A Natural Photonic Crystal

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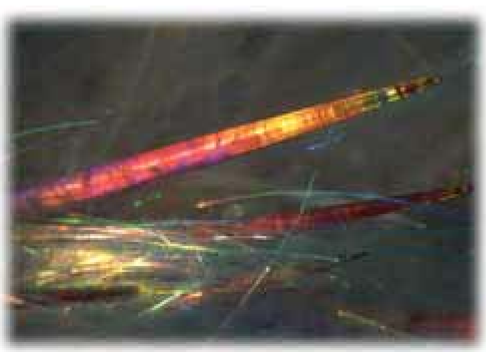
From left: Dr Nicolae Nicorovici, Professor Ross McPhedran and Professor Dave McKenzie.

An emerging area of optics is called biomimetics, in which living systems with striking optical effects are studied to see how those effects are achieved, and whether Nature's designs can enrich our technology. An interesting example of this field is provided by the sea mouse (Aphrodita sp., Polychaeta: Aphroditidae). The sea mouse is a bottom-dwelling creature whose spines show striking iridescence, which is amongst the strongest iridescence known among marine creatures. The problem of how this iridescence is achieved was brought to the attention of Professors Ross McPhedran and David McKenzie and Dr Nicolae Nicorovici, by Dr Andrew Parker, then at the Australia Museum, now a Royal Society Fellow at Oxford.

Andrew and David performed optical measurements, which showed that the reflectance of the spines in the red, its most prominent colour, is close to 100%. David had electron microscope images made of the cross section of the spines, which to our astonishment revealed a highly regular array of air holes in the material, chitin, of which the spines are made. The diameter of the air holes is about the same size as the wavelength of red light, and the regularity of their arrangement means that the reflections from each of the 88 layers making up the spine wall all add up. This is how the sea mouse is able to make such a good reflector, when it only has access to materials whose refractive index is close to that of water.


Reflectance of light by a sea mouse spine, showing strong colouration in the red. (Credit: Dr. Greg Rouse, now with the Museum of South Australia.)

Ross and Nicolae performed an optical analysis of the structure revealed by the electromicrographs, treating the structure as 88 diffraction gratings arranged one behind the other. They showed that its strong reflectance, and the way the reflectance changed with the angle between the light and the spine axis, could be explained in terms of the spine acting like a photonic crystal. A photonic crystal is a device in which a two- or three-dimensional array reflects light of a specified range of wavelengths and therefore prevents those wavelengths from passing through the device. The range of wavelengths prevented from being transmitted is called the band-gap and the sea mouse spine has a partial band-gap centred in the red region of the spectrum.

The study of photonic crystals is a topic of intense interest to research groups around the world, which are trying to fabricate for light analogous structures to those of semiconductors, materials at the base of the electronic revolution of the second half of the twentieth century. The humble sea mouse achieves its iridescence using a structure equal to the best able to be manufactured by the leading group at Sandia Labs in the USA, with multi-million dollar apparatus like that used in the semiconductor industry. It does this by molecular assembly, in a way that, if we could duplicate it, would open up new opportunities for precision optical materials. A group at the Optical Fibre Technology Centre at the Australian Technology Park is currently developing a new type of optical fibre in polymer, with a structure bearing an uncanny resemblance to that of the sea mouse spines.

A micrograph of the wall of a sea mouse spine, showing hexagonally-packed voids in a chitin matrix, with a spacing of 0.51 μm.

All in all, the sea mouse provides a remarkable example of biomimetics, and of how sophisticated and elegant Nature's designs can be!

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