Two negatives; one positive

Forty years ago, a Russian scientist wondered if permittivity and permeability – key electromagnetic properties – could actually be negative and, if they could, what the result would be.

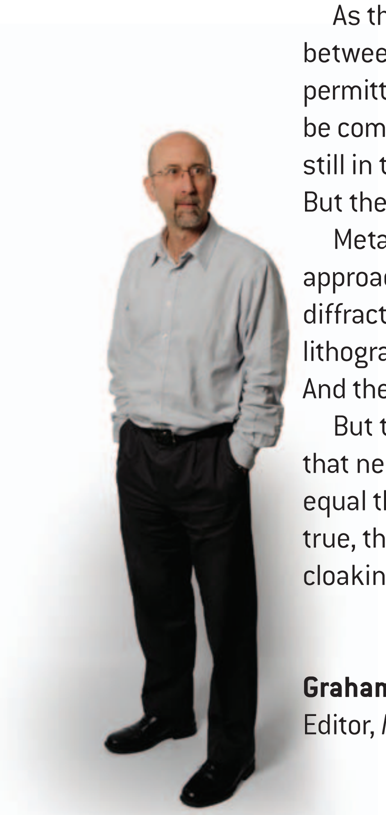
He suggested that if a material had negative permittivity and permeability, it would also have a negative refractive index. That started people looking at the basic equations governing electromagnetic behaviour.

If the behaviour of a material could be modified – or a material created that demonstrated unusual behaviour – a range of potential applications might open up. Because real world materials don't exhibit negative permittivity and permeability, the composites that do show unusual behaviours have become known as metamaterials.

As the Cover Story in this issue discusses, there's a big gap between research and application. It took 30 years for negative permittivity to be demonstrated and another couple of years for it to be combined with negative permeability. Even 40 years on, we're still in the early days of finding uses for these novel composites. But they appear to have huge potential.

Metamaterial pioneer Professor Sir John Pendry showed the approach could used to create a lens that focuses beyond the diffraction limit. This would help to overcome the limitations of lithographic technology, enabling ever smaller chips to be made. And there are applications in medical imaging.

But the physics can make your head hurt. Prof Pendry suggests that negative refractive index materials are actually grabbing an equal thickness of negative space alongside and annihilating it. If true, that holds the possibility, albeit remote, of creating the cloaking technology beloved of *Star Trek* script writers.



Graham Pitcher,
Editor, *New Electronics*

Metamaterials are composites whose behaviours seemingly defy the Laws of Physics. But interesting applications are being found for them, including medical scanners and semiconductor fabrication equipment.

Digi-Key is pleased to partner with *New Electronics* to explore the potential of metamaterials in the electronics industry.

Mark Larson,
President, Digi-Key

As an extension of its commitment to providing top quality product, Digi-Key is pleased to partner with *New Electronics* to provide relevant, useful information to UK engineers.

The left hand of nature

In the late 1960s, Russian physicist Victor Veselago pondered whether two key electromagnetic properties – permeability and permittivity – could ever be negative. If they could be, he contended, so too would the refractive index of that medium. This demanded a new look at some of the equations that determine electromagnetic behaviour and raised intriguing possibilities for materials with negative refractive indices.

One result was the prediction that a light ray entering a transparent material with negative refractive index would bend the 'wrong' way relative to the surface normal. The reason behind this lies in the group and phase velocities of a wave. Refractive index is a ratio of phase velocities. So, the phase velocity of a light wave has to turn negative when the wave encounters a medium with a negative refractive index, while its group velocity can remain positive.

An array of split ring resonators made at the University of California at San Diego

Interest waned until, in 2000, Professor Sir John Pendry and colleagues from Imperial College and the University of California at San Diego showed it was, indeed, possible to build an artificial material – or metamaterial – with negative permittivity.

Negative permittivity can be seen naturally. A metal below the plasma frequency – the point at which it becomes transparent to light – shows the effect, which comes from free electrons in the metal screening external electromagnetic radiation. Metal gratings show the same kind of effect. But it was only once work started on attempts to combine negative permeability and permittivity that the effect was reinvestigated.

The plasma frequency depends on the density of carriers and their effective mass. In a wire lattice, the geometry controls both parameters – thinner wires make it possible to increase the effective mass of the charge carrier which, in turn, reduces the effective plasma frequency.

In principle, using wire meshes or gratings, it is possible to achieve negative permittivities all the way from low radio frequencies into the optical spectrum.

Prof Pendry's team proposed a structure for negative permeability. The split ring resonator – an almost complete circle of metal – behaves like the inductive-capacitance (LC) resonator of an electrical filter circuit. When the resonator sits in a magnetic field that changes with time, charge builds across the gap in the ring. At low frequencies, the currents that oscillate within the resonator stay in phase with the driving field. At higher frequencies, the currents start to lag, generating an out of phase response – which produces the effect of negative permeability at those higher frequencies.

The next step was to create a composite material that could exhibit negative permeability and permittivity, albeit over a narrow frequency range where the effective range of the resonators and wire gratings overlap. This step was taken by researchers at the University of California at San Diego, who demonstrated a negative refractive index, as predicted by Veselago. The idea of a 'left handed' material became a reality.

Applying a negative refractive index to waves of a certain frequency range was only the starting point to explore the kinds of manipulations made possible by carefully designed surfaces. Earlier this year, Professor Bumki Min and colleagues at the Korean Advanced Institute for Science and Technology built a structure that demonstrated, for terahertz waves at least, the highest positive refractive index

Chris Edwards goes beyond the idea of an invisibility cloak to find more practical applications for metamaterials

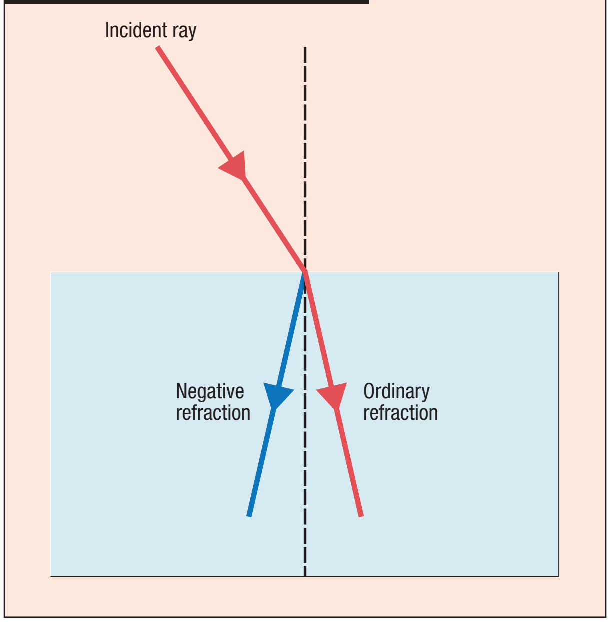


Fig 1: Negative and ordinary refraction

Normally, refraction through a solid causes light to disperse at each interface, according to Snell's Law

ever recorded. This peaked at 38.6, more than an order of magnitude greater than that of diamond.

The structure in this case was a polymer film that carried a pattern of gold or aluminium H-shapes, depending on the target wavelength. These were arranged into square unit cells that sat close to each other, but were not allowed to touch. The shapes were designed to keep permeability at normal levels, but to boost permittivity artificially by using linearly polarised light to create electric fields between the metal shapes. At resonant frequencies, the electric field increased and boosted the refractive index to its maximum.

To overcome the innate electromagnetic parameters of a bulk material, the surface features need, in principle, to be smaller than the wavelength of light they are expected to affect. In terms of electromagnetic interactions, the wavelength determines whether a collection of surface features can be considered a material. If they can be grouped and treated as bulk properties, then the features become, in effect, artificial atoms. As Prof Pendry, together with metamaterial pioneers David Smith and Mike Wiltshire, explained in a 2004 review paper in *Science*: "Although such an inhomogeneous collection may not satisfy our intuitive definition of a material, an electromagnetic wave passing through the structure cannot tell the difference. From the electromagnetic point of view, we have created an artificial material or metamaterial."

A left handed material that bends light the wrong way or, at extreme angles, the right way is interesting intellectually, but does not immediately suggest an application. But such control over light has potential benefits.

Normally, refraction through a solid causes light to disperse at each interface, according to Snell's Law (see fig 1). A material with a negative refractive index can refocus the light rays, making new types of lenses possible (see fig 2). Using these metamaterials, a diverging lens can be turned into a converging lens, or *vice versa*.

Potentially of more use, Prof Pendry showed, in another experiment, that a material with a negative refractive index could focus an image beyond the conventional diffraction limit. Normally, diffraction limits the resolution of an image focused by a lens to double the wavelength of light used. Semiconductor companies have struggled with this problem for more than a decade (see feature on p32). But negative refractive index materials can recover the information lost by conventional lenses, allowing subwavelength focusing.

Prof Pendry and his colleagues argued the term 'lens' is a misnomer when dealing with metamaterials. "A more accurate description of a negative index material is negative space ... it is as if [a slab of material] had grabbed an equal thickness of empty space next to it and annihilated it."

This effective destruction of space opens the possibility of more unusual applications: for example, a Harry Potter style invisibility cloak. If a cloak can remove space, then one that is thick enough could remove an entire object from view, when illuminated with light of the right wavelength. In practice, a broadband cloak is likely to remain the stuff of fantasy for many years. And conventional camouflage may be just as effective and lighter.

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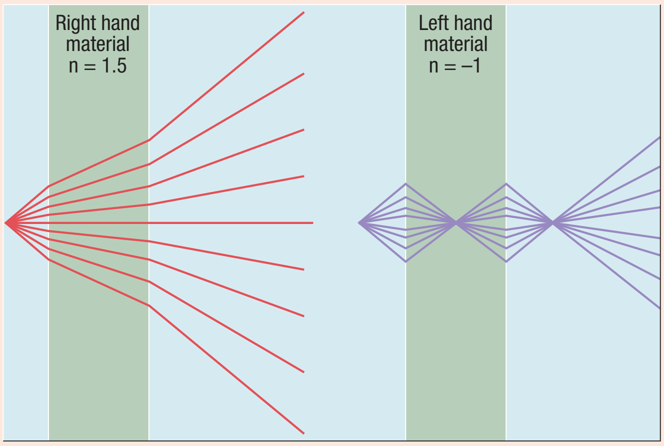
Fig 2: The difference between positive and negative refractive index effects



The most offbeat use so far is as a demonstration of the impossibility of time travel. Using a metamaterial intended to model some of the conditions present shortly after the Big Bang, Igor Smolyaninov and Yu-Ju Hung of the University of Maryland built a metamaterial in which one of the spatial coordinates could be considered to have 'timelike' behaviour, based on a rewriting of some key equations. The pattern of light within the metamaterial, when illuminated by a laser, could then be considered to be its 'history' within its confines: a 2D+1 'toy' representation of spacetime.

Originally, the researchers had attempted to use the metamaterial to create closed timelike curves – circular paths in spacetime that allow particles to return to where they started: something allowed by one solution to the equations of General Relativity. The researchers wanted to create a model of the highly curved spacetime that existed in the initial moments after the Big Bang. But they found restrictions on the way that light rays can move through a metamaterial. Although some could return to their starting point, they did not perceive the supposedly timelike variable as truly timelike: they were behaving as ordinary rays in space.

One of the first real world applications for metamaterials has been the artificial magnet. Researchers realised that turning a non magnetic material into an artificial magnet could provide a new way of building magnetic resonance imaging (MRI) scanners.

MRI scanners work by bathing the body in a strong magnetic field that oscillates at radio frequencies. This changing field causes the nuclei of hydrogen atoms to resonate and to generate their own, much weaker field.

Electron shielding changes the resonance frequency, revealing detail about the molecular environment of each hydrogen atom. The scanner detects this change in resonance by sweeping the source field through a range of frequencies. Computers then reassemble the incoming data into an image.

In practice, it is hard to generate a strong magnetic field that oscillates at high frequency. Instead, MRI scanners use a strong – of the order of 1Tesla – to make the body's nuclei align. Then a weaker RF electromagnetic pulse excites them enough to precess around the main field. A material to focus the RF field or transport weak magnetic flux to a detector helps, but only if it does not perturb the stronger field, which enables the high resolution of a body scanner.

A material with a negative refractive index can refocus the light rays, making new types of lenses possible

If an artificial magnet can be made to respond only to a time varying field – to be effectively invisible to the static field – it becomes much easier to focus the RF field without disrupting the image. In MRI scanners, the wavelengths are so long that only the effective permeability of the metamaterial matters. This can be controlled using a structure known as the Swiss Roll – an insulated metal sheet wrapped around a cylinder. Around 10 turns on a 1cm diameter cylinder brings the resonant frequency into the range of an MRI pulse. The resulting metamaterial is an array of these rolls.

At the resonant frequency, the slab of Swiss Rolls behaves like an array of magnetic wires. A magnetic field that hits one side of the slab is conveyed to the other side, where it can be detected. Using a metamaterial for its negative refractive index can also be used to focus and shift the RF field.

In 2008, researchers from the University of Seville found that negative refractive index can extend the range of a scanner's receiving coil by effectively shifting the magnetic field from inside a patient to the outside – taking advantage of 'negative space'. An MRI scanner, without the metamaterial, could yield a usable image of one knee. WIth a slab of metamaterial sandwiched between the

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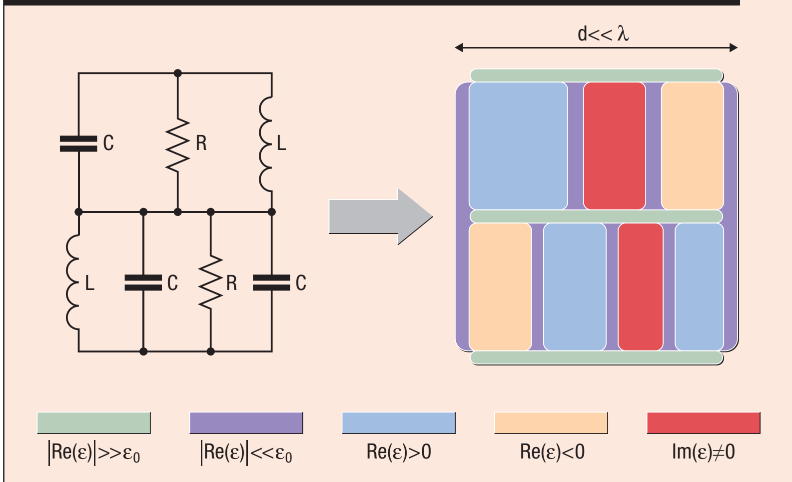
Fig 3: How nanocomponents might be arranged in an Engheta/Alù optical circuit



knees, usable images were captured from both knees. In principle, this may allow deep, high resolution imaging without having to increase the strength of the static field, which runs the risk of creating hotspots within the patient.

But a metamaterial designed to focus the RF field can distort the very weak signal generated by the hydrogen nuclei. Further work at Seville has resulted in a tunable metamaterial. The team used split ring resonators with a twist – putting diodes into the ring so that, when hit by a strong field, they 'short out' and become invisible. The weaker response fields do not close the circuits and are focused by the resonators.

There are other ways to tune a metamaterial. One way is to excite photocarriers in a GaAs substrate on which is printed an array of split ring resonators. These charges, which remain for around 1ns, shift the frequency resonance of the metamaterial temporarily. With shorter lived photocarriers, it becomes theoretically possible to build switches that operate in the terahertz regime and this opens the prospect of purely optical computers that can be microfabricated in a similar way to conventional electronic ICs.

Nader Engheta of the University of Pennsylvania and Andrea Alù of the University of Texas believe it may be possible to design and build optical circuits using techniques similar to those used to develop RF electrical circuitry. Instead of trying to build what looks like a bulk material to photons in the target frequency range, they would use different types of nanoparticle to create analogues of capacitors, resistors and inductors (see fig 3).

In principle, the techniques used to design RF circuits – such as simplifying the circuit into a collection of lumped elements – also apply to optical frequencies. Unfortunately, the material properties of metals do not scale so well. Materials that are simply conductive at RF and microwave frequencies shift into plasmonic resonance at optical wavelengths – where optical signals couple with conduction electrons at the metal's surfaces.

These 'metananocircuit' elements are leakier than those found in microwave circuits: where dielectric materials can isolate components such as resistors and capacitors. The biggest issue remains manufacture; the individual component shapes need to have overall dimensions of just tens of nanometres and that is at the limit of today's fabrication techniques.

The work may lead to low power interconnects. Alù and Engheta have proposed the use of nanoantennas for optical frequency photons could be more efficient than conventional waveguides and offer a free space alternative in which multiple signals could be received and multiplexed by a single antenna from a number of sources.

Metamaterial construction techniques may not even be needed for some applications. In March 2011, scientists at the Lawrence Berkeley National Laboratory in California developed 'superlenses' that could demonstrate the subwavelength focusing properties of negative refractive index materials using the crystal structure of perovskite materials.

Unlike metamaterial lenses, the perovskite coated structure does not work with propagating waves. Instead, it reconstructs the evanescent waves that are normally lost by conventional lenses. Potentially, the superlensing activity can be turned on and off electrically, due to the nature of perovskite crystals.

In just 40 years, an intellectual exercise has led to the development of a new family of techniques for handling electromagnetic properties – potentially bringing applications for machines that make full use of the interactions between photons and electrons.

Researchers believe it may be possible to create optical circuits using analogues of capacitors, resistors and inductors. However, the circuit elements would need to be at the nanoscale; the limits of today's fabrication technology