feature article

Shaping optical space with metamaterials

Martin Wegener and Stefan Linden

By controlling the local electric and magnetic properties of a material, researchers can tailor the flow of light and create exotic optical devices.

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In 1887, while discovering RF waves in his Karlsruhe Polytechnikum laboratory, Heinrich Hertz already knew that light could also be described as an electromagnetic wave. As such, one could say it "walks on two legs": For a single plane wave, light has an electric leg, a perpendicular magnetic leg, and a walking direction normal to both of them. Thus, obtaining complete control over light in materials or structures requires the ability to independently manipulate both legs. During the centuries that scientists have been striving to do that, however, natural substances have allowed only the electric-field component of a light wave to be directly controlled. The interaction of atoms with the magnetic-field component of light is normally just too weak.

With artificial materials known as metamaterials, that limitation was overcome a decade ago, an achievement that enabled independent control of the electric- and magnetic-field components, at least up to microwave frequencies until more recently (see the article by John Pendry and David Smith in PHYSICS TODAY, June 2004, page 37). Key to the magnetic control are subwavelength building blocks—sometimes also called meta-atoms or photonic atoms—such as the split-ring resonator (SRR) or variations on it shown in figure 1a. The SRR can be viewed as an *LC* circuit composed of an inductor—one winding of a wire coil—and a capacitor formed by the ends of the wire. Each SRR essentially acts as a miniature planar electromagnet in which the light field induces an oscillating electric current. As usual, that current gives rise to a magnetic dipole moment normal to the plane of the ring. If densely packed together to form an effective material, the magnetic dipoles give rise to a macroscopic magnetization **M**.

Interestingly, the electric current can be induced in two different ways: by a time-dependent magnetic flux enclosed by the ring—that is, via Faraday's induction law—or by an electric-field component of the light parallel to the slit of the ring, which leads to a voltage drop over the two ends of the

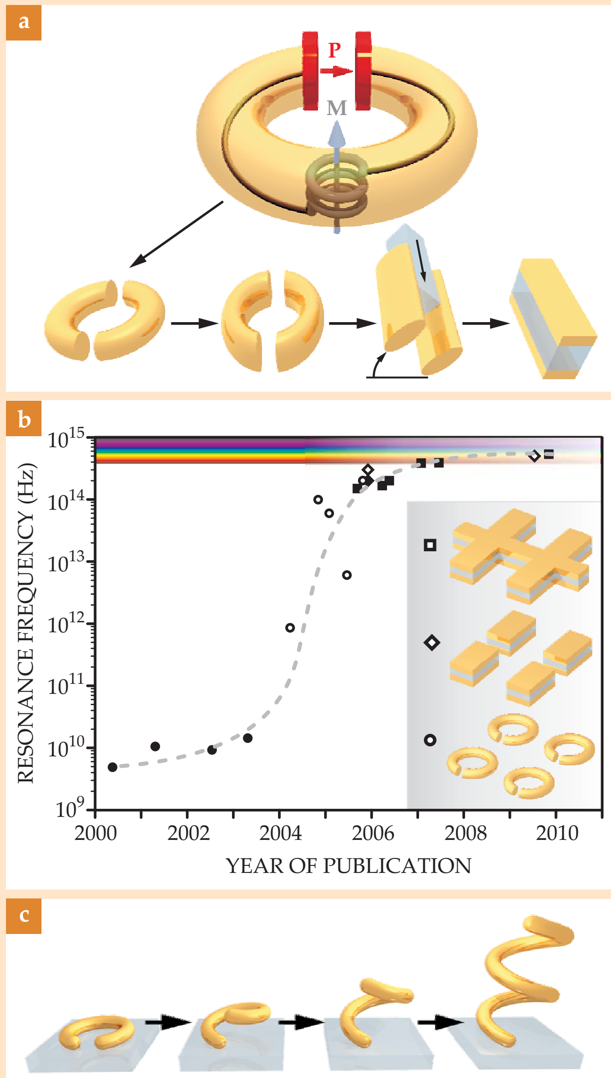

Figure 1. (a) A split-ring resonator (SRR) is essentially a miniature inductive–capacitive circuit. If many such circuits are packed together, they effectively become a material with a polarization **P** and magnetization **M**. A sequence of continuous deformations, connected by arrows, turns the SRR into a cut-wire pair separated by a dielectric (gray). Such resonators form the basis for artificial magnetism at optical frequencies. **(b)** The dramatic increase in resonance frequency in magnetic (open symbols) and negative-refractive-index (filled symbols) metamaterials achieved by several research groups over a few short years started to level off in 2006 due to a metal's finite plasma frequency, which imposes a fundamental limit on the resonance frequency.[7,8] **(c)** A three-dimensional metal helix can be formed by pulling one end of an SRR out of the plane. In the metal helix, **M** can point parallel to the electric field and lead to giant optical activity and circular dichroism.

metal wire. In the first case, magnetic dipoles are excited by the magnetic field; in the second, they're excited by the electric field. Likewise, an electric-dipole density or polarization **P** can be excited by the electric field or by the magnetic field.

In linear optics, if no static magnetic fields are involved, these four electromagnetic couplings can be summarized by the following set of constitutive material equations for the electric field **E**, the magnetic induction **B**, the electric displacement field **D**, and the magnetic field **H**:[1]

$$\mathbf{D} = \varepsilon_0\mathbf{E} + \mathbf{P}(\mathbf{E},\mathbf{H}) = \varepsilon_0\varepsilon_r\mathbf{E} - i\xi/c_0\mathbf{H}$$

$$\mathbf{B} = \mu_0\mathbf{H} + \mathbf{M}(\mathbf{E},\mathbf{H}) = i\xi/c_0\mathbf{E} + \mu_0\mu_r\mathbf{H}\,,$$

where c_0, ε_0, and μ_0 are, respectively, the speed of light, the electric permittivity, and the magnetic permeability in a vacuum and where, for simplicity, we have written as scalars the relative permittivity (or dielectric function) ε_r, the relative permeability μ_r, and the chirality parameter ξ. In the more general bianisotropic case, ε_r, μ_r, and ξ are tensors. (For notational convenience, we drop the r subscript throughout the article.)

Guiding light

Meta-atoms need not all be identical. The freedom to subtly alter their structure allows researchers to assemble different meta-atoms into spatially inhomogeneous structures and design exotic optical devices. (For a non-metamaterial example, see the Quick Study on page 72 of this issue.) Suppose you want to force light to take certain predefined pathways. According to Fermat's principle in optics and the geodetic principle in general relativity, a light ray follows a path between two points that corresponds to the shortest travel time. By tailoring the local phase velocity of light—via the local refractive index $n(\mathbf{r}) = \pm\sqrt{\varepsilon\mu}$—it's possible to minimize the travel time for selected pathways. That reasoning is intuitive. But for an explicit construction principle, one can turn to the mathematics of transformation optics.[2–6]

Transformation optics starts from a possible fictitious distortion of space—or spacetime, more generally—that corresponds to the desired pathways. In general, the distortion is not unique; infinitely many valid options are possible. A particular choice can be described by the metric tensor $g(\mathbf{r})$, which is also used in general relativity. With a suitable transformation of Maxwell equations, the distorted empty space (where $\varepsilon = \mu = 1$) can then be mapped onto a Cartesian coordinate system filled with a metamaterial whose electric permittivity and magnetic permeability tensors vary spatially but are equal to each other.

From the perspective again of Fermat's principle, the optical path length is what matters. For an infinitesimally small path element, the optical path is simply the product of the geometrical path length and $n(\mathbf{r})$. Thus a change in geometrical path length can be mimicked by a change in refractive index. The condition that $\varepsilon(\mathbf{r}) = \mu(\mathbf{r})$ simply guarantees that the wave impedance is globally equal to the vacuum impedance $Z_0 = \sqrt{\mu_0/\varepsilon_0} = 376.7\ \Omega$, leading to vanishing reflections of light at all points in the material.

Many of those aspects have been well known for decades. So what is new in the field? The ability to dramatically miniaturize the meta-atoms has recently taken researchers all the way from the microwave to the optical regime. This article illustrates how that progress in nanotechnology has become manifest in the design and implementation of metamaterials.

Magnetism goes optical

Maxwell's equations are scalable. Thus, one might expect that reducing the size of an SRR by a factor of 10^4, from submillimeters to less than 100 nanometers, should also reduce its resonance wavelength by the same factor—provided the properties of the metal that forms the SRR remain unchanged. Metallic properties, however, change with frequency: As the frequency of light interacting with a metal even remotely approaches the metal's plasma frequency, the free-electron gas no longer acts like a perfect conductor and plasmonic effects come into play.[7,8]

For an intuitive picture, consider what happens as the circuit is scaled down. Both the capacitance C and the usual geometric inductance L of the SRR are proportional to its size. Thus the magnetic energy $\tfrac{1}{2}LI^2$ necessary to draw a current

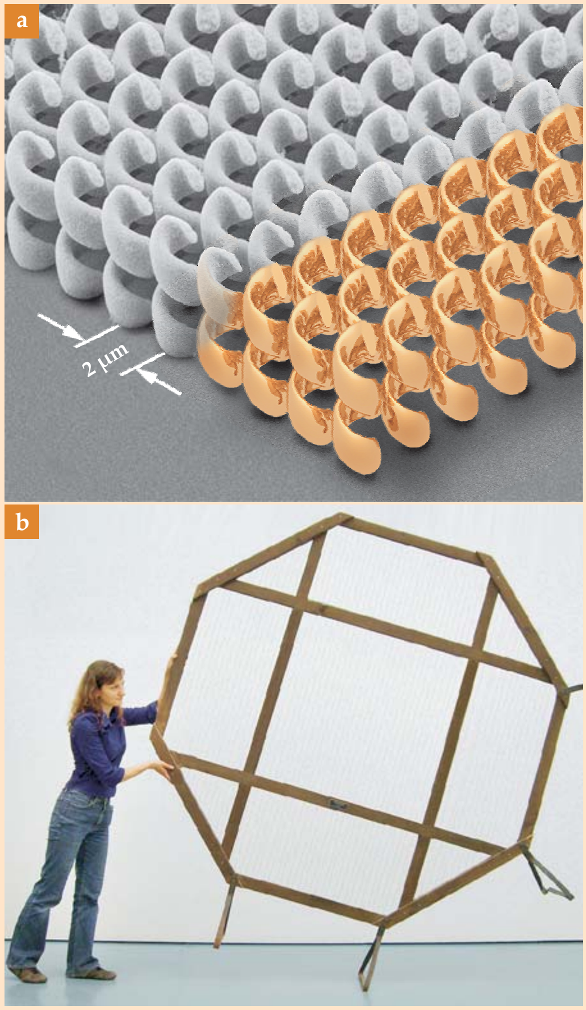

Figure 2. Circular and linear polarizers. (a) This metamaterial is composed of submicron gold helices arranged into a square lattice.[9] An oblique-view electron micrograph (gray) of the actual structure is shown in the background, with its theoretical blueprint (gold) in the foreground. The metamaterial can be used as a compact circular polarizer with more than one octave bandwidth—between wavelengths of about 3.0–6.0 µm—and is the circular analogue of the wire-grid polarizer **(b)** used in Heinrich Hertz's 1887 pioneering experiments on electromagnetic waves in Karlsruhe, Germany. Today, his wire-grid polarizer, with so much empty space between the wires, could be called a diluted-metal metamaterial.

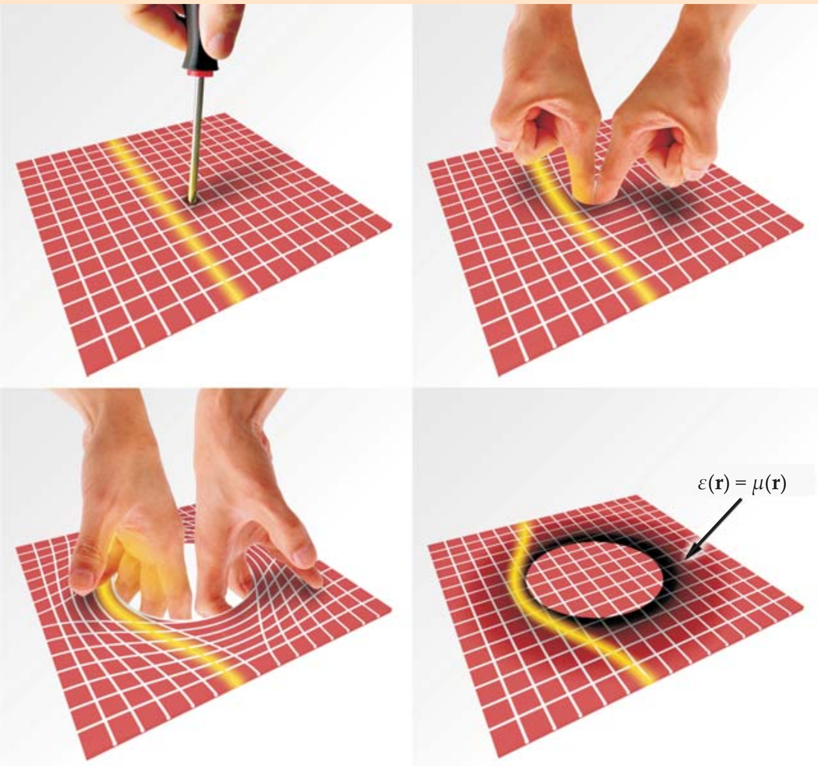

Figure 3. Using concepts of general relativity, transformation optics enables researchers to map a fictitious distortion of spacetime, illustrated here by a rubber sheet, onto a Cartesian coordinate system. A hole opened by a screwdriver is transformed to a macroscopic region of space, around which a light beam (yellow) can be guided. The key is to fill the space around the hole with a metamaterial engineered to have the appropriate refractive-index profile, with the permittivity and permeability tensors, $\varepsilon(\mathbf{r})$ and $\mu(\mathbf{r})$, constrained to be equal. From the light beam's perspective, the two situations shown in the bottom panels are equivalent. Because light never penetrates the hole, any object located therein is invisible from the outside.

I through the inductance L decreases as the size of the metal ring decreases. But the kinetic energy of N electrons moving in the ring at speed v gives rise to an additional contribution to the inductance—a so-called kinetic inductance L_{kin}. And that kinetic energy $\frac{1}{2}Nmv^2 = \frac{1}{2}L_{\text{kin}}I^2$ increases inversely with size. Hence, the kinetic energy exceeds the magnetic energy at small sizes. Because the product $L_{\text{kin}}C$ is independent of size, the resonance frequency $\omega_{LC} = 1/\sqrt{(L + L_{\text{kin}})C}$ saturates at small sizes.

To make matters worse, the ohmic resistance R of the SRR also scales inversely with size, which leads to an undesired increase in circuit damping at small sizes. One way to counteract the frequency saturation is to decrease the capacitance by design. For example, by widening the slit or by fabricating several slits—that is, several capacitors in series—the net capacitance can be reduced at fixed size and the limiting resonance frequency increases. This reasoning explains the S-shaped pattern formed by the plot in figure 1b—the resonance frequency achieved versus year—as researchers miniaturized and redesigned their metamaterials. The plot summarizes data from groups led by Steven Brueck (University of New Mexico), Vladimir Shalaev (Purdue University), both of us in Karlsruhe, and Xiang Zhang (University of California, Berkeley). Magnetic responses for $\mu \neq 1$ as well as negative phase velocities with $n < 0$ have been directly measured interferometrically, even up to visible frequencies.[8]

Nevertheless, several challenges remain. The increase of limiting resonance frequency with a decrease in capacitance also means that the ratio of operation wavelength to the meta-atom's size decreases. As a result, the behavior of a metamaterial can deviate considerably from the simple picture suggested by the electromagnetic constitutive equations on page 33. Specifically, spatial dispersion may have to be included in a detailed quantitative description. Furthermore, interaction effects among the meta-atoms can strongly modify the material's behavior, as we discuss below. The introduction of gain into the system may help compensate for the significant energy dissipation in metals at near-IR and visible wavelengths, but it remains a huge challenge. And finally, most nanostructures typically fabricated by electron-beam lithography have only a few functional layers—in some cases a single planar layer—normal to the propagation direction of light. One would hardly call that a "material." Indeed, some researchers have begun calling such structures metafilms or metasurfaces.

Giving light yet another twist

The fabrication of truly three-dimensional metamaterial structures that operate at optical or IR frequencies has been a serious challenge for nanotechnology. However, some phenomena requiring high-frequency magnetism, such as chirality, exist only in three dimensions. Eugene Hecht's famous textbook *Optics* uses chiral metal helices as a model for explaining optical activity on a classical basis. Three-dimensional helices such as those shown in figure 1c obviously lack inversion symmetry—a prerequisite for a nonzero chirality parameter ξ. It's intuitively clear, for example, that the interaction of circularly polarized light with matter that also has a helical structure depends on the relative handedness between the two.

As early as 1920, Karl Lindman fabricated many individual helices by hand from copper wire, each helix wrapped in an electrically isolating cotton ball. Thus, by randomizing the helix-axis orientations in a dense packing of the cotton balls, he realized an isotropic 3D metamaterial sensitive to microwave frequencies. In 1950 John Krauss introduced indi-

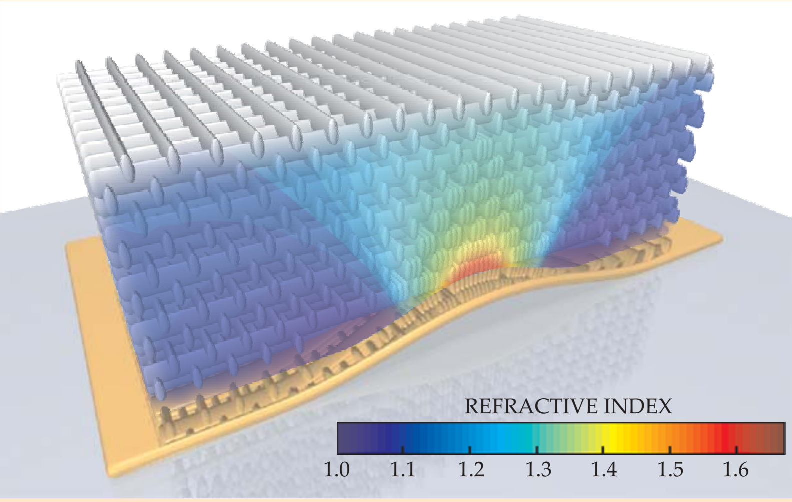

Figure 4. A three-dimensional carpet cloak. Looking through a spatially inhomogeneous region of the "woodpile" photonic crystal shown here, a bump in the gold film—the carpet—appears as a flat metal mirror. The local refractive-index profile $n(\mathbf{r})$ needed to create the illusion is calculated using the laws of transformation optics and can be realized by adjusting the local volume-filling fraction of the polymeric woodpile that leads to locally nearly isotropic optical properties.[13]

vidual metal helices as "end-fire" helical antennas. Today, such subwavelength antennas are used in numerous local area networks.

The fabrication of miniature metal helices as a metamaterial sensitive to optical or IR frequencies, however, remained out of reach until last year. Thanks to direct laser writing (DLW), which can be viewed as the 3D analog of 2D electron-beam lithography, one can tightly focus femtosecond laser pulses into a small volume of polymer photoresist and scan the focus spot across the photoresist to fabricate almost any 3D polymer structure. Lateral line widths of about 100 nm are now routine (see, for example, http://www.nanoscribe.de). By using tricks based on stimulated emission depletion, a fluorescence microscopy technique introduced by Stefan Hell in the mid-1990s, the DLW technique is no longer bound by the diffraction limit.

To convert the resulting polymer nanostructures into metal structures, techniques such as chemical-vapor deposition, atomic-layer deposition, and electroplating can be used. As an example, consider the gold-helix metamaterial shown in figure 2, which our group in Karlsruhe has made and studied.[9] With circularly polarized incident light propagating along the helix axes, optical spectra show that one circular polarization is almost completely transmitted, whereas the other circular polarization is almost completely blocked. That behavior can be intuitively understood by analogy to that of an array of end-fire helical antennas: For example, the circulating electric current in a right-handed metal helix leads to emission of an electromagnetic wave with right-handed circular polarization along the helix axis. When light's propagation direction is reversed, the antenna turns from a transmitter into a receiver. One incident circular polarization interacts with the antenna, the other does not. That is simply the behavior of a compact circular polarizer. Whatever the polarization state of incident light on the gold helix, the emerging light has nearly circular polarization.

Amazingly, the spectral bandwidth of such a circular polarizer is about one octave, much greater than SRRs can deliver. The unusually large bandwidth stems from the interactions of the different pitches, or turns, of the helix. For example, in a helix with two pitches, one pitch can be viewed as the primary coil of a transformer and the other as the secondary coil. Magnetic induction and electric interactions between pitches break the degeneracy of the damped but discrete eigenmodes of a single helix pitch.

For many helix pitches, that strong interaction eventually leads to the formation of a broad band of magnetization waves—the classical analogue of quantum mechanical magnons in solids. Such gold-helix metamaterials are ready to be used, for example, in spectroscopic sensing of molecular fingerprints of chiral biomolecules at IR wavelengths. (Fabricating the metamaterial inexpensively over a large area remains an important challenge, though.)

At first sight, such down-to-earth applications may appear less attractive than those based on negative refractive indices, which first won metamaterials their widespread appeal. But identifying and developing actual products has become an important endeavor for the entire field. Other groups—for example, those headed by Willie Padilla (Boston College), Harald Giessen (University of Stuttgart), and Gennady Shvets (University of Texas, Austin)—currently work on the design and fabrication of photonic metamaterials that neither transmit nor reflect light. As perfect absorbers, the devices turn what are usually large and undesired losses of light into a virtue. Sensing applications also turn a seeming disadvantage into a virtue by exploiting the narrow resonances that make metamaterials sensitive to their dielectric environment. For one vision of a metamaterial future, see the essay by the University of Southampton's Nikolay Zheludev.[10]

Invisibility cloaks in sight

Many researchers in optics and photonics are driven not only by applications but also by the intellectual fascination of being able to do things previously believed impossible—for example, effectively distorting optical spacetime, as mentioned in the introduction. Suppose you take the rubber sheet shown in figure 3. An observer looking perpendicular to the sheet sees an undistorted Cartesian grid. But as the sheet is stretched in the plane or pulled into the third dimension, the observer will notice a distortion in the grid lines, any of which represents the potential path of a light ray. Through such distortions, any light path can be tailored. Figure 3 makes the point graphically: A screwdriver punches a hole that can be manually enlarged in the rubber sheet. No grid lines pass through the hole; and by analogy, no light enters the hole, which renders the region inside invisible (see PHYSICS TODAY, February 2007, page 19).

The goal is to rewrite the vacuum Maxwell's equations for the new, distorted coordinate system. Amazingly, Maxwell's equations have the same form in any coordinate system, although the spatial distribution of the (real) tensor quantities $\varepsilon(\mathbf{r})$ and $\mu(\mathbf{r})$ will change. Transformation optics tells us explicitly how to go back to a Cartesian coordinate system and construct the cloak such that $\varepsilon(\mathbf{r}) = \mu(\mathbf{r})$ from the metric tensor for the complete set of Maxwell's equations[2,3] or for the approximate Helmholtz equation.[4] (For reviews of transformation optics, see references 5 and 6.)

So why isn't that fantastic possibility exploited in every optical system now designed? In general, one needs a magnetic response that suffers very little loss at optical frequencies, which is difficult to achieve with metamaterials. Furthermore, the values of the tensor elements of $\varepsilon(\mathbf{r}) = \mu(\mathbf{r})$ usually become infinite or zero at some positions in space, and certain anisotropies may be needed. After all, the grid on the rubber sheet in figure 3 can appear to an observer as elongated in one direction but not in the direction perpendicular to it.

Another complication is that we live in a 3D world, which means that metamaterial devices need, at least in principle, structures whose electric permittivity and magnetic permeability tensors are engineered to vary in three dimensions. The difficulty of doing that, combined with having to compensate for losses, is just too much for today's nanofabrication, except for rare cases in which nature is particularly kind. The so-called carpet cloak is one such fortunate exception. In that case, the metamaterial designer can achieve the desired effect with a purely dielectric, locally isotropic response in three dimensions.

Suppose that a thief wants to hide his stolen goods by shuffling them under a metallic carpet. In 2008 Jensen Li and John Pendry, both from Imperial College London, predicted he should be able to hide the resulting bump by using transformation optics to tailor a graded-index structure that makes the carpet appear flat and unsuspicious.[11] Soon after Li and Pendry's theoretical work, groups headed by David Smith (Duke University), Zhang, and Michal Lipson (Cornell University) performed 2D waveguide experiments on the carpet cloak.[12] In those experiments, had an observer looked at the bump from a direction normal to the 2D waveguide plane, however, the "invisible" would immediately have become visible.

To fashion a 3D carpet cloak, which presents the illusion of a flat surface from all directions, DLW again comes to the rescue. Figure 4 illustrates the blueprint, in which a locally varying refractive index can be realized by a local variation in the volume-filling fraction, or thickness, of polymeric rods arranged as a "woodpile." Although the structure is not locally isotropic—the lattice structure has diamond symmetry—its optical properties *are* nearly isotropic locally. And provided the wavelength of light used is sufficiently large compared to the typical periodicity or lattice constant, the structure can be viewed as an effective material with a certain refractive index at each coordinate.

To test a cloak, the most straightforward experiment is to simply look at the structure with any available polarization of light and from many different directions. Because the fabricated structures are microscopic, one needs an optical microscope for the inspection. An objective lens with a large aperture and unpolarized light can do the job. Figure 5 compares a cloaked and an uncloaked bump in the metallic carpet. The structure is tilted, a perspective commonly referred to as the dark-field mode because a flat metal film appears dark. The uncloaked bump is immediately visible by light scattering from one of its side slopes. In the presence of the cloak, however, that scattering almost completely disappears.[13]

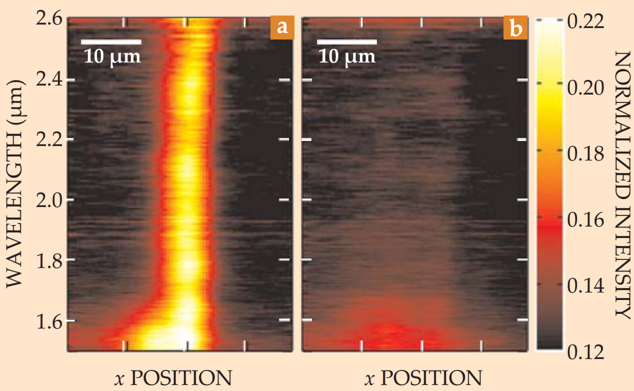

Figure 5. Dark-field microscopy and spectroscopy are performed on an actual three-dimensional carpet cloak. **(a)** The bump in the metal film is immediately visible by the scattering of light. **(b)** The scattering almost completely disappears once a cloaking structure is added. The measured cloaking extends over a fairly large bandwidth ranging in wavelength between about 1.5 and 3.0 μm.[13]

No serious applications are yet foreseen. But invisibility cloaking is considered a benchmark example of the far-reaching ideas of transformation optics, largely because the phenomenon seemed impossible until a few years ago and is intellectually appealing for scientists and laymen alike. Other fascinating aspects of transformation optics include the possibility of designing new devices, such as the perfect magnifying lens;[14] optical "black holes," which are akin to perfect light absorbers;[15] and artificial event horizons.[16] It's also possible to mimic the Big Bang using metamaterials that follow a hyperbolic dispersion relation[17] or even to make an apple look like an orange.[18] The fascinating physics, challenging nanofabrication, and novel applications on the horizon are sure to fuel the field of photonic metamaterials for years to come.

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