty but often, of the utmost importance, for communication [1-3]. Colours in nature emerge due to the presence of chemical entities, physical

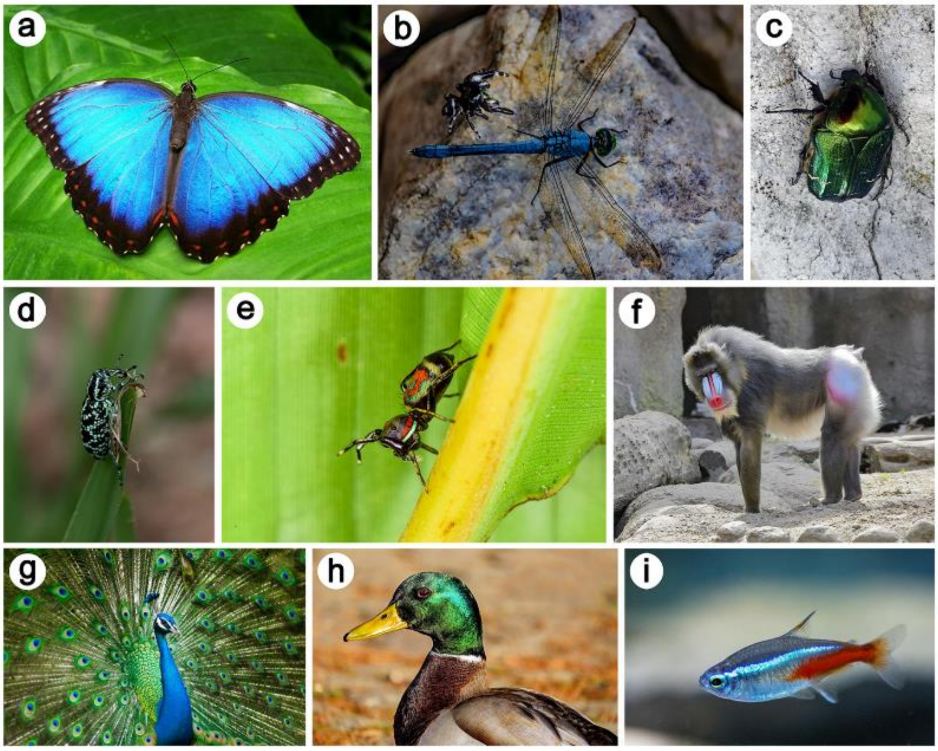

Figure 1. Many examples of structural colours are found in the integuments of natural organisms such as: (a) Morpho peleides, (b) dragonfly species, (c) the green rose chafer Cetonia aurata, (d) the Botany Bay diamond weevil Chrysolopus spectabilis, (e) some jumping spider species, (f) the mandrill Mandrillus sphinx, (g) the Indian peafowl Pavo cristatus, (h) the mallard Anas platyrhynchos, and (i) the neon tetra fish Paracheirodon innesi. Reproduced from https://pixabay.com/ accessed on 27 July 2022.

structures, or combination of both mechanisms. Structural colours, as a specific class of colouration, arise from the interaction of light with structured, periodically arranged materials, so called “photonic crystals”. Natural photonic structures occur most often in insects, birds, and reptiles. They stand out due to their complexity and distinct characteristics with respect to pigmentary colours (Fig. 1).

Besides the fundamental importance of revealing the link between natural photonic geometries and their optical response, the presented research is also vital for developing new applications in photonics and material science [2].

2. DISCUSSION

Using both holographic and nonlinear optical techniques, we unveiled correlations among the geometries, optical, and dynamic responses of natural photonic structures. Nonlinear optical methods provide a comprehensive understanding of the molecular properties of biomaterials due to their inherent sensitivity to symmetry [5]-[7]. Thanks to holography, we were able to observe detailed dynamic behaviour of nanostructures subjected to an external stimuli, such as heat generated by a laser light [4]. Alongside these techniques, we employed scanning electron microscopy (SEM) and transmission electron microscopy (TEM) to capture detailed images of *Trictenotoma childreni* (Fig. 2) as well as the nanostructures present in the wings of the *Nymphalidae* butterflies (Fig. 5A,5B).

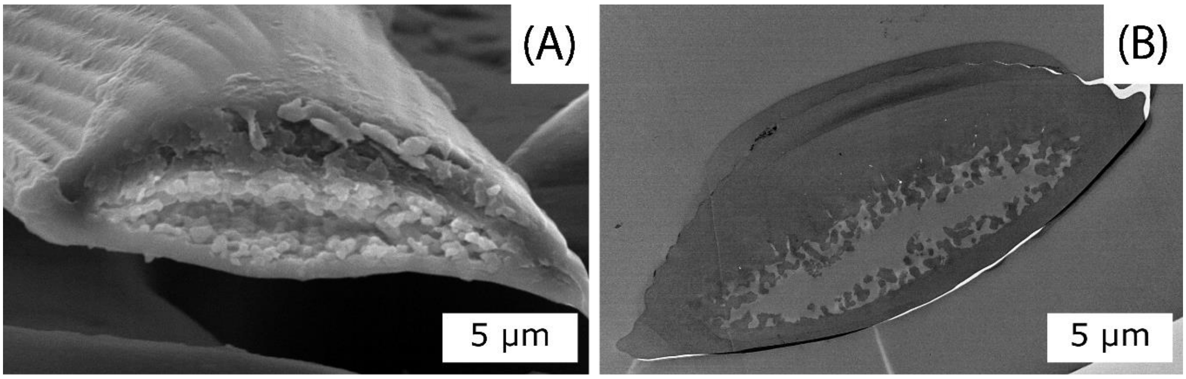

Figure 2. By using (a) SEM and (b) TEM images, we were able to observe a disordered structure present within the scales of T. childreni. Reproduced from Ref. [5] with permission from John Wiley and Sons.

Nonlinear optical analyses allowed us to elucidate the relationship between natural photonic structures and their optical response [3]-[8]. For instance, we were able to perform Second Harmonic Generation (SHG) images of the

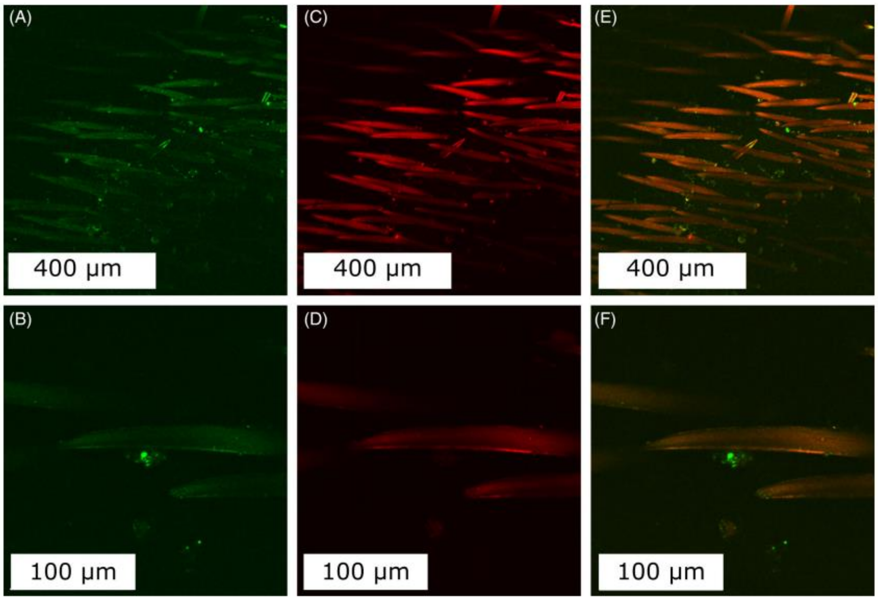

Figure 3. (a, b) SHG response, (c, d) 2PF response, and (e, f) superimposing of both signals (SHG + 2PF) from T. childreni's scales with a fundamental wavelength of 1000 nm. The six images clearly depict the scales. In (e) and (f), orange/yellow pixels represent the areas with both SHG and 2PF signals, while green and red pixels indicate the regions with only SHG and only 2PF signals, respectively. Reproduced from Ref. [5] with permission from John Wiley and Sons.

scales covering the elytra of *Trictenotoma childreni*, longhorn beetle, using a femtosecond laser with excitation wavelength of 1000 nm (Fig. 3).

The same excitation wavelength has also been used to measure the two-photon fluorescence (2PF) response (Fig. 4) [5]. All sharp spectral peaks in Fig. 4 correspond exactly to half of the excitation wavelengths, confirming that the signal originates from SHG. In cases where the excitation wavelengths were 900, 1000, and 1100 nm, a broader peak located around 550 nm is attributed to 2PF [5]. These results are consistent with the observations made in the multiphoton micrographs (Fig. 3), where a clear SHG signal was detected. Additionally, the 2PF spectra reveal that even at higher excitation wavelengths, such as 1200 nm and 1300 nm, a significant SHG signal persists.

However, our results show that the intensity of the SHG signal varies depending on the excitation wavelength (Fig. 3,4). Notably, the most intense SHG peak is observed at the wavelength that corresponds to the fluorescence emission maximum. This finding provides additional evidence to support the idea that the fluorophores are the origin of the SHG. The results suggest that the fluorophores are non-centrosymmetric or that their distribution within the scales is non-centrosymmetric and, therefore, non-random [5]. As it is widely recognised, second-order effects, such as SHG, are only possible in non-centrosymmetric media. This likely random distribution of the fluorophores might appear during the pupa stage of the beetle's scale development.

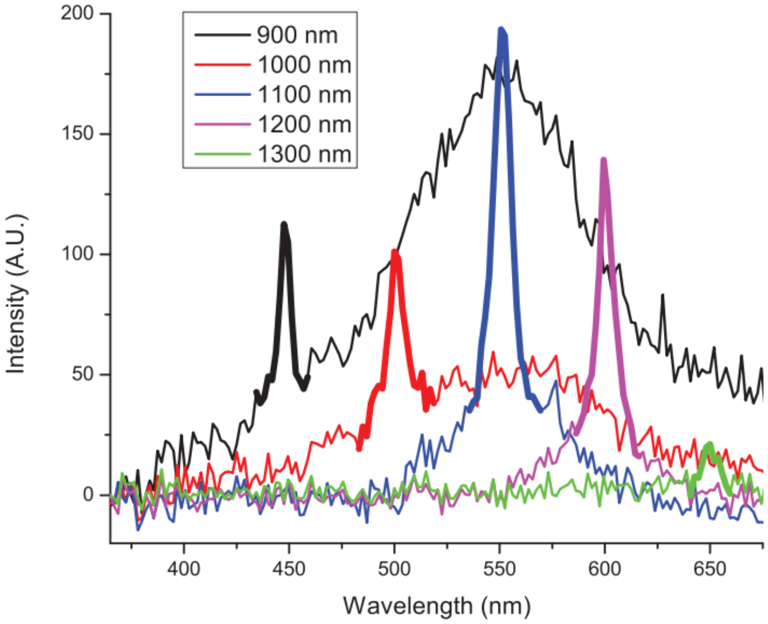

Figure 4. Multiphoton emission spectra of T. childreni's scales excited with wavelengths ranging from 900 to 1300 nm. A distinct SHG peak at half the respective wavelengths (indicated by thick lines) is observed with all excitation wavelengths. The broader peaks observed around 550 nm with all selected excitation wavelengths, except 1200 and 1300 nm, are attributed to 2PF. These results are consistent with the observations made using multiphoton microscopy (Fig. 3). Reproduced from Ref. [5] with permission from John Wiley and Sons.

Figure 5. SEM images of (a) Apatura ilia, and (b) Morpho didius butterflies; Example of (c) holographic image, and (d) holographic reconstruction for Apatura ilia sample.

Our holographic investigation reveals thermal management and dynamics of natural photonic structures in *Apatura ilia* (Fig. 5C,5D) and *Morpho didius.* Our findings demonstrated a notable correlation between thermal management and the photonic band gap.

3. CONCLUSION

Our study relying on holography and nonlinear optics techniques sheds light on the relationship between the optical response of natural photonic structures, their geometry, and dynamics. These insights help to enhance our understanding of the role of fluorescence in insects. The findings of this study are crucial for the development of future applications of natural photonic structures in optics and material science.

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