

Blueprints for real-world invisibility

Philip Ball*

Making objects invisible has never been easy. A seventeenth-century magic spell for growing “beans of invisibility” instructed that they should be buried with the severed head of a man who committed suicide. For H. G. Wells’s “invisible man” in his famous 1897 novel, the process was more scientific, involving the use of mysterious rays related to X-rays that would alter the refractive index of a transparent substance to match that of air.

Wells was on the right track. Invisibility surely does require some means of both eliminating light scattering from the object’s surface and ensuring that refractive effects are not permitted to distort the rays’ paths. That kind of exquisite control of light optics, guiding rays along well defined paths without significant scattering, is now promised by the field of transformation optics [1, 2], in which an optical medium is granted unusual properties that bear analogies with the “plastic” distortions of spacetime itself induced by mass in the theory of general relativity.

In theory, almost anything is possible by this means. By imposing suitable, hypothetical reconfigurings of spatial coordinates, transformation optics has been shown to allow objects not just to be invisible but also to take on very different appearances: to imitate other objects [3], say, or to expand or shrink so that “portals” in walls can be “hidden” in the manner of those invoked in works of fantasy such as the Harry Potter books [4], or to rotate the appearance of an object [5].

Putting these ideas into practice is another matter. What manner of materials permit the kinds of distortions of light rays that transformation optics seems so casually to invoke? The field took off around a decade ago in a rather spectacular and attention-grabbing manner, when Smith, Pendry and their coworkers outlined a scheme for making an “invisibility shield” using so-called metamaterials [2]: structures that control the absorption and transmission of electromagnetic radiation in well defined ways at each point in space, thereby shaping the paths of rays almost at will. For an invisibility shield, or cloaking device, the notion was that light would be guided smoothly around some central cavity and then returned to its original path, ideally with minimal scattering as it impinges on the cloak.

These devices were soon thereafter realized in two dimensions at microwave frequencies, using metamaterial “atoms” made from antenna-like structures etched onto printed circuit boards and organized into arrays [6]. Making such components at the scale of visible wavelengths is much more challenging, and so far “invisibility” in this region of the spectrum has been a more compromised affair, demanding approximations that enable some control of light-ray paths in existing materials with optical anisotropy, at the cost of accepting some reflection and scattering at the device interface [7, 8]. In this way, objects have been “hidden” from light for several incident directions over a rather broad frequency band.

The challenge of making cloaks, or indeed simply “invisible” solid objects, thus involves a balance between what transformation optics says is possible and what can be achieved with realistic materials parameters. The kind of coordinate transformations required in theory, for example, might be attained by employing transparent materials with a graded refractive index, not unlike the way this has long been used in the cladding layers of optical fibres to reduce their transmission losses.

Chen and coworkers [9, 10] now describe two approaches to making objects “invisible” that strive for this balance between what might and what realistically can be done with existing materials, while achieving an effect worthy of the name. They describe two designs for virtually perfect invisibility over a small range of wavelengths using materials parameters that could feasibly be engineered.

The two approaches embody alternatives that have existed since the early days of transformation optics. One of them uses a notion of optical conformal mapping, first introduced by Leonhardt [1], in which the coordinates defining the ray paths can be mapped from one geometry to another – for example, from a flat onto a curved plane, not unlike the way the surface of the earth is mapped onto a flat sheet in the Mercator projection. In practice this distortion of grid coordinates might be induced by a gradient of refractive index – a striking example involves the creation of a focusing lens from a flat slab of material.

One such long-postulated structure is called a Mikaelian lens, which in the usual formulation is a cylinder that focuses rays propagating along the axis. Xu *et al.* [11] previously used such a structure to design a de-

*East Dulwich, London SE22, UK. E-mail: p.ball@btinternet.com
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vice that should be almost perfectly invisible from all incident directions in two dimensions while using feasible refractive indices (requiring these values to be nowhere greater than 5.21). Now Xu *et al.* report a full analysis and simulation of the optical properties, verifying that it performs as predicted [9].

The second approach to invisibility here makes use of a “light concentrator”, in which light impinging on the outer (circular) surface is guided to a concentric inner core as if focused to a greater intensity. Here it establishes a resonant mode, as in a standard Fabry–Pérot cavity in which partial reflection from the boundaries sets up a standing wave – in this case, of shorter wavelength than the original. Because these boundaries are only partial mirrors, this concentrated radiation can escape and be returned by the “concentrator” outer layer to its original mode, which continues to propagate as before.

The concentration of the field happens because of the mapping of coordinates defined by a particular choice of permittivity and permeability in the device. That results in the cylindrical space between the outer surface and the inner core having essentially no representation within the reconfigured coordinate space: it acts as a kind of optical void. As a result, all radiation that impinges on the outer surface shows up within the smaller core, and all that exits the core reappears at the surface of the device.

This design has also been reported before by Chen and coworkers using relatively simple material parameters [12], but showed a small amount of scattering. The current refinements show how to reduce this scattering to minimal values, or – in the case of one instance – to zero. In one design, the magnetic permeability of the material is essentially irrelevant, so that it could be realized using a pure dielectric material in which only the permittivity matters. Here a gradient of refractive index might be engineered by drilling a grid of holes in the material.

This second idea essentially enacts the kind of scheme proposed for invisibility cloaks by Pendry [2]. Thus the two devices proposed here by Chen and coworkers recapitulate the two embodiments of transformation optics outlined in the nascent stages of the field. Crucially, both can eliminate almost all scattering at their boundaries by matching of refractive index – in effect a matter of impedance matching, familiar in electronic and optical engineering. Both methods, moreover, will tolerate a small range of wavelengths, whereas the original designs based on metamaterials with anisotropic and inhomogeneous parameters, proposed by Pendry, work only at a single resonant frequency. And both designs require optical properties that can at least imaginably be obtained in existing materials.

Whether these structures can actually be made, and will perform as predicted, remains to be seen. But they show that true invisibility might not be quite as fantas-

tical or magical as the old stories suggest.

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