

## PHOTONICS

# Metamaterials in the sunshine

Artificial materials composed of either structured or random subunits far below the wavelength of light can be designed to display fascinating physical properties. Recent advances in fabrication technology have established the great potential of such metamaterials for applications.

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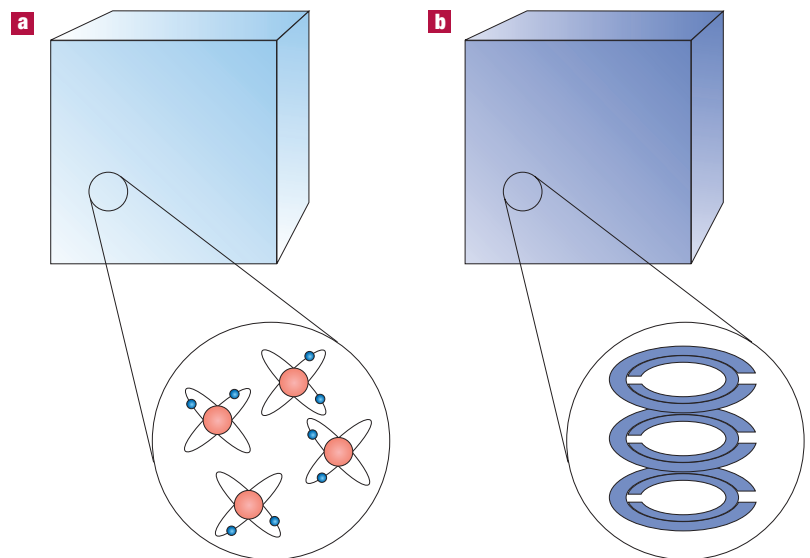
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Interaction between light and materials is the key to exploiting and controlling the properties of light. From this simple observation follow the major contributions of the science of optics: camera lenses, optical fibres and lasers, to name only a few. These optical properties can be tailored by adjusting the chemical composition of the material. We might, for example, add lead to glass and raise its refractive index to use it for optical prisms or for decorative glassware.

More recently it has been realized that the internal microstructure of a material can be just as important as chemistry in determining its optical properties. In fact, by exploiting both chemistry and microstructure, materials can be produced with properties never found in nature and of great potential commercial value. This new class of materials, metamaterials, achieve that effect through a structure that is smaller than the wavelength of radiation in the region of interest. They give access to materials with a hugely expanded range of electromagnetic properties and hence the excitement at a recent conference *Photonic Metamaterials: from Random to Periodic* held in the Bahamas at the beginning of June.

Figure 1 illustrates the concept of a metamaterial in which subwavelength-engineered units replace atoms and molecules as the determinants of electromagnetic properties. At optical frequencies, these units, or metamolecules as one might call them, would therefore need to be nanoparticles of diameter much less than the wavelength of visible light. However, the concept is applicable to electromagnetic radiation of all frequencies. At mobile telephone or radar frequencies with wavelengths of a few centimetres the component units can be as large as a few millimetres across and still satisfy the subwavelength requirement. Not surprisingly, metamaterials are easier to make for operation at these frequencies. There has been much progress already, particularly in creating materials with the elusive property of negative refraction — in which light entering the material is bent away from the

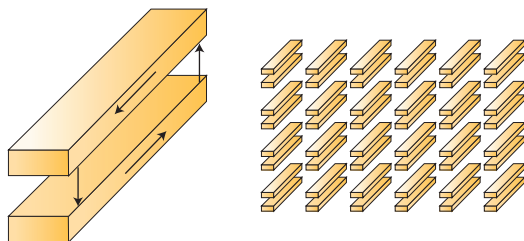


**Figure 1** Photonic metamaterials. **a**, In a conventional material, the response to electric and magnetic fields, and hence to light, is determined by the atoms and molecules. **b**, In a metamaterial, the response is engineered through many tiny identical structural units, or metamolecules, with dimensions much less than the wavelength at the operating frequency. In effect, the engineered units behave like giant molecules.

normal, not towards it as in materials with positive refractive index. Investigated theoretically by Victor Veselago almost forty years ago<sup>1</sup>, negative refraction has never been found in a conventional material. Therefore, metamaterials provide the key and the first negatively refracting sample was demonstrated at 5 GHz by David Smith and colleagues<sup>2</sup>.

At the Bahamas meeting, emphasis was on pushing negative refraction into the visible range of frequencies. Veselago set the requirement for negative refraction: that the electrical permittivity  $\epsilon$  and magnetic permeability  $\mu$  both have to be negative, and showed that this leads to a negative refractive index. The challenge is to engineer the metamolecules so that they can be made easily and possess minimum transmission losses that otherwise tend to diminish the benefits of negative refraction.

**Figure 2** Metamaterials at optical frequencies. The building block for such a metamaterial (left) consists of a pair of gold nanorods. In an array of pairs (right) the electron resonances (arrows) result in a negative  $\epsilon$  and  $\mu$ . Hence the structure has a negative index of refraction.



At the meeting, a main contender for the commercially attractive materials with negative refraction near visible wavelengths was the twin rod structure in which the metamolecule, shown in Fig. 2, consists of two parallel nanoscopic gold rods. Two groups reported their results for this system: that of Vladimir Shalaev (Purdue University, Indiana, USA), who first proposed the structure<sup>3</sup>, and Frank Garwe and colleagues (Institute for Physical High Technology, Jena, Germany). Indeed, experimental data for transmission of light through a two-dimensional array of nanorod pairs showed negative refraction. Losses are still a major issue at optical frequencies, and the structures need to be further elaborated into a fully isotropic three-dimensional (3D) metamaterial. Nevertheless, the achievements were impressive.

Metamaterials did not hog all the limelight at the meeting, and some exciting experiments on disordered systems were presented. Disorder poses some of the hardest problems when trying to model diffraction of light in a regime where diffusion is suppressed due to many strongly scattering structures virtually trapping and localizing light. Transmission of light through such samples decays on average exponentially with thickness, and is characterized by extreme fluctuations in which very occasionally at isolated frequencies the transmission coefficient approaches unity. Originally it was believed that these anomalous peaks were due to tunnelling through an isolated resonant state near the centre of the sample. Some years ago, however, several theorists predicted independently that the fluctuations were much more subtle and beautiful than that: the dominant mode of transmission is through chains, or 'necklaces', of resonances strung out across the sample that act like a series of stepping stones across a river.

The necklace states have previously never been observed experimentally due to the difficulty of

producing a well-characterized disordered sample. Two groups have now managed that feat: Diederik Wiersma and colleagues (Florence, Italy) at optical frequencies and Azriel Genack's group (Queens College, New York, USA) at microwave frequencies.

In the Florence experiments perfectly flat layers of porous silicon were prepared. The porosity of the material is chosen to produce two alternating sets of layers with distinct refractive indices. The thickness of these layers was chosen randomly to create an almost ideal disordered 1D system. Indeed, transmission measurements showed the characteristic spiked structure of a disordered system. Furthermore, the experiments enabled the team to infer the number of resonances contributing to each spike in the transmission coefficient. Sure enough, the measurements revealed the predicted number of resonances contributing to the necklace states.

In the Queens experiments, randomly spaced slabs were inserted into a waveguide that created a 1D transmission line. In this configuration, the electromagnetic fields are probed along the waveguide. Again the conclusion was that transmission is dominated by necklace states.

Experimental confirmation of the existence of necklace states consolidates a key building block of our understanding of transport of light in localized systems. Although experiments were conducted on 1D systems, theory predicts that necklace states also dominate transport in 2D and 3D localized systems. In contrast to tunnelling through a single resonance, a necklace of resonances offers a relatively broad band of frequencies, and a rapid transit time for light. Furthermore, absorption rapidly diminishes transport through a single resonance because of the long dwell time during transit — contrary to necklaces, which are much less susceptible to absorption.

We hear that experimental work is in progress on localization in 3D disordered optical systems. Clearly, the study of such highly complex media will open the way to a new understanding of this phenomenon.

#### REFERENCES

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