Butterfly wing color: A photonic crystal demonstration

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ABSTRACT

We have theoretically modeled the optical behavior of a natural occurring photonic crystal, as defined by the geometrical characteristics of the Teinopalpus Imperialis butterfly. In particular, following a genetic algorithm approach, we demonstrate how its wings follow a triclinic crystal geometry with a tetrahedron unit base. By performing both photonic band analysis and transmission/reflection simulations, we are able to explain the characteristic colors emerging by the butterfly wings, thus confirming their crystal form.

1. Introduction

In the last years artificial periodic and quasi-periodic photonic structures, respectively known as photonic crystals [1] and photonic quasi-crystals [2,3], have been matter of deep research to the extend that nowadays a number of commercially available devices exploit these geometrical characteristics. Many are the applications resulting from dielectric periodic and quasi-periodic devices, such as Raman silicon lasers [4,5], optical fibers [6–11], optical filters [12,13], high-Q photonic cavities [14,15], all-optical switching [16–18] and THz optics [19,20]. Recently, also plasmonics has been exploited in order to enhance the potentiality of periodic structures, for example to develop devices for photocatalysis [21,22], highly temperature sensitive sensors [23], single/few molecules detectors [24–29], photovoltaic cells [30–35], magnetoplasmonics [36], metamaterials [37], light tailoring [38–40] or even for high energy functionalization [41]. Furthermore, periodic structures also appear in the natural environment [42–44], for example as scales of butterfly [45,46]and weevil [47–49], or in sea mouse spine [50]. From a fabrication point of view, the methods to realize periodic structures are usually based on top-down techniques employing the use of electron beam lithography and/or focus ion beam machining [51–53], however when low refractive index materials such as polymers are taken into account, alternative fabrication techniques can be considered [54,55].

Here, we shall focus on the origin of the optical response from the wings of the Teinopalpus Imperialis butterfly, known to reflect a green/yellow-like color when irradiated with white light. By using a genetic algorithm approach we have reconstructed, through comparison with TEM images [57], the three dimensional geometry of the Teinopalpus Imperialis wings, which following a periodic pattern, can be described with a triclinic Bravais lattice and a tetrahedron unit cell. In order to verify this configuration, we have compared the experimental optical response from the wing with the calculated photonic band structures and transmission simulations obtained with plane-wave expansion method (PWE [58]) and rigorous coupled wave analysis (RCWA [59]). Our results show that the combination of a triclinic cell with a tetrahedron unit base well explains the green/yellow-like color reflection from the wings.

2. The model

For three dimensional systems crystallography identifies 7 crystal systems divided into 14 Bravais lattices. The triclinic system has the least number of point group symmetries, in fact it is defined by a base unit of three vectors having different lengths and being non-orthogonal to one another. There is only one Bravais lattice associated to a triclinic system and, having the lowest degree of symmetry, is the only one showing no planes of symmetry. From a photonic point of view, a periodic structure can provide specific colors reflection under external illumination whether an optical band gap is formed at the corresponding wavelengths. If the band gap crosses all the optical range the crystal is said to have a full band gap otherwise, if it includes only a specific range of wavelengths, it is said to have a partial band gap. By considering that the higher the symmetry, the higher the chance to have a structure with full band gap, it is immediately understood how a triclinic crystal will probably show only a partial band gap at most, regardless of the refractive index contrast. In fact, the overall

symmetry of a crystal depends also on the symmetry of its unit cell. Clearly, unit cells formed by a single sphere possess the highest possible degree of symmetry. In such a case the crystal overall symmetry would be imposed solely by its Bravais lattice. However, in the present study we are dealing with a triclininc Bravais lattice and a tetrahedron unit cell which further reduces the chance of obtaining a full band gap by having a reduced degree of symmetry.

Importantly, the crystal final degree of symmetry cannot be higher than the lowest symmetry level between its Bravais lattice and its unit cell. This has important physical consequences especially when Neumann's principle is taken into account: the symmetry group of any physical property of crystals will include the symmetry elements of the point group of the crystal. In different words, the physical properties of a crystal strictly depend on the symmetry of the crystal itself.

We have started the optical analysis of the Teinopalpus Imperialis wings by setting up a genetic algorithm capable of determining all the possible triclinic configurations satisfying the geometrical constrains as in Argyros et al. [57]. The chosen object solution of the genetic algorithm was green/yellow color reflection from the wing. This approach aimed to limit the theoretical analysis of the triclinic–tetrahedron structure to the configurations matching the TEM analysis performed in Argyros et al. In particular, by starting from an initial geometrical configuration defined by parameters casually extracted within the aforementioned geometrical constrains, the genetic routine evolves this configuration towards an optimum condition. It does not guarantee the reaching of the best possible solution, but "good enough" solutions are surely found. In fact, the data illustrated here, showing a very good match with the experimental findings (green/yellow color), are the result of this approach. In Fig. 1 the reconstructed unit cell reproducing the wing structure with its geometrical parameters is
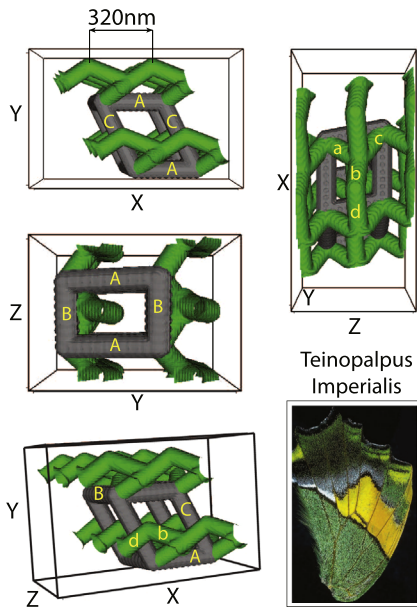
illustrated. Both the tetrahedron shape forming the wing structure (green rods) and the triclinic Bravais lattice (gray) are clearly visible. In particular, the unit base vectors in real space is defined as

$$A = (A_x, 0, 0), \quad B = (B_x, 0, B_z), \quad C = (C_x, C_y, C_z)$$

which leads to a base in the reciprocal space defined as

$$A' = 2\pi \left(-\frac{1}{A_x}, \frac{C_x B_z - B_x C_z}{A_x C_y B_z}, \frac{B_x}{A_x B_z} \right) \equiv (1, 0, 0)$$

$$B' = 2\pi \left(0, \frac{C_z}{C_y B_z}, -\frac{1}{B_z} \right) \equiv (0, 0, 1)$$

$$C' = 2\pi \left(0, -\frac{1}{C_y}, 0 \right) \equiv (0, 1, 0)$$

where the Miller notation has been used (see Fig. 2).

3. Photonic band structure calculation

The first numerical approach after setting up the wings structure obtained from the genetic analysis was oriented to the calculation of the photonic band structure. In this regard, considering the purely dielectric nature of the material (cuticle $n = 1.56$) [56] forming the wings structure, namely no need of treating neither absorption nor dispersion, we have employed the very efficient PWE method. Fig. 2 shows both the photonic band structure and the first Brillouin zone corresponding to a triclinic Bravais lattices which satisfy the object solution of green/yellow reflection from the wing. In fact, it was found that a number of solutions from the genetic analysis do
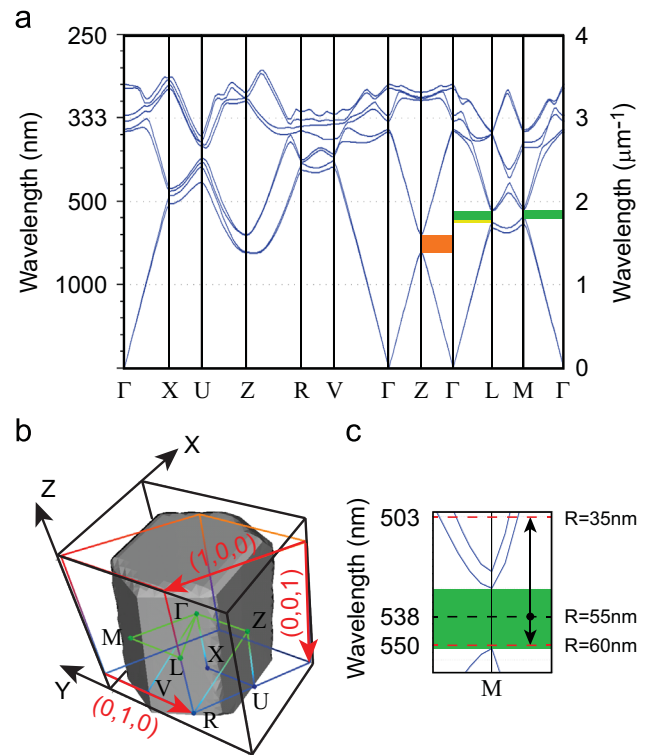

Fig. 1. Simulated structure shown in the three plane views *XY*, *XZ* and *YZ* together with the isometric profile. It is shown the tetrahedron base unit of the wing geometry (green). The triclinic periodicity is also illustrated for clarity (gray). The capital letters $A = 267$ nm $\pm$ 24 nm, $B = 212 \pm 26$ nm and $C = 325$ nm $\pm$ 24 nm represent the three unit vectors of the unit cell. The four lower letters are associated to the rods forming the wing structure with values $a = 190$ nm ± 31 nm, $b = 190$ nm ± 15 nm, $c = 190$ nm ± 32 nm and $d = 130$ nm ± 19 nm. Finally, the angles between the rods are $\widehat{ab} = 86° \pm 9°$, $\widehat{ac} = 72° \pm 12°$, $\widehat{ad} = 135° \pm 9°$, $\widehat{bc} = 59° \pm 8°$, $\widehat{bd} = 128° \pm 12°$, $\widehat{cd} = 145° \pm 14°$. The radius of each rod was set in the range 35–60 nm [57]. At the bottom right corner an image of the butterfly wing is shown (credit to S.S. Heaton, California Academy of Science). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

Fig. 2. (a) Photonic band structure of the triclinic structure as in Fig. 1 with rods radius equal to 55 nm. The local band gaps associated to green/yellow reflection are highlighted. (b) First Brillouin zone where the points of high symmetry and the reciprocal space unit vectors are shown. (c) Close view of the band structure around the high symmetry point M. The center of the green band gap, indicated by the dashed lines, shifts up to 50 nm according to the radius R of the rods (considered radius range 35–60 nm). (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)