Controlling sound with acoustic metamaterials

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Abstract | Acoustic metamaterials can manipulate and control sound waves in ways that are not possible in conventional materials. Metamaterials with zero, or even negative, refractive index for sound offer new possibilities for acoustic imaging and for the control of sound at subwavelength scales. The combination of transformation acoustics theory and highly anisotropic acoustic metamaterials enables precise control over the deformation of sound fields, which can be used, for example, to hide or cloak objects from incident acoustic energy. Active acoustic metamaterials use external control to create effective material properties that are not possible with passive structures and have led to the development of dynamically reconfigurable, loss-compensating and parity–time-symmetric materials for sound manipulation. Challenges remain, including the development of efficient techniques for fabricating large-scale metamaterial structures and converting laboratory experiments into useful devices. In this Review, we outline the designs and properties of materials with unusual acoustic parameters (for example, negative refractive index), discuss examples of extreme manipulation of sound and, finally, provide an overview of future directions in the field.

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Acoustics is the branch of science that studies the propagation of sound and vibrational waves. Audible acoustic waves are ubiquitous in our everyday experience: they form the basis of verbal human communication, and the combination of pitch and rhythm transforms sound vibrations into music. Waves with frequencies beyond the limit of human audibility are used in many ultrasonic imaging devices for medicine and industry. However, acoustic waves are not always easy to control. Audible sound waves spread with modest attenuation through air and are often able to penetrate thick barriers with ease. Electronic devices are able to amplify and manipulate sound signals, but only after they are converted to electronic form. New tools to control these waves as they propagate, in the form of new artificial materials, are extremely desirable.

Materials have been used to control wave propagation for centuries, and optics is a prime example. By precisely shaping lenses, it is possible to make various optical devices for focusing and manipulating light. In nature, this strategy is demonstrated by, for example, the lenses in animal eyes, which are used to manipulate light, and by the melon organ that Cetaceans use to focus sound waves for underwater echolocation. These organs use relatively simple materials to achieve control of wave propagation. By designing and engineering artificial materials with more complex properties, unprecedented functionalities can be obtained. The science of designing and engineering such materials is the subject of the field of metamaterials (BOX 1), and the subset of this field, in which the aim is the control of acoustic waves, is acoustic metamaterials.

Metamaterials are artificial structures, typically periodic (but not necessarily so), composed of small meta-atoms that, in the bulk, behave like a continuous material with unconventional effective properties. The science of waves propagating in periodic structures goes back decades[1]; however, our modern appreciation of the use of engineered structures to control wave properties began with photonic[2] and phononic[3] crystals. Research in this area rapidly expanded with the understanding that relatively simple, but subwavelength, building blocks can be assembled into structures that are similar to continuous materials, yet have unusual wave properties that differ substantially from those of conventional media.

In acoustics, the first artificial metamaterial[4] used rubber-coated spheres to create locally resonant and deeply subwavelength structures that responded to incident acoustic waves. An assembly of these meta-atoms into a bulk metamaterial exhibited peculiar, but useful, acoustic properties. Building on this work, and taking inspiration from developments in electromagnetism[5], the field of acoustic metamaterials has focused on developing artificial structures that are capable of controlling the propagation of sound in new ways, made possible by the creation of unusual material properties. These efforts have been successful on many fronts. For instance, it is now possible to design acoustic metamaterials that can acoustically conceal an object, acting as cloaks of 'inaudibility'. Also, acoustic metamaterials with a negative refractive index can be designed to bend sound the 'wrong' way when insonified by a loudspeaker, enabling new ways of focusing and shaping sound fields.

Over the past 15 years, the field of acoustic metamaterials has branched out in many directions, and it has been shown that acoustic waves can be manipulated and controlled in ways not previously imagined. In this Review, we describe the advances in the field and identify the technical challenges and possible future directions for research. We focus on metamaterials designed to control the propagation of acoustic waves in fluids such as air and water. Beyond this topic, there is ever-expanding research on elastic metamaterials that control vibrations, waves and the motion of solid materials[6]. Another subject that exceeds the scope of this Review is phononic crystals, materials in which resonant scattering of periodic structures can create wave-band structures with unusual, but useful, properties[3].

Box 1 | **Metamaterials**

The term metamaterial is now broadly applied to engineered materials, usually composites, in which an internal structure is used to induce effective properties in the artificial material that are substantially different from those found in its components. The term originated from the field of electromagnetic materials, in which metamaterials were engineered to control light and radio wave propagation, and is used specifically to indicate materials composed of conducting structures that, by generating controlled electric and magnetic dipole responses to applied fields, result in a negative refractive index[152]. This property is not found in any known natural material. The term metamaterial is not very precisely defined, but a good working definition is: a material with 'on-demand' effective properties[153], without the constraints imposed by what nature provides.

For acoustic metamaterials, the goal is to create a structural building block that, when assembled into a larger sample, exhibits the desired values of the key effective parameters — the mass density and the bulk modulus — as discussed in BOX 2. The most common approach to constructing acoustic metamaterials is based on the use of structures whose interaction with acoustic waves is dominated by the internal behaviour of a single unit cell of a periodic structure, often referred to as a meta-atom. To make this internal meta-atom response dominant, the size of the meta-atom generally needs to be much smaller (about ten or more times smaller) than the smallest acoustic wavelength that is being manipulated. By contrast, in so-called phononic (for sound) or photonic (for light) crystals, unusual wave behaviour is created via the mutual interaction (multiple scattering) of unit cells whose dimensions are typically about half of the operating wavelength (although recent work[40] has shown how local and multiple scattering responses can be combined in a single structure to achieve interesting effects, blurring the line between these different classes of artificial media).

This subwavelength constraint ensures that the metamaterial behaves like a real material in the sense that the material response is not affected by the shape or boundaries of the sample. This equivalence will not hold for periodic materials in the phononic crystal regime, in which long-range interactions and spatial dispersion dominate the response. Instead, when the material response is determined by the local meta-atom response, effective bulk-material properties can be defined and estimated from simulations or measurements of very small samples. The fact that the effective parameters of a metamaterial composed of thousands or millions of meta-atoms can be determined using simple and efficient methods is one of the most powerful aspects of the metamaterial approach to artificial material design.

Metamaterials with negative parameters

Sound-wave propagation is controlled by the mass density and the bulk modulus of a material (BOX 2). In conventional media, both of these parameters are positive and cannot be easily altered because they are directly associated with the chemical composition and the microstructure of the material. However, if metamaterials are constructed using resonant subwavelength meta-atoms that enhance sound–matter interaction, then it is possible to engineer the wave properties to obtain values of the effective acoustic-material parameters that are not observed in nature. One of the most unusual regimes for acoustic metamaterials arises when the real parts of the effective mass density and bulk modulus are negative in the same frequency range. This regime is analogous to negative-index metamaterials for electromagnetic waves. These materials, developed in the early 2000s, use metallic structures that generate out-of-phase (negative) electric and magnetic dipole responses to incident electromagnetic fields, leading to a negative phase velocity and a negative index of refraction[7,8].

Materials with tailored parameters are attractive for applications such as steering of waves and super-resolution imaging. In particular, there has been a focus on negative parameters and imaging, which has led an initial surge in research into acoustic metamaterials. In what follows, we discuss various illustrative examples in which artificial materials are engineered to have parameters with negative or near-zero values (FIG. 1). These media enable metamaterials designers to construct devices with surprising effects, such as energy flow in the direction opposite to that of the wave vector or sound propagation without phase variations. Such materials allow for the guiding and focusing of acoustic signals at diffraction-unlimited scales.

Acoustic metamaterials were initially created for use in sound-attenuating applications[4]. The first acoustic meta-atoms were spherical metal cores coated with a soft rubber shell packed to a simple-cubic lattice in a host material, which could exhibit a Mie-type resonance frequency far below the wavelength-scale Bragg resonance frequency of the lattice[4,9–11].

Depending on the underlying mechanical motion in such resonances, negative effective values of the mass density and of the bulk modulus can be obtained. In the context of spherical and cylindrical scatterers, monopolar modes give rise to a resonant response of the bulk modulus, whereas the dipolar modes create resonances in the mass density[12]. Numerical simulations of rubber spheres suspended in water, which have recently been experimentally verified[13], show that these modes can coexist, leading to a band in parameter space characterized by a negative index of refraction[13,14].

Other architectures for acoustic metamaterials involve segments of pipes and resonators in the form of open and closed cavities. In 1922, a seminal paper by G. W. Stewart[15] that discusses lumped acoustic elements for filter applications characterized these structures as simple oscillators. However, these elements were not used to form artificial media until 2006, when metamaterials composed of a waveguide loaded with an array of coupled Helmholtz resonators were constructed. Helmholtz resonators are closed cavities connected to a waveguide via a narrow channel (FIG. 1b). At their collective resonance frequency, a low-frequency stopband is formed, the origin of which can be traced back to the negative effective bulk modulus K — which occurs when a parcel of fluid compresses under dynamic stretching — of the loaded waveguide[16]. Altering the volume of the cavity results in a change in its resonance frequency. Thus, attaching a series of open side-branches to the waveguide produces resonators with very low resonance frequency, and sound waves are entirely reflected up to the frequency at which the sign of the bulk modulus changes[17]. Designing an entire panel of these open side-branches creates a so-called 'acoustic double fishnet' structure that sustains this attenuation band for a wide range of frequencies and angles, and that can provide acoustic shielding to block environmental noise[18,19].

Box 2 | **Acoustics principles and material parameters**

Acoustics is the science of vibrational wave propagation in fluids such as air or water, including the familiar audio frequency waves in air that we know as sound. For the purposes of controlling sound propagation with acoustic metamaterials, a key step is the identification of the material parameters that control wave propagation. Linear acoustics describes small pressure fluctuations that form a travelling wave of low intensity. One defining equation of acoustics comes from Newton's second law ($F=ma$) and connects the acoustic particle perturbation velocity $\mathbf{v}$ to the acoustic pressure p as

$$\rho\frac{\partial \mathbf{v}}{\partial t}=-\nabla p \qquad (1)$$

Here the scaling constant is the fluid mass density ρ, which is one of the two critical constants that control acoustic wave propagation. To connect the motion of a non-viscous and stationary (not flowing) fluid with its compression and expansion, we express the conservation of mass through the continuity equation. Assuming that acoustic wave propagation can be regarded as isentropic (adiabatic and reversible with constant entropy), which means that thermal processes can be neglected, the continuity equation is

$$\frac{\partial p}{\partial t}+K\nabla\cdot\mathbf{v}=0 \qquad (2)$$

Here the scaling constant is the bulk modulus K, which is essentially the compressional stiffness of the fluid, and which is the second of the two critical material constants. When these two equations are combined into a single equation for the pressure p, the scalar wave equation emerges

$$\frac{\partial^2 p}{\partial t^2}=\frac{K}{\rho}\nabla^2 p \qquad (3)$$

The acoustic wave velocity, which controls changes in wave direction at interfaces, is thus given explicitly by $c=\sqrt{K/\rho}$. It can also be shown that the acoustic wave impedance, which controls wave reflection and transmission amplitudes at interfaces, and which is defined as the ratio of pressure to fluid velocity in the wave, is $Z=p/v=\sqrt{K\rho}$. Therefore, the fluid mass density ρ and bulk modulus K are the two fluid parameters that control the propagation of acoustic waves. Consequently, these are the parameters that we wish to control when designing metamaterial structures.

Although there are some fundamental differences between acoustic and electromagnetic waves (such as their longitudinal and transverse natures, respectively), the two acoustic parameters are in many ways analogous to the two parameters that control electromagnetic wave propagation, the electric permittivity and the magnetic permeability. This is why the field of acoustic metamaterials has been able to borrow concepts so successfully from electromagnetic metamaterials.

Insight into the nature of acoustic responses facilitates additional metamaterial design approaches. If a fluid segment accelerates out of phase with respect to the acoustic driving force, then a negative mass density is possible, as implied by equation (2) in BOX 2. This acoustic response can be created using membranes fixed at the rims of a tube or an array of holes[20–22] (FIG. 1c). Furthermore, changing the size of the membranes or loading them with a mass makes it possible to alter the resonance over a spectrally extended range. If either the effective bulk modulus K or the mass density ρ are negative, then fully opaque materials with purely imaginary phase velocities are possible. However, in a similar manner to the coexistence of monopolar and dipolar bubble resonances, composing a structure of Helmholtz and membrane units for which ρ and K are simultaneously negative (FIG. 1d) creates a band in which energy can propagate instead of attenuate, as happens when only one of these parameters is negative. This energy propagates with a negative refractive index, which causes energy to flow in the direction opposite to that of the wave[23]. This counter-intuitive effect forces an incident wave impinging on such a structure to refract in the opposite way compared to what happens with natural materials, enabling new ways of controlling sound waves.

Several other metamaterial-based approaches for realizing unusual acoustic refraction have been demonstrated. By coiling up space with labyrinthine structures, the sound propagation phase is delayed such that band folding with negative dispersion ($\rho<0$ and $K<0$) is compressed towards the long-wavelength regime[24–26]. This approach has the advantage of creating negative refraction with a relatively simple metamaterial structure. Another strategy to obtain negative refraction relies on stacking several holey plates to form an anisotropic structure with hyperbolic dispersion. Owing to the hyperbolic shape of the dispersion contours, refraction of sound can take place at negative angles for almost any direction of incident sound[27,28]. Finally, an interesting regime in which the effective mass density is close to zero has recently been explored and tested for advanced phase control and super-squeezing of sound waves in narrow channels[29,30]. Such media transmit sound waves with no distortion or phase change across the entire length of the material and enable new sound imaging and detection modalities.

Most of the acoustic metamaterial designs described above make use of periodic structures. The same is true for the overwhelming majority of acoustic (and electromagnetic) metamaterials, primarily for ease of fabrication. But given that the concept of acoustic metamaterials is based on the local, internal mechanical response of the structure (BOX 2), there is no reason why metamaterials cannot be made from aperiodic architectures, provided the average number of inclusions per unit volume remains fairly uniform on the scale of a wavelength. This idea is beginning to be explored using metamaterials composed of a soft matrix containing an unstructured array of bubbles of a second material[13,31,32].

Implementing all of these different acoustic metamaterial designs requires techniques to compute the effective acoustic properties of a given structure. Such

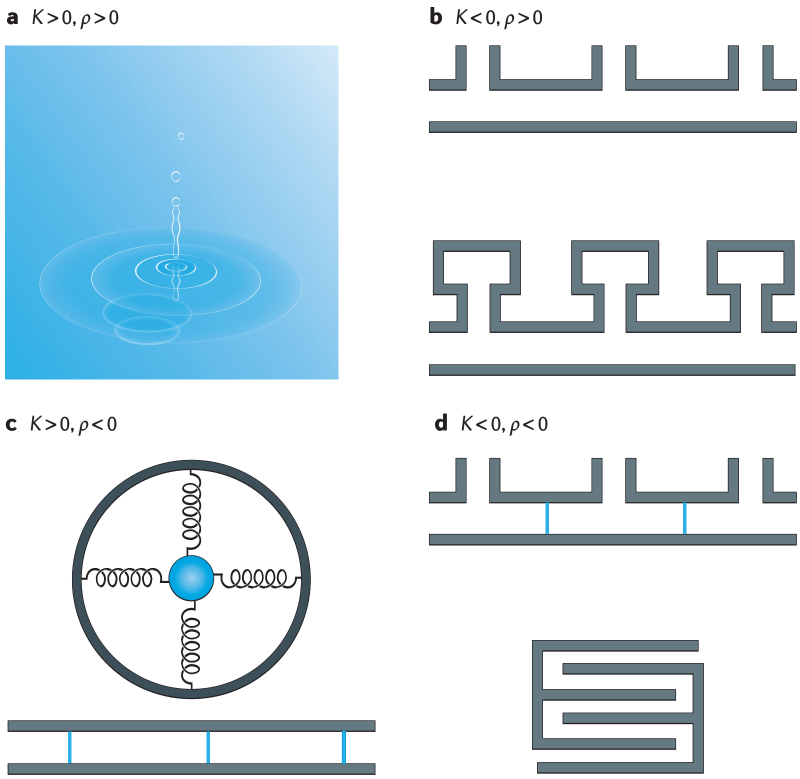

Figure 1 | **Parameter space for mass density ρ and bulk modulus K. a** | For all known natural materials, the acoustic constitutive parameters are strictly positive ($K > 0$ and $\rho > 0$). **b** | Metamaterials with $K < 0$ and $\rho > 0$ can be obtained with open and closed cavity resonators[16,17]. **c** | Metamaterials with $K > 0$ and $\rho < 0$ are typically membranes or coated-bead structures[4,20]. Along the positive K axis ($\rho = 0$), super squeezing of sound is possible[29,30]. **d** | Space-coiling or coupled filter-element structures give rise to double-negative ($K < 0$ and $\rho < 0$) metamaterials[24–26].

techniques have been developed to describe composite materials[33,34] and are suitable for many types of artificial media, providing the valuable possibility of efficiently describing the material response in terms of its effective mass density and bulk modulus.

Materials designs for acoustic imaging. Imaging has been repeatedly mentioned as a target application for many of the acoustic metamaterials described above. Acoustic imaging beyond the diffraction threshold is challenging but essential for detecting features on scales much smaller than the wavelength of the incident wave. Small cracks in structures such as buildings, and early stage tumours scatter not only weak far-field acoustic radiation, but also evanescent waves that are associated with their subwavelength details (FIG. 2a). To obtain the highest imaging resolution, near-field techniques are used to collect and exploit the evanescent fields that contains the minuscule features in the nearest proximity to the object. A prominent technique for imaging in this context, originally introduced for light waves, was brought forward by John Pendry's 'perfect lens'. He suggested that a material with a negative index could amplify evanescent waves emitted by a source in such a way that, in principle, unlimited imaging resolution might be possible[35]. This idea, illustrated in FIG. 2b, has inspired the implementation of perfect lenses for acoustic waves as well, and suggests that negative refraction of sound as well as a negative mass density in the quasi-static limit may lead to the desired result[36,37]. Although this concept is noticeably hampered by material and viscous losses, some experiments have shown promising results[38–40].

Anisotropic metamaterials that extend deeply into the near-field of emitting subwavelength features can convert the evanescent information of an object into propagating waves via magnification (FIG. 2c). This behaviour has been predicted by numerical simulations of lenses containing locally resonating rods and experimentally observed for perforated fin structures, which demonstrates that acoustic far-field imaging beyond the diffraction limit is possible[41,42]. The core concept of such imaging methods builds on dispersion relations that must be able to carry evanescent waves and expand them into far-field radiation, as defined by the anisotropy of the given material. Another technique, inspired by the canalization principle[43], has been used in holey-structured acoustic metamaterials. Fabry–Perot-type resonances within the apertures can be sustained for both propagating and evanescent wave excitation. If an object emits sound at this resonance frequency, deeply subwavelength features can be funnelled through these structures and mapped onto acoustic images[44–46]. Channelling, or 'squeezing', the near-field through a slab has recently been shown to be possible in materials with a near-zero mass density[47,48].

There are some alternative strategies to control and image sound at subwavelength scales. Time-reversal techniques, for instance, are powerful ways to enable subwavelength focusing in general. As in many other metamaterial contexts, these imaging functionalities were first successfully demonstrated for electromagnetic waves[49,50] but have been subsequently extended to acoustic waves through a series of experiments using soft-drink cans[51,52]. In this approach, the temporal response in an array of subwavelength acoustic resonators is recorded. Then, these data are flipped in time and radiated back, such that sub-diffraction-limited focal spots are generated at their origin.

Another strategy relies on the excitation of guided acoustic modes within a fluid slab (FIG. 2d). Numerical calculations predict that a slow medium with a relatively high positive index would support trapped modes of pronounced flat dispersion. This flat dispersion entails a broad spectrum of parallel momentum and is sufficient to reconstruct spatial details that are smaller than half the wavelength[53]. A related approach uses an acoustic metamaterial that is designed to transmit only subwavelength information to create edge-based acoustic images with resolutions that are much smaller than the wavelength[54].

Many of the acoustic structures used in the studies described above involve relatively narrow fluid propagation channels surrounded by solid material. In this scenario, there can be substantial viscothermal dissipation[55] in boundary layers on the solid surfaces, which highlights the critical issue of loss and absorption in these acoustic metamaterials. Loss and absorption can be limiting factors in metamaterial applications, and devising approaches to minimize or mitigate them remains an active area of research, as discussed below. This deficiency can be turned into an asset, however, when used to create metamaterials that maximize sound absorption. The challenge of creating thin, sound-absorbing materials is the focus of an active research area[56] that includes the study of controlled thin-channel resonators[57] and lossy resonant membranes[58,59].

Metasurfaces. The quest to enhance wave–matter interactions and to manipulate waves using the smallest possible amount of space has led to the exploration of acoustic metasurfaces. Metasurfaces belong to the family of wavefront-shaping devices with thicknesses much smaller than the wavelength. In acoustics, their building units are, for example, coiled elements, Helmholtz resonators or resonant membranes that enable wave steering and focusing through designs based on spatial phase gradients[60–62]. Strictly speaking, metasurfaces are monolayer materials that are able to impart an arbitrary phase and amplitude modulation to the impinging wave, and constitute an alternative to bulky crystals, whose performance may be hindered in some cases by material losses. These ultra-thin materials are able to support curious effects, such as scattering of waves with anomalous reflection and refraction angles[63,64]. Akin to the principle of a graded-index lens, a properly designed metasurface can also act as an ultra-thin, planar acoustic lens whose focal length and position is engineered through the in-plane phase profile[65]. On account of these effects, suitably designed metasurfaces with a 2π phase span could potentially generate unconventional wave steering abilities. Metasurfaces thus provide an elegant way to control and focus sound using the thinnest and, hence, smallest possible structure.

Transformation acoustics and cloaking

The development of materials with unusual constitutive acoustic parameters has led to new ways to mould the flow of sound. One of the most powerful tools that can be used to design materials to control sound (including those with the ability to hide or cloak objects from sound), and one that ultimately relies on acoustic metamaterials for physical realization, is the concept of transformation acoustics. Like many ideas in metamaterials, this idea emerged from concepts that originated in electromagnetism and optics. The coordinate-transformation invariance of the Maxwell equations for electromagnetism implies that any coordinate-transformation-based deformation of electromagnetic fields, such as stretching and squeezing, can be physically created with the right distribution of the electromagnetic material properties[66]. The material properties that are required to obtain such effects are usually complicated and difficult to implement, but the generality of the concept implies that even complex deformations of electromagnetic fields, such as those required for cloaking[66], can in principle be obtained using the right materials; such deformations have been experimentally demonstrated at radio[67,68] and optical frequencies[69].

This concept of transformation optics raised the question of whether similar manipulation can be applied to other types of waves, in particular acoustic waves[70], where it would have many potential applications. This question was ultimately answered, first in two[71] and then in three[72] dimensions, by showing that the equations of linear acoustics take the same form as certain equations governing electromagnetic waves. In three dimensions, the analogous equations are those of electric current and conductivity, which have been shown to be transformation invariant[73]. Interestingly, and in contrast to electromagnetism, transformation acoustics theory is not independent of the velocity of the background fluid[74], although at low flow speeds the effect is fairly modest.

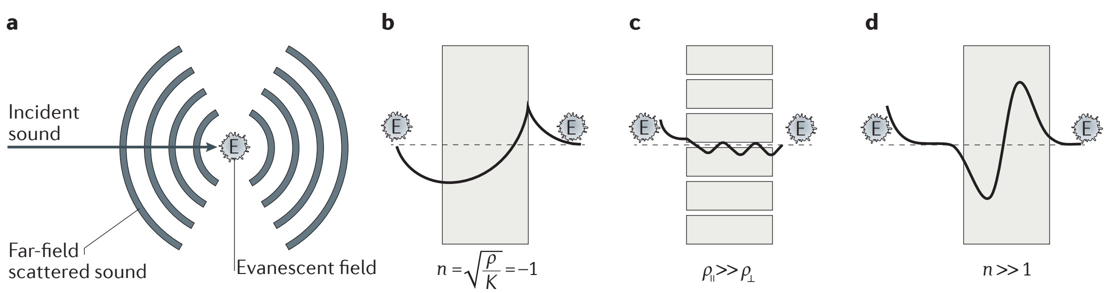

Figure 2 | **Subwavelength imaging with acoustic metamaterials. a** | When an incident acoustic wave impinges over a tiny object such as that indicated by the letter 'E', sound is scattered in all directions as a result of propagative radiation[45]. The evanescent field, which is concentrated in the near-field of the object, is characterized as a wave with high parallel momentum that exhibits exponential decay with distance. Several types of metamaterial lenses can be used to project these subwavelength features onto images. **b** | Amplifying evanescent waves through a negative-index ($n<0$) 'super lens' can create images with perfect resolution on the slab far-side[35,36,39]. **c** | Anisotropy of the mass density allows the coupling of near-fields, as emitted by subwavelength objects, to propagating waves. The stronger the anisotropy, $\rho_{\parallel} \gg \rho_{\perp}$, in which $\rho_{\parallel}$ ($\rho_{\perp}$) is the mass density in the direction that is parallel (perpendicular) to that of the impinging wave, the better the imaging resolution[41,42,44,45]. **d** | A slab with a high-index contrast to its surrounding can reproduce subwavelength images through the excitation of waveguide resonances[53].

A further theoretical step forward in the field of transformation acoustics was the finding that there are available degrees of freedom[75,76] offering a wide range of acoustic material properties that can realize a specific coordinate transformation, instead of the one-to-one mapping available in electromagnetism. From this result, two distinct classes of fluid-like materials emerged: inertial and pentamode metafluids[76]. These materials are often referred to as metafluids because, although fluid-like in some ways, they possess properties not found in simple fluids such as air or water. Inertial metafluids are fluid in nature and are defined by a single, scalar compressibility or bulk modulus, and a tensor (and thus anisotropic) mass density. Pentamode metafluids are fluid-like in that they have vanishing shear stiffness, but are defined by a compressibility tensor, rather than a scalar[76,77].

Collectively, these findings show that the transformation-based design approach (FIG. 3) can be used to design devices that are capable of manipulating acoustic waves in very complex ways, including those to achieve cloaking, provided that some unusual acoustic material properties can be realized. The common thread between inertial and pentamode metafluids is the need to make materials with controllable inhomogeneity (that is, spatially varying material properties) and controllable anisotropy (that is, directionally varying material properties). Although some natural solid materials exhibit these properties, fluid or fluid-like materials rarely do, and the specificity of the values that emerge from the transformation acoustics design process implies that acoustic metamaterials are an effective way to achieve the required metafluid properties. Inertial metafluids are generally composed of meta-atoms in which solid inclusions are surrounded by a host fluid[78,79]. Pentamode metafluids can be constructed from an interconnected lattice of solid struts, but must be carefully engineered to exhibit a small-to-vanishing shear stiffness[77].

Experimental studies have explored acoustic-metamaterial implementations of inertial metafluids and have shown that they are relatively simple to make. For example, a rotationally asymmetric arrangement of simple scatterers in a fluid naturally homogenizes to yield an anisotropic effective mass density[80]. By exploiting a previous result[81], it was also shown how thin alternating layers of fluids can, in principle, be assembled to yield the inhomogeneity and strong anisotropy needed to create an acoustic cloak[82,83]. More physically realizable structures made of elongated rigid scatterers surrounded by a background fluid were shown in simulation[78,79] and experiment[84] to behave as a fluid in which the anisotropy in the effective dynamic mass density is tunable.

This conceptual work set the stage for experimental demonstrations of acoustic cloaking using inertial metafluids. These studies used the metamaterial design approach summarized in FIG. 4, in which simulations of single meta-atoms are used to determine the structures that are needed to approximate the different ideal acoustic-material properties that emerge from the transformation design process. A full metamaterial structure is then constructed from these meta-atoms. The first experimental cloaking effort used an acoustic metamaterial designed to control two-dimensional wave propagation, at ultrasound frequencies and in a thin layer of water using a structure composed of narrow channels and cavities, in an aluminium substrate[85]. Subsequent air-based experiments demonstrated 'carpet cloaking' (REF. 86) — hiding an object on a reflecting surface — in two[87] and three[88] dimensions, and illusion cloaking — making one object scatter like another — in a two-dimensional corner structure[89]. These experimental demonstrations in air all used some form of rigid perforated plate structure[78,79] to create the required anisotropy in the effective mass density. Collectively, these results validate the concept of using acoustic metamaterials to create transformation acoustics devices that manipulate sound waves in ways that are not possible using traditional acoustic materials.

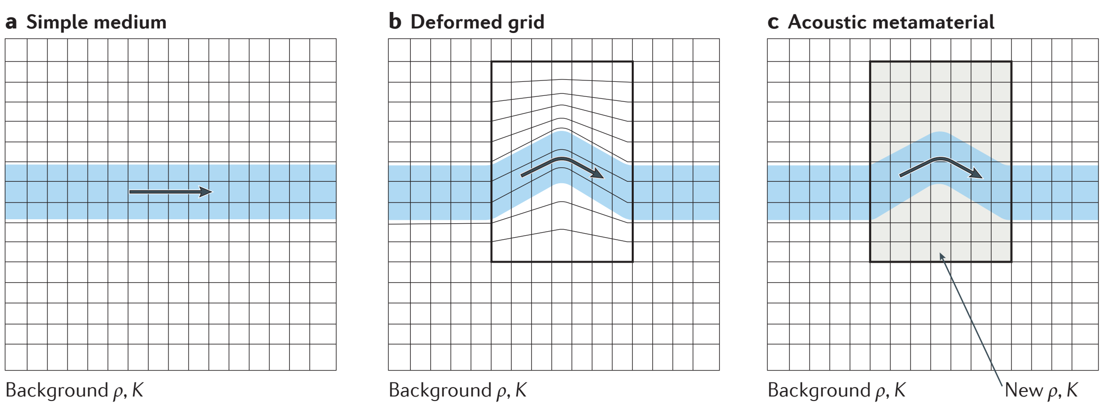

Figure 3 | **Conceptual illustration of transformation acoustics. a** | An acoustic wave propagates through a simple medium with known acoustic material properties. **b** | The acoustic wave is deformed in a finite region via a coordinate transformation that stretches or twists the underlying coordinate grid. This is what we want the acoustic wave to do. **c** | Through the mechanics of transformation acoustics, one can determine the acoustic material properties that will deform the acoustic wave in precisely the way that the coordinate transformation did. These material parameters will be, in general, difficult to obtain; to implement them into a physical medium, metamaterials are required.

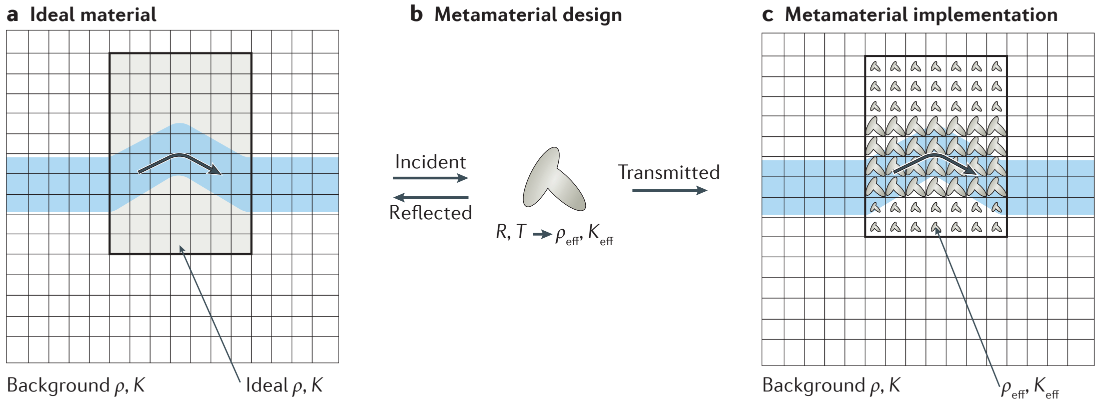

Figure 4 | **Example of transformation design with acoustic metamaterials. a** | Ideal wave behaviour with ideal continuous materials, as introduced in FIG. 3c. **b** | A reflection and transmission (*R*/*T*) unit-cell design is used to approximate the ideal material parameters (ρ, K) with effective ones (ρ_{eff}, K_{eff}). **c** | Near-ideal wave behaviour is obtained using a discrete-metamaterial implementation of ideal material parameters.

Although pentamode acoustic metamaterials are more challenging to create than inertial ones, they potentially offer greater flexibility for designing transformation acoustics devices. An important step towards acoustic cloaking using pentamode metamaterials[90] has been taken through the fabrication of nearly pentamode, low-shear-modulus metamaterial structures[91–93]. Pentamode metamaterials are potentially advantageous for water-based applications in which neutral buoyancy can be designed into the structure[75]. Demonstrating density and modulus anisotropy that are useful for transformation acoustics in water-based structures remains a research target for the acoustic metamaterials community, although some designs[94] and material concepts[95] suitable for water-based metamaterials have been developed. Extending the concept of acoustic cloaking to more general vibrational waves has been demonstrated in several areas, including surface water waves[96], elastic waves in thin plates[97,98], static pressure[99] and seismic waves[100].

Research on transformation-based acoustic cloaking has also spurred broader thinking about reducing wave scattering from objects and yielded other cloaking concepts that rely on different physical principles. Instead of eliminating the interaction of waves with the target object via cloaking shells, these designs are predominantly based on cancelling the object scattering through the placement of additional materials. One demonstration of this concept, which was first introduced in electromagnetism[101] and, more recently, has been theoretically developed in acoustics in several forms[102–106], requires thin shells of homogeneous materials. Interesting sensor concepts have emerged from this line of thinking, such as cloaked sensors that measure a sound field without disturbing it[107,108] and a metamaterial-based acoustic sensor that passively amplifies the incident acoustic pressure[109]. A different implementation of scattering cancellation involves the optimized placement of scattering objects made from conventional materials [110] to produce net-zero scattering in specific directions at the design frequency. One further possibility involves parity–time-symmetric acoustic materials[111], which are able to absorb and re-emit an incident signal, leading to the development of invisible objects or sensors (discussed below)[112]. Cloaking applications have spurred interest in exploring metamaterials with active inclusions, which potentially represent one of the most interesting frontiers in acoustic metamaterials research.

Active acoustic metamaterials

Although metamaterials have helped to advance acoustics technology in the past decade, researchers have mostly relied on linear, passive and static meta-atoms, as described in the previous sections. However, these properties limit the applicability of metamaterials and their general impact on technology. Passivity, linearity and time-invariance impose fundamental bounds on the available choices of acoustic parameters. For example, the frequency dispersion of passive linear acoustic materials is bound by Kramers–Kronig-like dispersion relations[113], which ultimately limit the bandwidth over which certain long-sought properties of metamaterials are available and, therefore, the spectrum of operation of some metamaterial devices. This is especially true when resonant and, hence, frequency-dependent inclusions are considered, as in many of the examples discussed in the previous sections, in which case passivity imposes a bound on the bandwidth of operation that scales with the size of the inclusions. The bandwidth problem is less stringent for acoustic metamaterials than it is for optical ones, owing to the large difference between the velocities of sound and light propagation, and to the much broader range over which the relevant material parameters vary in nature[114]. This partly explains the success of using non-resonant broadband inclusions for acoustic metamaterials.

The applicability of passive acoustic metamaterials is also hindered by the inherent presence of losses, which affects the overall efficiency of devices. High-frequency signals are commonly dampened even in natural materials, and as sound propagates in metamaterials, especially in volumetric samples with thicknesses of multiple wavelengths, the energy is partially, and often largely, dissipated. This problem is especially relevant in the case of resonant inclusions. Finally, the typically static effective properties of metamaterials tend to limit the applicability of this technology because complex systems can benefit from reconfigurability and tunability.

For all these reasons, there has been a growing effort to explore active acoustic metamaterials, which could potentially overcome the challenges described above and increase their effectiveness in relevant applications. Active unit cells for metamaterials with unusual acoustic properties have been considered in several designs. The term 'active' is used quite generally to indicate inclusions that can provide energy to the impinging wave and feedback to the acoustic system, that can be controlled or that are externally biased. The most common elements used in active meta-atoms are active transducers, micro- or nano-electromechanical systems, piezoelectric materials and electrically loaded acoustic elements (FIG. 5). These architectures have enabled reconfigurability and real-time tunability, among other features[63,115–129].

Figure 5a shows an example of a metamaterial composed of an array of masses with variable mechanical connectivity, whose effective material properties can be tuned in real time with properly controlled piezoelectric discs[128] (FIG. 5b). Piezoelectric materials provide an ideal platform to tune and control the acoustic properties of a metamaterial in a compact way, because they respond strongly to electrical signals and can be controlled with relatively simple electronics[118,119] (FIG. 5c). Piezoelectric effects may also be exploited in semiconductor substrates[124], and these materials may be used to provide effective acoustic gain, that is, to amplify the acoustic wave as it propagates through them. A similar route to acoustic gain and active control of the acoustic properties of a metamaterial may be provided by loading loudspeakers, which, similar to piezoelectrics, convert airborne acoustic waves into electric signals and vice versa, using electronic circuitry (FIG. 5d). These strategies have been successfully used, for instance, to obtain controllable acoustic gain and loss in a lumped element configuration[112,118].

Parity–time-symmetric acoustic metamaterials. One particularly interesting subclass of active metamaterials, briefly mentioned above in the context of cloaking, is that in which active elements pumping energy into the incoming wave are paired with their time-reversed images, which correspond to absorbing elements. Such a combination of elements satisfies a balanced loss–gain condition that has been shown to provide unusual acoustic responses. This field of research has stemmed from theoretical research in the area of quantum mechanics, where it was shown that a special class of Hamiltonians that commute with the parity–time (PT) operator can support real energy eigenvalues even though they are non-Hermitian[130,131]. A few years ago, this theoretical discovery, which is still debated in the quantum-mechanical community, was extended to classical wave phenomena, owing to the mathematical analogy between quantum PT-symmetric systems and optical systems characterized by balanced distributions of gain and loss[132,133]. It was shown that PT-symmetric optical metamaterials can support lossless propagation and loss compensation, unidirectional invisibility and threshold-free lasing, among other things.

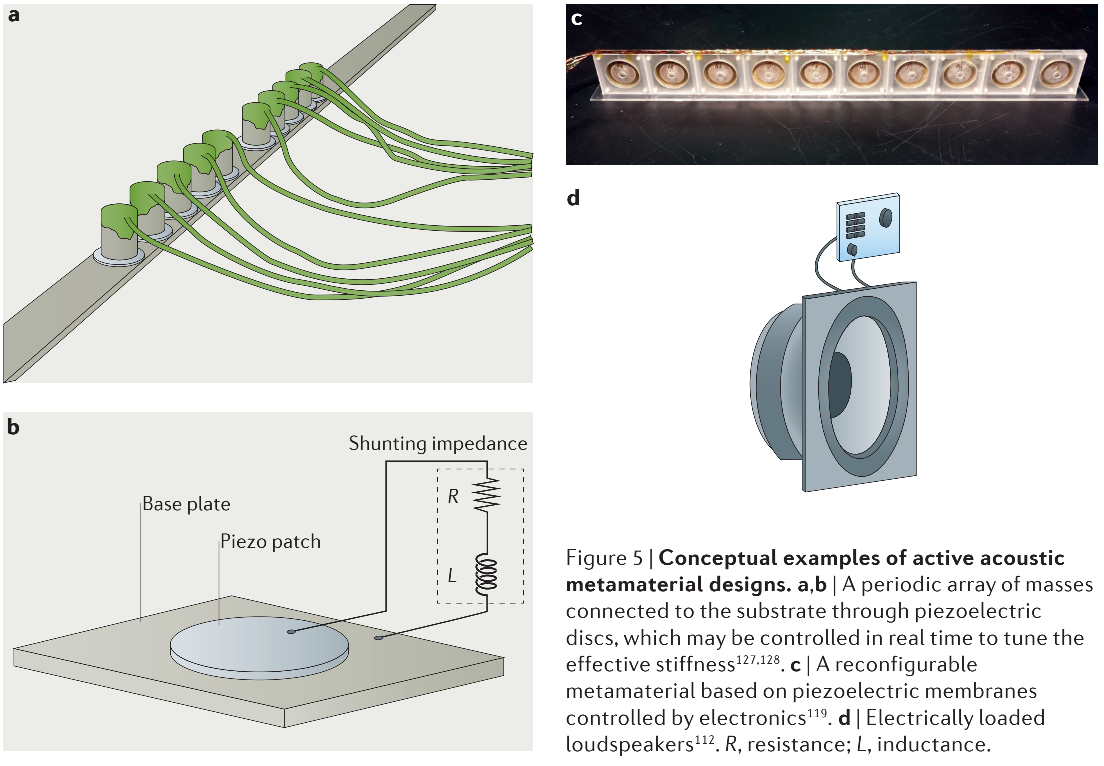

Figure 5 | **Conceptual examples of active acoustic metamaterial designs. a**,**b** | A periodic array of masses connected to the substrate through piezoelectric discs, which may be controlled in real time to tune the effective stiffness[127,128]. **c** | A reconfigurable metamaterial based on piezoelectric membranes controlled by electronics[119]. **d** | Electrically loaded loudspeakers[112]. *R*, resistance; *L*, inductance.

Recently, PT symmetry has become relevant to the field of acoustic metamaterials, in which gain and active components are much more readily available than they are in optics, as detailed in FIG. 5 and in the above discussion. PT-symmetric acoustic metamaterials have recently been explored theoretically and experimentally[111,112], which has provided a basis for novel acoustic devices, including new cloaks for sound with highly asymmetric scattering responses[111,134] and advanced sensors with minimal scattering[112]. Some examples of applications of active acoustic metamaterials are given in FIG. 6. By pairing a resonant acoustic sensor, which absorbs a substantial portion of the impinging energy, with its time-reversed image (FIG. 6a), under proper conditions it is possible to realize a system that can absorb the incoming wave without creating shadows or reflections. There is an interesting connection here with the field of time-reversal imaging mentioned in the previous section; however, the functionality of this PT-symmetric system is based on eigenmodal resonances, and therefore does not require external feedback or control.

Non-reciprocal acoustic metamaterials. Another area of research in the field of active acoustic metamaterials is that of non-reciprocal metamaterials, in which the breaking of time-reversal symmetry as well as one-way propagation and isolation are allowed. In conventional media, sound travels symmetrically in the sense that if it is possible to transmit a signal from A to B, then it is usually possible to transmit it with the same intensity from B to A (FIG. 6b). This symmetry, known as reciprocity, is a fundamental property of many wave phenomena and is attributable to the fact that wave propagation in conventional media is time-reversible. However, reciprocity is not necessarily desirable, especially when the goal is to isolate a source from its echo or separate signal flows travelling in opposite directions. Full-duplex sound communications, that is, those for which it is possible to transmit and receive an acoustic signal from the same transducer on the same frequency channel, could be enabled by breaking reciprocity and could lead to more efficient sonars and ultrasound imaging devices.

Although it is well known that reciprocity is broken when sound travels in a moving medium[55,135], the levels of isolation and non-reciprocity that are achieved in slowly moving materials are typically very low. Recently, several non-reciprocal metamaterial devices providing large isolation levels have been proposed that exploit greatly enhanced Doppler effects in resonators loaded with a spinning fluid[136], suitable forms of spatiotemporal modulation in coupled resonating cavities[137] and enhanced nonlinearities[138–140]. More specifically, a first-of-its-kind subwavelength acoustic circulator was built in the form of a basic three-port non-reciprocal device that allows one-way rotation of the input signals from port 1 to 2, 2 to 3, and 3 to 1, while preventing transmission in the opposite direction[136]. Figure 6d shows a basic power splitter for airborne acoustic waves, formed by a radially symmetric cavity connected to three waveguides. At resonance, an input sound at port 1 splits equally between the output ports 2 and 3. The device is reciprocal and, therefore, the same transmission levels are expected when sound is input at each port. In this system, a very large isolation of over 40 dB was realized for airborne acoustic waves upon filling the subwavelength acoustic ring cavity with a rotating fluid (FIG. 6e). Because the filling fluid had a modest velocity, about 0.65 m s^{-1}, resonant transmission was shown to be strongly asymmetric, and the acoustic waves impinging at port 1 were routed to port 2, isolating port 3. For design simplicity, air was selected as the fluid and circulation was achieved using fans. The non-reciprocal circulation of sound was provided here by the fluid motion; therefore, exciting the same structure from port 2 would provide strong transmission to port 3, breaking the symmetry in transmission as sketched in FIG. 6b.

Although it is interesting to see how such a basic active component can modify the way sound propagates, mechanical motion of the filling material is not always convenient or practical. Therefore, this design was extended to an equivalent meta-atom in which fluid motion was replaced by proper spatiotemporal modulation of three strongly coupled resonators, with the aim of realizing a circulator for ultrasound waves[137]. The equivalence between a spinning fluid in a cavity and spatiotemporally modulated elements was first proved in electromagnetism for the realization of a circulator for radio waves[141], and is related to the growing field of topological manipulation of wave dispersion using modulation[142,143].

Nonlinearities also provide a route to isolation and non-reciprocal transmission. A basic scheme involves asymmetric frequency conversion and suitable filtering, which may be achieved in its simplest form by combining a nonlinear medium with a frequency-selective mirror (FIG. 6c): for example, using a phononic crystal that filters the fundamental frequency but not the second harmonic. When excited from the side of the filter at the fundamental frequency, the structure is highly reflective; however, if excited from the opposite side, then the nonlinear medium converts most of the impinging energy to the second harmonic, which tunnels unaltered through the frequency-selective mirror, breaking reciprocity. More refined schemes to exploit nonlinearity and active components for isolation have been proposed[140,144,145] and have led to larger isolation and better efficiency.

These compact devices for acoustic isolation in turn become meta-atoms of complex artificial materials. Recently, some of the described non-reciprocal elements and other related components have been properly embedded in periodic lattices to realize topologically non-trivial band diagrams, in connection with recent advances in topologically non-trivial photonic crystals[143]. This area of technology drew its inspiration from recent advances in condensed matter physics. Topological states in electronic materials, including the quantum Hall effect and topological insulators, spurred a number of developments in photonics and, more recently, in acoustics[146–148]. As discussed above, the careful tailoring

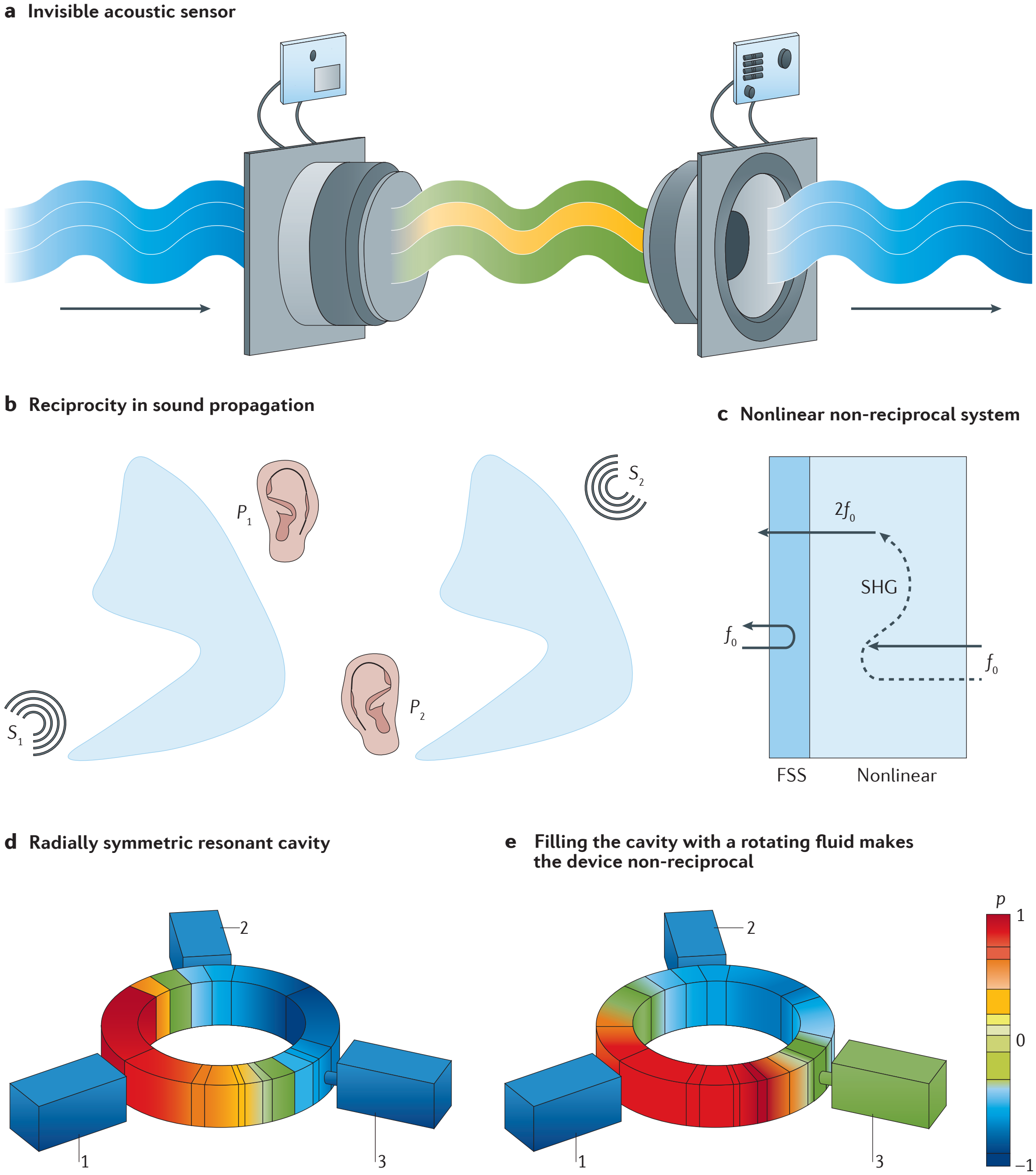

Figure 6 | **Functionality and possible applications of active metamaterials. a** | An invisible acoustic sensor based on parity–time-symmetric metamaterials. The figure shows a passive loudspeaker (left), which is tuned to resonantly absorb a substantial portion of the impinging sound, paired with its time-reversed image. This is obtained by loading a second identical loudspeaker with active circuitry[112]. **b** | Reciprocity in sound propagation implies that, after reversing source and sensor, the transmission is the same. It suggests that the transmitted (S_1, S_2) and received (P_1,P_2) signals are related by $S_1P_2 = S_2P_1$. In other words, the transmission through a reciprocal channel is time-reversal symmetric. **c** | A basic nonlinear non-reciprocal system for free space isolation composed of a frequency-selective surface (FSS) and a nonlinear material for second-harmonic generation (SHG), which converts an incoming wave at frequency f_0 to $2f_0$. **d** | An acoustic radially symmetric resonant cavity connected to three waveguides (labelled). **e** | The same structure becomes a non-reciprocal device, an acoustic circulator, as the filling fluid is moved with moderate rotation velocity[136]. *p*, pressure.

of frequency, wave vector and phase propagation has led to advances in the areas of phononic crystals and metamaterials. Topology, the study of the properties and spatial relations that remain unaffected by continuous changes in shape or size, can provide an additional degree of freedom to tailor sound propagation in robust ways. In optics, carefully designed systems with non-trivial topologies in wave-vector (reciprocal) space can lead to the emergence of new states of light, consistent with the physics of conventional topological insulators that allow dissipation-free electron transport along the edges, with robust propagation even in the presence of impurities. By building on these ideas, and by connecting non-reciprocal meta-atoms such as those described above in a lattice, it was possible to realize topologically protected and one-way sound propagation at the edge of metasurfaces[146–148], enabling new directions in the field of metamaterials with applications in reconfigurable one-way waveguides and tunable, broadband isolation.

Acoustic metamaterials have exploited the use of nonlinearities associated with sound propagation in several ways other than by breaking non-reciprocity; for example, nonlinear metasurfaces were shown to have imaging capabilities[149]. Moreover, the large field concentration and the enhanced sound–matter interactions enabled by metamaterials in both resonant and non-resonant ways[30,150] provide a basis for achieving very large nonlinear acoustic effects. These effects are particularly interesting because even reciprocal acoustic metamaterials are known to support large nonlinearities compared with other wave phenomena.

Tunability and reconfigurability are other desirable characteristics for acoustic metamaterials, which could be enabled by active unit cells with feedback and control[63,121–125]. These characteristics could be especially useful when combined with self-control and the ability to learn to adapt to changes in the background. It is possible to envision the utility of active self-reconfiguring metamaterials and smart materials for several applications, such as camouflaging and advanced imaging. An important issue that needs to be considered in dealing with active elements is their stability[118], which requires careful design and which is expected to fundamentally limit the available bandwidth of operation for a certain degree of design complexity.

Conclusions and outlook

For a little more than a decade, the field of acoustic metamaterials has expanded tremendously, propelled in part by ideas first conceived and tested in other branches of physics and materials science. We now know how to engineer structures that can manipulate acoustic waves in ways that would have seemed outlandish not long ago; however, much remains to be done before the promise of material parameters on demand and sound manipulation at will can be realized.

Many of these challenges lie in the practical implementation of acoustic metamaterials. The structures that are used to experimentally demonstrate ideas are not always well suited to real-world applications because of their size, mechanical robustness and manufacturability. New designs and fabrication techniques will be needed to enable the production of acoustic metamaterials for practical use. The recent rapid increase in additive manufacturing, or 3D printing, has been very beneficial to the field, because the materials used and the range of available sizes are well suited for metamaterials that manipulate audio-frequency airborne sound. Similarly, nanoscale manufacturing has been used with great success to fabricate very complex, small-scale structures. Ways to combine fine-scale control with a large-scale final size are needed. Soft, unstructured materials[13] offer a different, but promising, path towards this same end.

Another challenge that is just beginning to be addressed is the design of metamaterials for operation in water or water-like fluids, which would be applicable to underwater acoustics and medical ultrasound imaging. The contrast provided by the many orders of magnitude that distinguish the acoustic properties of air from those of most solids makes it particularly easy to design acoustic metamaterials with a range of effective parameters when the target device works in air. Metamaterials for water or water-like materials, such as human tissue, on the other hand, are more challenging to design because that same contrast is only approximately one order of magnitude. This results in the transmission of a substantial fraction of the incident acoustic energy into the solid structure, which can limit the range of obtainable effective material parameters[151].

Although a lot of progress has been made in the field, there are some promising directions that have yet to be fully explored. The basic concepts of acoustic metamaterials have been extended to other mechanical wave systems, such as earthquakes. However, this extension has not yet been explored to its limit, especially with respect to the control of waves and vibrations in the more complicated solid, that is, elastodynamic materials by using elastic metamaterials[6].

Optimization of the acoustic metamaterial design process is another promising area. There are degrees of freedom that can be exploited throughout the process, such as transformations and material specifications in transformation acoustics, and fine-tuning of the structure of individual meta-atoms for the control of the effective material properties. Modern computational power enables huge areas of the design space to be explored relatively quickly. We anticipate that design optimization will be a key component of the transition from proof-of-concept experiments to acoustic metamaterials that have application-specific properties.

Passive and fixed structures have remarkable acoustic properties and performances, but, with active structures, even greater performance can be achieved. This is partly due to the relatively slow timescale (of the order of a millisecond) of human-perceived audio frequencies, during which considerable processing and actuation can be performed. The research reviewed here has demonstrated how extreme manipulation of sound can be achieved in ways that are not possible with conventional or passive materials, but at the cost of increased complexity that must be carefully considered for any practical applications.

New ideas in the context of acoustic metamaterials, beyond those reviewed here, will certainly emerge in the coming years, driven by the range of applications in which the ability to manipulate sound in new ways would prove useful — consumer audio, ultrasound imaging, underwater acoustics and sonar, and architectural acoustics and sound recording, to name just a few. Given the progress over the past decade, it can be safely concluded that the future of acoustic metamaterials is sound.

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Competing interests statement

The authors declare no competing interests.