Replication of Photonic Responses from Natural 3D Structure by Design of Simulated Architected Metasurfaces

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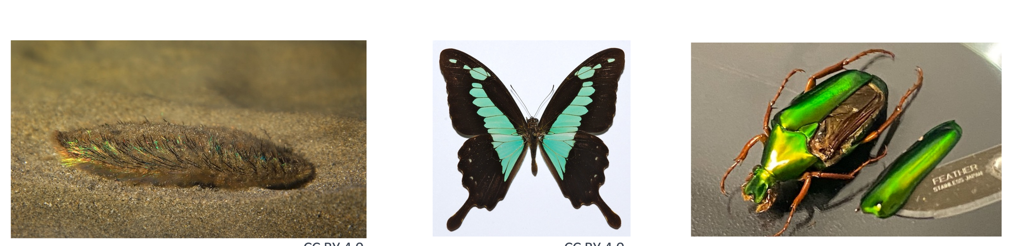
Abstract

Fibrous tissue is a crucial factor in diseases like Alzheimer's, heart disease, fibrosis, and cancer, but conventional optical microscopy is unable to precisely visualize its nanoscopic structural properties. An engineered solution could provide quantitative, label-free, and clinically compatible visualization of fibrous tissue for improved disease diagnosis. With an engineered Metasurface, all-optical and quantitative colorimetric mapping of tissue orientation angles can be achieved. In this project, **our primary objective is to comprehensively characterize the structures of three samples using a combination of SEM imaging and Optical Microscopy techniques.** Quantifying the color effects by analyzing optical spectra obtained under a microscope. **Subsequently, replicating the color response by architecting a similar structure of a selected sample through Multiphysics simulations**. By correlating the measured and simulated results, the aim was to demonstrate precise control over the outcomes. This alignment between natural phenomena and simulation could allow us to identify trends and causations. Advancement in Metasurface design has the potential to significantly enhance disease research, materials science, optical communication, sensing, display technologies, and even security / anti-counterfeiting.

Introduction

Organisms exhibit structural coloration due to evolutionary advantages such as increased visibility for attracting mates or deterring predators, camouflage for blending into the environment or mimicking other objects, UV protection, temperature regulation, and species recognition for successful reproduction. These colors are produced by micro- or nanostructures interacting with light waves, providing organisms with diverse and advantageous coloration strategies. Understanding their structural properties could provide significant advances for innovative applications in many areas.

Our project aims to characterize the structures of the Flower Chafer Beetle *Chalcothea smaradgdina*, the Green Swallowtail Butterfly, *Papilio blumei*, and the Sea Mouse, *Aphrodita aculeata*.



By carefully examining and understanding the surface morphology, topography, and composition, one can extract valuable information about their structural properties.

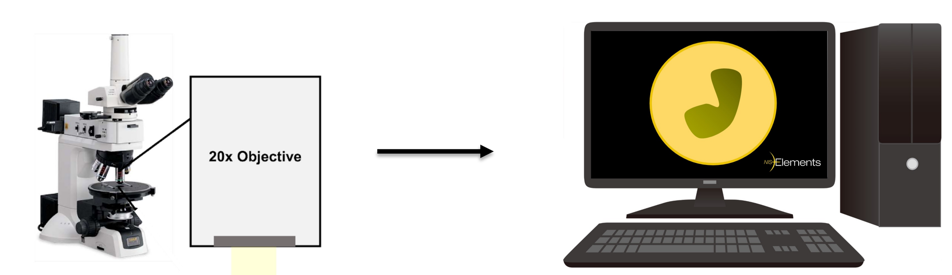
After characterizing the samples, structural color will be re-created through mimicking a selected samples geometry using COMSOL Multiphysics simulation. This software platform allows simulation of complex geometries and their interaction with light.

Ultimately, by understanding response to different lighting conditions and exploring their colorimetric properties, these simulations will provide insights into the relationship between the structural features and observed color effects.

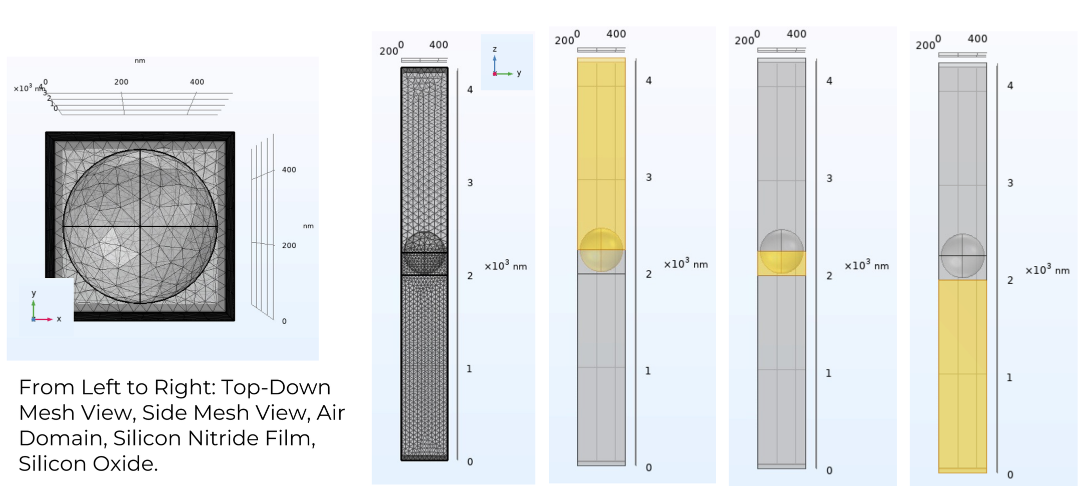
Methodology

<u>SEM Characterization</u> samples were prepared by cutting butterfly wing and beetle shell into 1x1 cm squares, attaching them to an SEM imaging disk with carbon adhesive tabs, and carbon-coating them. Sea mouse whiskers were extracted, cleaned, attached to the disk with a carbon adhesive tab, broken in half, and gold-coated for analysis. An FEI Quanta 600 SEM machine was used to perform the imaging.

<u>Optical Characterization</u> was performed on a Nikon Eclipse LV100ND Microscope and NIS Elements Software. Samples were viewed under a 20x objective using both a circular and linear light. Spectral Power Density Plots were obtained with an ISOplane 160 Spectrometer and Lightfield software.

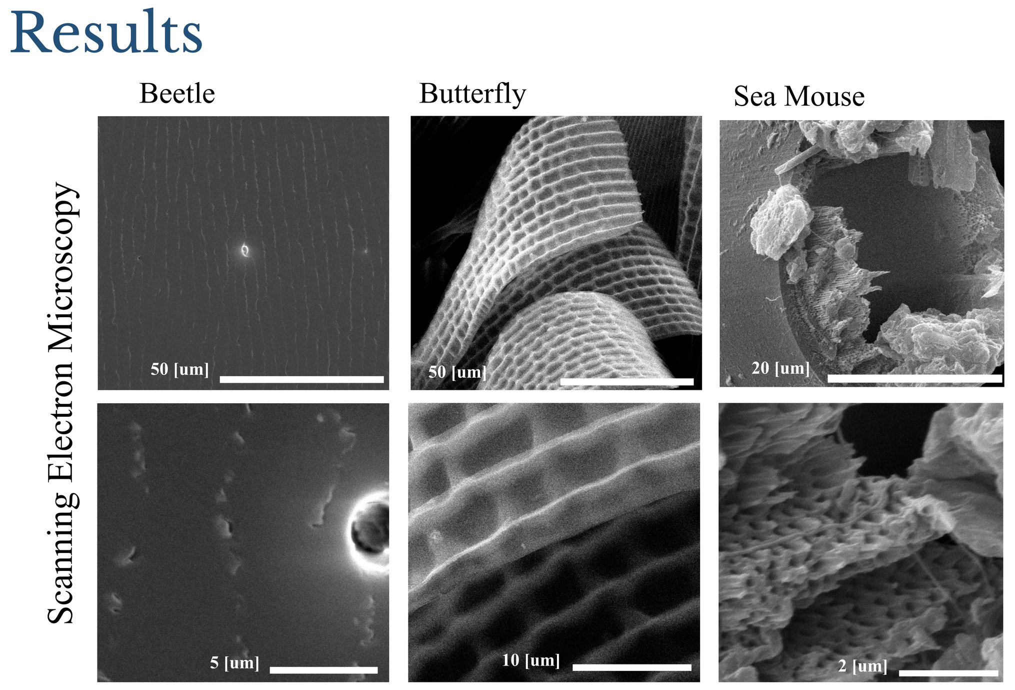


<u>COMSOL Multiphysics</u> provided a simulation environment appropriate for replicating structural color. With the wave optics module, wave propagation, diffraction, interference, and scattering phenomena can be accurately simulated. The simulated structure was a 10:1 scale factor reduction of the characterized structure. This was to retain feasible simulation times. To simulate real world fabrication, a glass substrate was placed underneath the sculpted silicon nitride (with n set as 1.55) thin film layer. An ellipsoid was defined as an air domain at appropriate height above the thin film to create the 3D architecture. Periodic condition definitions in the x and y plane created an infinite lattice to simulate a Metasurface interaction. Hexagonal lattice as observed in the wind structure (see results) used too much compute for the time frame.



From Left to Right: Top-Down Mesh View, Side Mesh View, Air Domain, Silicon Nitride Film, Silicon Oxide.

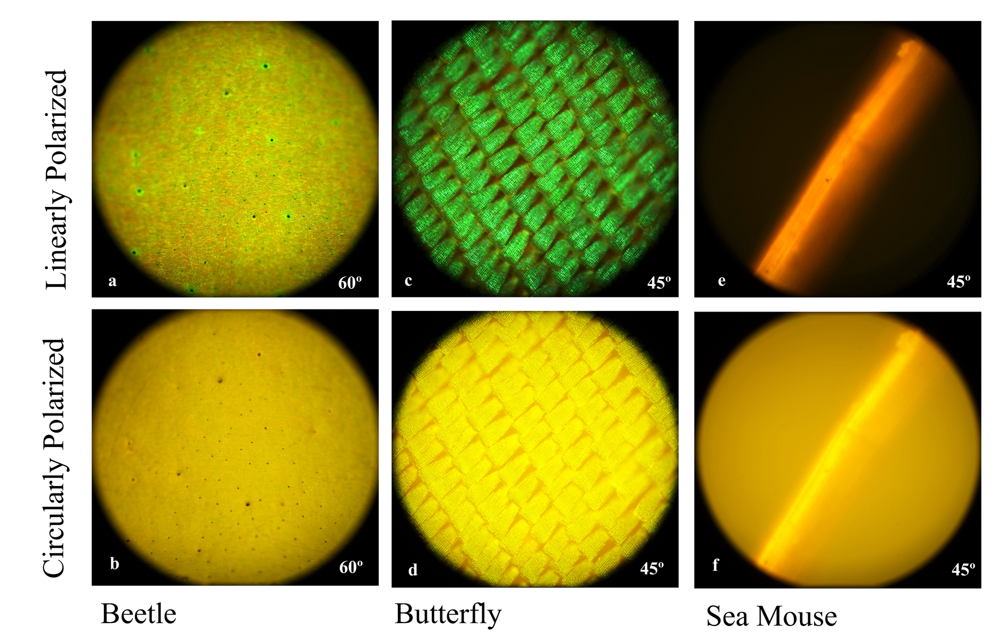
Results



Results Cont.

SEM yielded the clearest geometry for the butterfly wing, which was characterized as 5um diameter concave structures patterned hexagonally with a 2.5um depth. This geometry was chosen for replication.

Polarized Light Microscopy revealed maximum intensity peaks under both linear and circular reflectance illumination at 60° for the Chalcothea smaradgdina Beetle and 45° for the Papilio blumei Butterfly and Aphrodita aculeata Sea Mouse. Spectra was taken at these angles.

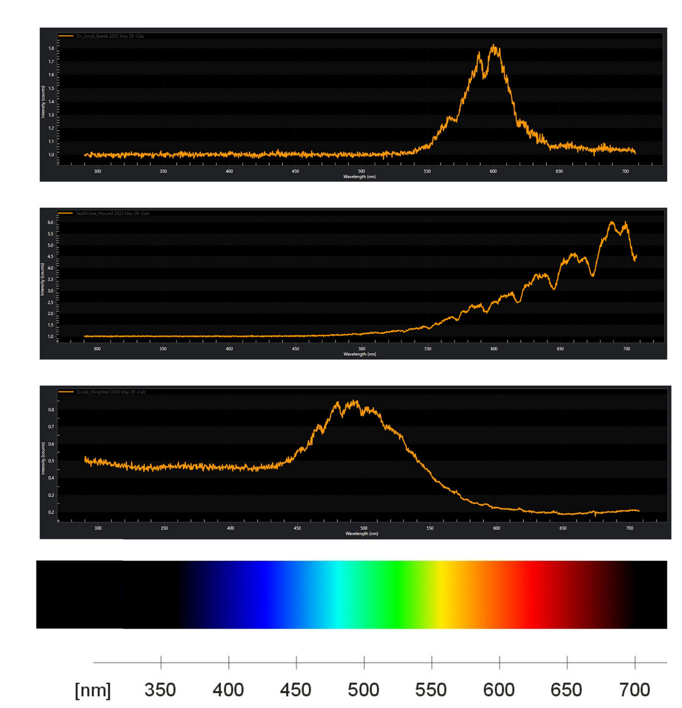


Spectra obtained at maximum intensities under linearly polarized light revealed clear peaks for the beetle shell and butterfly wing. The sea mouse signal was tough to discriminate and lamp interference is suspected.

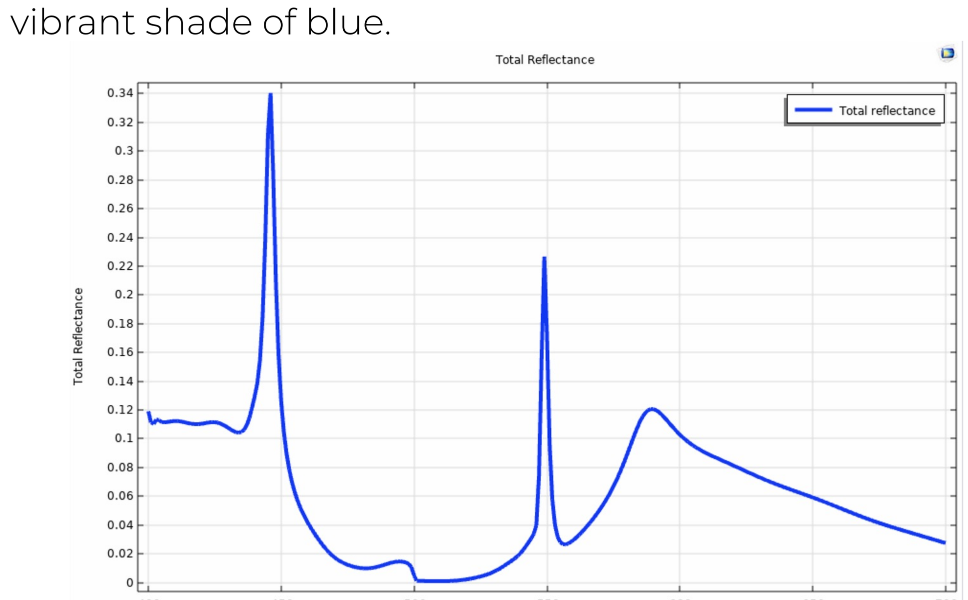
Beetle Shell: Strong double peak at 587 and 600 nm. Reflects the dark orange and yellow appearance.

Sea Mouse: Peaks between 550-700nm. Periodicity indicates possible halogen lamp interference.

Butterfly Wing: Strong peak at 500 nm. Expected as wing has Green appearance.



Simulated spectra demonstrated a peaks at 548 nm and 447 nm. A spectral peak at 548 nm corresponds to a distinct green color, while a peak at 447 nm represents a vibrant shade of blue.



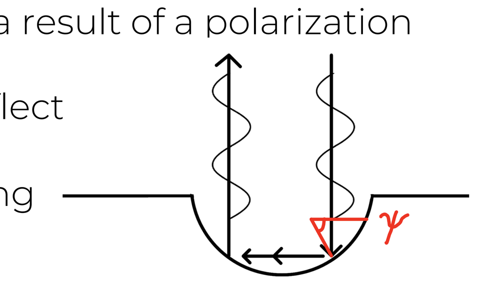
Conclusion

The SEM images of the sea mouse whiskers showed an arrangement of hexagonal when viewing the cross-sectional area. The outside of the whiskers appeared to be very smooth and without distinct features.

The beetle shell appeared to have a Lamellar structure as very little surface features were evident. Small ridges or ~1 um were accompanied by dispersed large concavities.

SEM images of the butterfly wing revealed two significant structures, one which appears to be supporting scaffolding for the iridescent scales on top. The interference pattern was interpreted as hexagonally arranged concavities.

The color effect is concluded to be a result of a polarization rotation due to a double reflection inside the concavity. The double reflect from the out-of-plane reflections at Each interface geometrically rotating the polarized light by an angle psi



Optical microscopy revealed an intense polarization effect for both sea mouse fibers and the butterfly wing. Large shifts in average intensities reflected light indicates obvious birefringent properties and makes these structures great candidate for potential real world applications. The clear spectral peaks of the simulation provide a high certainty that this modified structure also demonstrates similar birefringence to the wing sample.

These scales are made of layers of chitin, a protein-based material, arranged in a way that creates interference and diffraction of light. By reducing the scale factor to 1:10, the dimensions of the ridges and spacing between them are also scaled down. This alteration in scale could result in modified interference patterns, causing the separation of spectral peaks and the appearance of two distinct colors.

The impact of work like this has large potential to spark colorimetric mapping of diseases and many optical sensing applications, the original motivation of the project.

Future Study

Further characterization of each sample would provide more insight into exact geometry, Atomic Force Microscopy, Micrography, of SEM after cutting of samples could reveal more details.

If budget and time permitted, color responses could be correlated to changes in geometry in the simulation (depth, periodicity, diameter of concavities)

Scaling up the simulation could provide more insight into the development of the two observed peaks from this work, simulations could be run through the supercomputer.

2-Photon Lithography of Atomic Layer Deposition could be employed to replicate these structures and run experiments.

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