Photonic crystals

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Nothing captures the eye more than the flutterings of colourful butterflies or a foliage of leaves and flowers. In their presence we forget the noisy and dull world we live in. But why are these coloured the way they are? It is natural to ascribe colours of leaves, fruits and flowers to the presence of specific chemicals, called pigments, in them. For instance, the green colour of the leaves is due to absorption of light by chlorophyll. This pigment absorbs weakly in the green but strongly at all other wavelengths of the white light spectrum. That there could be a physical origin for colours seen in nature was first pointed out in 1801 by Thomos Young, the propounder of the wave theory of light. He argued that a multilayer stack of two alternating dielectric plates exhibits a near total reflection in a band of wavelengths. In literature a dielectric multilayer is also called a *photonic crystal.* Photonic crystals come in all sorts of shapes and structures and one very active area of current research in optics has been their discovery and the fabrication. Here we look at some new and interesting photonic crystals that surfaced in literature during 1998.

Since the time of Young a constant search has been going on to identify and establish this physical mechanism in the manifestation of colours seen in a variety of situations. Many examples have been found not only in the inanimate world of minerals and gems but also in the world of animals like fishes, insects and birds. Recent investigations have revealed that this process operates in plants too[1]. It now appears that feathers of birds are also in this class. Generally the blue colour of the feathers of birds is attributed to the Rayleigh scattering from the air pockets in the feather. It was shown by Prum *et al.*[2] that this explanation is wrong. These authors studied in detail scattering of light from the blue feather barbs of the plum-throated cotinga. Their analysis indicates that the cavities are not only of same size but they are also arranged three-dimensionally in space, like the atoms or molecules of a crystal. Further, they found that the spacing between the cavities is smaller than the wavelength of light. Thus, Rayleigh scattering cannot account for the blue coloration. Detailed calculations based on the model of a periodic array of air vacuoles support the observed reflection spectra. The authors suggest that possibly the same mechanism is operating in producing the green, blue and violet colours found in other feather barbs. In short, the feathers of birds hide in them photonic crystals.

It is exhilarating to discover such a photonic crystal in nature. But a greater pleasure lies in making it in the laboratory. Eight years ago Yablonovitch *et al.*[3] fabricated such a crystal. They drilled holes in a block of a dielectric such that the criss-crossing of the drilled holes produced a crystal with the connectivity of a diamond-like structure. This process by its very nature is not easy to execute if we want to design a photonic crystal of desired specificity. Another way of making hollow crystals has been suggested recently by Zakhidov *et al.*[4]. These authors synthesized what they call *inverse opals.* These are interesting variations of the opal structure. By a slow crystallization (over ten months) of monodispersed aqueous colloid of SiO_2 spheres they made opal crystals. This was later sintered to get a packing of SiO_2 spheres with voids. By means of a chemical technique these voids were later filled up with carbon to result in a continuous interconnected carbon structure. Later they removed chemically, the SiO_2 spheres. Interestingly, these authors have made structural inverses of not only natural opals but also those of diamond, graphite and glassy carbon. These carbon inverse structures strongly diffract light and exhibit optical opalescence. Instead of filling with carbon, inverse structures filled with titanium oxide have also been made. This has spherical cavities surrounded by a titanium oxide scaffolding. This structure was reported a few months earlier by Holland *et al.*[5]. So it appears that we can imitate nature in fabricating photonic crystals of air.

In a conventional multilayer dielectric, it is impossible to achieve total reflection at all angles of incidence. This is due to the fact that light polarized in the plane of incidence will simply go through if it is incident at the Brewsterian angle corresponding to the interlayer boundary. Thus we expect for this polarisation, a 'hole' in the reflection spectrum which will exist at all wavelengths. Recently, Fink *et al.*[6] overcame this problem in a clever way. It is easy to see that when the angle of incidence varies from 0° to 90° the corresponding angle of refraction at the first dielectric slab will be decided by the Snell's law of refraction. Therefore, we can so choose the materials that the maximum angle of refraction inside the multilayer is less than the Brewester angle for the multilayer. This will completely avoid the 'hole' in the reflection spectrum. Thus this is a total reflector for all angles of incidence from 0° to 90°. In short, it is an omnidirectional one-dimensional photonic crystal. These authors have fabricated such a system with alternating layers of polystyrene and tellurium. This reflects strongly in the wavelength band of 10 to 15 micrometers.

We now come to our last example of a photonic crystal which is very different from the normal ones. In fact, it could be called a photonic fibre as it has been designed to act as an optical fibre. Light is guided in normal fibres by total internal reflection which arises from the fact that the refractive index of the central core is greater than that of the surrounding cladding. Recently Knight *et al.*[7] fabricated a totally different type of optical fibre. Effectively it has a core of a lower refractive index compared to that of the cladding. In this sense it is an inverse structure. Also the mechanism that guides light through the fibre is entirely different. Light is guided in these structures by exploiting the properties of a photonic crystal. The fibre is essentially a periodic array of holes, of nearly 75 nanometers diameter running through the length of the fibre. These holes are arranged on a honeycomb lattice with a near neighbour spacing of 1.9 micrometers. Further, instead of being a perfect lattice of holes the fibre has a large extra hole of 0.8 micrometers at the centre of the fibre. Light is sent down this central hole. For wavelengths within the band gap of the surrounding periodic structure light will not leak out due to Bragg reflection and thus gets guided through the central hole. In this case only light of wavelengths in the band 458 to 528 nanometers (obtained from an argon-ion laser) could be guided through the central hole of the fibre. At other wavelengths light 'fills' the entire fibre. Another extraordinary property of this fibre is its strong birefringence. The velocity for linearly polarized light is different for any two orthogonal azimuths. Hence, light, as it propagates through the fibre, will retain its linear polarization even in the presence of twists and bends in the fibre.

Nature in all her grandeur and cleverness has come up with any number of tricks to paint herself in different hues and shades. And scientists are not far behind in following her. Here we dwelt upon only one of these tricks namely synthesis of photonic crystals. Even in this game there exists a variety that would baffle anyone. We have learnt a lot about these photonic crystals by observing nature. This has not only enriched our understanding of nature but has also led to the fabrication of unusual photonic crystals with surprising optical properties.

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