WATER-BASED METAMATERIALS

Negative refraction of sound

Porous rubber microbeads suspended in a gel are found to exhibit a negative acoustic index of refraction, which makes these metamaterials promising for underwater acoustic applications.

Bogdan-Ioan Popa and Steven A. Cummer

The index of refraction characterizes the propagation of physical waves through materials. For hundreds of years, the refractive index of physical materials was thought to be an intrinsically positive quantity: as waves move from one medium to the next, they bend but maintain their direction relative to the interface between the two media (Fig. 1a). However, Victor Veselago showed in 1968 that the index of refraction could be negative[1]. Indeed, according to Snell's law, waves crossing the boundary between media reverse their direction relative to the interface[2] (Fig. 1b). This finding opened the door to a wide range of intriguing behaviour and led to research efforts aimed at designing so-called metamaterials with negative index of refraction for various classes of waves, including electromagnetic and acoustic waves. Writing in *Nature Materials*, Thomas Brunet and co-workers now show that designed resonant acoustic metamaterials made of soft silicone-rubber microbeads suspended in a water-based gel (Fig. 1c) act as isotropic negative-index fluids, suitable for underwater acoustic applications[3].

Negative-index metamaterials have attracted attention due to their potential applications as high-performance antenna components and as improved aberration-free lenses in particular. They have also been shown to restore the amplitude of evanescent waves that would otherwise decay exponentially away from the source[4], a quality relevant to the so-called superlenses (lenses capable of forming, in principle, infinitely sharp images).

Acoustic metamaterials (also called metafluids) aim at manipulating sound waves. To obtain metafluids characterized by a negative index of refraction, researchers have relied on exploiting rigid structures via careful control of their geometry[5–7]. However, most metamaterials reported so far work in air, and designing metafluids with mass density, fluid compressibility — and consequently, refractive index — beyond what is available in natural fluids, and adapting these designs to water-based applications has been difficult. In fact, sound propagating in dense fluids tends to couple strongly with any rigid structures, generating a complicated mix of elastic waves in the metamaterial. Although such a behaviour can be useful for some applications, it usually disrupts the desired effect[8,9]. For instance, significant effort has been dedicated to the development of

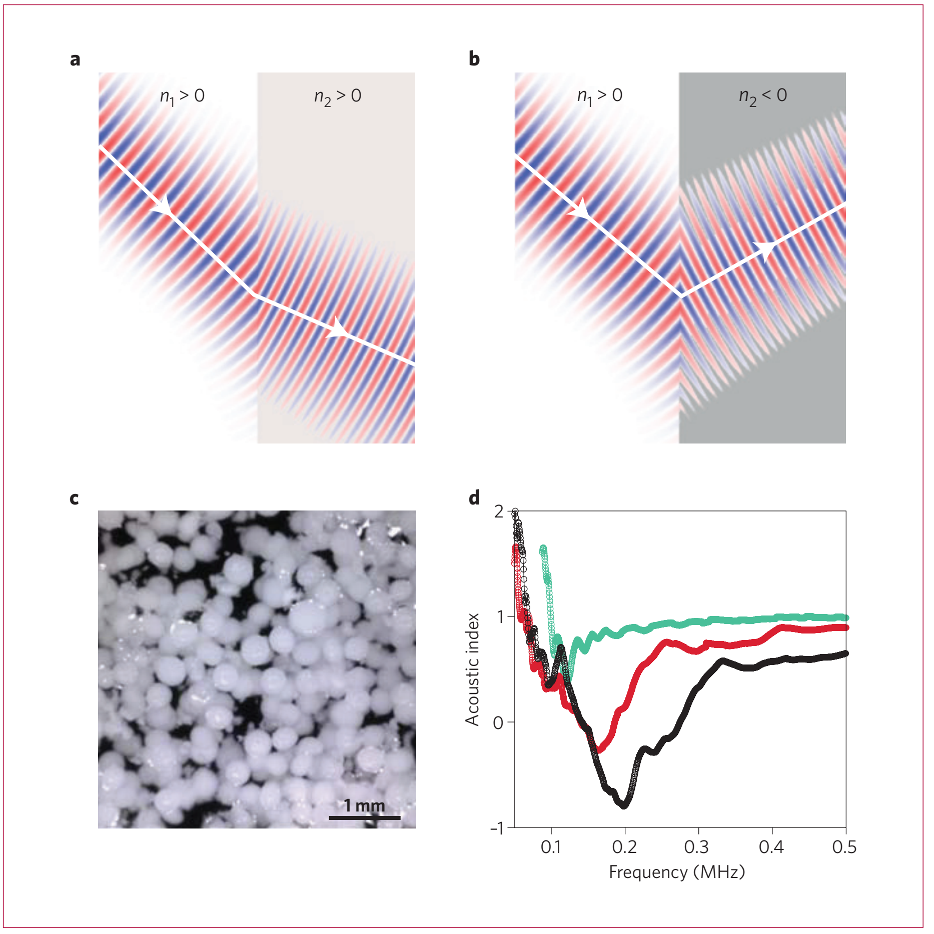

Figure 1 | Metafluids with negative index of refraction. **a**, When crossing the interface between fluids with positive index of refraction $n_2 > n_1 > 0$, acoustic waves are deflected to the opposite side of a plane that is perpendicular to the media interface. **b**, According to Snell's law, at the boundary between fluids with positive (left) and negative (right) index of refraction, acoustic waves are deflected at negative angles; this means that the refracted waves propagate on the same side of a plane that is perpendicular to the media interface as the incident wave. **c**, Optical microscopy image of the negative-refractive-index metafluid fabricated by Brunet and colleagues and composed of porous silicone rubber microbeads embedded in a water-based gel. **d**, Effective negative index of refraction for microbead volumetric concentrations of 0.2% (green), 15% (red) and 20% (black). For concentrated composites (20%), the refractive index approaches the value of −1. Panels **c**,**d** reproduced from ref. 3, Nature Publishing Group.

scattering-reducing coatings ('invisibility cloaks'), which require careful control of the sound field inside them. However, the sound incident on the boundary between the surrounding fluid and the cloaks' rigid structure generate significant shear waves in the latter. The resulting mix of pressure and shear waves is much harder to control and typically gives rise to additional scattering that cancels the cloaking effect.

Brunet and colleagues solved this problem by avoiding rigid and structured materials altogether. Instead, they used an ensemble of porous silicon rubber microbeads with a mean radius of 160 µm, randomly dispersed in a water-based gel matrix that can simulate the acoustic behaviour of water. These microbeads exhibit monopole and dipole acoustic resonances strong enough to drive the effective refractive index of their composite to a negative value in a finite frequency band (140–275 kHz). The refractive index is measured directly by sending Gaussian pulses through metafluid samples of various thicknesses and observing the wave phase as sound exits the samples.

The magnitude of the acoustic response and, consequently, the effective material properties of the composite are controlled by varying the concentration of microbeads. For a microbead concentration of 20% of the total volume, Brunet and colleagues report a refractive index approaching the value of –1 (Fig. 1d). This has been a long-standing research target because it is the critical value at which superlensing occurs[4]. Importantly, the random distribution of the microbeads inside the metafluid makes it inherently isotropic or direction-independent. This is a desirable property in many applications, such as in acoustic imaging, but is hard to realize using rigid and periodic structures.

Naturally, the current implementation of this new class of metafluid has some shortcomings. Although these structures are promising for water-based applications, their applicability may be limited due to their imperfect impedance matching with water. Consequently, less than 1% of the energy carried by an incident sound wave coming from a water background would enter the material. In addition, as is the case with most passive negative-index materials, the resonant nature of the metafluid of Brunet and colleagues leads to significant energy absorption in the porous rubber, and acoustic waves are not able to propagate beyond one wavelength before attenuating. Finally, although orders of magnitude better than other bubbly media, the metafluid life span does not go beyond several days.

Nevertheless, the metamaterial design approach of Brunet and co-workers shows great potential for obtaining negative acoustic indices of refraction in metafluids, and it could be developed further for obtaining unusual values for other acoustic parameters. These include near-zero mass density and bulk modulus, which are properties relevant for advanced design techniques such as transformation acoustics[10,11] as they allow a high level of control over the propagation of acoustic waves. In this context, the work of Brunet and colleagues represents a significant step towards realizing metafluids for acoustic-wave control in underwater applications. ❐

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VAN DER WAALS HETEROSTRUCTURES

Mid-infrared nanophotonics

The confinement and scattering lifetimes of graphene plasmons are improved when graphene is sandwiched between layers of thin hexagonal boron nitride. This finding should pave the way for nanophotonic applications in the low-loss regime.

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The confinement and subsequent manipulation of light at sub-diffractional nanoscale dimensions using surface plasmons is at the heart of the fields of nanophotonics, plasmonics and metamaterials. Relevant research has exploited different materials in an effort to decrease the losses in such systems. It has recently been shown that sandwiching graphene between two (insulating) hexagonal boron nitride (hBN) crystals dramatically improves the mobility of charge carriers and significantly increases graphene's electronic quality, allowing its intrinsic direct current (d.c.) transport properties, especially near the Dirac point, to be revealed[1]. Now, Frank Koppens and colleagues report in *Nature Materials* that similar enhancements can be seen in the plasmonic properties of graphene when encapsulated in such heterostructures[2] (Fig. 1a). In particular, the researchers demonstrate that hBN/graphene/hBN heterostructures lead to reductions in plasmon losses and to exceptional light confinement, the latter provided by the birefringent, dielectric properties of hBN (ref. 2).

Most of the work in plasmonics has focused on noble metals (in particular silver and gold), but it is now apparent that they suffer from high optical losses, which combined with their short free-space operational wavelengths, result in limited propagation lengths for waveguides, broad resonance linewidths, low efficiencies of optical devices, and sub-diffractional confinement that is limited to length scales about one order of magnitude smaller than the free-space wavelength. To circumvent these limitations, efforts have centred around the use of alternative materials for nanophotonic applications[3,4]. Among the various candidates, graphene has attracted much attention[5] due to its monolayer