physicsworld
physicsworld.com
Volume 24 No 7 July 2011

# INVISIBILITY

Tricks and techniques for making things vanish from view

# Into the visible

Invisibility is now a reality. But scientists are not satisfied and still search for the holy grail: a cloak of invisibility that hides macroscale objects viewed from any angle using unpolarized visible light. **Wenshan Cai** and **Vladimir Shalaev** map out the road ahead on this quest

**Wenshan Cai** is a postdoctoral research fellow at Stanford University, US, and **Vladimir Shalaev** is the Robert and Anne Burnett Professor of Electrical and Computer Engineering at Purdue University, US e-mail shalaev@purdue.edu

When the first invisibility cloak was created at Duke University in 2006, we enthusiastically told friends, students and even high-school kids all about it. After all, was this not one of the ultimate dreams of the inner child within us all – the stuff of stories and legends brought to life and a true triumph of modern science? The most tangible thing to show the expectant audiences was an image of the circular-shaped device (see p24). But we were met with puzzled looks. On reflection the confusion was understandable, and the fault was on our side.

We scientists feel comfortable and excited at seeing the suppressed scattering of a 9 GHz electromagnetic wave. But for the general public, the word "microwave" means no more than a useful kitchen device to reheat yesterday's leftovers, and the detection or non-detection of such an unperceivable wave does not seem momentous. The word invisibility, anyway, is derived from vision, which is literally connected to what can be seen by the eye. In particular, we naturally limit our interest to the visual sensation perceived by the human eye. Although many bees can see the ultraviolet and various snakes can sense the infrared, our naked eye can see radiation within only a very confined range of the electromagnetic spectrum, with its violet end at a wavelength of about 380 nm and its red end terminating shorter than 780 nm.

The holy grail of invisibility research is therefore to make everyday objects vanish in plain sight. What this means is that the performance of any invisibility cloak should be insensitive to the colour of visible light, the angle of observation and the source of illumination. And because light can exhibit a range of different polarization states, defined by the orientation of the oscillation of its electric field, a good cloak should be independent of this property as well. We also tend to hope that the cloak can conceal macroscopic objects larger than 0.1 mm; objects smaller than this are already invisible to the unaided eye, and rendering them unobservable using special apparatus is probably of only technical interest. So what progress have we made so far towards this holy grail, and what challenges must we face before we can realize an ideal cloak?

## At a Glance: Visible invisibility

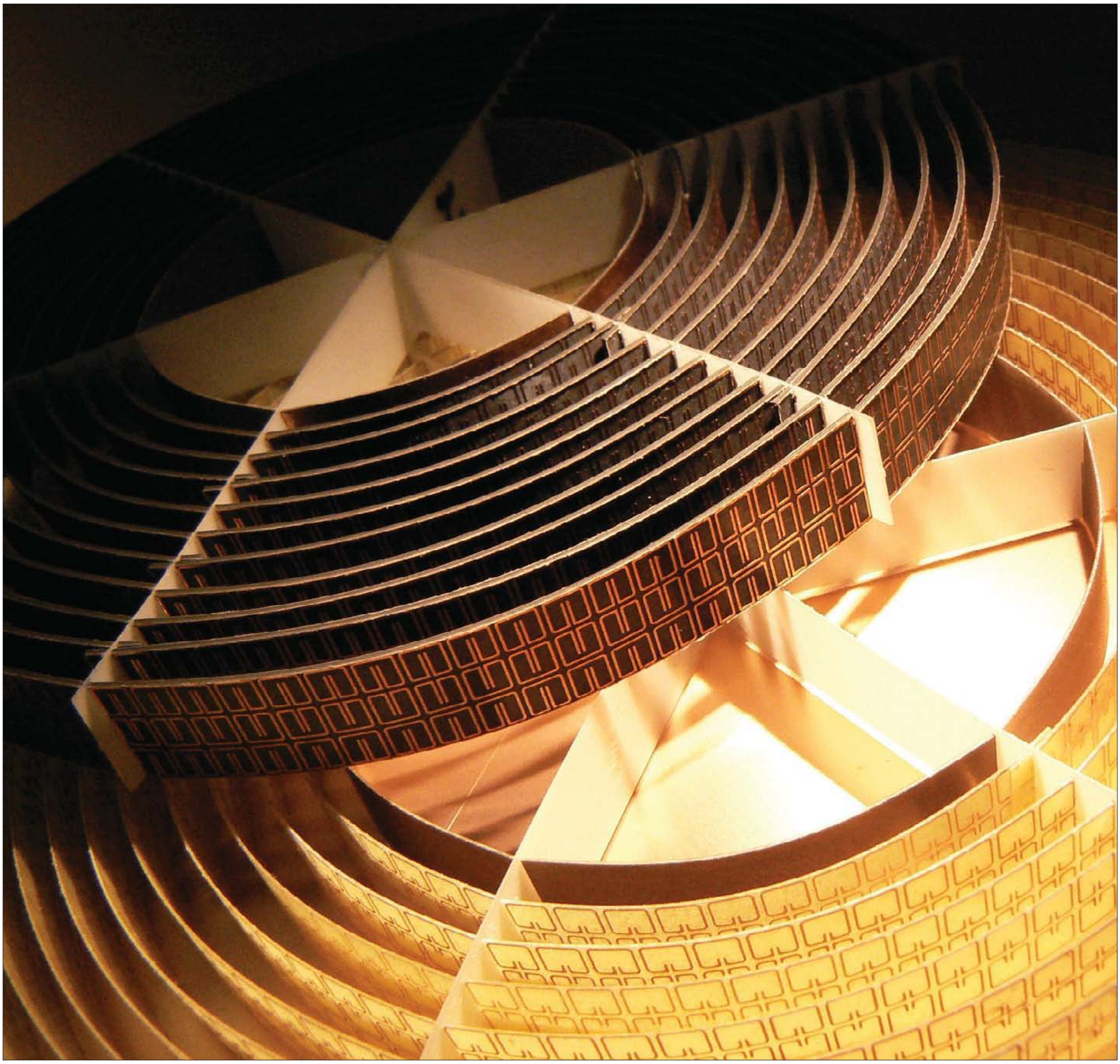
- Invisibility can be achieved by guiding light along indirect paths to fool the eye. The pathway of light is governed by the distribution of material properties in the space through which light travels
- The materials needed to make an ideal invisibility cloak should be inhomogeneous, anisotropic and magnetically active, as determined by a design tool called "transformation optics"
- These three requirements are difficult to achieve in practice and the realization of an optical cloak needs to surmount or bypass these problems. Recent demonstrations of invisible carpets and calcite cloaks have shown exciting possibilities but are not there yet
- There is still much ground to cover towards the holy grail – a fairy-tale-style cloak that makes things vanish in plain sight for all colours, directions and polarizations of light

### Light-bending basics

There is a growing tendency for the word "cloak" to be misused or abused, so let us first clarify the essential nature of a cloaking device, and how it differs from other schemes for invisibility. If we were to define invisibility as the state of an object that is situated in plain view of an observer without being seen, then a variety of approaches were adopted by nature or smart engineers long before the recent surge of research based on the spatial transformation of Maxwell's equations. For example, many species of animal can camouflage themselves because their surface colours or patterns make them indiscernible from their surrounding environment. Another way of making an object impossible to detect is to prevent information about the object from reaching detectors – an approach that is widely exploited in various stealth techniques for military craft (see "Invisibility rules the waves" by Chris Lavers *Physics World* March 2008 pp21–25). This is usually accomplished by using absorbing surfaces along with special shapes and materials, all intended to reduce the cross-section of the object against radar sources. However, the ultimate version of invisibility is to make an object reflect no light and absorb no energy. That is, the object should possess the same scattering properties as those of free space. This last method of invisibility is the ultimate goal for cloaking devices.

One way for an object to neither reflect nor absorb light is to bend the light around itself. This may sound complicated, but we can observe a simple version of this in everyday life. If we want a straw to appear to bend by a few degrees, we could place it in a glass of water. The straw is partly in air and partly in water, and appears to bend because the refractive indices of the two media are different and it is this property that defines the path taken by the light. For more complicated pathways, the material parameters required for light to trace out a certain shape can be calculated using transformation optics, a mathematical tool discovered by pioneers such as L S Dolin and E G Post half a century ago.

This approach usually starts by defining the indirect route the light wave should take and then figuring out how the properties of the material carrying the wave should vary with position to ensure that the pathway is



Duke University/David Schurig

**The real deal**
Invisibility cloaks built by David Smith and his team at Duke University look less impressive than Harry Potter's, at least for non-scientists.

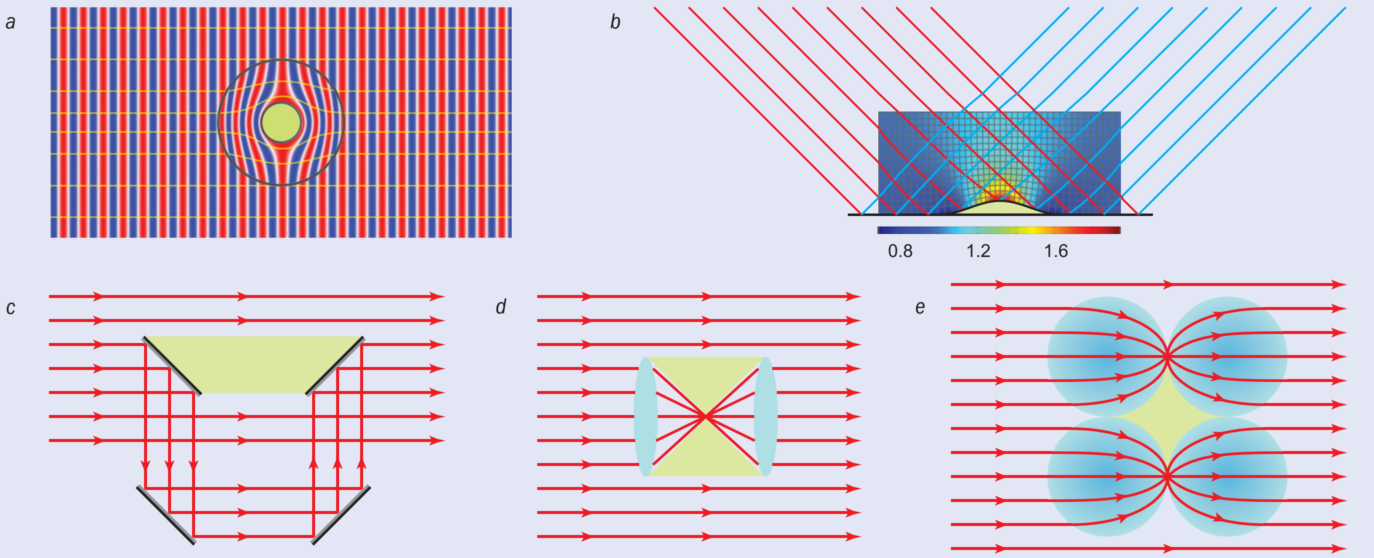
followed. Mathematically, this involves calculating a coordinate transformation from a Euclidean space, in which the wave propagates along a straight line, to a distorted coordinate system in which the wave travels along the desired path. This coordinate transformation is then translated into a set of spatially dependent material parameters, including the electric permittivity, $\varepsilon$, and the magnetic permeability, $\mu$.

A cross-sectional view of a cylindrical cloak is illustrated in figure 1*a*, in which incoming waves flow around the inner region and are fully restored afterwards, thus forming a cloaked area. A less attractive but much more realistic alternative, called a "carpet cloak" or ground-plane cloak (figure 1*b*), converts a curved conducting surface into a flat one, and therefore gives the curved carpet, along with anything underneath it, the appearance of a flat, reflecting surface. What is crucial for an invisibility cloak is to have no distortion in the optical wavefront – neither of the amplitude nor the phase. But recovering the trajectory of a plane wave is not in fact a sufficient condition for cloaking. Although we can certainly realize such an effect using four mirrors, two lenses, or a pile of spherical lenses (figure 1*c*–*e*), these configurations should not be taken as cloaking devices.

### The thorny three

Since the first invisibility cloak at a microwave frequency was unveiled five years ago by David Schurig and colleagues at Duke University, substantial efforts have been devoted to pushing the operational band of cloaks towards the visible part of the electromagnetic spectrum. This has not been easy because transformation optics determines that three special material properties are required for a perfect cloak, and these are tough to achieve; in fact, it is easier to fabricate a device with exactly the opposite qualities. First, the material from which the invisibility cloak is made should typi-

## 1 Optical cloaking: tools and toys



(*a*) Cylindrical-shaped electromagnetic cloak working in free space, which has been realized experimentally for microwaves. A horizontally travelling plane wave flows from left to right around the cloaked region represented by the inner circle. Yellow lines indicate the direction of energy flow. (*b*) A carpet cloak proposed by Jensen Li and John Pendry, and now realized at micro, infrared and visible wavelengths, renders anything hidden underneath the deformed mirror invisible. The red and blue rays represent the incident and reflected waves, respectively. The multicoloured surface plot shows the spatial distribution of the dielectric constant in a carpet-cloaking device. Conformal mapping is used, as indicated by the grey grid lines. Toy examples can restore ray trajectories of plane waves using, for example, (*c*) a set of four mirrors, (*d*) a pair of identical convex lenses or (*e*) a pile of Luneburg lenses. The latter was proposed by Asger Mortensen of the Technical University of Denmark. In each configuration, the region shown in light green is invisible to outside observers.

cally be anisotropic, which means that the medium acts differently along different directions. Second, it should be inhomogeneous, i.e. the material parameters need to vary spatially, although there are some exceptions to this rule. Third, the material should be magnetically active, i.e. it can respond directly to the magnetic-field component of light. This last feature is extremely hard to obtain at optical frequencies, let alone achieve a delicate control over in all locations and directions.

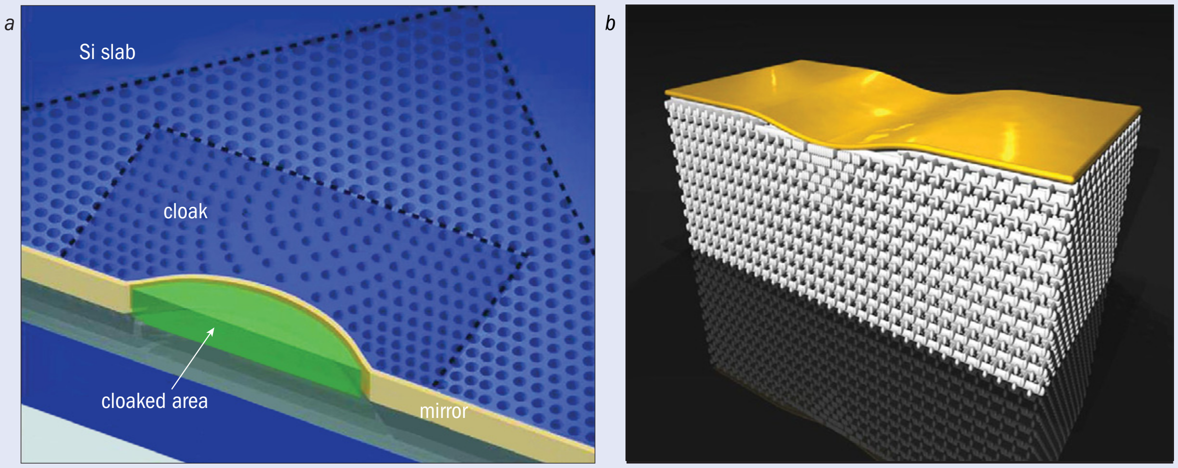
Although the first microwave cloak was a masterpiece that elegantly surmounted all of the three obstacles, downscaling its design for optical wavelengths is not quite feasible because of both fabrication difficulties and material constraints. In 2007 we calculated, however, that one of the hurdles – the need for the material to be magnetically active – can be bypassed if the pathway of the light is not spatially distorted along the direction of its magnetic field. Furthermore, the carpet cloak proposed in 2008 by Jensen Li and John Pendry at Imperial College London indicates that the concern of anisotropy can also be substantially mitigated by using a transformation technique called "conformal mapping", which, as pointed out by Ulf Leonhardt from the University of St Andrews in 2006, forces the 90° angle between virtual grid lines in space to be preserved during the transformation.

We now have to overcome just one remaining obstacle: the need for inhomogeneity, which is also seemingly the least demanding. The design protocol of the carpet cloak determines a specific distribution of the refractive index (figure 1*b*). What needs to be done experimentally is to build a structure that has this position-dependent refraction index. Although most common optical media are bulk materials with well-defined values of the refractive index, we can, however, turn to the new field of metamaterials, where crafting an artificial medium with a spatially varying refractive index is a central task. This involves designing and incorporating small bits of material, or holes, with a different refractive index from that of the foundation material. The distribution of these artificial "atoms", which must be much smaller than the wavelength under consideration, changes the local refractive index of the structure.

One of the first prototypes of a carpet cloak at optical frequencies was demonstrated by Xiang Zhang's group at the University of California, Berkeley, where a refractive-index profile similar to that in figure 1*b* was achieved by creating nanoscale voids in a microscale slab of silicon (figure 2*a*). A focused ion beam was used to mill out cylindrical voids, the sizes and separations of which were substantially smaller than the operational wavelength of about 1.5 $\mu$m, so that the optical response is determined by the distribution of the effective refractive index, rather than diffraction or interference as seen in photonic crystals.

Similar demonstrations have been reported by other teams at the universities of Cornell and Colorado, and at the Georgia Institute of Technology. More notably, a 3D carpet cloak working in the near-infrared has been reported by a group led by Martin Wegener at Karlsruhe Institute of Technology, Germany (figure 2*b*). This polymer device makes a bump in a metal surface appear flat, and then renders anything hidden in the bulge invisible to outside observers even under illumination with unpolarized light. All of these devices work for a reasonably broad range of wavelengths because the dispersion, which defines how sensitive the material properties are to the frequency of light, is not a big concern when the entire structure is made from dielectric components, in which dispersion is always very weak.

## 2 Magic carpets



J Valentine *et al.* 2009 *Nature Materials* **8** 568

T Ergin *et al.* 2010 *Science* **328** 337

Carpet cloaks for the near-infrared. (*a*) An all-dielectric invisibility carpet for guided optical waves in a silicon slab. The device, which has voids drilled into it in a distribution that changes the refractive index locally, was designed and built by Xiang Zhang's group at the University of California, Berkeley. (*b*) A 3D carpet cloak demonstrated by Martin Wegener's team at Karlsruhe Institute of Technology, Germany. The fine features of the 3D structure were carved in a polymer matrix using direct laser writing.

### Visible headache

These attempts represent solid steps towards the realization of an ideal cloak of invisibility. But are they close enough? Probably not yet, for at least two reasons. First, the size of objects that can be concealed underneath such a magic carpet is smaller than we can see anyway. The volume of the bumps in all of these demonstrations is no more than tens of cubic microns, and obtaining bigger volumes does not seem to be feasible because the nanofabrication methods are so complex. Second, these cloaks work for a wavelength range outside the visible spectrum. A carpet cloak for the visible spectrum would require a material other than silicon, which strongly absorbs all visible photons as these have more energy than the bandgap of silicon. More critically, the fabrication of structures similar to those in figure 2 for visible light becomes extra demanding because, for the effective-medium approach to prevail, the fine details in the architecture must be much smaller than the wavelengths of visible light.

These daunting challenges have prompted researchers to conceive other options for cloaking-like phenomena for visible light. For example, a team led by Igor Smolyaninov at the University of Maryland has observed reduced visibility for a special light wave bound to the surface of a metal, or "surface plasmon", as well as the routing of light in a tapered waveguide formed by two metal films with a gradually varying separation. The latter work was accomplished in collaboration with the Purdue University team led by one of us (VS). These smart ideas, however, deviated even further from the dream version of an optical cloak.

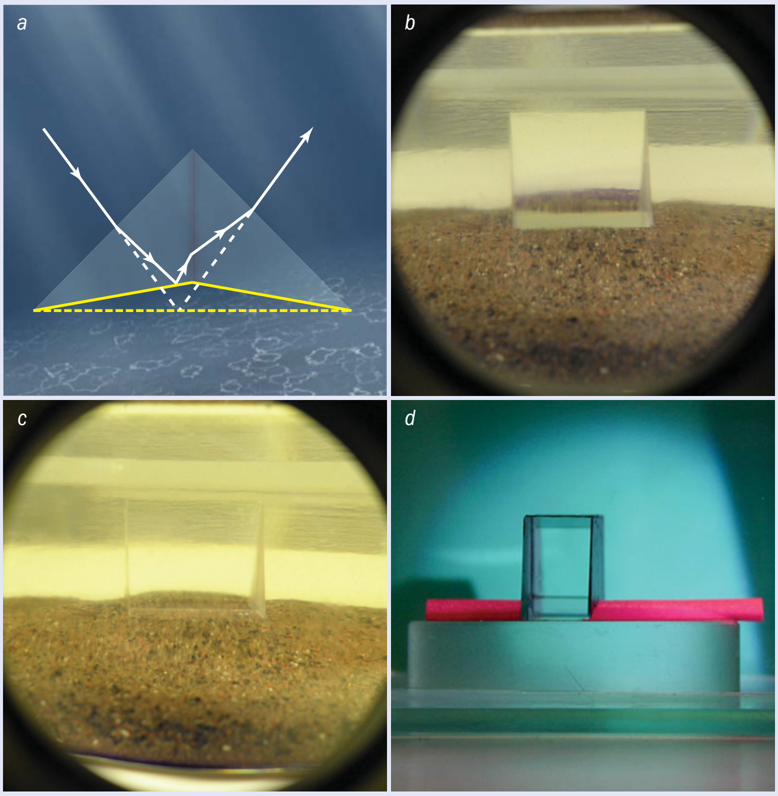
As we mentioned previously, while the easiest sort of optical cloak to fabricate would be homogeneous, isotropic and non-magnetic, the qualities required for an ideal invisibility cloak – as determined by transformation optics – are the exact opposite and tough to fabricate: a material that is inhomogeneous, anisotropic and magnetically active. It is clear that a bulk piece of uniform dielectric, which is homogeneous, isotropic and non-magnetic, has little to do with invisibility.

But there are smart ways to bypass one or two of the three requirements, and not every property is needed to make an imperfect cloak. This is done by modifying dielectric materials to have cleverly designed structures. For example, all reported carpet cloaks at infrared wavelengths, including the two beautiful versions shown in figure 2, are both isotropic and non-magnetic, and the sole aim in the implementation is to satisfy the required inhomogeneity. The problem, though, is that the fewer of the properties the material has, the more contrived and complicated the structure has to be. Moreover, compensating for properties by manipulating the structure compromises the invisibility: the resultant devices exhibit a non-zero scattering (so strictly speaking they are more or less visible) and they only work for light that has a particular illumination direction and polarization.

But are there any other alternatives? Considering the immense challenge of achieving a controllable magnetic response for light waves, we are bound to go for the easier option of artificially changing either the homogeneity or the isotropy. From a nanofabrication point of view, tailored inhomogeneity, which is usually achieved by combining two materials with prescribed percentages, seems to be easier than artificially introduced anisotropy because the latter typically relies on shaped particles arranged in an ordered manner. (Think about how easy it is to mix rice and beans, but how much harder it would be to align every rice grain in a particular direction.)

There are smart ways to bypass one or two of the three requirements, and not every property is needed to make an imperfect cloak

**3 Macroscopic mirage**



Shuang Zhang, University of Birmingham (b and c)

Baile Zhang and George Barbastathis, Singapore-MIT Alliance for Research and Technology (d)

(*a*) Light rays are bent multiple times in this calcite cloak, as if they were directly reflected from a flat mirror. Solid yellow lines represent reflective coatings, while the dashed yellow line indicates a virtual ground plane. Anything within the yellow lines is invisibly cloaked. (*b* and *c*) Performance of the calcite cloak in a liquid. The image of sand behind the triangular-prism-shaped crystal (20 mm in height) is normally distorted, as shown in (*b*). However, under certain illumination conditions the calcite cloak, together with anything hidden in the triangular recess, vanishes and no visual distortion of the sand is observed when looking through the device. (*d*) A piece of pink-coloured paper is inserted through the deformed bottom side of a calcite cloak (15 mm in height). The central part of the paper is rendered invisible while the background pattern is unaltered.

## Nature knows best

When thinking of new and inventive cloaking schemes, there is one thing worth bearing in mind: nature may have already done some of the work for us. While every naturally occurring solid material is, by definition, homogenous, which we do not want, anisotropy is present in a broad range of crystalline substances; it is an intrinsic property derived from the lattice structure. So can we construct an optical cloak that is both isotropic and non-magnetic, and that makes use of the anisotropy present in nature? This is the idea behind a macroscopic, broadband optical cloak for visible light reported by a team led by Shuang Zhang from the University of Birmingham and Pendry at Imperial, and, independently, by George Barbastathis' team at the Singapore-MIT Alliance for Research and Technology.

Interestingly, both macroscopic cloaks were made from the crystalline material calcite, which was found to show optical anisotropy and double refraction by the Danish scientist Rasmus Bartholin as long ago as 1669. This new version of a carpet cloak uses a triangular-shaped bump rather than a smooth one, and mathematical analysis shows that when an appropriate transformation is used, the constituent material above the ground plane can be made from simple non-magnetic, homogeneous materials. More importantly, the level of anisotropy necessary is not particularly severe and can be readily fulfilled using birefringent crystals. As a result, a very rare case in transformation-based devices is reached: a spatially varying index profile is no longer required, which paves the way to entirely eliminating the time-consuming and money-draining need for nanofabrication.

A schematic of the device shown in figure 3*a* illustrates how light is bent to fool the eye. Two pieces of calcite with different crystal directions are glued together to form a pyramid with an obtuse triangle-shaped recess in the metal-coated underside. The light beam is deviated multiple times before exiting the crystal, in such a way that it appears to be reflected directly from a planar mirror. The researchers successfully concealed several centimetre-scale objects, including a paperclip, a small steel wedge and a piece of paper (figure 3*b*–*d*). The cloaks work reasonably well across the entire visible spectrum, from red to blue, thanks to the relatively weak dispersion in the transparent crystal. An invisibility cloak should hide objects at all incident angles; this is also confirmed, as long as the illumination is on one side of the pyramid and the observer is on the other.

## Cloaking contemplations

Let us take a step back from the flurry of excitement of the two splendid calcite-cloak demonstrations and ask: how close are we to an ideal cloak? Well, unfortunately you can tell that a calcite cloak is there because the devices only work for polarized light and operate inherently in a 2D configuration. Also, the cloaking performance is compromised when it is used in free space rather than immersed in a high-index liquid. Furthermore, we would prefer a direct see-through effect in air rather than seeing a strange piece of mirror lying on the ground, which is the appearance of current carpet cloaks and gives the game away somewhat.

But we should not be too pessimistic either, because technology keeps on moving and surprises us time and again. Indeed, as we were writing this article, the same two groups behind the masterpieces in figure 2 both reported making visible-light counterparts of their structures with much smaller feature sizes and more delicately crafted materials (M Gharghi *et al.* 2011 *Nano. Lett.* DOI:10.1021/nl201189z; J Fischer *et al.* 2011 *Opt. Lett.* **36** 2059). Yet, while what has so far been achieved in invisibility science has been a *tour de force* of physics and engineering, our children will probably still have to wait some time for that real Harry Potter cloak. ■

## More about: Visible invisibility

P Alitalo and S Tretyakov 2009 Electromagnetic cloaking with metamaterials *Materials Today* March pp22–29
W Cai and V M Shalaev 2010 *Optical Metamaterials: Fundamentals and Applications* (Springer, New York)
H Chen, C T Chan and P Sheng 2010 Transformation optics and metamaterials *Nature Materials* **9** 387
X Chen *et al.* 2011 Macroscopic invisibility cloaking of visible light *Nature Communications* **2** 176
U Leonhardt 2009 Towards invisibility in the visible *Nature Materials* **8** 537