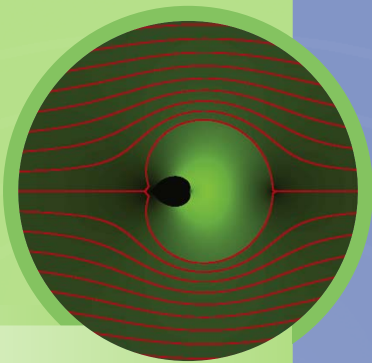
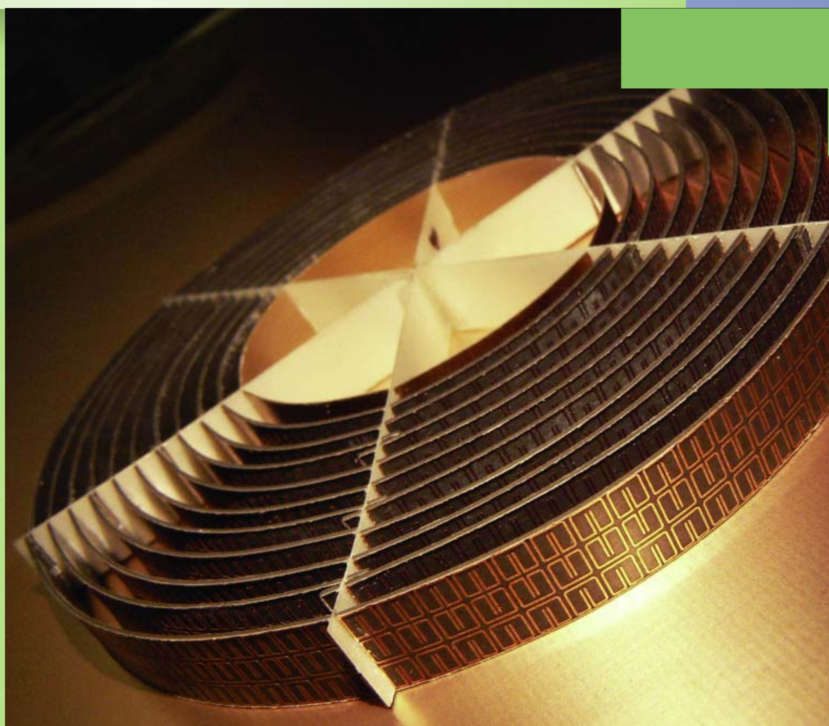
IOP Institute of Physics

Structured composites with remarkable optical properties



Metamaterials



VISIONS 21

BRIEFING PAPERS FOR POLICY MAKERS

Light takes a new direction

Recently, a new class of unusual materials has come to the fore, which interact with light in a way that appears to break the laws of physics. Their unexpected optical properties do not arise from their atomic or molecular composition – as is usual – but from larger-scale arrays of specially designed microstructures. These so-called metamaterials are causing great excitement. Their extraordinary behaviour could not only lead to major improvements in telecommunications and data storage, but also to totally new applications such as 'super-lenses' and 'invisibility cloaks'.

The most significant characteristic of metamaterials is that they are composed of tiny artificial features – conducting loops and wire networks. These interact with light, just as atoms or molecules do, to produce bulk physical effects such as optical refraction. When a light ray is bent, or refracted, as it passes from air to, say, glass, it is responding to the overall effect of the atomic structure of glass rather than the individual atomic details. Light responds to the manmade features of a metamaterial in a similar way. However in a metamaterial, the 'artificial atoms' can be designed to make light react 'unnaturally'. For example, its path can be made to bend in the opposite direction from normal – negative refraction (bottom left image).

The secret of how this happens lies in the very nature of light, which consists of moving oscillating electric and magnetic fields – an electromagnetic wave. The electromagnetic spectrum covers wavelengths from gamma-rays through X-rays and visible light to the longer microwaves and radio waves. When light interacts with a material, the electric field jostles the constituent atomic electrons to and fro (electric response) while the magnetic field induces a circular motion (magnetic response); the light wave loses energy, slows down and changes direction – hence refraction. The refractive behaviour depends on the strength and nature of these two responses, which in turn depend on the electronic structure of the material.

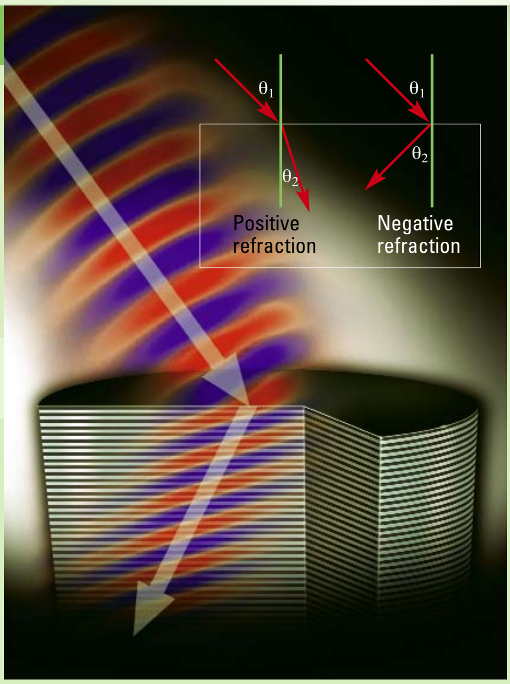
In most materials, the electric and magnetic responses are positive – the electrons move in phase with the oscillating field. But 40 years ago, a Russian physicist, Victor Veselago, speculated that if a material could be made with both responses negative – in other words, the electrons move out of phase with the oscillating field so end up opposing it – then it would bend light in the opposite direction from normal. However, although some metals do show a negative electrical response – a natural material with an analogous negative magnetic response was unheard of.

A single element showing the Swiss roll structure that gives rise to a negative magnetic response

A negative response

The idea of negative refraction was forgotten until the late 1990s when Sir John Pendry, a physicist at Imperial College London, with Mike Wiltshire and colleagues at Marconi, came up with an ingenious way of fabricating a material with a negative magnetic response. It consisted of an array of plastic-backed copper sheets wound into millimetre-sized Swiss rolls (top left image) so that the metal surfaces did not touch. When an electric current is passed through the structure, it induces a sea of tiny circulating currents – magnetic poles – with a negative response to an external magnetic field. This artificial magnetic material, which works for radio waves, is now being developed by Wiltshire at the Hammersmith Hospital in London for magnetic resonance imaging (MRI). The result may be cheaper, highly sensitive medical scanners that could allow clinicians to see extremely small structures in the body.

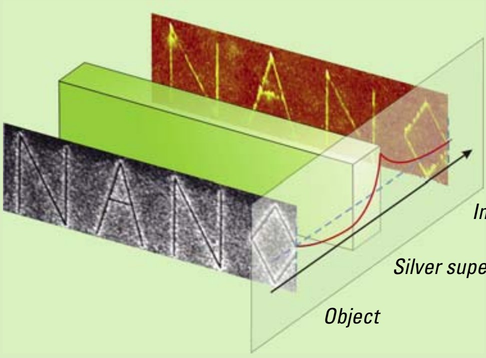
Taking Pendry's concept, David Smith and Sheldon Schultz



Negative refraction

Keith Drake / NSF

THANKS GO TO PROFESSOR SIR JOHN PENDRY AT IMPERIAL COLLEGE LONDON



A team at the University of California at Berkeley have created a 'superlens' from a silver film (far left). The images show the word 'NANO' (the scale bar is 2 micrometres), seen with UV light. The top image, made with the superlens, is much clearer than the bottom one

of the University of California, San Diego went on to make the very first negatively refracting material in 2000. They combined an array of copper wires with rows of circular copper structures, called split-ring resonators, to create the respective negative electrical and magnetic responses to light at microwave wavelengths. Although the results were contested at first, other research groups also demonstrated negative refraction, thus verifying the principle.

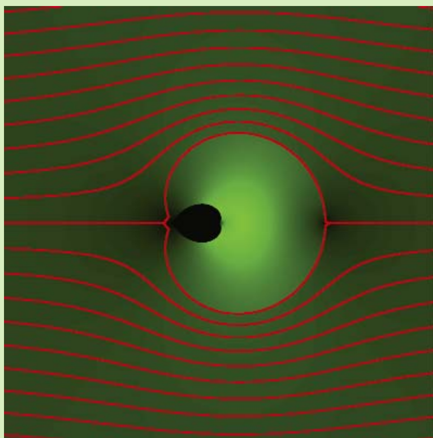
Towards a perfect lens

How could negative refraction be exploited? Negatively refracting materials are thought to have super-resolving powers. Light emitted from an object consists of not only propagating waves that can be collected and focused by a conventional lens, but also more localised 'evanescent' wavelets which quickly die away over distance, so are lost. They contain fine structural detail in the object, which is not normally captured because the scale is below the wavelength of light. However, theory shows that a negatively refracting slab would amplify and refocus these elusive waves, thus behaving as a 'superlens' and giving a perfect image (above images). Such resolution would enable biologists to see details inside a living cell not seen before. Experiments around the world have shown that the superlens idea is feasible – although challenging to achieve.

Super-resolving negative materials have promise in many technological areas. They would allow the optical etching of 10 times-finer features on silicon microchips, and 100 times more data to be stored on a DVD. Perhaps one of the most intriguing applications is to create a negatively refracting system that steers light around an object, concealing it to create a 'cloaking' device – as favoured by aliens in the TV series *Star Trek*. Using slightly different theoretical approaches, both Pendry and Ulf Leonhardt at the University of St Andrews published such schemes in 2006 (bottom right image). David Smith, now at Duke University in North Carolina, and colleagues went on to demonstrate the concept in two dimensions, using a series of concentric, structured copper rings to manipulate the path of microwaves.

Most of the devices relying on negative refraction so far have worked in the microwave region of the electromagnetic spectrum, and there are potential applications in making more sensitive antennas for devices like mobile phones, as well as stealth technology. The ground-breaking material of Smith and Pendry was structured at the millimetre scale. To make negative metamaterials that work for shorter wavelengths of light is more difficult: it requires much smaller structures, and they tend to lose a lot of the light during operation. Nevertheless, many research groups, including UK teams, are trying to push the technology towards the visible-light range, using ingenious nano-fabrication techniques to create arrays of nano-sized metal wires and rods, or thin layers of metals and nonconducting materials.

Today, the palette of candidate materials for such schemes is large – from nanostructured semiconductors and superconducting materials to liquid crystals and other molecular assemblies – so many ideas are being investigated. Negative refraction has thus brought into focus a new field of complex materials designed to manipulate light – and electromagnetic fields – in unusual ways. We can expect some fascinating, and probably unexpected, discoveries and applications in the near future.



Negative refraction can be used to create a cloaking device by bending light around an object

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Front cover:
A two-dimensional cloaking device made from a metamaterial
David R. Smith / Duke University

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