

OPTICAL METAMATERIALS

Invisibility cup

Cloaking devices for visible light come a step closer to reality by combining the modern form of a Roman technology with ideas from ancient Greece.

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One of the things the Romans did for us was the invention of the first optical metamaterial — ruby glass. They probably did not know it, but their recipe for ruby glass contained one crucial ingredient¹: tiny gold droplets, typically 5–60 nm in size. These gold particles colour the glass in an extraordinary way, as demonstrated by the exquisite Lycurgus Cup (Fig. 1). In daylight the cup appears a greenish colour, but illuminate it from the inside and it glows ruby. On page 224 of this issue, Cai *et al.*² present theoretical simulations that show that a modified Roman cup based on modern nanofabrication technology will act as an invisibility device, albeit for one polarization and one specific colour of light. Any object you put inside will disappear as if dissolved in air, provided it is viewed through polarizing tinted glasses of precisely that colour.

Instead of gold nanoparticles embedded in glass, Cai *et al.* used nanosized metal wires in their calculations, which play a similar role. They show that if the metal wires are small enough (subwavelength) and of the correct geometry, they form an optical metamaterial that potentially acts as an invisibility cup for visible light. In effect, the tiny wires act like artificial atoms and have a resonance with light that depends on their shape and size. For example, the length of the wires determines the wavelength of incident light for which the cup would make objects inside appear invisible. The team take the example of a silica tube embedded with silver particles, each the shape of a sphere but stretched along one axis. Their simulations show that the device can effectively cloak a metal cylinder, approximately 1 μm in diameter, at a wavelength of 632.8 nm.

Thanks to advances in modern nanotechnology and the science behind it, engineers can now make carefully



Figure 1 Lycurgus Cup (British Museum; AD fourth century). This Roman cup is made of ruby glass. When viewed in reflected light, for example in daylight, it appears green. However, when a light is shone into the cup and transmitted through the glass, it appears red. The cup illustrates the myth of King Lycurgus. He is seen being dragged into the underworld by the Greek nymph Ambrosia, who is disguised as a vine.

controlled subwavelength structures with designs based on accurate theoretical predictions, whereas Roman technology mostly relied on trial and error. The next challenge for the metamaterials community is to actually fabricate and experimentally demonstrate such an invisibility cup that operates in the optical regime.

The purpose of an invisibility device is to guide light around any object put inside. The device itself should be invisible, and so it must be made of a transparent material, but this alone is not sufficient. The inspiration for invisibility does not come from Roman technology, but from Greek geometry and the optics of illusions. In about AD 150, the Greek polymath Heron of Alexandria noticed

that the route taken by light between two points upon reflection from a mirror is always the shortest possible. In 1662, Pierre de Fermat suggested that nature always acts by the quickest and simplest path. In particular³ light rays try to pass through regions of low refractive index, where light is fast, and tend to avoid regions of high refractive index, where light travels relatively slowly; light rays bend to optimize their travelling times. Such light bending in transparent materials causes many illusions. Picture a mirage in the desert. The tremulous air above the hot sand conjures up images of water in the distance, but it would be foolish to follow these deceptions. They are not water, but images of the sky, bent

by the hot air above the sand that has a lower refractive index than the cooler air.

The illusion is created because the material changes the proportions of space for light; it defines a curved spatial geometry. Around 300 BC, the Greek mathematician Euclid developed the geometry of ordinary flat space where parallel lines stay parallel. Suppose the optical geometry of the material meets Euclid's parallel axiom. In this case, light enters and leaves the material in parallel lines, as if propagating through empty space, which is precisely the condition for invisibility. Using the mathematical tools of geometry one can calculate the refractive-index profile that turns invisibility from an idea into reality^{4–6}.

Recently, Schurig *et al.*⁷ demonstrated the first cloaking device that combined Euclidean ideas with the technology of metamaterials. Their device provides invisibility for microwaves. Like light, microwaves are electromagnetic waves, but with wavelengths of a few centimetres, much longer than that of visible light (about 400–700 nm). The cloaking device guides microwaves around an object without causing much distortion. The wave propagating through the cloaking layer catches up with the wave that passes outside.

Clearly, the wave on the detour inside must travel faster than the wave outside, faster than the speed of light in a vacuum⁶. Superluminal light velocities are possible in principle, but only for electromagnetic waves of essentially one wavelength, and they are not easy to achieve, relying on the very latest designs of metamaterials.

Schurig *et al.*⁷ make their metamaterial by etching millimetre-sized cells out of a copper circuit board, in which the cells serve as the artificial atoms. The copper structures act as electromagnetic resonators that are tuned by slightly changing their shapes. The wavelength at which the metamaterial operates as a cloaking device depends on the size of the cells: the smaller they are, the smaller the wavelength. In principle, for creating invisibility for visible light, all one has to do is to manufacture such cells in sizes below the wavelength of light, on the nanoscale. However, the problem is that metals absorb light more strongly than microwaves, because they have a much greater electrical resistance at visible light frequencies. Cai *et al.*² get round this problem by designing their wires to have as little resistance as possible. The wires resemble the structures they applied in their pioneering demonstration⁸ of negative

refraction of near-visible light, but negative refraction is not needed for invisibility. It should be noted that their approach is not the only option for making an invisibility device; one could also use other design concepts^{3,4} that do not rely on metals at all.

One central problem remains before invisibility devices are likely to become remotely practical: the need for superluminal media⁶. Such materials inevitably restrict cloaking to one wavelength, to one colour. The illusion of the invisibility cup disappears on removing the tinted glasses. For broadband invisibility, new post-Euclidian ideas are needed as well as further advances in optical metamaterials and new combinations of nanotechnology with highly abstract ideas, all in the best tradition of the ancient world where Rome gave us the technology and Greece the ideas.

References

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POLARIZATION TWIST

Orienting out of a tight spot

Changing the polarization of tightly focused light could be important for future high-resolution imaging and data-storage applications. Researchers have now shown that a simple lens can do the task without the need for polarizers.

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It is common practice to use a polarizer to select the desired polarization component from incoming unpolarized light. Now, researchers from Finland and Sweden experimentally show that a simple lens can do a similar job, turning randomly polarized light into fully polarized light at certain locations in its focal plane¹.

A crucial element for high-density data storage, high-resolution microscopy and state-of-the-art photolithography is

the objective — a strong lens with a high numerical aperture (NA) that operates at the margins of the diffraction limit and creates a small, tightly focused spot of light. Recently, optical scientists have been working hard to find ways to shape or twist the polarization of tightly focused light, believing that it could pave the way to higher-resolution imaging or useful material-interaction effects on the nanoscale.

In a high-NA objective, 'marginal rays' (rays of light that hit the edge of the lens and have a large focusing angle) couple the transversely *x*- and *y*-polarized fields in the pupil to fields in the focus with a polarization along the optical *z*-axis^{2,3}, as shown in Fig. 1. As a result, it is well known that the spatial field distribution of tightly focused light

depends on the polarization of incident light. In the past, it has been pointed out that the size of the focal spot can be squeezed using radially polarized incident light^{4,5}. Ultimately, engineering both field polarization and amplitude distribution in the pupil can provide full control over the three-dimensional field distribution in the focus⁶. For instance, by using annular illumination and favouring the marginal rays, one can create strong axial *z*-field components⁷. Meanwhile, subtly designed incoming phase fronts offer control over local phase singularities carrying subwavelength structure in the focal region^{8,9}.

So far, most of the studies on the polarization properties of tightly focused light have concentrated only