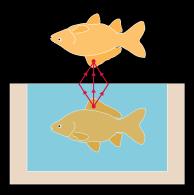


METAMATERIALS John Pendry

NewScientist

NEW OPTICS, NEW THEORIES

LIGHT REFRACTED BY MATERIAL WITH A NEGATIVE REFRACTIVE INDEX MAKES FISH APPEAR AS IF IT'S OUT OF THE WATER

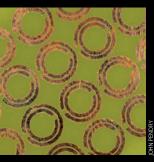


The Russian engineer Victor Veselago was one of the driving forces behind the early development of metamaterials. In 1967, he predicted the possibility of materials with a negative refractive index which would bend light the "wrong" way (see diagram, opposite).

All materials in nature have a positive refractive index. The refractive index is a measure of the property that makes submerged objects appear closer to the surface than they really are, and swimming pools shallow when they are not. The greater the refractive index of a material, the closer to the surface an object within it appears. The logical consequence of this law is that a fish in a pond filled with a negatively refracting material would appear to have jumped right out of it (left). Veselago's argument that negative refraction

should be possible was complex. Light consists of both electric and magnetic fields, with energy shared equally between the two. Light propagates by tossing energy between the fields as if the electric and magnetic components were in a dance. Atoms in a material with a positive refractive index - water, glass or most other transparent materials - respond by aligning their own electric and magnetic fields to the applied fields so as to slow down the dance.

Veselago imagined a material that aligned its electric and magnetic fields in the opposite direction to those in the light beam. This, he reasoned, would reverse the dance and create the effect of negative refraction. His dream was only realised with the advent of metamaterials.



This array of copper split rings was the first metamaterial to have negative magnetism meaning that its internal magnetic field aligns in the opposite direction to an applied magnetic field. It was manufactured at GEC-Marconi in 1998 by Mike Wiltshire and was designed to respond to microwaves with a wavelength of about 3 centimetres. The copper rings are approximately 0.5 centimetres across

THE ROAD TO METAMATERIALS

The idea that a material's internal structure could influence its response to light has been debated since before the time of James Clerk Maxwell, the 19thcentury Scottish physicist who demonstrated how light, magnetism and electricity are all aspects the same phenomenon.

In the 1950s, researchers studying long-range radio communication built structures made from thin metallic wires to simulate how Earth's ionosphere interacts with radio transmissions. But it wasn't until the 1990s that we finally realised just how radically a material's structure could influence its properties.

I helped the GEC-Marconi company to produce a so-called split-ring structure. Manufactured by etching a copper circuit board with rings a few millimetres across, it had a particularly strong response to radar signals, which produced electric currents in the copper that in turn produced an induced magnetic field (see image, above left).

This structure had another interesting property. Most magnetic materials align in the same direction as the applied field, like a compass needle pointing north. In contrast, the new metamaterial aligned its magnetism in the opposite direction. In 2000, David Smith, then at the University of California, San Diego, took this split-ring structure and used it to make the first material capable of bending radiation in the opposite direction to normal materials such as glass. This was the negative refraction whose existence had been predicted decades earlier by Victor Veselago.

A decade on, and we now have metamaterials with exquisitely intricate structures, like the ones fashioned from microscopic helices of gold by Martin Wegener's group at the Karlsruhe Institute of Technology in Germany (see image, bottom right). When light shines on the material, electric currents are induced in the helices. Interestingly, the size of the currents depends strongly on whether the light is left or right-circularly polarised. The response is stronger than even a solution of sugar, one of the most "optically active" natural substances.

Metamaterials have been built for radar waves (main image, and right, top) and visible light (right, bottom)



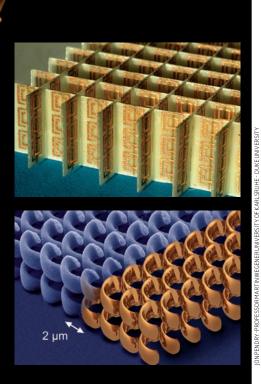
David Smith was working at the University of California, San Diego, when he adapted the split-ring structure to create the first metamaterial with a negative refractive index (below, top). The copper loops change the magnetic response, while thin copper wires on the surface behind provide the required electrical response. Smith's group has made extensive contributions to the development of metamaterials, including the first working invisibility cloak in 2006. It, too, operated at radar frequencies

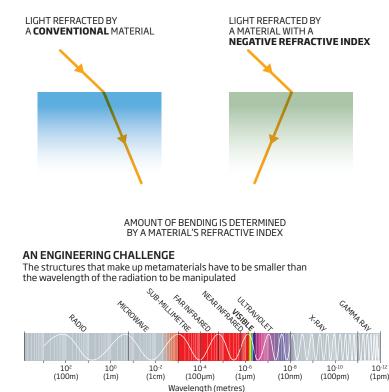
HISTORY OF METAMATERIALS

How a material affects light falling upon it is dictated in part by its chemical composition, but its internal structure can have an even stronger influence. Silvered mirrors are highly reflecting, but blackand-white photographs also owe their blackness to silver – billions of nanometre-scale spheres of the metal embedded in the film. This dramatic difference arises because the silver spheres are much smaller than the wavelength of light.

Metamaterials extend this concept with artificial structures that might be nanometres across for visible light, or as large as a few millimetres for microwave radiation. Their properties are engineered by manipulating their structure rather than their chemical composition.

The possibilities these materials open up are limited only by our imagination, and not by the number of elements in the periodic table. As a result, metamaterials research has exploded during the past decade. It has given us optical properties we once thought were impossible, including negative refraction never found in nature, and novel devices such as invisibility cloaks.





NEGATIVE SPACE AND THE PERFECT LENS

General relativity predicts that extremely massive objects will cause severe distortions to the surrounding space. Perhaps the best known of these objects are black holes - singularities in space-time from which even light cannot escape. Some people have asked if metamaterials can be used to mimic black holes, but this is not possible as metamaterials lack the built-in energy source required to produce the "Hawking radiation" that real black holes emit.

But there is something metamaterials can do that is even more spectacular: they can create "negative optical space". Think of space as a sheet of rubber that can be compressed. By pushing hard enough on the sheet, it should in principle be possible to fold space back on itself so that light moving in the folded space passes the same point three times. A fish swimming in this space would come into focus three times, the middle focus being inverted.

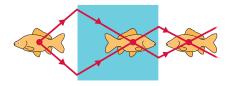
Transformation optics tells us that a portion of the folded space must have a negative refractive index. This negative optical space has a remarkable property. Light leaving an object can be thought of as defocusing as it travels away in all directions. Negative optical space cancels out this effect. As a result, a lens made of a metamaterial that creates negative optical space is optically perfect. It effectively eliminates the space separating the object and image, so that the object and image coincide.

Another limitation of ordinary lenses is that they can never resolve details smaller than the wavelength of the light being used. That's because light diffracts or bends around objects of a similar size to its own wavelength, so it can never be focused to a sharp point. The lens is said to be "diffraction limited".

When I calculated in 2000 that a negatively refracting lens breaks the diffraction limit, the result caused a furore, so entrenched was the notion that lenses cannot be used to see anything smaller than the wavelength of light. Several experiments have since shown my prediction to be correct. In particular, Nicholas Fang, working at the time with Xiang Zhang at the University of California, Berkeley, demonstrated a lens that could resolve details as small as one-sixth the wavelength of visible light. Subsequent work has improved resolution to 1/20th of the wavelength.

Such lenses are challenging to make, however, because they are extremely sensitive to imperfections.

A SLAB OF NEGATIVELY REFRACTING MATERIAL CAN FOCUS DETAILS SMALLER THAN THE WAVELENGTH OF LIGHT



A CLOAK OF INVISIBILITY

To be invisible seems somehow magical. People have dreamed of the possibility for centuries, but only with the advent of transformation optics and metamaterials has the dream of an "invisibility cloak" approached reality.

Such a cloak must have two properties. First, it must reflect no light and ensure that no light is reflected from the object it is cloaking. This is relatively easy to achieve with a pot of black paint or its equivalent for whatever wavelengths we want to be invisible in. In essence, this is how the stealth technology used by the military operates.

Second, the hidden object must cast no shadow. Removing a shadow is a much greater challenge, but one that transformation optics has successfully addressed.

Our brains assume that light travels in a straight line to reach our eyes, as if it travelled along a rigid rod. Now suppose that the rod were not rigid, but could be bent so that it curves around the object that we want to hide. Our brains would be none the wiser because the light rays would reach our eyes exactly as before with no hint of the curved path that they had in fact taken. Metamaterials can make light flow like water around the hidden object, smoothly closing in behind the object to leave no trace of its presence.

The eye is fooled in the same way by certain natural phenomena that cause light to travel in a curve. When the sun heats the desert sands, the air immediately above the sand is also heated. It becomes less dense and therefore less refracting. This effect tails off with height, creating a gradient in the air's refractive index. As a result, light from the sky is bent so that it can appear to originate from the desert itself, as if part of the surface were covered with water. Hence the



TRANSFORMATION OPTICS

We need a clever design tool to make the most of metamaterials' potential. In conventional optics, light travels in a straight line until it hits the boundary between two transparent materials, at which point it abruptly changes direction. Metamaterials are much more sophisticated. They can force light to travel along a curved path, thereby opening up the possibility of devices such as invisibility cloaks.

The mathematical tool that tells us what kind of metamaterial will bend light along the desired path is known as transformation optics.

"An invisibility cloak prevents reflections and shadows from an object"

disappointment of a thirsty traveller who thinks he has seen an oasis. Making an invisibility cloak then becomes a matter of devising a suitable refractive index gradient to bend light in precisely the right way. Transformation optics enables us to work out the exact properties a

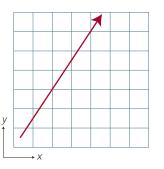
metamaterial would need to achieve

the required bending.

It is a huge challenge to actually build an invisibility cloak - particularly at visible wavelengths where interest is naturally strongest. But at radar frequencies, progress has been rapid. There have been more limited successes with visible light, with cloaks just a few wavelengths across.

A ray of light travelling through space behaves as i

space behaves as if it were "nailed" to the coordinate system, even when space becomes warped. To control the ray in the way we want, all we have to do is to warp the coordinates . Einstein gave us a formula that lets us work out the refractive indices that will do this



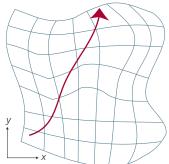
A LITTLE HELP FROM EINSTEIN

A remarkable experiment conducted during a solar eclipse in 1919 showed that the sun acts like a giant lens, bending starlight that passes close to the sun's disc. It vindicated Albert Einstein's prediction in his general theory of relativity that the sun's gravitational field would distort space.

As far as light is concerned, the warped space near to the sun appears to have a large refractive index. Very helpfully for metamaterials, Einstein produced a formula relating the distortion of space to changes in effective refractive index. Furthermore, Einstein's formula is an exact transformation of Maxwell's equations, which govern all electromagnetic phenomena.

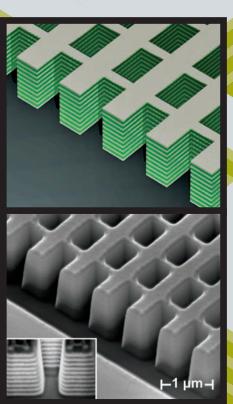
What transformation optics seeks to achieve is to take a ray of light and distort its trajectory in whatever way we please. We could do this by distorting space itself using extremely massive objects, but thanks to Einstein's insight this is not necessary. Simply changing the refractive index will have the same effect as far as light is concerned.

Transformation optics can be used to calculate the required refractive indices. All that is then needed is to construct metamaterials that meet these specifications.





The wavering path taken by light from the road makes it look wet



This layered metamaterial works at visible wavelengths

ACTIVE METAMATERIALS

What if metamaterials could alter their properties in response to an electric current or a powerful light source? Such "active" metamaterials, as they are called, would be far more versatile than their ordinary counterparts.

For example, a metamaterial containing a semiconductor will conduct more electricity when illuminated with light of the right frequency to excite charge carriers in the semiconductor. This change in conductivity will, in turn, alter how the metamaterial responds to a second light beam, providing a way to modulate the intensity of the second beam or alter the direction in which it is bent.

The superior control provided by metamaterials is making light almost as controllable as electrons in computer chips - a fact that could open the door to faster telecommunications. At certain stages in a conventional fibre-optic network, the light signal has to be converted to easy-to-manipulate electrical signals and then back into light. Metamaterials will allow us to manipulate light signals without this time-consuming and wasteful step.

However, metamaterials themselves can absorb energy from light travelling through them, and this effect can greatly reduce their usefulness, particularly as some of the more unusual properties of metamaterials, such as negative refraction, require that light be trapped inside the material while it is manipulated. For example, Xiang Zhang's group at the University of California, Berkeley, has made a structure from alternating layers of silver and magnesium fluoride designed to have a negative refractive index for visible light (above left). Light is trapped between the layers of silver, but this also means it gets absorbed over time.

To deal with such losses Vladimir Shalaev's group at Purdue University in West Lafayette, Indiana, introduced a dye into the structure. A powerful light source pumps the dye molecules into an excited state, enabling them to give up their energy to a second light beam and amplify it. Here serendipity intervenes: the trapping effect that made the layered structure absorb light is now an advantage. The longer light can remain in the structure, the more time it has to benefit from the amplification process.

FRONTIERS OF METAMATERIALS

Metamaterials seemingly bend the rules of traditional optics, opening up a host of new applications and possibilities. Experimentalists are augmenting their capabilities by using them in combination with other exciting materials like quantum dots and dyes, while theorists are coming up with novel ideas for metamaterials that are getting ever harder to manufacture with the precision required.

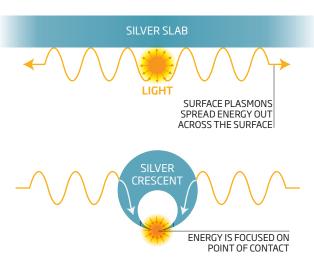
HARVESTING LIGHT

Often we want to collect light and harness its energy to detect a molecule, switch a nanoscale electronic circuit, or simply power a device. Nature has long used the feat of light harvesting in the process of photosynthesis: chlorophyll molecules in leaves absorb light with a wavelength hundreds of times their size, and convert its electromagnetic energy into chemical energy.

Transformation optics offers a systematic route to this harvesting process. The strategy I favour is to start from a system that is well understood, yet doesn't have the desired properties, and then use transformation optics to reshape it into something useful.

The starting point is an area of science called plasmonics - the study of how electrons in a slab of a metal such as silver wobble back and forth like jelly and create strong electric fields outside the slab. When these wobbles occur on the surface of the slab, they are called surface plasmons. It turns out we can use them to harvest light.

Suppose light from an excited atom shines on an infinite sheet of silver. Surface plasmons capture the light and transport its energy away towards infinity along the surface of the metal. This is a widely studied



effect, but it does not achieve our goal, as the harvested energy is dispersed to infinity.

What we want to achieve is the reverse: we want to capture light from infinity and concentrate it to a point. A transformation known as an inversion shows us how to do this. It maps points at infinity to the origin, and the origin to infinity, with all points in between mapped into reverse order (see diagram, below). So the source of light is now at infinity, and the surface plasmons are now incoming waves focused on what was the origin. The silver slab becomes a crescent-shaped object which gathers energy at its outer regions and funnels it down to the cusp. In theory, a metal crescent of the order of 100 nanometres in diameter should be an excellent light harvester.

However, transformation optics tells us more. As the light slows in its journey to the cusp, its energy density is increasingly concentrated and would reach infinite concentration at the cusp were it not for losses in the silver. Such theoretical studies show that very large concentrations of energy should be possible.

Other structures can also harvest light. Two metal spheres in contact with each other will concentrate light at the point where they touch. As ever, the challenge is to manufacture devices on a nanometre scale to the required precision. Several groups, including one led by David Smith, who is now at Duke University in Durham, North Carolina, have done this to develop effective harvesting structures.

"Metamaterials make light almost as controllable as electrons in computer chips"

John Pendry



is professor of physics at Imperial College London. He works on the theory of metamaterials and other problems in electromagnetism



THE BIG CHALLENGE REALISING OUR DREAMS

The advent of metamaterials has inspired renewed interest in the fundamentals of electromagnetism. In part, our dreams of what can be achieved with these materials have been realised, but to some extent they have outrun our capacity to make them happen. What are the stumbling blocks?

Fundamental to the metamaterial concept is the ability to structure a material on a scale less than the wavelength of the radiation you want to manipulate. This is not a problem with the microwaves used for mobile phone signals, with a wavelength of around 30 centimetres, which is why much of the early experimental work was with microwaves.

Visible light presents a greater challenge: whereas traditional technologies used to manufacture mirrors and glass lenses have required tolerances of better that 1 micrometre, metamaterials have to be constructed to nanometre-scale accuracy. Though technologies such as ion beam etching can do this, they are expensive and handle only small samples. Further progress will require investment in nano-manufacturing.

The performance of a metamaterial is ultimately determined by the characteristics of the ingredients from which it is made. Metallic metamaterials perform well at the frequencies used by mobile phone networks but not at visible wavelengths, where metals tend to absorb visible light.

One approach is to compensate for such losses by introducing an amplifying medium, such as dye molecules or an array of quantum dots.

What is not in doubt is the excitement created by the new metamaterial world, which has liberated theorists to dream of things that were previously thought impossible, and challenged experimentalists to make them happen.

RECOMMENDED READING

A selection of articles at both advanced and popular level can be found at my website (bit.ly/cBXmF4) and at David Smith's site (bit.ly/bmFgh7)

Optical Metamaterials: Fundamentals and applications by W. Cai and V. Shalaev (Springer)

Physics and Applications of Negative Refractive Index Materials by S. Anantha Ramakrishna and Tomasz M. Grzegorczyk (CRC Press)

Cover image David Schurig