A lens less ordinary

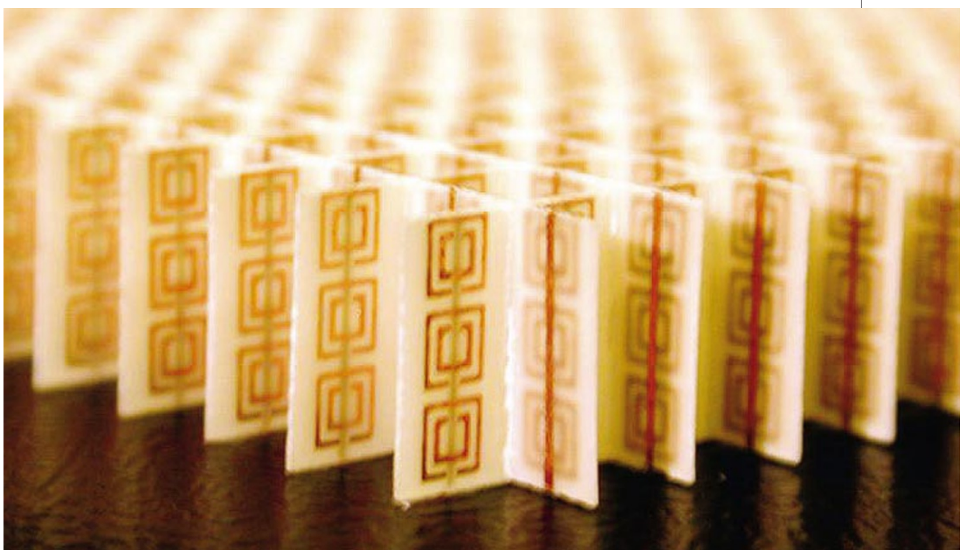
In the 1960s, a Russian physicist considered the properties of a material that didn't yet exist. Now researchers appear to have fulfilled his predictions — but is everything as it seems? Liesbeth Venema investigates.

There are some truths in physics on which we have come to depend. Light rays, for example, bend when they cross the boundary between two materials. That's why an oar dipped into water appears to bend towards the surface, and why the pool itself looks shallower than it really is.

But this familiar phenomenon, called refraction, is beginning to look less straightforward. In the lab of David Smith, a physicist at the University of California, San Diego, a strange array of metal wires and loops has been pieced together. In April 2001, Smith and his team showed that this construction, which they refer to as a 'metamaterial', has a peculiar property: it bends electromagnetic waves in the opposite direction to normal materials[1].

If a pool of water had this property, known as negative refraction, oars would bend away from the surface, and the pool would appear deeper than it really was. But Smith's construction is more than an interesting oddity. Some in the field believe that it could lead to what John Pendry, a physicist at Imperial College in London, has dubbed "the perfect lens" — a device that can produce flawless visual images. "These materials have electromagnetic properties never seen before," says Sheldon Schultz, a colleague of Smith's. "This is a whole new ball game."

The idea of negative refraction first arose during the 1960s, when Victor Veselago, a physicist then at the P. N. Lebedev Physical Institute in Moscow, considered the optical properties of an imaginary material. Every material has a refractive index, which measures how fast it transmits light and how light is bent on entering the material — the higher the index, the slower the propagation and the stronger the deflection. All naturally occurring materials have a positive index — air is 1, glass about 1.5 — but Veselago, who now heads the magnetic materials laboratory at the General Physics Institute in Moscow, was interested in how light would behave in a hypothetical material with a negative index.



Positive result: this experimental 'metamaterial' appears to have a negative refractive index.

REF. 1

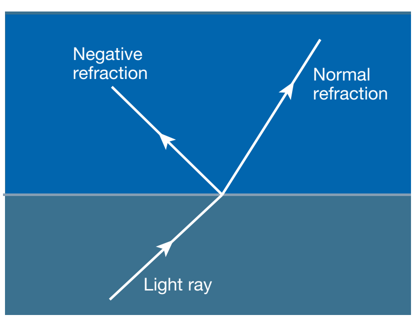
Negative thoughts

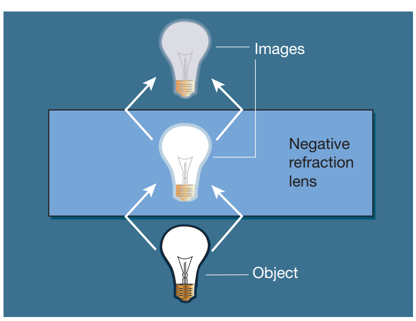
A material's refractive index depends on its response to the electric and magnetic components of an electromagnetic wave, measured by its permittivity and permeability, respectively. Most materials have positive permittivities: place one in an electric field, and the direction of the field induced inside the material will have the same orientation as the applied field. Most materials also have positive permeabilities, and react to magnetic fields in a similar way.

But Veselago was interested in a hypothetical material with a negative permittivity and permeability, and hence a negative refractive index. The fields inside such a substance would be orientated in the opposite direction to the applied fields. And, as Veselago showed, this has some interesting consequences[2]. Light entering such a material would take a sharp turn at the boundary, for example, so a rectangular slab of material would act as a lens, creating an image inside the slab and then again on the other side of the slab (see diagram).

With no materials available on which to test Veselago's theories, researchers could not follow up his ideas. But during the late 1990s, Pendry and his colleagues at Imperial College, together with researchers at Marconi, a telecommunications and computing company also based in London, began to produce structures with the right kind of properties.

The negative permittivity to visible light of some metals, such as silver, had been established well before Veselago's original studies. Pendry, who was developing devices to control the microwaves used in radar systems, was interested in developing materials with negative permeability. Both permittivity and permeability depend on the collective response of the electrons within a material to the applied electric and magnetic fields. To control this response, Pendry created an array of closely spaced, thin, conducting elements, such as metal hoops, which as a whole behaved as a kind of 'composite' material. In 1999, Pendry described how he adjusted the





Out of line: negative refraction (left) bends light in an odd way, and could be used to create a lens (right).

array's properties, such as the spacing between the elements, to create an array with negative permeability[3].

Following up on this work, Smith set about making a material with a negative refractive index. His group created interlocking units of thin fibreglass sheets imprinted with copper rings and wires (see previous page). Last spring, his team sent a beam of microwaves through a small sample of the metamaterial and found that Veselago's original calculation was correct: the microwaves were bent in the opposite direction from normal[1].

Akhlesh Lakhtakia, a physicist at Pennsylvania State University in University Park who had been following the developments, says that he really began to take notice when Smith's results came out. He points out that the microwave beam did not make a small deviation — it turned through almost 80°, which would give the material a refractive index of about −2.7. "This is very convincing," he says.

But not everyone agrees. This April, Prashant Valanju and his colleagues at the University of Texas at Austin, who are also working on metamaterials, suggested that there is something fundamentally wrong with the literature on negative refraction[4]. Real electromagnetic waves are made up of a mixture of individual waves of different frequencies, and each component has its own velocity. When researchers measure the direction and strength of the main wave, they actually record the combination of these components.

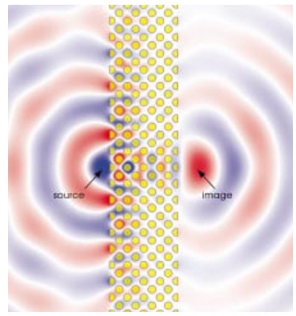
Valanju's group modelled what would happen when a wave made up of two frequencies enters a material with a negative refractive index. They found that although the components would be refracted negatively, they would combine to give a wave that was positively refracted. The result seems paradoxical, but for physicists who are used to the odd ways in which waves of different frequencies can combine, it is plausible. Valanju's analysis also showed that the different components should quickly spread out and weaken the signal.

According to Valanju's team, Smith's results were an experimental artefact resulting from the fact that he used a thin sample — the phenomenon would disappear if a thicker piece of the metamaterial was used. Lakhtakia agrees that some of the points made by Valanju raise questions about the experiments. When Smith measured the angle of transmission, for example, he placed his detector very close to the sample, and so could have missed the dispersion predicted by Valanju's model.

P. VALANJU/UNIV. TEXAS AUSTIN

Prashant Valanju (left) and his team dispute the fact that negative refraction has been achieved.

P. PENDRY



REF. 7

Focused: John Pendry's simulations (right) suggest that photonic crystals may have negative refractive indices for visible light.

Frontal assault

But Smith and Pendry responded with their own theoretical analysis of a two-frequency wave. Rather than considering an infinitely wide wavefront, as Valanju had done, they looked at a more realistic, finite beam of radiation, and found that it should indeed be negatively refracted[5]. Their findings are also backed up by recent experiments. Claudio Parazzoli and colleagues at Phantom Works, the Seattle-based research and development unit of aerospace firm Boeing, have built a larger metamaterial. In unpublished work, they describe negative refraction of microwaves, which they managed to detect tens of centimetres away from their metamaterial. Together with Smith and Pendry's study, this is enough to convince most researchers that Valanju's criticisms have been answered and that negative refraction exists.

So if the phenomenon is real, what can it be used for? Pendry began thinking about applications before Smith's study. In 2000, he considered the properties of a rectangular lens made out of a negatively refracting material. Some of the waves emitted or reflected by ordinary objects decay very quickly, preventing normal lenses from transmitting them. As a result, the detail contained by these 'evanescent' waves is lost — even when the highest-quality lens is used. But Pendry predicted that materials with negative refractive indices would amplify evanescent waves, thus retaining the information they contain[6].

Pendry's idea has since attracted its fair share of comments and criticisms in journals and preprint servers, in part fuelled by his provocative use of the term "perfect lens" to describe the concept. "Maybe the title was not such a good idea," admits Will Stewart, chief scientist at Marconi, who has worked with Pendry. Some researchers say that even a tiny amount of absorption in the lens would prevent amplification of the evanescent waves. Others disagree, and the jury is still out on whether or not a perfect lens can be created.

As the debate rumbles on, other groups are trying to create a material with a negative refractive index for visible light. Interest centres around photonic crystals, materials with alternating regions of different refractive indices. A slab of transparent material with an array of holes drilled into it is one example. Like metamaterials, photonic crystals can be designed to transmit light in different ways, and theoretical studies suggest that negative refraction should be possible[7,8]. John Joannopoulos, a photonic-crystal expert at the Massachusetts Institute of Technology, predicts that experimental confirmation will come in the next two years.

Few concrete suggestions for applications have emerged so far, although researchers have noted potentially useful properties of flat lenses. They would be easier to make than conventional curved lenses, for example. They would also create an image of an object placed anywhere along their length, unlike curved lenses, which only focus objects placed in front of them.

For the normally quiet world of electromagnetic materials, such excitement is unusual. But Smith's experimental work, together with Pendry's provocative ideas, has turned a lot of heads. And if one of the groups trying to make a perfect lens succeeds, interest is likely to snowball. Veselago, who continues to work on the theory of magnetic materials, has had to wait many years for his idea to take off, but now it seems to have a life of its own. ■

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