

iments will be able to probe deep enough into these promising materials to reveal the exotic behavior they expect to be there. As Matthew Fisher of the University of California, Santa Barbara, sees it, spin liquids are the cleanest example of a strongly correlated quantum system that has qualitatively different behavior from Fermi liquids and other simple, well-understood phases.

Barbara Goss Levi

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Designer materials render objects nearly invisible to microwaves

Coordinate transformations and curved spaces, the traditional tools of general relativity, are finding applications in optical engineering.

Optical design is largely a matter of choosing the right material for the job and then optimizing its geometry—say, a glass lens to form images, a metal cage to screen sensitive electronics, or a polymer film to reduce surface reflections. But the range of electromagnetic properties available to optical engineers from materials found in nature falls far short of what is theoretically possible.

In 1999 John Pendry and colleagues from Imperial College London dramatically extended the palette of realizable electromagnetic properties by proposing a variety of artificial structures—metamaterials—whose response to radiation could be custom-designed.¹ Although the field of artificial materials dates back to the 1940s, it took advances in computation and fabrication technology made in the 1990s, along with a surge of interest in negative refraction, to set the stage for engineering composite materials whose effective magnetic permeability tensor μ and electric permittivity tensor ϵ could be tailored.

Essentially miniature inductive and capacitive circuits composed of copper loops built into a repeated array of unit cells, Pendry's metamaterials owe their electromagnetic properties to subwavelength details of geometric structure rather than to chemical composition. As long as the size and spacing of circuit components are small compared to

wavelengths of interest, incident radiation cannot distinguish circuits from conventional materials. Adjusting a circuit's geometry tunes its resonant frequency and the strength of its electromagnetic response to the incident radiation.

To understand how, think of each circuit as a magnetic atom. Just as a magnetic atom produces a net magnetic dipole in response to a field, so do these metamaterials, at least in the microwave regime where metals react strongly to applied fields. A time-varying electromagnetic field induces an electromotive force that drives a current in a conducting loop. A gap in the loop introduces a capacitance into the circuit and produces a resonance at a frequency set by the loop's geometry. Similarly, the electric component of the field induces an electric dipole that oscillates with a large amplitude near its resonant frequency. Because the resonant frequency of a metamaterial can be set to virtually any value, one has tremendous control over ϵ and μ .

Armed with this powerful design flexibility, researchers have since created metamaterials with properties impossible to find in nature. If fashioned so that both ϵ and μ are negative at some frequency, for instance, metamaterials can form exotic lenses that bend light at that frequency in a direction opposite



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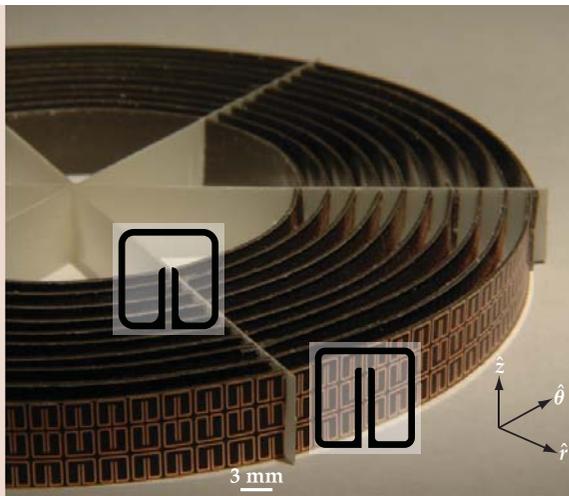


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Figure 1. An invisibility cloak, made up of 10 nested concentric fiberglass cylinders filled with metallic split-ring resonators, scatters incident microwaves around its innermost cylinder. The effect prevents the waves from interacting with whatever lies inside. Adjusting the length of each split and the curvature in the square corners of each unit cell shifts the frequency of the electric and magnetic resonances so that engineers can custom-design the value of the electric permittivity ϵ and magnetic permeability μ in each cell. (Adapted from ref. 2.)



that of ordinary materials and produce images with a level of detail beyond the diffraction limit (see the article by Pendry and David Smith in *PHYSICS TODAY*, June 2004, page 37).

Pendry, along with Duke University's Smith and postdoc David Schurig, has taken the notion of flexible design to its logical conclusion: If, they reasoned, something can be constructed with ϵ and μ varying independently and arbitrarily throughout the material, then one can redirect electromagnetic waves at will. The researchers set themselves a problem straight out of *Star Trek*—electromagnetic cloaking, the deflection of waves completely around an object so that the waves return to their original trajectories on the other side, which effectively renders the object invisible.² Five months later they had a working device.³

Curved spaces

Designing an invisibility cloak is straightforward, in principle: Find the coordinate transformation that distorts in just the right way the underlying space and thus the paths that electromagnetic fields are constrained to follow. The desired effect is to squeeze space from a volume into a shell. Interestingly, Maxwell's equations are form-invariant to coordinate transformations, so only the components of ϵ and μ would be affected, each multiplied by the same factor. Pendry and company "are essentially applying the recipes of general relativity, mapping free space into curved space," explains Ulf Leonhardt, a theorist from the University of St. Andrews in Scotland who has outlined a similar protocol to achieve cloaking.⁴ The anisotropic variation in ϵ and μ takes the place of mass in de-

flecting the light rays to avoid certain regions of space, in this case a hole where an object might be hidden.

Building a cloak is more complicated. The tensor quantities ϵ and μ are each three-dimensional matrices, whose components are spatially varying. To simplify the problem, Schurig and coworkers restricted their implementation to an effectively 2D one and adopted a reduced set of parameters

using cells that are diagonal in the cylindrical basis. So although the r , θ , and z components of ϵ and μ each vary with radius in an exact transformation, the actual cloak accounts only for radial variation in μ_r . The only other relevant parameters are μ_θ and ϵ_z , and they're held fixed.

The cover and figure 1 show the device: 10 nested fiberglass cylinders, each containing hundreds of wire loops, or split-ring resonators, that scatter incident microwaves through the cloak and around the innermost cylinder. Although variations in the unit-cell geometry affect both ϵ and μ , Schurig found that he could tune the values of both parameters independently through minor adjustments in the length of the split and the curvature at the corners of each square loop. That curvature and the amount of metal at each corner have little effect on the area threaded by the magnetic flux, but they tweak the electric coupling between adjacent unit cells enough so that ϵ_z can be held constant while μ_r is increased.

To test the degree to which their device approximates perfect invisibility, the researchers placed it in a parallel-plate waveguide and measured the electric-field amplitude and phase inside and outside the cloak as polarized

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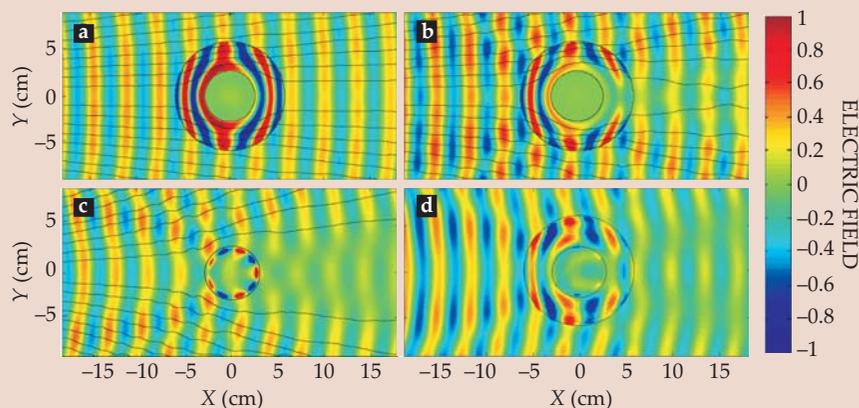
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Figure 2. Snapshots of the electric-field patterns and direction of power flow (black lines) reveal the effect of perfect and imperfect cloaking as polarized microwaves approach from the left. The cloak lies in the annular region between black circles and surrounds a copper cylinder. (a) Simulation of waves dispersing within an ideal cloak whose material properties ϵ and μ correspond to an exact coordinate transformation. (b) Simulation of a cloak whose simplified values of ϵ and μ are those of the actual device. (c) Experimental measurement of a bare copper cylinder, uncloaked. (d) Experimental measurement of field patterns in the actual cloak. In each case the electric field is measured or simulated at various points along a Cartesian grid. (Adapted from ref. 2.)



microwaves were directed toward it. Figure 2 compares theoretical simulations with those experimental results, revealing deviations from the ideal. In each case, as waves propagate through the cloak and approach the inner radius, the wavefronts begin to lag with a concomitant compression in wavelength and a reduction in intensity. The

penalty for using the reduced parameter set for ϵ and μ is nonzero reflectance of the incident radiation, as pictured in figures 2b and 2d. Real materials, of course, also absorb some fraction of incident radiation. Nevertheless, the device dramatically reduces backward and forward scattering of microwaves, compared with the case where the

waves are incident to an uncloaked copper cylinder (figure 2c).

Other researchers have recently proposed alternative invisibility schemes.⁵ In 2005 the University of Pennsylvania's Andrea Alù and Nader Engheta proposed the use of a plasmonic shell that suppresses scattering by resonating in tune with the incident radiation. The

physics update

Supplementary material related to these items can be found at www.physicstoday.org.

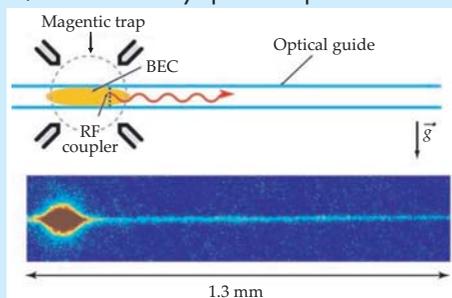
Ball lightning in the lab. Seen infrequently and never scientifically studied in nature, the meandering globes of light known as ball lightning have nevertheless been reported thousands of times over the past few centuries, usually in the warm summer months when thunderstorms abound. Many dozens of theories



have arisen, but few can explain the most puzzling properties of the atmospheric phenomenon—the balls, which can range in size from 1 cm to 1 m, last up to 10 seconds and move unpredictably through the air. They have even entered houses through chimneys and squeezed through small openings. One recent theory says that ball lightning arises from silicon nanoparticles that form in the soil when silicon oxides react with carbon. When a lightning strike vaporizes the oxides into metallic silicon, the vapor subsequently condenses in the air, electrostatically bound and glowing with the heat of oxidation. A team of physicists and chemists in Brazil has now given credence to that so-called Abrahamson–Dinniss theory. They mounted a silicon wafer on a steel plate and completed an electric circuit by touching the wafer with a movable tungsten or graphite electrode. When the electrode was slowly removed, an electrical arc formed with hot tiny silicon fragments flying everywhere. But at a separation of about 1–2 mm, luminous

spheres formed and also flew off. The resulting balls were 1–4 cm across, had lifetimes up to 8 seconds, moved at speeds of 5–30 cm/s, and decayed with no trace. The figures show one such ball, at 80-ms intervals, passing through a small gap under an electrical conductor. The experiments were done in conditions not very different from those found in nature: room temperature, normal atmospheric pressure, and 70% relative humidity. (G. S. Paiva et al., *Phys. Rev. Lett.*, in press.) —SGB

Guided atom laser. A trapped cloud of atoms chilled into a Bose–Einstein condensate is a single coherent structure. When extracted from the trap and allowed to propagate, it acts like a laser beam, except that the coherent waves are of matter rather than light. In a typical atom laser, the atoms are released and accelerated by gravity, a process that decreases the atom laser's de Broglie wavelength. Now, physicists from the Institut d'Optique Graduate School in Palaiseau, France, have coupled atoms from an optomagnetic BEC trap to a horizontal optical waveguide, which generated a quasi-continuous atom laser, impervious to gravity and having a constant de Broglie wavelength of 0.5 μm . The RF coupling converts the atoms from a magnetic to a nonmagnetic state, and they emerge with a typical velocity of 9 mm/s and a velocity spread of just a few $\mu\text{m/s}$, driven along a confining beam of light, as shown in the figure. Changing the RF coupler's frequency can tune the de Broglie wavelength, and changing its power can alter the atom laser's density. In addition, the



exciting electromagnetic field induces in the shell a series of multipole moments that effectively cancel some of those of the object inside it. But the properties of the object being cloaked and of the cloak itself would have to be carefully matched. The scheme thus lacks the generality that Schurig and his colleagues achieved: In their device anything—from mouse to missile—can be cloaked, provided it fits within the cloak's dimensions.

Romulan dreams

Because the cloak is dispersive—as it must be since the phase velocity of waves inside the cloak exceeds the speed of light in free space—the bandwidth over which it works well is narrow; Schurig and coworkers performed their proof-of-principle demonstration at a single frequency of 8.5 GHz. The microwave-frequency region has plenty of relevance in today's world, though, and one can imagine an eventual replacement to radar evasion and stealth technologies in aircraft—à la Romulan cloaking of *Star Trek* fame. According to the University of Rochester's Allan Greenleaf and col-

leagues, invisibility is not restricted to passive objects. Active sources and sinks—cell phones and computers, say, or anything else that emits or receives a signal—may also be cloaked, at least in principle.⁶

Metamaterials based on a nonresonant circuit design might overcome the bandwidth problem to some degree. But extending the response to optical frequencies is trickier. Today the nanometer-scale lithography required to shrink circuit components to fractions of the wavelength of visible light is routine. But the electric permittivity of metals at optical frequencies is several orders of magnitude lower than it is in the microwave region. Electrons simply can't follow the oscillations in the electric field nearly as well at such high frequencies.

Creating 3D cloaks isn't easy either. The difficulty lies in designing a cloak's configuration to produce all the needed variations in the tensor components of ϵ and μ . Traditional metamaterials are assembled from 2D planar sheets that typically intersect each other in a cubic lattice. The Duke–Imperial College design veered from tradition by bending

sheets into cylinders to form a metamaterial that is semicrystalline—periodic in θ and z but amorphous in the radial direction. The next-generation design may incorporate spherical circuit configurations and more exotic topologies. But according to Pendry, that shouldn't surprise us. "The more you think about Maxwell's equations, the more you realize that geometry is at their heart."

Mark Wilson

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researchers showed that the coupling is 100% efficient; no atoms are lost during extraction and transport along a 1-mm guide. The new atom laser opens promising prospects for applications in atom interferometry and more fundamental studies of matter-wave propagation. (W. Guerin et al., *Phys. Rev. Lett.* **97**, 200402, 2006.) —PFS

A prism for x rays. With far more energy than visible light, x rays reflect from surfaces only at glancing angles and with little wavelength-dependent spreading. Bragg diffraction in a crystal allows for scattering of x rays through larger angles because the incoming x rays scatter from numerous atomic planes beneath the surface. With a normally cut crystal, though, there is still little dispersion. Physicists using the Advanced Photon Source at Argonne National Laboratory have now spread out a beam of x rays into a rainbow of colors with the help of an asymmetrically cut crystal, whose atomic planes are not parallel to the crystal surface. The effect is strongest when the reflecting atomic planes are nearly perpendicular to the surface; then exact backscattering occurs not at normal incidence to the planes but at an angle that depends on the x-ray energy. The diffracted x-ray beam is spread out prismatically into its component wavelengths. In the experiment, an incoming beam of 9-keV x rays with angular spread of only 1 microradian was backscattered into a rainbow with an angular dispersion of 230 μrad . According to team leader Yuri Shvyd'ko, the new technique can lead not only to a new type of x-ray monochromator and to very-high-resolution x-ray spectrometers but also to compression of x-ray pulses in time. (Y. V. Shvyd'ko et al., *Phys. Rev. Lett.* **97**, 235502, 2006.) —PFS

A piconewton force sensor. Many forces in the world of cell biology are at the piconewton (10^{-12} N) level. Examples include the force applied by the kinesin molecular motor protein to

transport vesicles (6 pN), the force needed to unzip a DNA molecule at room temperature (9–20 pN), and the force needed to rupture a DNA molecule by pulling on opposite ends (65 pN). Biophysicists need a cost-effective force sensor in this range that works reliably in water and other solvents, and Steven Koch and his colleagues at Sandia National Laboratories are working on one. The core of their device is a spring 0.5 mm long but only a micron thick, fabricated using a standard micromachining process and having a spring constant of about 1 pN/nm. (The figure shows a stiffer and shorter—186 μm long—spring between the combs.) Mounted on a substrate, the spring can be used in a number of ways: For example, it can be entrained to move with the push or pull of a biological sample, or it can be made sensitive to magnetic fields and function as a field sensor. It is also relatively insensitive to its environment, including temperature and solvent. The displacement of the spring is currently viewed with 2-nm precision by a video camera, but faster and more precise methods are possible. Koch says the most likely applications of the new sensor will be to measure forces on magnetic microspheres used in single-biomolecule experiments and to calibrate the electromagnets used in deploying microspheres. The Sandia sensor could also be adapted to apply an adjustable tension to single DNA molecules in order to study protein binding or enzymatic processes. (S. Koch, G. E. Thayer, A. D. Corwin, M. P. de Boer, *Appl. Phys. Lett.* **89**, 173901, 2006.) —PFS ■

