A new class of metamaterials

Conventional metamaterials that show negative refraction suffer from high intrinsic losses and are difficult to fabricate. A novel anisotropic semiconducting metamaterial offers a solution.

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The significant and varied interactions of materials and light enable the construction of technologically relevant devices — from computers to mobile phones, from televisions to MP3 players — which no doubt have shaped the modern world. Although there has been significant progress in harvesting light–matter interactions within the past hundred years or so, scientists were recently surprised to learn that the range of response from natural materials represents only a small fraction of what is theoretically possible, because artificially structured composites can extend material response to create materials with unparalleled properties. On page 946 of this issue, Anthony Hoffman and colleagues introduce a new material that facilitates further advances in electromagnetism1. They report the development of a semiconductor-based material, which exhibits all-angle negative refraction, thus adding to available materials for the construction of novel devices.

This work builds on exciting developments in a field — called

by Herzig et al. use 0.58-µm-diameter spheres of silica, but a key advantage of interfacial assembly is that only the surface properties of the particles matter. Herein lies a key distinction from bicontinuous phases that form in equilibrium mixtures of liquid with a molecular surfactant: in the latter case the separating membrane is fluid and its properties cannot readily be altered. When using particles as the interfacial agent, however, only their surface chemistry matters and the cores can be composed of (for instance) metal, semiconductor or polymer; they could have a catalytic function or they might respond to magnetic fields, temperature or chemical changes. The particles could perhaps be nanometre-sized or micrometre-sized, allowing precise tuning of the size of the interstitial pores between the assembled particles. Moreover, polymers could be used instead of simple liquids, and added nanoparticles might stabilize a bicontinuous structure that could be solidified and selectively etched. In contrast, if the two fluids were replaced with miscible ones, then the membrane might serve as a size-selective filter with enormous area. Miscible fluids have no interfacial tension, so this step would first require that the particles become permanently attached to one another, either covalently or by means of surprisingly strong van der Waals interactions between ligands1–3. Finally, on the basis of their computer simulations, Stratford et al.4 proposed that the bicontinuous material might be ideal for micro-reactors that expose oil-soluble and water-soluble reactants to one another over a large area while allowing reactants and products to flow in and out.

Mixing fluids and suspended particles might seem an uncontrolled approach to a designed structure, but experiments are showing that, with careful attention to interfacial and colloid chemistry, the process can lead to exquisite control of features at small and large scales simultaneously.

References
electromagnetic metamaterials — that has the potential to fill critical voids in the electromagnetic spectrum where material response is limited. These mesoscopic systems are built from the bottom up, at the unit cell level, to yield specifically designed electromagnetic properties. Individual components of these metamaterials respond resonantly to the electric and/or magnetic components of the electromagnetic field. In this way, metamaterials can be tuned to yield nearly any desired response at nearly any desirable frequency. In the past few years, metamaterials have been experimentally demonstrated over a very large portion of the electromagnetic spectrum.

The initial rapid growth and excitement towards metamaterials was due to their ability to achieve a negative index of refraction — a feat impossible to achieve with natural materials. A negative index of refraction, first proposed theoretically in 1968 by Victor Veselago, is only one of several laws of physics that is reversed when a material obtains a simultaneous negative electric and negative magnetic response. At the time of Veselago’s publication it was unknown how to obtain a single material that fulfils both of these criteria. Unfortunately, both Veselago’s work and the curiosity about the theory of negative refractive properties seemed to have passed out of the consciousness of many in the field.

Then, in 2000 David Smith and colleagues, building on the work of John Pendry, demonstrated experimentally an artificially structured composite material that exhibited a negative index of refraction. This verification of a previously unexploited realm of electromagnetism showed the importance of designer materials and resulted in a frenzy of activity by scientists working in optics, electromagnetics, physics, engineering and materials science.

The key to this demonstration was the realization that these new designer metamaterials permitted the construction of a single material with simultaneous negative electric permittivity and magnetic permeability (Fig. 1a). The crucial issue was to achieve the desired magnetic response, for which a material composed of planar metallic rings with gaps in them (so-called split-ring resonators) was used. The response from these split-ring resonators was predicted to be resonant and, if great enough, could achieve a negative permeability. These resonators, when combined with shaped metals for a negative electric response (Fig. 1a), resulted in a material with a negative refractive index.

The initial demonstration of a negative refractive index was performed at microwave frequencies. However, researchers moved quickly to demonstrate these effects at ever-increasing frequencies, from millimetre wave, terahertz and mid-infrared to near-infrared, and recently, the optical frequency regime. However, there was a problem lurking — loss. The metals used to create the aforementioned resonances are accompanied by a large amount of loss that peaks near the negative response. Although metamaterials had already been demonstrated at relatively high frequencies, the negative index exhibited by these structures was weak. It seemed that this would be an insurmountable problem for devices, because loss is a fundamental and undeniable property of metals.

Hoffman and colleagues, however, have demonstrated a different and elegant approach for the construction of artificial materials. Rather than sculpting metamaterials from metals, they have used semiconductors, thereby considerably reducing the loss. Their fabricated material operates on the principle of anisotropy, in which the electromagnetic response varies depending on the direction of the propagation. The authors fabricated alternating layers of semiconductors with conducting and insulating properties (Fig. 1b). Conducing layers then achieve a response to the electric component of incident electromagnetic fields. The net result is a new metamaterial that negatively refracts and operates at mid-infrared frequencies with a 9-µm wavelength.

Another prominent feature of their design is the demonstration of negative refraction for transverse-magnetic polarized light at all incident angles, thereby avoiding the necessity of constructing metamaterial elements for response to each spatial dimension.

However, potential applications of this new metamaterial still require considerable improvements. The semiconductor-based metamaterial does not yield a negative refractive index, but rather exhibits negative refraction similar to what has been achieved in photonic crystals. The loss is still relatively high and may need to be further reduced to enable efficient devices to be made. Nonetheless, these results are an impressive first step in extending the types of material that researchers may use for the construction of metamaterials. This design is significantly easier to construct than existing metamaterials, and may facilitate the incorporation of metamaterials into existing electro-optical semiconductor devices.

The outlook for metamaterial research and applications is bright, and the extended palette of available metamaterials demonstrated by Hoffman et al. will undoubtedly have a key role in this by providing access to new materials for novel electromagnetic responses.

References