METAMATERIALS

# Neither solid nor liquid

A new design for elastic metamaterials that can behave either as liquids or solids over a limited frequency range may enable new applications based on the control of acoustic, elastic and seismic waves.

John Page

If you can design the properties of a material from the smallest scale up, then the possibilities in shaping its properties are almost endless. This is why research in metamaterials — artificially structured materials with electromagnetic, acoustic or elastic properties not found in nature — continues to grow. Writing in *Nature Materials*, Zhao-Qing Zhang and colleagues now describe a new elastic metamaterial that, depending on the frequency and direction of propagation, can behave like an elastic solid or a fluid[1].

The origin of most metamaterials' unusual behaviour is small building blocks whose size is much smaller than the wavelength of the acoustic or optical waves they are interacting with. It is therefore possible to define average properties for the metamaterial that mimic those of a homogeneous regular material, but which are not necessarily known from nature. One example is superlenses, which promise almost unlimited optical-imaging resolution and therefore beat the performance of lenses made from any natural material.

However, although such electromagnetic metamaterials have been studied intensively, elastic metamaterials have seen much less attention. This is despite the fact that elastic materials offer a richer behaviour, because they enable both longitudinal and transverse waves to propagate. They therefore combine characteristics of optical and acoustic waves.

The metamaterial designed theoretically by Zhang and colleagues traces its roots back to 2004, when an acoustic double-negative metamaterial for longitudinal waves was proposed, made by embedding soft silicone rubber spheres in a fluid matrix[2]. In this acoustic double-negative metamaterial, acoustic resonances of the spheres overlap, so that for a narrow range of frequencies both the bulk modulus and density are negative. A negative bulk modulus means that the medium expands when compressed, and a negative mass density means that the spatially averaged acceleration and force are out of phase with each other. As a result, the wave vector is real but negative, leading to propagating waves in a so-called negative dispersion band. Since then, a number of acoustic double-negative metamaterials have been shown theoretically and experimentally using two different types of scattering unit — one to ensure negative modulus and the other to ensure negative density[3,4]. By contrast, if only one of either the modulus or density is negative, the waves are evanescent and therefore do not propagate, giving rise to very large reflection and small transmission coefficients, which can be exploited for sound-insulation applications[5,6].

Zhang and colleagues now take the study of metamaterials in a new direction by discovering a novel way of constructing an elastic solid that exhibits double-negative behaviour. The key to their discovery is the

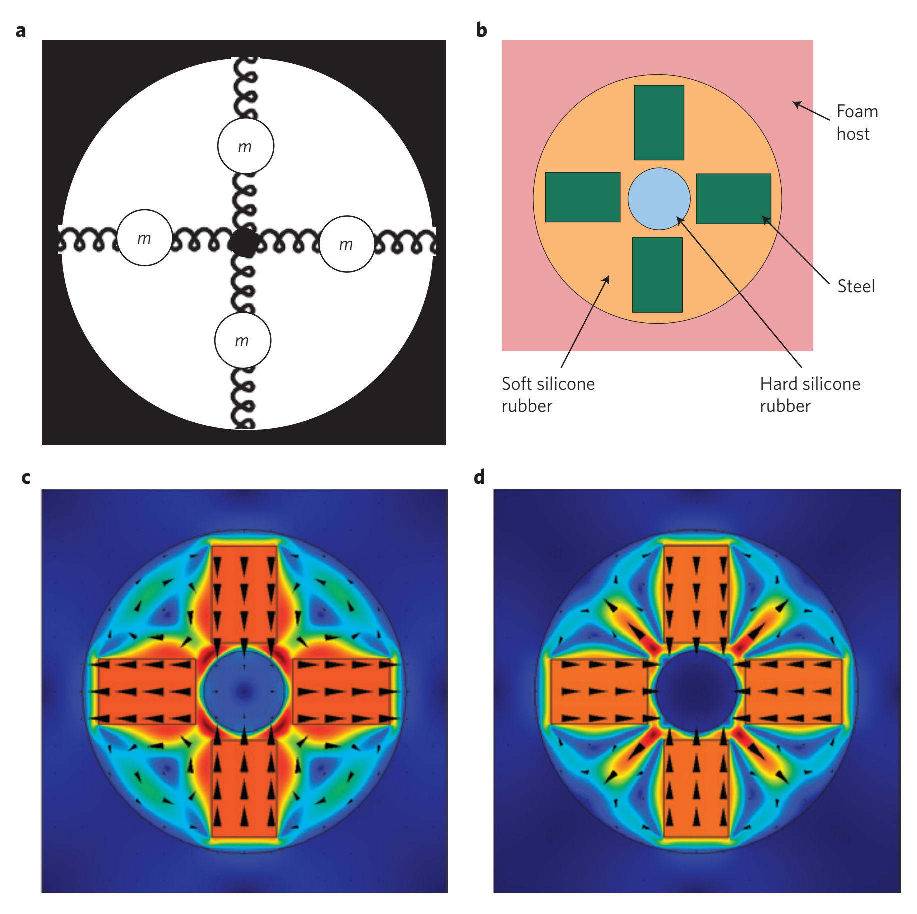

**Figure 1 |** Hybrid elastic metamaterials. **a**, Hybrid elastic metamaterials that show both fluid- and solid-like behaviour conceptually consist of building blocks made of masses ($m$) and springs. **b**, The proposed practical implementation uses steel, rubber and foam arrangements. **c**,**d**, Examples of quadupolar (**c**) and monopolar (**d**) resonances of the steel rods for the structure illustrated in **b**. The colours indicate the magnitudes of the displacements (red and blue correspond to large and small values, respectively), with arrows specifying the displacement vectors. Figure reproduced from ref. 1.

design of a complex building block that is a practical realization of a system of four coupled masses and springs, as illustrated in Fig. 1. In their approach, this unit cell consists of four rectangular steel rods that are arranged around a central hard silicone rod and contained inside a larger soft silicone rod, with the entire unit embedded in a soft foam matrix. When these units are arranged in a simple square lattice, this two-dimensional system has a quite wide range of frequencies in which the effective dynamic mass density is negative owing to a dipolar resonance of the four steel rods. Within this range of frequencies, the relative motion of the steel rods also supports monopolar and quadrupolar resonances, leading to two narrower frequency regions where one of the effective elastic moduli of the crystal is negative. As a result, in one of these frequency bands only longitudinal waves can propagate, with shear waves being evanescent, implying that the solid behaves as a liquid in this frequency range. The second negative band allows only longitudinal waves to propagate along one of the principal directions of the crystal and only shear waves in the other principal direction, leading to a material with a fluid-solid mixed behaviour and very unique anisotropic properties that have not previously been shown to be possible in solids.

The way that this double-negative behaviour has been achieved, by tuning monopolar and quadrupolar resonances to occur in the same range of frequencies as a dipolar resonance, is very innovative, and the results are likely to initiate significant new developments, both experimental and theoretical, in future metamaterials research. Zhang and colleagues also point to possible applications, which they say may include wave polarizers and new ways of controlling elastic and seismic waves, including negative refraction and superlensing of both longitudinal and transverse waves. ❐

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GRAPHENE

# The long and winding road

The main challenges to face before graphene can become part of realistic applications were discussed at a recent dedicated meeting.

Mark S. Lundstrom

These days articles about graphene need little introduction. Its unique electronic, thermal and mechanical properties have sparked enormous scientific interest. Much of this interest in graphene comes also from the expectation that this material will have a profound technological impact. But how far along the way to applications are we? And what are the most promising applications? These were the questions addressed at the conference organized by Nature Publishing Group — 'Graphene: The Road to Applications' — that took place in Boston from 11 to 13 May.

The meeting gathered scientists and engineers from academia, government, and large and small companies to assess the state of graphene technology. Rolf Landauer wrote in 1996 about the "need for critical input"[1]. This meeting provided a rare opportunity for dialogue between researchers exploring graphene science and technology and those who understand the broader technology landscape. More specifically, aside from presentations by leading scientists in the field surveying the latest results, each session also included a 'sanity check' by someone familiar with technological developments and the challenges that each type of technology poses. Overall, the meeting gave attendees an opportunity to think more generally about how we turn new science into new technologies.

The most outstanding aspects that emerged, at least in the eyes of someone working on electronic materials and devices like myself, were the remarkable progress in manufacturing large areas of high-quality graphene and the advances leading to applications such as displays and electronic circuits. Rod Ruoff (University of Texas at Austin) discussed the large-area growth of graphene on metal substrates, a method that could enable many applications and one that received a lot of subsequent attention in the meeting. In just seven years, the field has progressed from exfoliating small flakes[2] to the direct synthesis of large-area high-quality crystals[3–6] (Fig. 1). The fact that graphene is highly conductive, transparent, mechanically strong and flexible opens up several possibilities. Roy Gordon gave an overview of the applications for transparent conductors and compared the various existing technologies with graphene. An important message from his presentation was that it is not possible to elect a single best material. It depends very much on the type of application. For example, graphene doesn't excel in terms of the conductivity divided by optical absorption figure of merit, but its combination of properties — high conductivity, transparency and flexibility — could enable applications such as flexible displays and solar cells.

Phaedon Avouris (IBM T. J. Watson Research Center) sent a very clear message regarding the kinds of electronics in which graphene is or is not likely to be successful. His view, shared by many others, is that graphene is not a suitable material for digital switches. The absence of a semiconductor bandgap is the main obstacle, and although progress has been made to induce a gap, it is still very unclear how long it will take before this can be achieved and whether or not it would produce a superior digital switch. On the other hand, analogue radio-frequency transistors are possible, and some impressive new results were discussed by scientists from IBM and Hughes Research Laboratories[7–9], suggesting that graphene could be successfully used in low-power