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Structural colours through photonic crystals

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Abstract

We discuss two examples of living creatures using photonic crystals to achieve iridescent colouration. The first is the sea mouse (Aphroditidae, Polychaeta), which has a hexagonal close packed structure of holes in its spines and lower-body felt, while the second is the jelly fish *Bolinopsis infundibulum*, which has an oblique array of high index inclusions in its antennae. We show by measurements and optical calculations that both creatures can achieve strong colours despite having access only to weak refractive index contrast.

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1. Introduction

Around 500 million years ago, living creatures developed eyes and control of colour became an important facet of their world. They developed many mechanisms to develop either colouration to make them stand out from their environment or blend in with it, but their means can basically be grouped into two classes [1]. Pigmental colouration relies on chemical means to achieve colour by selective absorption and reflection, and is generally used by creatures living in environments where light is plentiful. Pigments are subject to photobleaching, so the animal's energy budget may need to include replacement of the pigments from time to time. Structural colouration uses physical means of interference or diffraction, and is not subject to photobleaching. It can also be very efficient in its use of light, and so is found in creatures living in low-light environments, such as the deep sea. It is also sometimes used by creatures to achieve colour effects not achievable by pigmentation.

Here, we consider two creatures which use structure in the form of photonic crystals to achieve iridescence. The first of these is the sea mouse, Aphroditidae, a bottom-dwelling and widely distributed sea scavenger. This has striking iridescence in both the thick spines on its lower

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body, and finer hairs or felt. We have previously commented on the hexagonal photonic crystal structure in the spines [2,3], and we complement this earlier work with studies of the optical properties and structure in the felt. We compare the structure of the spines and hairs with that found in the newly developed microstructured optical fibres [4,5], in an example of optical biomimetics—the emerging field in which nature's optical systems are studied to discover parallels or precursors for man-made devices.

Our second example is a jelly fish, *Bolinopsis infundibulum*, which has iridescence in its tentacles. We show this to be due to a photonic crystal having a parallelogram unit cell. Because of this low symmetry, the photonic band structure resulting is complicated and strongly direction dependent, and careful behavioural studies may be required to deduce the functional reason for this design.

2. The sea mouse

The sea mouse is a bottom-dwelling marine animal that has iridescent hair and spines on the lower part of its body. The thicker spines show a bright red colour in normally incident light, which changes to green and blue with increasing incidence. (Colour images of this may be seen on our web site: http://www.physics.usyd.edu.au/~nicolae/seamouse.html.) The finer felt hairs can show gold colours, changing to green and blue.

We have examined both a spine and a hair electronmicroscopically, with the results shown in Fig. 1. Both exhibit a structure of holes arranged in hexagonal packed fashion, with spacing around 0.5 μm. In the case of the spine, it has an annular structure, with the voids occurring in its wall. The holes are presumably filled with sea water (refractive index around 1.33), and occur in a matrix of chitin, a biological material with an index round 1.52. From the spine micrograph of Fig. 1, we determined the geometric parameters (hole diameter and spacing) of the 88 layers constituting the spine wall. We then calculated the reflectance of a stack of 88 gratings with just those parameters, for normally incident radiation and for both principal polarizations (E and H, with respectively the electric field and the magnetic field of the incident wave along the axes of the cylindrical holes). The results are shown in Fig. 2.

Note the strong reflectance peaks in the red and blue, with those for E polarization being stronger and wider than those for H polarization.

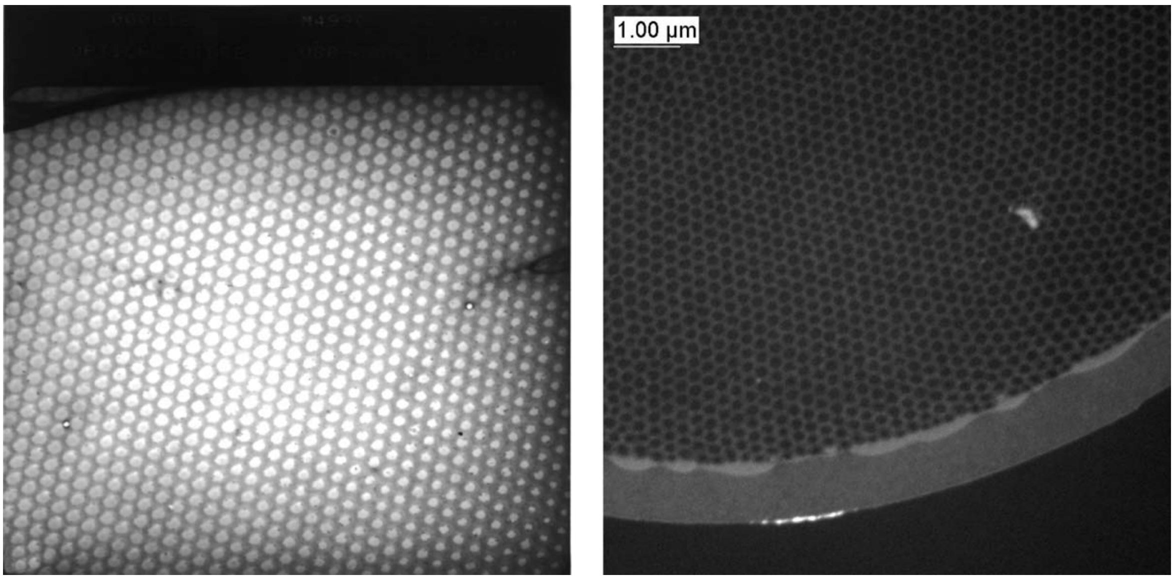

Fig. 1. Sea mouse spine (left) and felt hair (right).

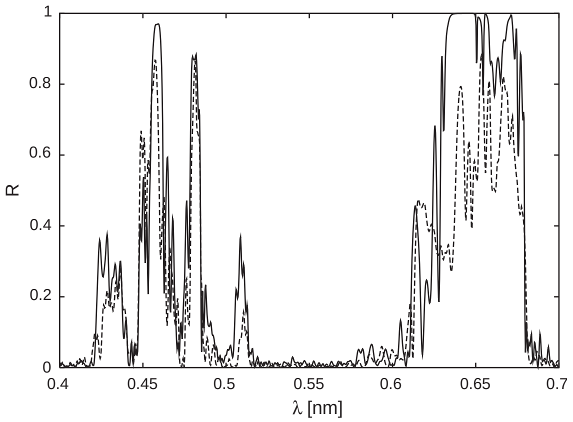

Fig. 2. E (solid curve) and H (dashed curve) polarization normal incidence reflectance for an 88 layer stack of gratings having the geometric structure of the sea mouse spine of Fig. 1.

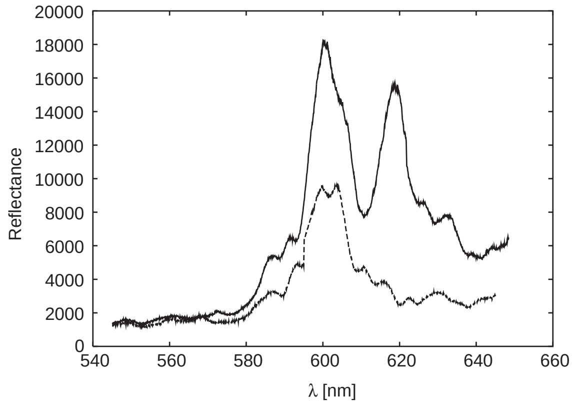

Fig. 3. Microreflectance measurements on a green-gold sea mouse hair.

By arranging multiple gratings in coherent fashion, the sea mouse is able to achieve a 100% reflectance in the red despite having only a weak refractive index contrast: 1.33 in 1.52.

If we increase the angle of incidence from zero, the reflectance peak in the red moves towards shorter wavelengths. We have correlated the reflectance behaviour in Fig. 2 with the photonic band diagram for a structure corresponding to the average spine structure in Fig. 1. The reflectance peak corresponds to a weak partial band gap which is opened up in the free space band diagram for the hexagonal array by the small perturbations represented by the holes in the chitin matrix.

We have also commenced reflectance calculations on the structure corresponding to the sea mouse felt in Fig. 1. The calculations show the felt structure to have reflectance peaks in the yellow, blue and green. Using a laser microreflectometer that consists of a femtosecond "white light" supercontinuum generated by a 100 fs pulse titanium sapphire laser, we have measured the reflectance of a sea mouse hair. This is a difficult measurement to make, and is also problematic to interpret, as the beam diameter and the hair diameter are of the same order of magnitude. The results from two measurements are shown in Fig. 3, and exemplify the narrow bandwidth of the reflectance peaks. The differences in results are caused by the laser spot that has a somewhat different spectral composition at different positions on the hair.

3. Iridescence in a jelly fish

We have also investigated the origin of the iridescence of the tentacles of the jelly fish *Bolinopsis infundibulum*. As might be imagined, the task of preparing a section of the tentacles for electronmicroscopy was a challenging one. Nevertheless, we have been able to achieve this, and have found that once again this marine creature exploits a photonic crystal to achieve its colour effects. This time, the crystal has low symmetry, with the unit cell being a parallelogram having the parameters: longer period $d_1 = 0.972\ \mu m$, shorter period $d_2 = 0.664\ \mu m$, angle between period axes 72°, hole radius 0.307 μm, refractive index of matrix 1.33, refractive index of cylinder 1.52. The result of this low symmetry is that the optical properties of the tentacles are strongly dependent on direction. For incidence on the long side of the unit cell, the reflectance peaks are sharp and frequent, tending to form a comb spanning the visible region. The result would be a white flash of light from this direction. For incidence on the shorter side, there are fewer peaks, located in the red, green and blue regions. This would give clear iridescence, of the sort

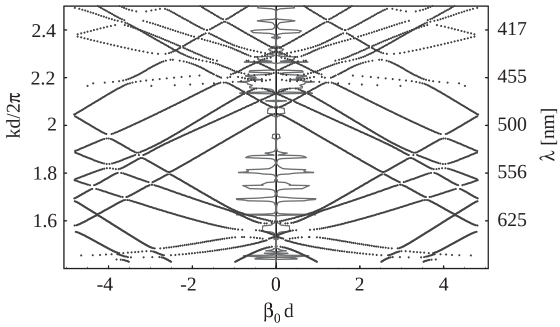

Fig. 4. Band diagram for E polarization and normal incidence on the long side of the unit cell. On the abscissa we represent the crystal momentum $\mathbf{k}_0 = (0, \beta_0)$ for normal incidence. The values of β_0 corresponding to each $k = 2\pi/\lambda$, are the eigenvalues of a scattering matrix [6].

evident in some images of *Bolinopsis*. Others tend to show white flashes of light in the tentacle region. We speculate that *Bolinopsis* is able to drape its tentacles either to display strong colouration as a warning signal, or to give white flashes resembling the fluctuating light due to reflectance off waves just above it.

The band diagram in Fig. 4 explains the occurrence of the many peaks evident in the superimposed reflectance curve. The low symmetry of the unit cell leads to the numerous bands evident, and the partial gaps between the bands are associated with the reflectance peaks. We are still investigating the best way to display the band diagram for this low-symmetry array.

4. Conclusions

Other photonic crystals have been identified in nature, particularly in butterfly scales [7,8], but the study of diffractive optical systems in living creatures is still in its infancy. The case of the sea mouse may well provide an exemplar for studies in this field: the structure adopted by the living creature is simple, and close to perfect, and the resulting iridescence is striking. Interest is added by the resemblance in form and dimensions between the sea mouse spine microstructure and that in the new generation of optical fibres under intense current study, called microstructured optical fibres [4,5]. The high-quality molecular engineering adopted by the sea mouse to fabricate its spine and hair microstructure suggests that molecular assembly techniques may well be a promising avenue to explore for the fabrication of optical fibres and other photonic guiding structures.

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References

[1] A.R. Parker, Invertebrate structural colours, in: E. Savazzi (Ed.), Functional Morphology of the Invertebrate Skeleton, Wiley, Chichester, 1999, pp. 65–90.
[2] A.R. Parker, R.C. McPhedran, D.R. McKenzie, L.C. Botten, N.A. Nicorovici, Nature 409 (2001) 36.
[3] R.C. McPhedran, N.A. Nicorovici, D.R. McKenzie, L.C. Botten, A.R. Parker, G.W. Rouse, Aust. J. Chem. 54 (2001) 241.
[4] J.C. Knight, T.A. Birks, P.St. J. Russell, D.M. Atkin, Opt. Lett. 25 (1996) 25.
[5] P. Russell, Science 299 (2003) 358.
[6] L.C. Botten, N.A. Nicorovici, R.C. McPhedran, C.M. de Sterke, A.A. Asatryan, Phys. Rev. E 64 (2001) 046603.
[7] P. Vukusic, J.R. Sambles, C.R. Lawrence, R.J. Wootton, Proc. R. Soc. London B 266 (1999) 1403.
[8] G. Tayeb, B. Gralak, S. Enoch, Opt. Photon. News 14 (2003) 38.