IDEAL FOCUS

An eye for detail: John Pendry.

Before they were touted as invisibility cloaks, metamaterials promised a perfect lens. **Geoff Brumfiel** reports on the struggle for superior vision.

As far as John Pendry is concerned, we are as good as blind. Sitting in his office at Imperial College London, the theoretical physicist gestures at the table in front of him. Assume, he says, that the fundamental limit of detail in the table is about the size of an atom. Then consider that the smallest feature the human eye can see, even using a high-quality optical microscope, is a few tenths of a micrometre across — roughly a thousand times bigger than an atom. That means that, even with 20–20 vision and the best optics, humans can access only 0.0001% of the information right before their eyes. "That's not much," he observes.

Nearly a decade ago, Pendry proposed a way to do thousands of times better using a film of silver just tens of nanometres thick as a 'superlens'[1]. The film would behave as a simple metamaterial, a substance with a small-scale structure that allows it to manipulate light in a way that no bulk composition could. This means that the film could capture details that elude conventional optical microscopes. In theory, the superlens could also etch nanometre-scale patterns on to a surface, which would make it very useful in the manufacture of microchips.

Pendry's idea brought many researchers into the field, and for a while expectations were high. But nine years on, those expectations have yet to be fully realized. Although there have been proof-of-concept devices for both the superlens and the related 'hyperlens', industry has switched its focus elsewhere. And the field of metamaterials has itself been diverted by another high-profile potential application: cloaking devices.

Making objects 'invisible' may have stolen the limelight, but one of the researchers behind that work believes that superlenses remain the most alluring idea yet proposed for metamaterials. "I think that the superlens will probably find more applications [than cloaking]," says Xiang Zhang, based at the University of California, Berkeley, who grabbed headlines in April for using metamaterials to create a primitive cloak[2].

> "It's a very, very simple technology. It's just a question of getting it right." — John Pendry

The key to all this comes down to the structures of metamaterials, which directly affect their optical properties. The composition of conventional substances, such as glass, is uniform at optical wavelengths, but metamaterials feature regularly patterned structures at those scales. When light of a certain wavelength interacts within the pattern, it sets up a resonance, similar to the way a musical tone triggers vibrations in a tuning fork. The resonance can cause light beams to be deflected in the 'wrong' direction and it can also enhance certain properties.

Pendry's initial work on metamaterials was aimed at beating a problem known as the diffraction limit, which says that optical instruments such as telescopes and microscopes are subject to a fundamental fuzziness. No matter how well they are made, their ability to resolve fine detail is constrained by the wavelength of the light being used. For optical microscopes, this means that any attempt to resolve features below around 200 nanometres will fail.

Pendry recognized a loophole: the diffraction limit does not necessarily hold for metamaterials. Although silver is not a perfect metamaterial, he showed that it would work well enough as a lens. If a silver film were placed close enough to an illuminated object, it could catch the 'evanescent waves' — short-range electromagnetic fields that carry the detailed, subdiffraction-scale information about the object, but that cannot be picked up beyond a few tens of nanometres from the object's surface. These evanescent waves would be amplified by resonances in the silver film, and their information would be carried through the film to create an exquisitely detailed image on the far side.

Window of opportunity

Richard Blaikie, an electrical engineer at the University of Canterbury in Christchurch, New Zealand, was excited by this concept — not as a way to see, but as a way to write. He thought that the superlens could help chip-makers in their struggle to create subdiffraction-scale circuit elements. But, as Blaikie soon learned, what looked elegant on paper was messy in the lab. "It's very easy to do some modelling," he says, "but the experiments are very hard."

Blaikie did manage to make a prototype superlens in 2005 that captured subdiffraction information[3]. But because the evanescent waves fade away over such a short distance, the silver film had to be fixed to the object being imaged. Similarly, whatever recorded the image had to be clamped tightly to the other side of the film. And even then, says Blaikie, "the images that we got, although good in terms of their resolution, were poor in terms of their fidelity". Even a few nanometres of variation in the silver's surface created hotspots that made straight lines appear jagged. Blaikie says his group has struggled to follow up that 2005 demonstration. "You haven't seen anything because we haven't had any success," he says bluntly.

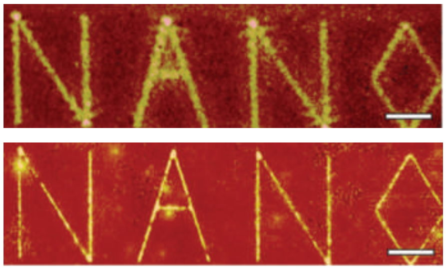
Hyper activity

In 2006, partly in reaction to the practical limitations of superlenses, two theoretical groups independently developed the hyperlens[4,5]. Instead of a single film, the hyperlens features alternating layers of a metal and an insulator. Experimentally, the layers are arranged to form a half-cylinder (see diagram). The object is placed in the centre of the cylinder and evanescent waves from it are caught by the lens and magnified as they pass through the various layers, emerging as light that shines freely. The hyperlens is more complex than the superlens, but has a major advantage in that it should be able to feed the light emerging from its surface into conventional optics. "I'm hopeful that this hyperlens could be a revolutionary instrument," says Nader Engheta, a theorist at the University of Pennsylvania in Philadelphia and one of the originators of the idea.

"You haven't seen anything because we haven't had any success."
— Richard Blaikie

Again, experimentalists rushed into the lab to build hyperlenses, and again they met with initial success. Less than a year after the idea was proposed, two groups had made proof-of-concept hyperlenses that beat the resolution of conventional optics. But, as with superlenses, the devil is in the detail. "The principle is working; on the other hand, you are limited by engineering problems," says Igor Smolyaninov of the University of Maryland in College Park, who built one of the demonstration hyperlenses. Smolyaninov's lens, for example, works in only one dimension. A two-dimensional version would be more complex to manufacture, he says. And then there is the problem of loss: imperfections at the interfaces between each metal–insulator layer can cause light to scatter randomly.

Progress on the perfect lens has now slowed considerably — although this is partly a result of the excitement over cloaking devices. Pendry was again the source for the idea when, in 2006, he showed that metamaterials could potentially bend light around an object, effectively shielding it from view[6]. Many researchers are now working on developing the metamaterial



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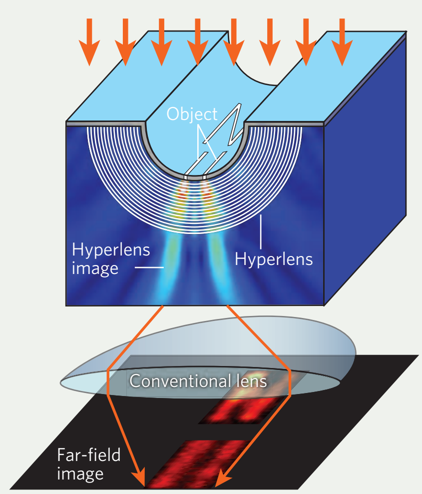
Superlens in action: a thin film of silver delivers a more detailed image (bottom) of nanometre-scale lines.

nanostructures required for the job. As a result, some scientists believe industry needs to start investing in super- and hyperlenses to give that technology a boost. But for both imaging and circuit etching, the lenses would be entering markets in which competing subdiffraction technologies are already further along in development. Semiconductor researchers can use nonlinear optics to write circuits below the diffraction limit. And for biological imaging, other groups are developing ways to beat the diffraction limit using a combination of fluorescent proteins and clever optics.

Biologists have shown only tepid interest in superlenses, admits Nicholas Fang, a researcher at the University of Illinois at Urbana-Champaign. Still, Fang and many others remain fiercely devoted to the superlens idea. If the lenses can be made to work, they would be able to image living biological specimens with unprecedented detail. Granted, he says, "there are many open issues that we did not realize at the very beginning". But he points out that this is hardly unusual with new technologies.

HYPERLENS

A hyperlens magnifies evanescent waves to produce information for conventional optics.



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Superlenses do work in theory, he contends, and many of the problems are "more of an engineering issue". For his part, he believes that the field may have to draw a little more from industrial expertise. For example, he has used industrial-grade germanium to deposit atomically flat films of silver[7] that can reduce the distortion seen by Blaikie.

Other groups are working to make hyperlenses more practical and, again, techniques from the semiconductor industry seem to be helping. In April, Stefan Mendach and his colleagues at the University of Hamburg, Germany, created a hyperlens by rolling up alternating layers of semiconductor materials[8]. The technique seems to be an easy way to make a hyperlens, although Mendach needs to get more layers in his system before it can work. And Vladimir Shalaev at Purdue University in West Lafayette, Indiana, is trying to build 'flat' hyperlenses. Although they are harder to make — the individual layers can no longer be uniform — they could prove easier to use, as the specimen would not have to be precisely positioned along the cylinder axis.

Zhang, meanwhile, is pursuing a simpler but related concept that he believes could revolutionize data storage. Rather than using a single superlens, he is using several 'plasmonic' lenses, which focus evanescent waves. When normal light strikes the lens it interacts with electrons on the lens surface. This concentrates evanescent waves into a single point, effectively creating a subdiffraction hotspot that could be used to write a piece of information on to an optical disk. Zhang has developed a prototype array of plasmonic lenses that does indeed write information far below the diffraction limit.

Back at his desk, Pendry is willing to wait for his revolution with a patience that is perhaps unique to theoretical physicists. Before he proposed superlenses, he spent years calculating the quantum mechanical forces arising between two blocks of glass flying past each other at near the speed of light, simply because the problem was theoretically interesting. Compared with that earlier work, realizing a perfect lens seems eminently practical. "It's really a very, very simple technology," he says. "It's just a question of being able to get it right." ■

Geoff Brumfiel is a senior reporter for *Nature* in London.

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