Investigating Naturally Occurring 3-Dimensional Photonic Crystals

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Submitted by Caroline Pouya to the University of Exeter as a thesis for the degree of Doctor of Philosophy in Physics
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Caroline Pouya
2012
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Abstract

This thesis describes my research into the highly tuned naturally occurring 3D photonic structures that are present on a selection of insects. The experimental and theoretical work presented in this thesis was performed in both the optical and microwave regimes.

The work performed in the optical regime included both the geometric and optical characterisation of the native photonic structures present on the beetle *Eupholus magnificus* and the butterfly *Parides sesostris*. The native photonic structures of these organisms were probed in order to determine their photonic responses and also to ascertain their geometries and structural classes. In cases where the geometry of a photonic crystal system has been determined, I have performed additional theoretical analysis of the structure to establish how it might be optimised for a particular optical function. The overall aim of the work performed in the optical regime is to further the understanding of the photonic structural designs present on a selection of beetles and butterflies, by both identifying and characterising their underlying structural geometries and consequent photonic responses.

*Eupholus magnificus* is a species of weevil that produces its coloured appearance from photonic structures that are present on its outer wing casing, producing a striped coloured pattern. The photonic structures that I discovered were present on this weevil were found to be contrasting in structural order. I used a wide-ranging variety of experimental and theoretical techniques in order to perform an extensive electromagnetic and structural characterisation of these contrasting structures. The two contrasting photonic mechanisms employed by *E. magnificus* were found to produce a similar optical response in terms of angle-independent colour whilst reflecting different coloured hues.

*Parides sesostris* is a species of butterfly that uses a gyroid photonic crystal structure, contained within scales, to produce green coloured patches on the dorsal side of its wings. In addition to this, *P. sesostris* uses embellishments to its scale morphology in order to produce a highly tuned
angle-independent optical response. The optical effects brought about by these structural embellishments were investigated with optical experimental techniques and they were found to diffusely scatter light and aid iridescence suppression. In addition to this, theoretical modelling was performed on a variety of gyroid geometries. The gyroid photonic structure found in the wing scales of *P. sesostris* was determined to be highly optimised to reflect the largest range of frequencies possible from this geometry, also aiding iridescence suppression. In addition to this, the arrangement of gyroid arrays within each scale was determined to produce the highest intensity possible by using the smallest possible number of unit cells.

In addition to the optical characterisations of the organic naturally occurring photonic structures found on these organisms, I also synthetically replicated the three fundamental naturally occurring triply periodic bicontinuous cubic photonic crystal structures for experimental and theoretical electromagnetic characterisation in the microwave regime. The microwave regime was selected to perform the characterisation as a high-resolution fabrication method can be employed in order to produce millimetre-scale structures, suitable for probing in this wavelength regime. A high resolution fabrication method is an absolute requirement for accurately replicating the complex geometries of constant mean curvature structures and retaining a high level of detail. I have electromagnetically characterised these three structures with the aim of gaining a better understanding of their polarisation-dependent photonic stop-band responses. Specifically, I have identified the origin of, and the dispersion of, photonic stop-bands produced by each unique structural geometry. I have principally focused on the characterisation of the electromagnetic responses of these structures, how they differ from each other and also why a linear polarisation dependence arises from these 3D photonic structures. In addition to this I have related the electromagnetic responses of these structures to analogous optical structures that naturally occur on the wings of the butterfly *P. sesostris* and elytra of the weevil *E. magnificus*. With this I aimed to gain a better understanding of the origin of the optical effects they provide the host biological system. This includes the characterisation of the gyroid photonic crystal structures, chosen to mimic that found in *P. sesostris* wing scales. The results from this were also subsequently used in the optical optimisation examination performed on the *P. sesostris* gyroid.

Finally, I have investigated a dynamic aspect of the 3D gyroid photonic crys-
tal, formed from a constant mean curvature surface. A compliant gyroid structure was fabricated for analysis in the microwave regime and a systematic compression force applied to it. I have measured the electromagnetic response of this compliant gyroid at each compression distance. Alongside this, I used theoretical modelling to electromagnetically characterise an analogous system under compression. In doing this I have identified the origin of the novel and complex photonic band-shifting behaviour produced by this 3D geometry.
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