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Metamaterials: Optical, acoustic, elastic, heat, mass, electric, magnetic, and hydrodynamic cloaking

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Metamaterials and devices that provide cloaking functionalities have strong potential to bring fundamental scientific and engineering developments including invisibility, sound and vibration mitigation, seismic protection, thermal and mass shielding, electrical and magnetic field isolation, and fluid flow concealing. In recent years, rational material design has allowed a wide range of new cloaking devices through the design and fabrication of metamaterials and metasurfaces that control electromagnetic and mechanical waves as well as heat, mass, and fluid flow. Here we review classical and recent advances and the evolution of new concepts and strategies to design and fabricate metamaterials that provide cloaking in multiple physical fields. We analyze the discovery of new ways to cloak light and sound, heat and mass flow, electrical and magnetic fields, and fluid flow via metamaterials and metasurfaces, and discuss their emergent functional responses and applications in a broad range of physical fields.

1. Introduction

In recent years, unprecedented materials and devices that prevent arbitrary objects to be noticed when placed in different physical fields have been designed and fabricated using metamaterial theory. With these remarkable advances, devices that can cloak objects from light and sound, thermal and mass gradients, as well as electric and magnetic fields have been introduced with applications in optics, acoustics, elasticity, heat and mass transport, electricity and magnetism, and hydrodynamics. In this review, we provide an overview and insights of several outstanding classical and newly developed modalities to design metamaterials that achieve cloaking for a wide variety of physical fields. We start by analyzing cloaking devices for classical waves by considering the seminal breakthroughs in the fields of optics and acoustics and connecting these developments with new approaches for cloaking. We follow by outlining exciting ways to cloak objects from thermal, mass, and light diffusion, and continue with cloaking devices for electric, magnetic and hydrodynamic fields. Due to the broad scope of this review, we focus on the breakthrough papers that contributed to initiate as well as further develop each field, in order to maintain the number of citations within certain limit. The review outline is chronological starting with cloaking of classical waves and expanding to more recent cloaking devices for non-classical fields. We also analyze in detail the evolution of cloaking devices, as we show how cloaking applications initially required rationally designed metamaterial structures with bulk anisotropic material properties, but a different cloaking approach, known as carpet cloaking, constituted a significant advance in removing complex material requirements making it easier to fabricate cloaking devices. More recently, a new paradigm for cloaking has been developed with the rise of metasurfaces, where the object are wrapped in order to make them invisible. All these recent and remarkable developments on cloaking approaches and devices demonstrate that objects can be made unnoticed using different metamaterial design strategies. The prospect of metamaterial cloaking devices is bright as cloaking metamaterials and devices have recently been expanded from waves to diffusion and they are now ubiquitous in multiple physical fields.

2. Optical cloaking

The long-standing goal of hiding objects from sight has propelled the field of optics into exploring unconventional materials for cloaking technology [1,2]. These unique non-naturally occurring metamaterials are rationally designed structures made of subwavelength units of metals or dielectrics. The discovery and design of metamaterials is

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critical in the development of cloaking technology that can guide incident light waves around an object, rendering the object invisible to an observer (Fig. 1a). The first proposal to achieve cloaking used the invariance of Maxwell's equations under coordinate transformations [1] to create a void in space and obtain permeabilities ε and permittivities μ for a metamaterial that will guide incident electromagnetic waves around the void (Fig. 1a). The proposed invisibility cloak consisted of a spherical cloaking shell that prevented incident waves from impinging on an arbitrary object inside the shell and maintained the external field unperturbed (i.e. cloaking), making the object invisible to an outside observer [1–4]. Soon after this seminal theoretical work, the first experimental realization of a cylindrical metamaterial cloaking shell made of split-ring resonators (SRRs) was introduced satisfying the required permeabilities and permittivities to achieve cloaking by means of resonances (Fig. 1a) [5]. The cloak concealed a copper cylinder of radius R_1 located at the center of the metamaterial shell with internal radius R_1 and external radius R_2, and operated in the microwave regime, creating cloaking effects in agreement with simulations and showing an unprecedented path to achieve invisibility (Fig. 1a). The coordinate transformation to cloak the object was obtained by compressing the cylindrical region $0 < r < R_2$ into the annular region $R_1 < r < R_2$, where (r, θ, z) and (r', θ', z') are cylindrical coordinates in the original and transformed system respectively. Such transformation can be written as

$$r' = \frac{R_2 - R_1}{R_2} r + R_1, \ \theta' = \theta, \quad z' = z$$

Applying the transformation [4] provides the permittivity ε and permeability μ tensor components for the cloaking shell. In the experiments, due to the z polarization of the electric field, the relevant permittivity ε and permeability μ tensor components were given by

$$\mu_r = \left(\frac{r - R_1}{r}\right)^2, \quad \mu_\theta = 1, \quad \varepsilon_z = \left(\frac{R_2}{R_2 - R_1}\right)^2$$

After initial demonstrations at microwave frequencies, research efforts were soon directed toward creating cloaking devices that operate at optical frequencies. At such higher frequencies however metamaterial shells made of SRRs are not effective since the SRRs reduce their resonance efficiencies at the small length scales required to cloak visible light. To overcome this limitation, new theoretical cloaking designs were subsequently introduced that avoided the use of SRRs metamaterial shells. A metamaterial cloaking shell was proposed made of an array of metallic wires within a dielectric [6] as well as a cloaking shell made of isotropic and homogeneous concentric cylindrical multilayers [7], both showing the ability to redirect light around the object to be concealed by computer simulations. Due to the difficulties associated with fabricating cloaking shells, an alternative method has been introduced via *carpet (or ground) cloaks* [8]. A carpet cloak is a metamaterial device that hides an arbitrary object placed on top of a planar reflecting surface (Fig. 1b). The advantage of carpet cloaks is that they can be constructed from simpler metamaterials, especially for operation at optical frequencies. The first experimental demonstration of a carpet cloak consisted of a copper-clad printed circuit metamaterial capable of cloaking 13–16 GHz microwaves [9]. After experiments at microwave frequencies, carpet cloaks were extended to optical frequencies by fabricating nanometer size metamaterial structures in silicon-on-insulator wafers, which cloaked micrometer-scale objects inside of a bump and operated at 1400–1800 nm wavelengths (Fig. 1 b) [10,11]. While these carpet cloaks proved that transformation optics can make an object invisible on a flat surface, the designs were limited to light incident on the plane of the cloak. A three-dimensional carpet cloak at optical frequencies was shortly designed and fabricated consisting of microscale dielectric woodpile photonic crystals, which hide a bump on a gold reflector for 1.4–2.7 μm wavelengths and a viewing angle up to 60° [12], showing for the first time optical cloaking for incident light in three-dimensions. A flurry of advancements took place with the prospects of achieving invisibility using optical devices capable of cloaking

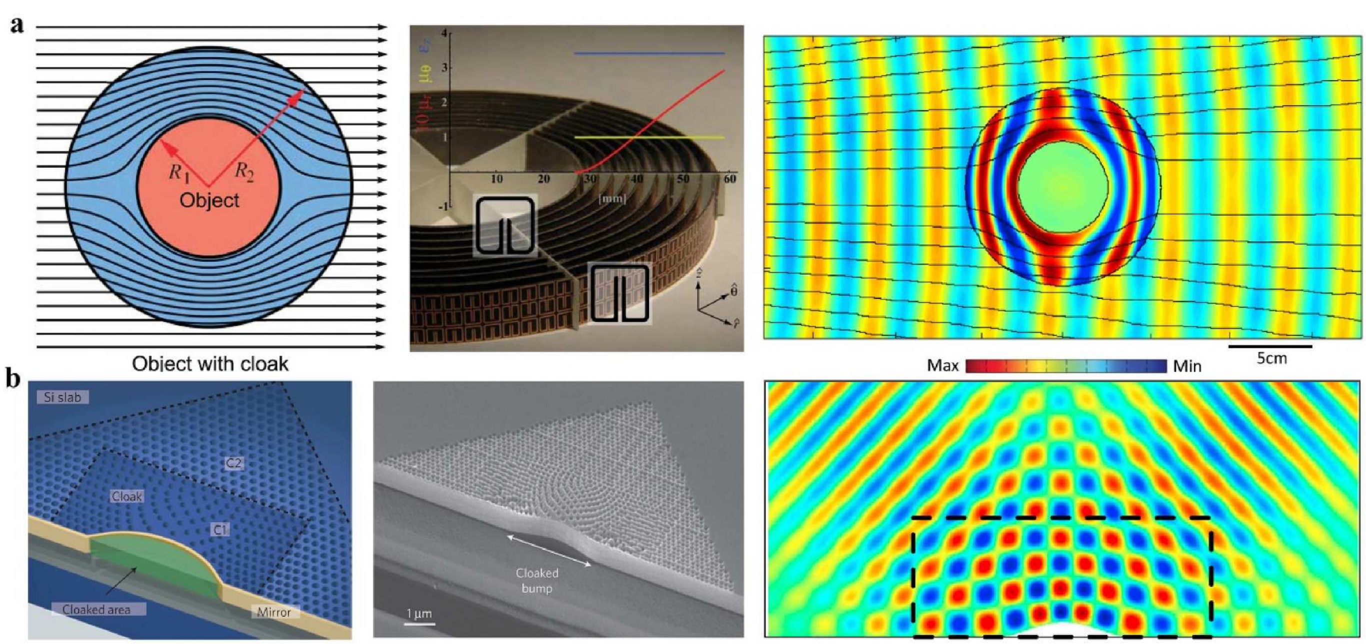

Fig. 1. Electromagnetic cloaking by metamaterials, a, Light ray trajectories within a cloaking shell are being redirected smoothly around the object at the center, making the object appear invisible to an outside observer since the rays outside are unperturbed (left). From [1]. Reprinted with permission from AAAS. Two-dimensional microwave cloaking shell made of split-ring resonators (insets) with plot of material parameters (center). From [5]. Reprinted with permission from AAAS. Simulation of electromagnetic wave propagation showing the reconstruction of the incident wave after passing through the cloak (right). From [5]. Reprinted with permission from AAAS. **b**, Carpet cloak schematic where the cloaking region is shown in green and regions C_1 and C_2 have gradient and uniform index, respectively (left). Reprinted with permission from AAAS [11]. Copyright 2009, Springer Nature. Image of a fabricated carpet cloak on silicon wafer (center). Reprinted with permission from [11]. Copyright 2009, Springer Nature. Simulation of electromagnetic wave propagation showing incident and reflected wave from the cloaked region (where any arbitrary object can be concealed) as if a flat object was there (right). Reprinted with permission from [8]. Copyright (2008) by the American Physical Society. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

three-dimensional objects much larger than previous studies. An invisibility carpet cloak from natural birefringent calcite crystals was introduced to cloak millimeter to centimeter size 3D objects [13], while a transparent carpet cloak made of two calcite pieces which served as the primary anisotropic optical materials was also reported [14]. This cloak can hide an object with a maximum height of 2 mm inside a transparent liquid environment. These macroscopic cloaking designs constitute a huge leap to avoid the use of complex nanofabrication processes.

With the purpose of cloaking larger objects, a new cloaking approach has been recently introduced by means of metasurfaces, which are artificial sheet materials with subwavelength elements on the surface that manipulate the phase of the scattered wave (Fig. 2) [15–18]. This new approach was demonstrated utilizing an ultrathin invisibility skin cloak that wraps around the object to be concealed (Fig. 2a) [19]. The cloak is only 80 nm thick and consists of a metasurface with distributed phase shifts in order to redirect visible light of 730 nm and render an arbitrarily object invisible when the object is wrapped by the skin cloak. More recently, a polarization-independent invisibility cloak for microwaves was fabricated by considering a 3D metasurface of closed ring resonators (CRR) on top of a square pyramid that surrounds the large-scale object to be concealed (Fig. 2b) [20]. Cloaking by metasurfaces has become an exciting research area and very recently a deep learning neural network algorithm has been implemented to allow for a self-adaptive metasurface to achieve cloaking for a non-deterministic system [21]. This adaptive metasurface cloak operates at microwave frequencies with a millisecond response time to a changing incident wave. Coupling advanced machine learning algorithms to the fast pace of growth for cloaking metamaterial and metasurface devices will help allow for cloaking devices to function in more complex environments and to bring us closer to having a fully operational optical cloak.

3. Acoustic and elastic cloaking

3.1. Introduction

The remarkable success in electromagnetic cloaking opened new avenues to explore cloaking of other physical fields such as mechanical waves. There are however key differences between electromagnetic and mechanical waves. In solids, mechanical waves propagate as longitudinal or transverse waves and are called elastic waves. On the other hand, in fluids, mechanical waves propagate only as longitudinal waves, which are called acoustic waves, since shear deformations are not allowed and transverse or shear waves cannot propagate. The question now becomes if coordinate transformations on the elastodynamic equations preserve the form of the equations, allowing the design and fabrication of cloaking technologies for acoustic and elastic waves.

3.2. Acoustic cloaking

In the search of ways to cloak mechanical waves, the conventional elastodynamic wave equations were first investigated and found to be in general not invariant with coordinate transformations. However, for specific cases, invariance under spatial transformation was obtained that could enable cloaking [22]. The first theoretical demonstration of cloaking of mechanical waves was introduced by demonstrating that the 2D equations for acoustic waves in fluids share identical invariance as the single polarization Maxwell equations [23]. The authors designed a cylindrical cloaking shell with anisotropic and inhomogeneous mass density and inhomogeneous bulk modulus, and demonstrated acoustic cloaking by simulating wave propagation around the cloaked object (Fig. 3a). An alternative method for acoustic cloaking was subsequently employed that utilized scattering theory to derive the required material parameters for a spherical cloaking shell [24]. A 3D acoustic cloaking shell using coordinate transformations was also proposed by mapping the acoustic wave equation onto the electrical conductivity equation

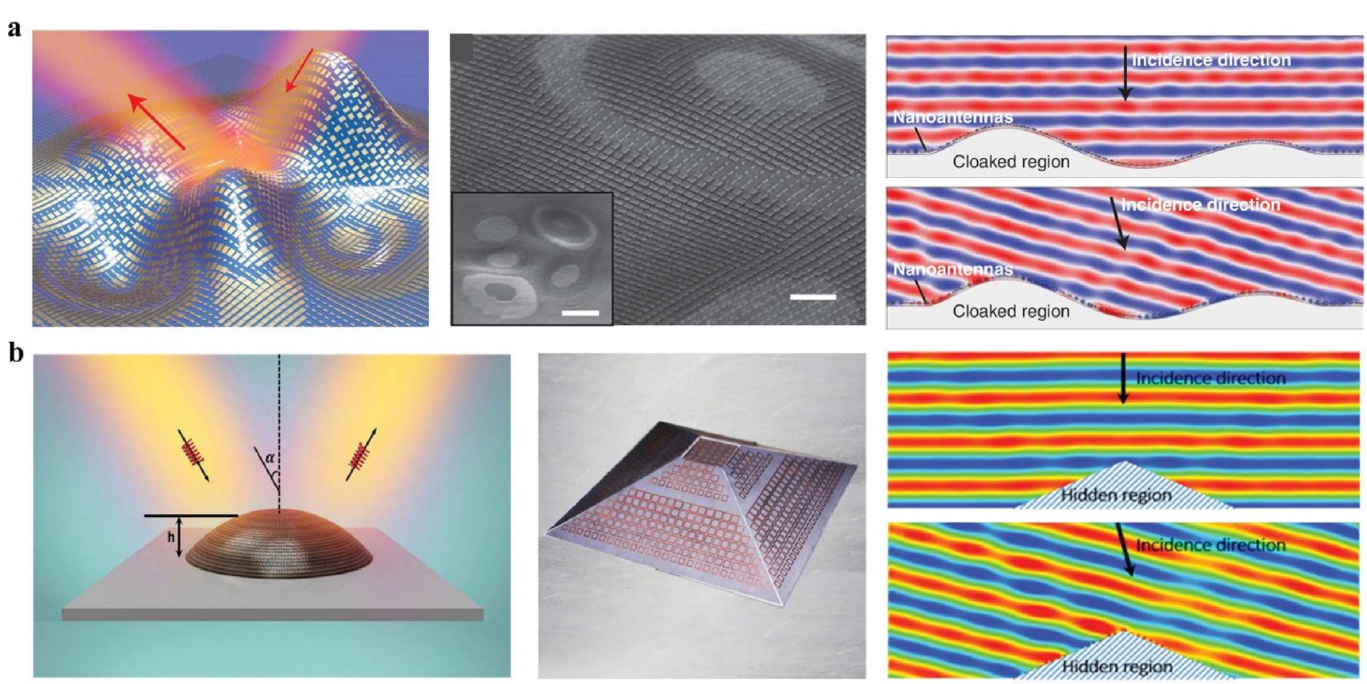

Fig. 2. Electromagnetic cloaking by metasurfaces, a, 3D schematic of a meta-surface skin cloak made of nanoantennas (gold blocks) over an arbitrary shaped object (left). Image of a fabricated metasurface (scale bar 1 μ m) and enlarged imagine (scale bar 5 μ m) (center). Simulated electric field distribution on a metasurface at normal and 15° incidence (right). For clarity only the reflected field is displayed, showing a reflection as if a flat object was there. From [19]. Reprinted with permission from AAAS. **b,** Illustration for a 3D full-polarization metasurface carpet cloak (left). Fabricated metasurface carpet cloak (center). Reflected transverse electric field distribution for normal and 15 ° incidence (right) [20]. © 2016 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

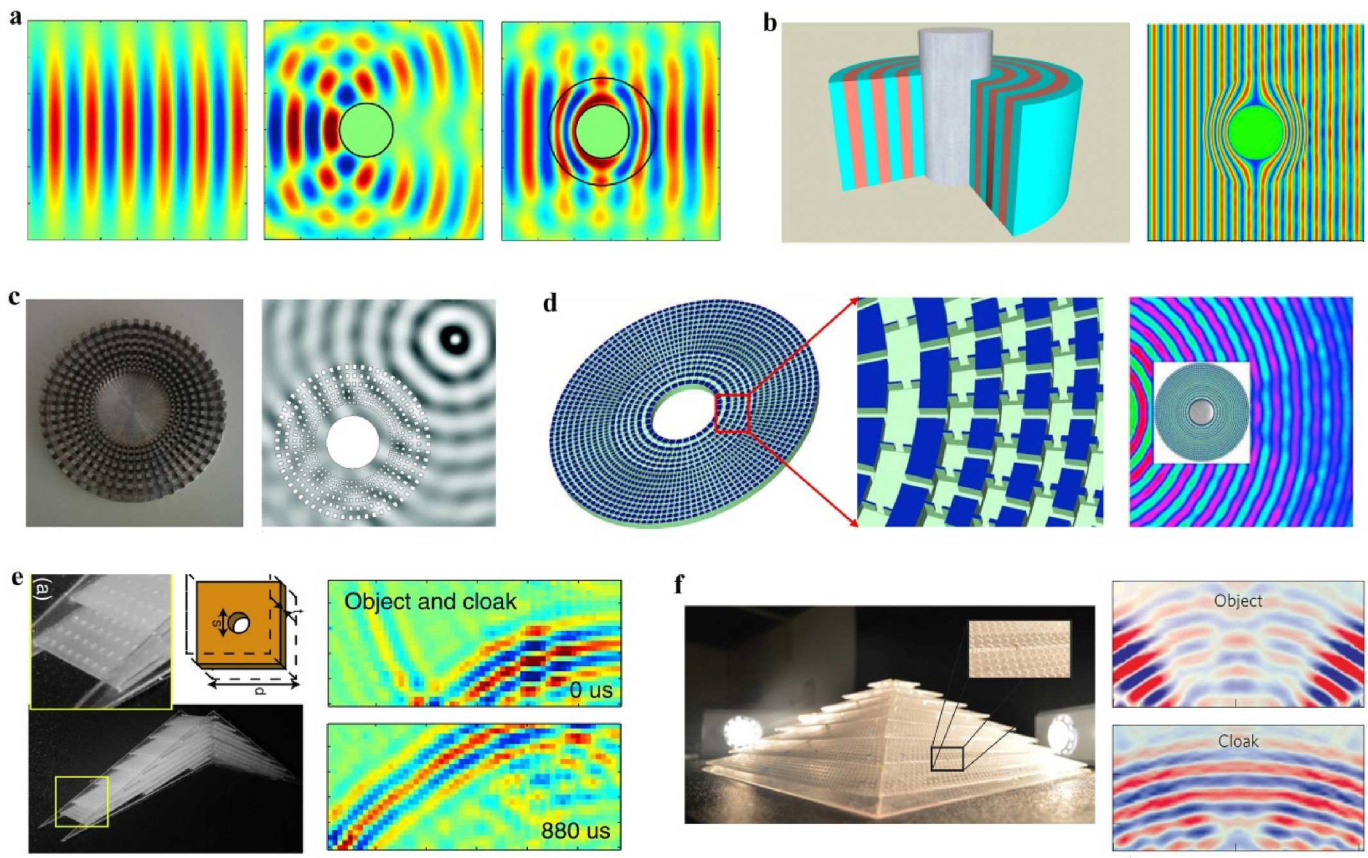

Fig. 3. Acoustic cloaking. a, A pressure wave propagating in a fluid without object (left), with object (center), with object and cloak (right). Note similar external fields for left and right panels [23]. © Deutsche Physikalische Gesellschaft. Reproduced by permission of IOP Publishing. **b,** A cylindrical cloaking shell made of two different layered materials (left). A cylinder is cloaked from an incident pressure wave in a fluid using the multilayer shell (right). Reprinted with permission from [26]. © Deutsche Physikalische Gesellschaft. Reproduced by permission of IOP Publishing. **c**, Shell structure to cloak an object from surface waves in a fluid (left). Experimental cloaking from surface waves at frequency 9.81 Hz originating at a point source (right) [27]. Copyright (2008) by the American Physical Society. **d**, Cylindrical shell to cloak an object from ultrasound waves in water (left). Measured pressure field at 64 kHz with the cloaking shell surrounding a steel cylinder (right). Reprinted with permission from [28]. Copyright (2011) by the American Physical Society. **e**, Ground cloak for acoustic waves in air, and unit cell in inset (left). Measured scattered field from the acoustic ground cloak at different times, showing nearly specular reflection. Reprinted with permission from [29]. Copyright (2011) by the American Physical Society. **f**, A three-dimensional acoustic ground cloak for sound in air (left). Measured pressure field for object (top) and object with cloak (bottom) (right). Reprinted with permission from [30]. Copyright 2014, Springer Nature.

[25]. The shells had anisotropic mass density and radially dependent bulk modulus and mass density and demonstrated theoretically acoustic cloaking in 3D. With these theoretical solutions in place came the first feasible approach toward fabricating a broadband 2D acoustic cloak by theoretically designing a multilayer cylindrical cloaking shell made of two isotropic and homogeneous materials that satisfied the anisotropic material properties required for cloaking (Fig. 3b) [26]. The cylindrically shaped multilayer structure was exposed to an incident planar acoustic wave in simulations and nearly perfect acoustic cloaking was obtained.

After the novel theoretical proposals for acoustic cloaking were introduced, the first experimental demonstration of cloaking for mechanical waves was achieved for surface waves in fluids [27]. Leveraging Stokes equation and assuming an incompressible, irrotational, and inviscid liquid leads to an invariant form for the liquid displacement equation. Using homogenization theory, the authors designed an effective anisotropic cylindrical cloaking shell characterized by a diagonal stress tensor. The cloaking shell with inner and outer radii of 41 mm and 100 mm, respectively, was divided into 100 angular sectors with seven rows of rods along the radial direction (Fig. 3c). The cloak redirected surface waves around a concealed object in a low viscosity liquid over a finite interval of 10 Hz frequencies (Fig. 3c). Notably, the cloaking of surface waves can potentially be scaled up to serve real-world applications such as protecting offshore platforms from damaging ocean waves.

The search for an acoustic cloak was still underway, and the first experimental broadband acoustic cloak was soon designed for ultrasound waves in water [28]. This cloak bends ultrasound waves with frequencies of 52–64 kHz around a cylindrical steel bar at the center of the cloak (Fig. 3d). The design approach used an acoustic transmission line method, which takes the similarities between lumped acoustic elements and electronic circuit elements. The acoustic cloak contained an array of subwavelength cavities that are interconnected with channels and provides good cloaking performance by preserving the phase of the incident ultrasound wave via resonances, demonstrating that underwater acoustic cloaking is a viable tool for hiding objects submerged in water.

Due to the complex fabrication of acoustic cloaking shells, research was subsequently directed to achieve acoustic ground cloaks [29]. Similar to electromagnetism, a carpet (or ground) acoustic cloak is a metamaterial device that hides an arbitrary object placed on top of a planar acoustically reflecting surface. The ground cloak design reproduced the anisotropic material properties required for cloaking by using easy-to-access perforated plastic plates (Fig. 3e). The plates have repeating unit cells of period 5 mm, thickness 1 mm, and perforation diameter 1.6 mm, which allowed cloaking sound waves with frequencies from 0 to 3 kHz from a triangular region. These two-dimensional acoustic ground cloaks were subsequently extended to three dimensions by hiding an object inside a square cloaking pyramid placed on a reflecting surface (Fig. 3f) [30]. In the pyramid, the air-filled cubic unit cells of 5 mm contained an acrylic perforated plate of 1.6 mm in thickness and a 0.85 mm perforation radius at the center, to operate at 3 kHz frequencies. A near omnidirectional sound pulse was sent toward the tip of the pyramidal cloak, which showed near-perfect cloaking performance in three dimensions.

More recently a new cloaking approach for acoustic cloaking has been introduced using acoustic metasurfaces [31–33]. Analogously to electromagnetism, new advances came with the experimental demonstration of acoustic metasurface carpet cloaking, where a thin metasurface is used to cover and hide an object from incident sound waves by restoring the reflected phase shifts through the use of acoustic resonances [34]. The metasurface was made of a periodic array of 3D printed Helmholtz resonators, which control the phase shift for the reflected wave by adjusting their resonance frequencies. Experiments demonstrated the thin carpet cloak to restore the field pattern by compensating the shape of the concealed object. Enhancements to the design for metasurface carpet cloaks were shortly reported where a surface impedance strategy was used for creating new unit cells that result in thinner metasurfaces, which can provide metasurfaces that are flexible, higher operational bandwidth, and low transmission loss [35]. With the purpose of simplifying the materials requirements, specially engineered diffraction gratings for acoustic carpet cloaking were recently designed and fabricated [36]. This experimental design uses a grating made up of periodically drilled cavities to specularly reflect two fundamental modes and experiments were performed on a conical-shaped grating device that was 3D printed and demonstrated excellent acoustic carpet cloaking for incident 17 kHz sound waves. In addition, a carpet metagrating for ultrasound cloaking in underwater was also recently demonstrated experimentally consisting of periodic modulating grooves that allow the rerouting of ultrasound waves with frequencies 100–900 kHz around arbitrary objects [37]. These exciting recent advances in metasurface based cloaking for arbitrary objects in both air and underwater settings constitute a new route for acoustic cloaking in addition to previous classical approaches based on bulk metamaterial cloaking shell devices.

3.3. *Elastic cloaking*

Following the success in cloaking acoustic waves in air and water, the next step was to achieve cloaking of elastic waves in solids. In comparison to acoustic waves, however, elastic waves are more difficult to cloak because Stokes wave equations do not generally retain their form under coordinate transformations. For elastic waves to acquire the same advancements as acoustic and electromagnetic cloaking, transformation based solutions needed to be found for simplified cases that permit the design of cloaking devices. The first theoretical work to achieve elastic wave cloaking was introduced via a cylindrical cloak for in-plane coupled pressure and shear elastic waves with 40 Hz frequencies in a 2D solid [38]. A scalar mass density and a fully nonsymmetric elasticity tensor were required for the cloaking shell after coordinate transformations. Building upon this success, further work for transverse waves, often referred to as bending or flexural waves, was introduced by investigating cloaking in thin elastic plates [39]. The authors theoretically introduced a cylindrical cloak with a radially dependent isotropic mass density and radially dependent and orthotropic flexural rigidity, obtained by coordinate transformations of the biharmonic equation. Thereafter, to overcome the limitations regarding the complex material requirements, an easy-to-make ultra-broadband elastic cloaking was theoretically introduced using thin plates that control flexural waves [40]. The cloak was comprised of concentric multilayers made of isotropic elastic materials and demonstrated numerically nearly perfect elastic wave cloaking by preserving the phase of an incoming plane wave with a frequency 250 Hz. After the theoretical works, the first experimental demonstration of a cloak for elastic waves was introduced by using twenty concentric cylindrical multilayers, where sixteen layers out of twenty have different effective elastic modulus (Fig. 4a) [41]. A plane wave was sent from the left of the cloak at frequencies ranging from 200 to 450 Hz and good elastic wave cloaking was achieved (Fig. 4a). These results demonstrated for the first time an experimental broadband elastic cloak that can serve for example in infrastructure protection for damaging earthquake waves.

In order to move beyond 2D and create 3D elastic wave cloaks, researchers have more recently turned toward a novel class of material structures called pentamode elastic metamaterials, which offer the capability to design structures with specific shear G and bulk modulus B. Pentamode elastic metamaterials have been fabricated recently with a ratio B/G as large as 1000 (which behave as a liquid since they are easy to deform and hard to compress) [42] and measurements were performed on various different 3D polymer based pentamode materials, extracting ratios for G and B [43]. Inspired by these advancements, the first experimental elastic cloak enabled by pentamode metamaterials was introduced consisting of a core-shell design for statically cloaking an arbitrarily shaped object inside of a rigid hollow cylinder (Fig. 4b) [44]. The core hollow cylinder with large bulk and shear modulus was inside a pentamode metamaterial shell to make the core-shell behave invariant to surrounding compression and shear. The pentamode cloaking shell and the environment consists of a polymer microstructure made of fcc unit cells (Fig. 4b). After applying compression and shear, the system was imaged from the sides and movies were recorded. Good elastostatic cloaking was obtained when pushing the structure from the top by a hard stamp, underlying the potential that pentamode metamaterials can have in elastic cloaking.

Interestingly, metamaterial elastic cloaks have also recently found uses in steering seismic waves. Initially, a plate model for cloaking elastic waves along the air-soil interface was introduced and the shielding of these waves around 50 Hz was demonstrated experimentally [45]. Methods from transformation optics were adopted to reroute surface elastic waves of frequencies 3–10 Hz in soil through the use of Luneburg lenses [46]. More recently, the necessary conditions for a full-scale experimental realization of seismic cloaking through the use of a grid consisting of cylindrical vertical holes in soil have been investigated, showing that metamaterial devices can help to reroute seismic surface waves around civilian areas [47].

In previous sections we have shown that metasurfaces had transformative impacts on cloaking of electromagnetic and acoustic waves. Since elastic waves are difficult to cloak, metasurfaces are particularly useful to avoid the complex material requirements of cloaking shells. Compact elastic metasurfaces have been recently fabricated using thick acrylic plates with ring-type unit cells with curved thin bar geometries to allow the redirecting of broadband flexural waves with minimal reflection (Fig. 4c) [48]. Numerical simulations and experiments for the ring-shaped metasurface were conducted to manipulate the flexural waves by shifting, transforming, and splitting a point source (Fig. 4c). Importantly, these results demonstrate how compact metasurfaces can manipulate elastic waves without the use of resonant mechanisms, and without involving the form invariance of the governing wave equations.

The current status of transformation elastodynamics has significantly extended past traditional transformation methods in optics and acoustics. Very recently, polar metamaterials have been theoretically shown to have the capability of cloaking full in-plane elastodynamics [49]. These metamaterials rely on rotational resonances that lead to a modified effect modulus, as well as an elasticity tensor that acquires degrees of freedom, chiral and polar. These two effects are responsible for loss of mirror and stress symmetry, enabling complete in-plane cloaking. Numerical results demonstrated cloaking of coupled pressure and shear waves along an incident angle of 30°. Following the theoretical proposal, the first experimental realization of elastic wave cloaking by polar metamaterials was accomplished by considering a 3D printed four-layered lattice embedded in an isotropic continuum medium that served as the cloaking device, where each layer played an essential role in the rerouting of stresses and distribution of torques between lattice

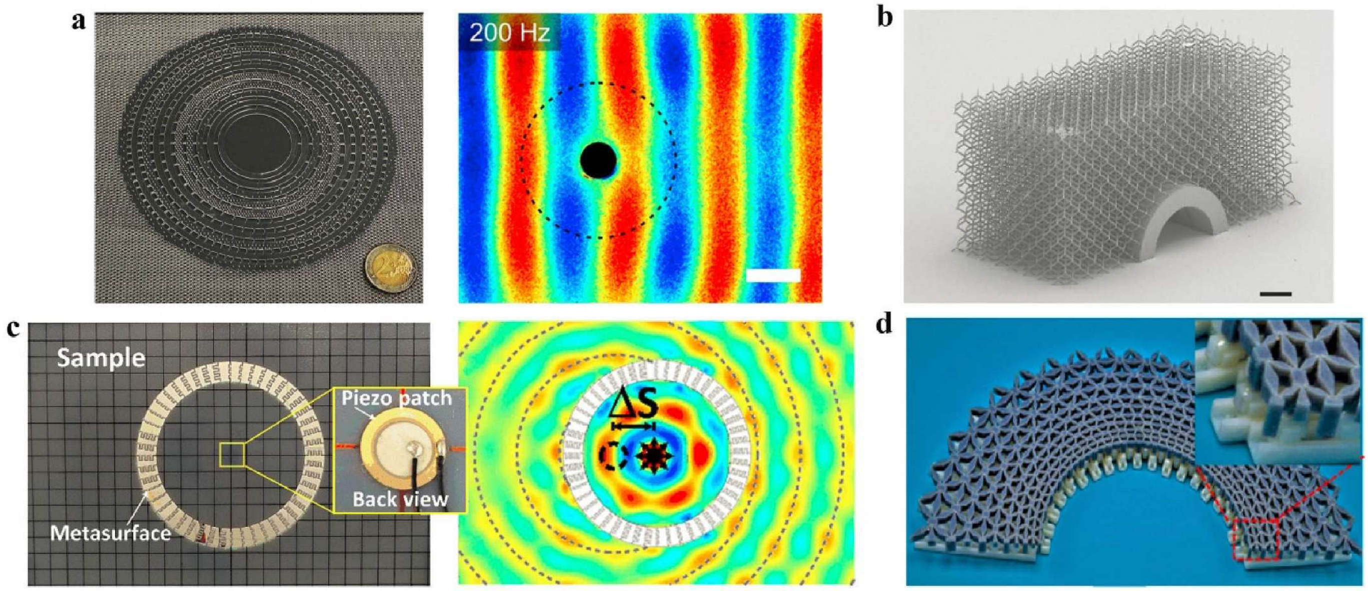

Fig. 4. Elastic cloaking. a, Cloaking shell for elastic waves made of concentric cylindrical layers of PVC and PDMS. The coin diameter is 25.75 mm (left). Experimental cloaking of a cylinder (black) using the shell (dotted line) from an elastic plane wave at frequency 200 Hz incident from the left (right). Scale bar 5 cm. Reprinted with permission from [41]. Copyright (2012) by the American Physical Society **b,** A pentamode carpet cloaking device for elastic waves, made of a hollow solid cylinder and surrounding cloaking shell and background pentamode structure. Scale bar is 200 μm. Reprinted with permission from [44]. Copyright 2014, Springer Nature. **c** Elastic metasurface shifter made of radially arranged coil unit cells. Inset: Piezo patch source (left). Experimentally measured elastic wave field at 12 kHz showing the point source to be displaced by $\delta S = 25$ mm. Reprinted with permission from [48]. Copyright (2017) by the American Physical Society. **d,** Polar-mechanical elastic cloak viewed from the top. The cloak is formed by four different stacked layers consisting of a cloaking lattice, rails, and connectors. Reprinted with permission from [50]. Copyright (2020) by the American Physical Society.

sites (Fig. 4d) [50]. Testing the cloaking capabilities for the cylindrical core-shell geometry was done by applying a global strain, and by measuring the displacement along the cloaking direction. Lattice based polar metamaterials have allowed for static cloaking of shear and pressure fields to be experimentally realized for the first time, and while the results are limited to statics, the cloak is capable of providing shielding from external loads and provide new opportunities to achieve a long-standing goal: cloaking all elastic wave polarizations simultaneously.

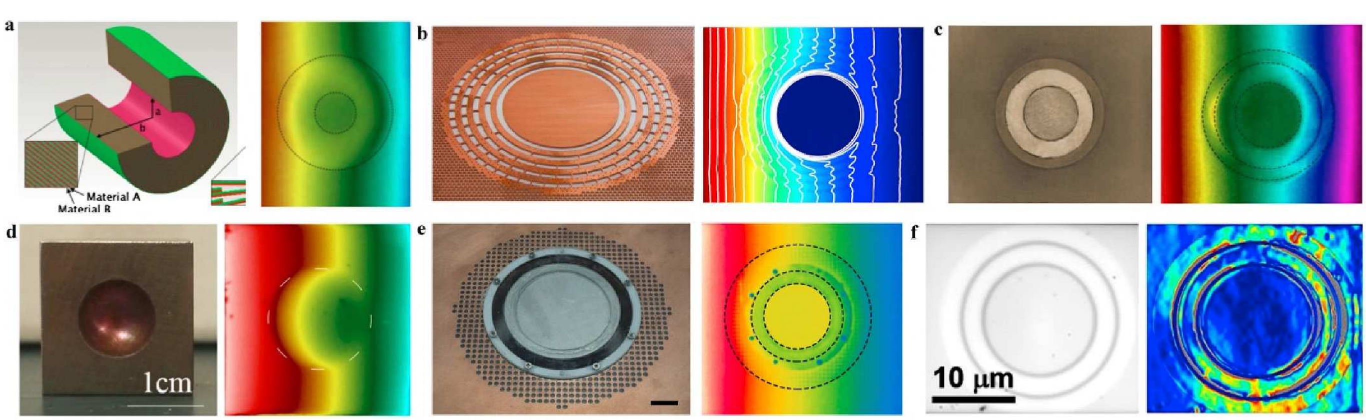

Fig. 5. Thermal cloaking. a, A cylindrical multilayer thermal cloak made of latex rubber (A) and silicone elastomer (B) (left). Experimental temperature distribution where the thermal cloak prevents heat flux from entering the core while maintaining the external temperature gradient unperturbed (thermal cloaking). Red: Hot. Blue: Cold (right). Reprinted with permission from [54]. Copyright (2012) by the American Physical Society. **b,** A thermal cloak for transient regime made of copper and PDMS (left). Temperature profile measured at 90 s, with iso-temperature lines in white (right). Reprinted with permission from [55]. Copyright (2013) by the American Physical Society. **c,** 2D bilayer thermal cloak made of a layer of polystyrene surrounded by nickel-based alloy layer (left). Measured steady state temperature profile showing cloaking effects (right). Reprinted with permission from [58]. Copyright (2014) by the American Physical Society. **d,** A 3D thermal cloak via molding a thin spherical copper shell into a stainless-steel block (left). Temperature profile recorded at 4.5 min where the air sphere is thermally cloaked by the device (right). Reprinted with permission from [59]. Copyright (2014) by the American Physical Society. **e,** A zero-index thermal cloak working in a copper background. The annulus is filled with water that rotates while the external layer is made less conductive than copper by drilling holes. Bar scale: 2 cm (left). Measured temperature profile by an infrared camera when water in the central channel is rotating (right). Reprinted with permission from [64]. Copyright 2019, Springer Nature. **f,** A microscale four-layer thermal cloak (left). Measured heat flux showing no heat flux (blue) towards the core (right). Reprinted with permission from [65]. Copyright (2019) American Chemical Society. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4. Thermal cloaking

A remarkable breakthrough in metamaterial theory is the realization that – besides wave propagation - heat conduction can be analogously manipulated via coordinate transformations since thermal diffusion equations have been shown to be form invariant [51–53]. This leads to metamaterial devices that guide heat flow around arbitrary objects without disturbing the external thermal gradient (thermal cloaking). The unique capabilities of these thermal metamaterials come from their prescribed anisotropy of the thermal conductivity, which is rationally designed by coordinate transformations and realized experimentally by using composites made of stacked macroscopic layers of easy to obtain isotropic materials. This new class of artificial thermal metamaterials was first employed to cloak an object from heat flux without disturbing the external thermal gradient by designing and fabricating a shell made of forty alternating cylindrical layers of natural latex rubber and silicone elastomer containing boron nitride particles all in agar-water background (Fig. 5a) [54]. These exciting experiments were soon extended to test the rerouting of heat flow under transient conditions by fabricating a thermal cloak for transient heat flow around an object in a metal plate (Fig. 5b) [55]. The device was comprised of equally spaced rings with alternating large and small effective ring thermal conductivities, made of a combination of copper and PDMS. The experiments show the cloak successfully working in keeping the central region cold and the external temperature unperturbed. Further experimental and theoretical evidence for thermal transient cloaking was introduced by employing multilayer metamaterials made of alternate isotropic and homogeneous layers to surpass conventional material capabilities in terms of thermal cloaking [56,57].

To simplify the material requirements for the cloaking shells, easy-to-fabricate thermal cloaks based on scattering cancellation were recently introduced using only two layers of bulk isotropic materials to achieve thermal cloaking in both 2D [58] and 3D [59]. In 2D, the cloaked object was at the center of the bilayer cloak which was formed by a cylindrical layer of polystyrene surrounded by a layer of a nickel-based alloy (Fig. 5c) [58]. Testing the bilayer thermal cloak showed excellent performance by maintaining a stable heat protection to the object inside the thermal cloak and maintaining the heat distribution outside. In 3D, the experimental demonstration was conducted using an ultrathin spherical copper layer with a thickness of 100 μm that surrounds an air sphere with a diameter of 1 cm and cloaks the sphere from an external thermal flux field in stainless-steel background (Fig. 5d) [59]. This 3D thermal cloak used some of the latest advancements in fabrication to produce the ultrathin spherical copper layer. The rapid development of manipulating thermal fields via metamaterials has also made a significant impact in seeking novel technologies for camouflage. A functional thermal camouflage device was demonstrated that transforms an objects thermal scattering profile to that from multiple isolated objects [60]. For this camouflaging effect, a bilayer cloak was adopted that uses copper and PDMS materials, and the device functioned exceptionally well in camouflaging the thermal profile of an object. Subsequently, elliptical bilayer cloaking devices were proposed for an invisible sensor and invisibility cloak, and these functionalities have been shown to switch when heat flows along different directions [61,62].

Significantly, the remarkable success in carpet cloaking for light, sound, and elastic waves, was also extended to thermal diffusion, and recently the first experimental thermal carpet cloak was introduced by designing a layered structure made of stainless steel and cork that creates a thermal carpet cloak without the need of knowing any properties of the object to be cloaked [63]. When exposed to a thermal gradient, the thermal carpet cloak maintained the internal region at constant temperature with minimal disturbance of constant temperature lines outside the cloak. The experimentally verified thermal carpet cloak allows for a new alternative to thermally shield an arbitrary shaped object on a surface.

Further advancing the capabilities of thermal cloaks into extreme environments, such as achieving cloaking in high thermal conductivity background materials, requires expanding upon the thermal conductivities available from natural materials. Towards this end, noting an exact equivalence between zero-index photonics and infinite thermal conductivity, a hybrid convection-conduction core-shell system was recently designed to cloak an object in a copper background [64]. The core layer is a water rotating channel surrounding the object while the shell is built by drilling holes in the copper background (Fig. 5e). In addition to cloaking in extreme environments, very recently, a novel approach was introduced to develop cloaking metamaterials at the microscale using focused ion irradiation, which allowed to locally control the thermal conductivity on a silicon membrane and provide a tunable range of 2–65 W/m·K values [65]. Using this technique, a microscale thermal cloak was designed by fabricating concentric rings with different thermal conductivities via ion writing (Fig. 5f). Significantly, this new form of fabricating microscale thermal metamaterials enables novel opportunities to explore thermal cloaking at small lengths scales.

Very recently optimization analysis for thermal cloaking has been reported showing that high efficiency can be obtained by using a multilayer shell composed of only three isotropic materials with optimally chosen thermal conductivities [66]. In the case of bilayer thermal cloaks, an optimization analysis has also been introduced to determine the optimal value of the thermal conductivity of the outer layer [67].

5. Mass diffusion cloaking

A close field of study that shares many analogies to heat conduction is mass diffusion. In order for mass diffusion to take advantage of previous advancements in thermal diffusion cloaking, transformation methods in thermodynamics were extended to Fick's second law of mass diffusion [68]. This results in metamaterials that guide mass flow around objects while maintaining the external mass concentration gradient (mass diffusion cloaking). A spherical cloaking device was theoretically demonstrated made of twenty fluid layers of varying diffusivity in order to cloak the flux of drug-delivery liposome particles in a water based solution. Experimentally, the first mass diffusion metamaterial cloak was recently introduced to enhance the lifetime of concrete foundations by cloaking chloride ions and preventing the ions from reaching the steel bars inside concrete [69]. The authors fabricated a multilayered cylindrical mass diffusion cloak made of six different types of concrete with varying amounts of cement, glue, and sand to satisfy required material parameters for cloaking. The chloride ion concentrations were measured and the ions were shown to be redirected around the steel bars located at the center. For extended periods, the ions entered the central region of the cloak but the cloak significantly reduced the time compared to if there was no cloak present. This work has impact on protecting and promoting the lifetime of civil engineering structures. Control of mass diffusion also takes a significant role in chemistry and biology where it is crucial to separate different species under diffusive processes. The use of metamaterials to separate mass diffusion has been proposed via a shell device capable of separating a mixture of oxygen and nitrogen by cloaking the nitrogen and concentrating the oxygen towards the center of the shell [70]. The proposed bifunctional device was formed by combining a diffusion cloak with a concentrator metamaterial shell. Achieving this dual functionality required two independent distinct coordinate transformations for each of the compounds, oxygen and nitrogen. More recently, using mass diffusion metamaterials, a new type of membrane was introduced to separate chemical species [71]. Prior separation methods relied on isotropic membranes, however, these engineered anisotropic metamaterial membranes permit control over direction and magnitude of mass flow resulting in significantly increased selectivities. A simplified version of such mass separation device via a simplified bilayer metamaterial shell was also recently proposed [72]. More recently, control of mass flow with metamaterials has been extended to include both diffusion and convection mechanisms as well as transient regimes, allowing the design of time-dependent mass diffusion cloaking as well as separation devices [73]. Mass diffusion is an active research area that it is critically important in chemical and biological transport and membrane processes and these results help to develop more efficient mass diffusion separation devices.

6. Light diffusion cloaking

In this brief section we focus on cloaking light propagation in the diffuse regime where light shows strong analogies with heat and mass diffusive processes and metamaterial concepts can be analogously applied. Cloaking of diffusive light was experimentally reported [74] by gathering inspiration from previous thermal cloaks that utilized a core-shell geometry to achieve cloaking [53]. The cloak fostered a hollow stainless steel cylinder as the core, coated with a thin acrylic white paint to serve as reflector. The shell was made of PDMS doped with 10 μm diameter dielectric particles, and the core-shell system was submerged in a tank containing deionized water and white wall paint. The cylindrical diffuse cloak was exposed to white light and significant cloaking of diffuse light was observed. In diffuse light cloaking, the phase is destroyed by the random processes inside of the diffusive metamaterial shell, in contrast to wave-based cloaking of light. The experimental realization of cloaking for diffuse light clearly shows the versatility of coordinate transformations and metamaterial concepts since light understood as a wave but also as a random motion of photons can both be cloaked by rationally designed metamaterials.

7. Electric and magnetic cloaking

In complete analogy to bilayer thermal cloaks shown in previous sections, cloaks for direct currents have been recently experimentally demonstrated by using bulk natural materials. In this case, the cloaks are made of air (internal layer) and copper (external layer) surrounded by stainless steel background (Fig. 6a) [75]. The electrical potential is measured outside the cloak, with and without the cloak, showing that when the cloak is present the profile is the same as if the object and the cloak were not there. In addition to electric fields, magnetic fields are also often required to be isolated from a region, which is usually achieved using superconductors or tailored metal composites. These materials require low temperatures and magnetic shielding is accomplished by distorting the external magnetic field. Metamaterial dc magnetic cloaking was first theoretically proposed [76] and subsequently experimentally realized using a hollow cylinder with a patterned array of superconducting and soft ferromagnetic elements (Fig. 6b) [77] involving polyimide, lead, permalloy, and chromium base along with photolithography techniques. A cylindrical bilayer magnetic cloak was also introduced to shield an area from a static magnetic field, and was fabricated using fewer materials such as superconducting tape (inner

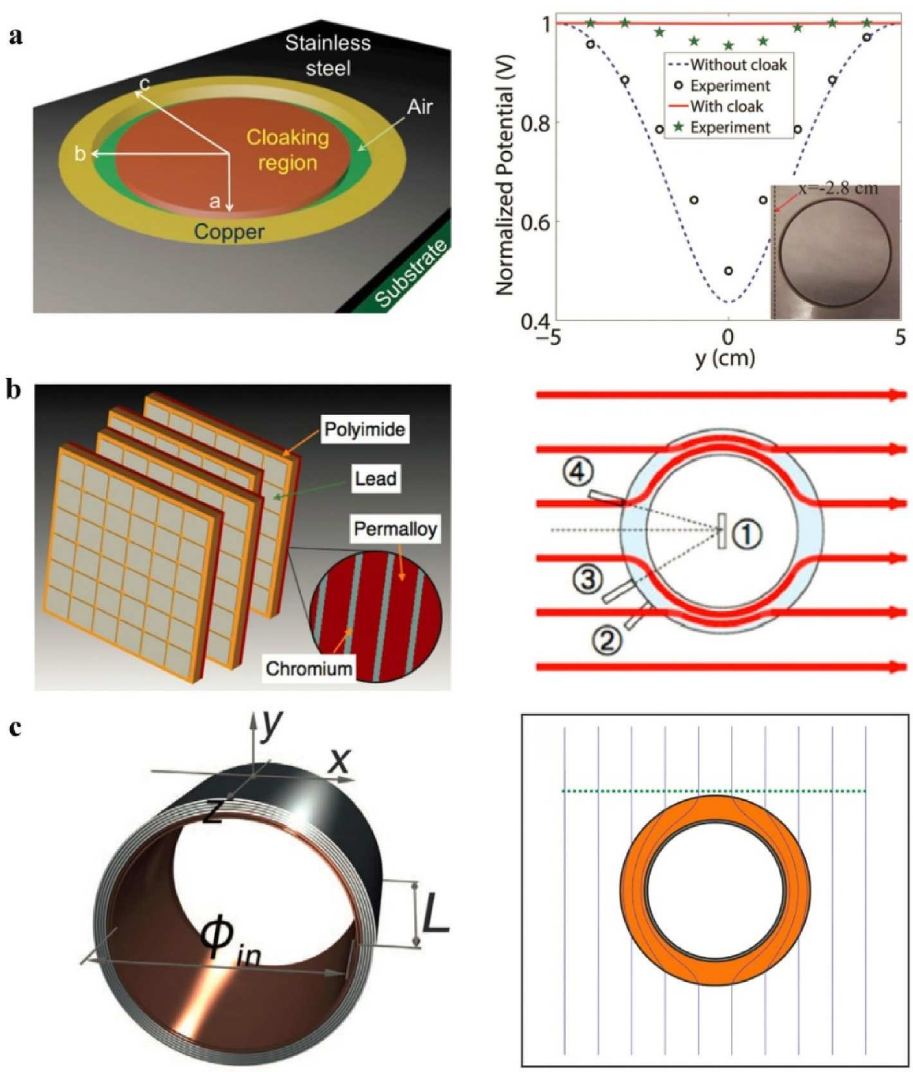

Fig. 6. Electric and magnetic cloaking. a, Direct current bilayer cloak (left). Nearly constant electrical potential measured along the vertical direction at $x = -2.8$ cm (right) [75]. © 2014 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim **b,** Magnetic cloak made of superconducting and soft ferromagnetic elements (left). Lines tracing the magnetic field around the magnetic cloak, with labels 1–4 measuring field intensity (right) [77]. © 2012 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim **c,** A bilayer magnetic cloak formed by superconducting tape (brown) and ferromagnetic sheet (gray) (left). Magnetic field lines cloaking a circular region, where the green dashed line indicates the measurements in the experiment (right). From [78]. Reprinted with permission from AAAS. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

layer) and a thick FeNiCr commercial alloy sheet (outer layer) (Fig. 6c) [78]. Measurements for the external magnetic field by sensors across different positions showed no distortions for the external magnetic field lines.

Moving beyond dc magnetic cloaking, a magnetic cloak was soon developed to operate from dc to 250 kHz [79]. In this case, a bilayer 3D design was employed consisting of a hollow spherical center where any arbitrary object can reside followed by a yttrium-barium-copper-oxide superconducting inner layer and a NiZn ferrite based ferromagnetic outer layer. Simulations and experiments at 77 K using a commercial metal detector provided the magnetic field, which showed little to no change in the external field over the range of magnetic field frequencies. A drawback to the operation of magnetic cloaks has been the use of liquid cooling to keep the superconducting material operational for its desired properties. To overcome this limitation, a functional 3D magnetic cloak that features ordinary metals and materials that can operate at room temperature within 5–250 kHz was demonstrated [80]. The magnetic cloak was made of a bilayer structure consisting of a spherical copper shell that enclosed an air volume, and was fitted with a shell of ferrite mixture made from NiZn powders to achieve tailored ferromagnetic response. Recently, experimental magnetic cloaking of irregular shapes was also developed [81], allowing to surpass the cloaking of spherical and cylindrical objects, thus moving the field into becoming more widely versatile in applications from military to medical fields where one can benefit from magnetic shielding.

8. Multifunctional cloaking

The rapid success in cloaking capabilities across various fields has been extended to the design of devices that cloak more than one physical phenomena at the same time. These multifunctional metamaterials devices were initially introduced theoretically to manipulate heat and electricity [82,83], while the first experimental multifunctional cloak was introduced to cloak both heat flux and electric current [84]. This bilayer cloak made of silicon redirects the incident electric and heat flux around an air cavity, which strong scatters both electric and thermal fields, while restoring the external flux profiles. Experimental results are shown in Fig. 7a where the bifunctional device exhibited good cloaking performance when placed under electrical and thermal fields. Another bifunctional electrical-thermal experimental metamaterial was reported to concentrate both fields simultaneously in the center of the device [85]. The design featured a fan-shaped structure made of eighteen alternating wedges of ABS thermoplastic and aluminum and measurements showed electric potential and temperature gradients increased in the core region. More recently, optimized structural topology for electric-thermal cloaks has also been proposed to better leave undisturbed the external voltage and temperature profiles [86].

Advances in electrical-thermal cloaking were made possible since both conduction fields are governed by Laplace equations. More recently, however, by realizing that electromagnetic, acoustic, and water waves can all be described by the Helmholtz wave equation, a metasurface made of split ring resonators was theoretically designed to restore the reflected phase for all these waves providing a novel multifunctional metasurface carpet cloak [87]. Further work was also recently developed to simultaneously cloak electromagnetic and acoustic waves based on surface coordinate transformation multiphysics [88].

Interestingly, another form of bifunctional cloaking was reported for coupled thermal conduction and radiation [89]. To control these two thermal fields an approximation to the Stefan-Boltzmann law is used which leads to the Rosseland diffusion equation for thermal radiation. By using this approximation, thermal radiation can be regarded as the diffusion of photons, leading to a conductive-type multilayer structure made of two isotropic and homogenous materials for cloaking radiation and conduction.

Very recently, cloaking devices capable of cloaking heat conduction

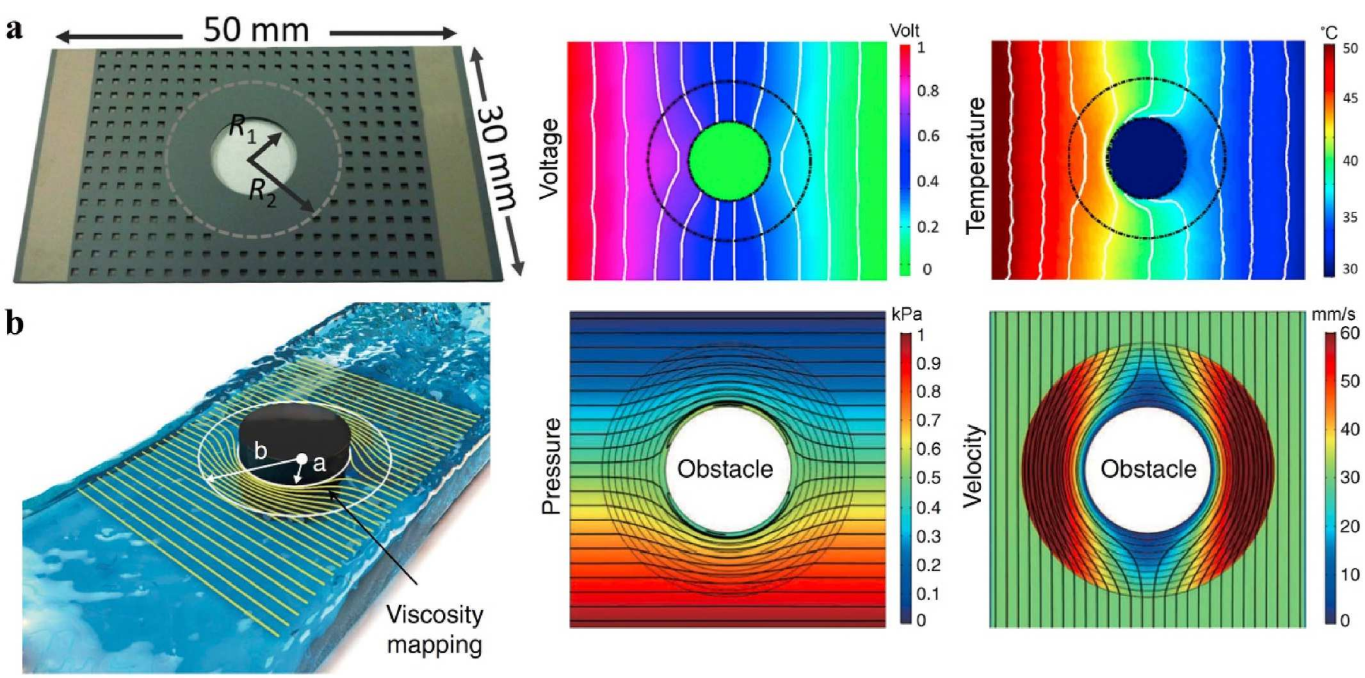

Fig. 7. Bifunctional and hydrodynamic cloaking. a, A bifunctional silicon-based electric and thermal cloak featuring a cloaking shell of inner and outer radius R_1 and R_2, respectively (left). Measured electric voltage, where white lines show the iso-potential contours normal to the current lines, and black lines describe the cloaking shell (center). Experimental temperature profile, where white lines show the iso-thermal contours normal to heat flux (right). Reprinted with permission from [84]. Copyright (2014) by the American Physical Society. **b,** Illustration of hydrodynamic cloaking showing fluid flow around the dark object and the cloaking shell, with yellow lines showing the iso-pressure contours (left). Pressure field with a ten-layer hydrodynamic metamaterial cloaking shell (center) and corresponding velocity field (right). Reprinted with permission from [94]. Copyright (2019) by the American Physical Society. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

and fluid flow were introduced theoretically by coordinate transformations of the permeability and thermal conductivity, enabling novel thermo-hydrodynamic cloaking [90–93]. Velocity and temperature profiles confirmed the effectiveness of the cloaking shell in leaving both the external fields unperturbed. Significantly, in recent years new advances have been made experimentally by designing and fabricating a shell that cloaks hydrodynamic flow via a transformed viscosity tensors that required ten layers of micropillars in the fluid (Fig. 7b) [94]. Furthermore, the prospects of manipulating and cloaking the three forms of heat processes (conduction, radiation, and convection) have recently been reported using metamaterials [95]. The advancements and methods from cloaking single physical systems have set into motion the next frontier of novel multifunctional cloaking devices that would be capable of much more than first imagined.

9. Conclusions

The longstanding goal to cast an object invisible can now potentially be realized through transformation optics and the ever growing development of metamaterials. The design and fabrication of electromagnetic cloaks that began theoretically, became reality through the use of metamaterial cloaking shells and carpet cloaks as well as advanced metasurfaces. These groundbreaking ideas found themselves to be translatable into other fields, and we showed how they sparked novel devices that control the flow of sound in air and water, elastic waves in solids, electric and magnetic fields, and most recently bifunctional devices capable of performing cloaking of two fields at the same time. The future of metamaterial cloaking devices is bright as there are still many unexplored fields, including quantum systems that remain to be fully investigated largely due to the complexity in experimentally verifying cloaking for such systems.

There are still important challenges ahead to further develop the field of metamaterial cloaking. To date, most works have been focused on macroscopic metamaterial cloaking for diverse physical fields. It would be a great advance in the field to design and fabricate metamaterials that operate at different length scales. Metamaterials operating at millimeter or nanometer lengths scales would allow multifunctional integrated cloaking devices, while at atomic length scales would enable the development of new fundamental physics.

In our natural world, the existence of multiple physical fields make the world extremely interacting. As shown in this Review with the development of unprecedented cloaking devices in the last years, we can move in the opposite direction. We can now create a transformed natural world where animals and objects do not interact. One can possibly be invisible to others, both optically and acoustically, vibrations such as earthquakes could be unnoticed in cities and towns, metallic devices could pass through electric and magnetic fields undetected, ships may navigate without bow waves, and more. Moving from an interacting to a non-interacting world using metamaterial cloaking devices would certainly be a game changer for technology and society, with many more unpredictable outcomes that defy our imagination.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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