brief communications

Photonic engineering

Aphrodite’s iridescence

The most intense colours displayed in nature result from either multilayer reflectors or linear diffraction gratings. Here we investigate the spectacular iridescence of a spine (notoseta) from the sea mouse *Aphroditida* sp. (Polychaeta: Aphroditidae). The spine normally appears to be deep red in colour, but when light is incident perpendicular to the axis of the spine, different colours are seen as stripes running parallel to the axis of the spine; over a range of smaller incident angles, the complete visible spectrum is reflected with a reflectivity of 100% to the human eye. The simple structure responsible for this effect is a remarkable example of photonic engineering by a living organism.

Photons are a branch of optics that concerns the control of photons, much as electronics depends on electrons, and photonic structures have been described in butterfly wings. The sea mouse has iridescent spines situated at the base of the dorsal surface, where they can be viewed laterally, with less strongly coloured threads being seen more readily from above (see http://www.physics.usyd.edu.au/~nicolae/submit.html). The biological function of the iridescence is unknown, but it may be related to species recognition or to courtship.

We prepared a spine with strong reflectance in the red for electron microscopy by mounting it in resin and slicing it with a microtome into sections transverse to the long axis. These sections were of constant thickness and were mounted on grids for transmission microscopy.

The micrograph in Fig. 1a shows an array of hollow cylinders, with the long axis of the cylinders along the spine. The image is of the wall region of the spine, the centre of the spine being hollow. The hollow cylinders have thicker walls near the edge of the spine, possibly for mechanical rigidity, but after a few layers their wall thickness decreases to a constant value. The cylinders are close-packed, with each cylinder having six nearest neighbours. The spacing of adjacent layers of cylinders is 0.51 μm, and remains constant throughout the wall cross-section, which contains 88 layers of close-packed voids. The cylinder walls are made of pure α-chitin (refractive index, 1.54; ref. 2).

To calculate the expected optical properties of the spine, we used a formulation for layered stacks of cylinder gratings. Figure 1c shows the reflectance of a 500-layer stack of gratings with period \( d = 0.51 \) μm, for radiation incident in the plane of Fig. 1a, with its electric vector perpendicular to the plane (\( E_0 \)). The grating consists of hexagonally packed cylindrical holes of radius \( a = 0.2 \) μm, filled with sea water (refractive index, 1.33), in a matrix of chitin. The bulk reflectance of chitin immersed in sea water is 0.54%, so the strong reflectance evident in Fig. 1c can only be achieved through the coherent stacking of scores of layers to form the crystal shown in Fig. 1a. Were the layers to be of irregular separation or composition, the peak reflectance for a given number of layers would be much lower and the iridescence less pronounced.

We calculated the total reflectance of this structure, for normal incidence, for free-space wavelengths in the visible spectrum (from 0.4 to 0.7 μm). Figure 1c shows a strong maximum in reflectance around the wavelength \( \lambda = 0.633 \) μm. To investigate the origin of this narrow-band reflectance, we calculated the photonic band diagram, which gives the frequencies...
of light waves able to propagate freely in the structure, for the hexagonal array of voids (presumably water-filled) in a chitin matrix. This is shown in Fig. 1b for H polarization, indicating that the region of enhanced reflectance in the red for the spine corresponds exactly to a partial photonic bandgap of the hexagonal struc-
ture (in the range \( \Gamma - M \)) — a circumstance in which light cannot propagate in a narrow range of wavelengths in the structure. Note that for H polarization of incident radia-
tion with the magnetic vector perpendicu-
lar to the plane of Fig. 1a, reflectance is similarly enhanced in the red, although there is not a clear-cut partial bandgap.

We have seen that the sea mouse achieves brilliant narrow-band coloring of its spines through a remarkable piece of photonic engineering. The regularity of the structure shown in Fig. 1a and the strong narrow-band reflectance shown in Fig. 1c suggest that growing optical filters by molecular self-
assembly is a technological goal worth pursu-
ing. These structures may have application in photonic communications, where there is much interest in fabricating photonic crystal fibres\(^1\) with similar morphology to that shown in Fig. 1a in order to improve band-
width and nonlinear properties.

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Oceanography
Vertical mixing in the ocean
The thermohaline circulation of the ocean results primarily from down-
welling at sites in the Nordic and Labrador Seas and upwelling throughout the rest of the ocean. The latter is often described as being due to breaking internal waves. Here we reconcile the difference between theoretical and observed estimates of vertical mixing in the deep ocean by pre-
senting a revised view of the thermohaline

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How wild are wild mammals?
In bacteria associated with humans, antimicrobial resistance is common, both in clinical isolates and in the less-studied commensal flora, and it is thought that commensal and environmental bacteria might be a hidden reservoir of resistance. Gilliver et al have reported that resistance is also prevalent in faecal bacteria from wild rodents living in northwest England\(^1\). Here we test the faeces of moose, deer and vole in Finland and find an almost complete absence of resistance in enterobacteria. Resistance is thus not a universal property of enterobacterial populations, but may be a result of the human use of antibiotics.

Bacterial resistance to antimicrobial agents has become a serious problem in modern medicine and a debated evolution-
ary question\(^1\). The use — and misuse — of antibiotics is generally blamed, but it has also been claimed that there must be other reasons for the increase in resistance\(^1\). This policy would be unnecessary. One way to test the effect of human activities is to com-
pare the resistance frequencies of popula-

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