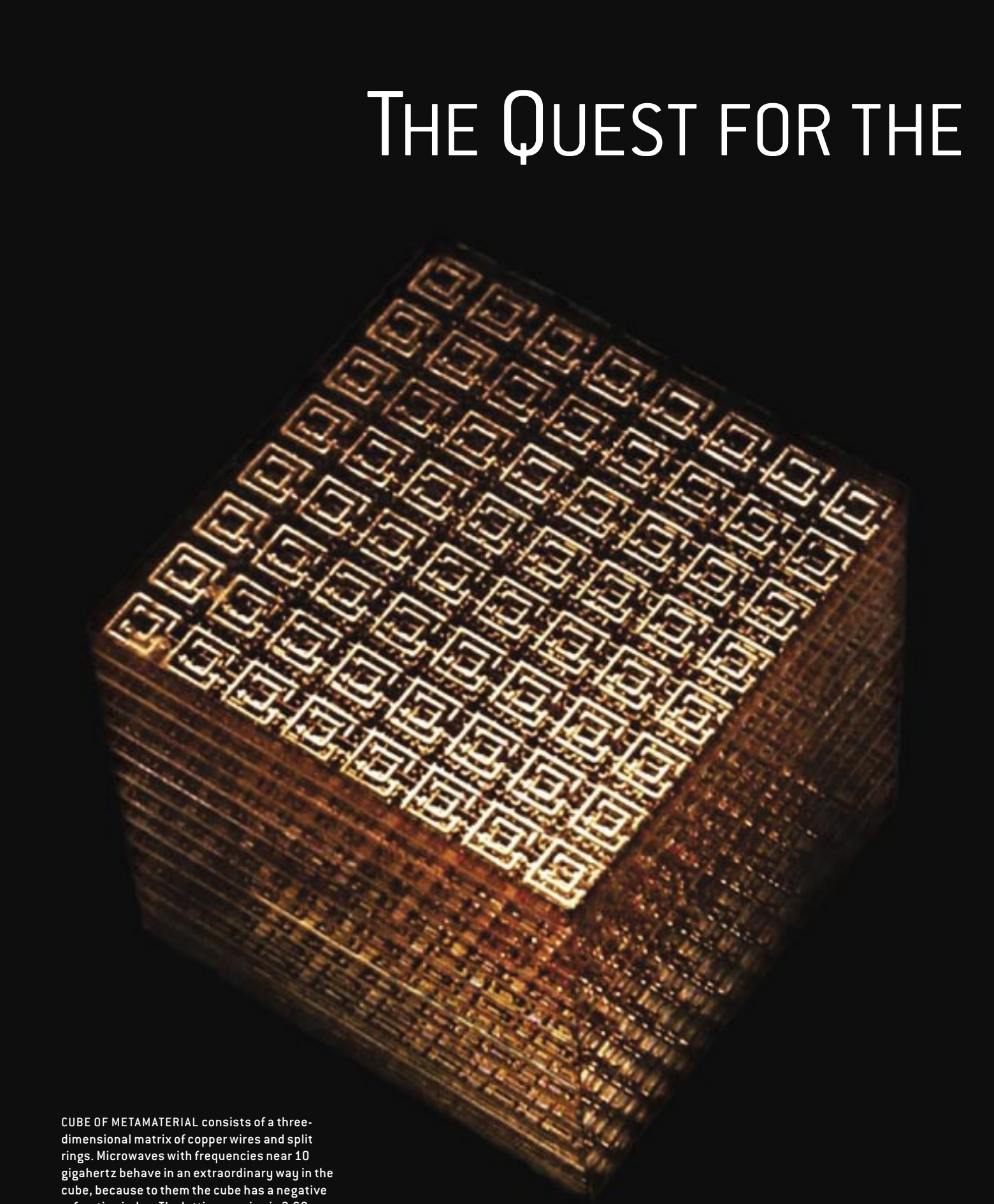
THE QUEST FOR THE



CUBE OF METAMATERIAL consists of a three-dimensional matrix of copper wires and split rings. Microwaves with frequencies near 10 gigahertz behave in an extraordinary way in the cube, because to them the cube has a negative refractive index. The lattice spacing is 2.68 millimeters, or about one tenth of an inch.

Superlens

Built from "metamaterials" with bizarre, controversial optical properties, a superlens could produce images that include details finer than the wavelength of light that is used

By John B. Pendry and David R. Smith

Almost 40 years ago Russian scientist Victor Veselago had an idea for a material that could turn the world of optics on its head. It could make light waves appear to flow *backward* and behave in many other counterintuitive ways. A totally new kind of lens made of the material would have almost magical attributes that would let it outperform any previously known. The catch: the material had to have a negative index of refraction ("refraction" describes how much a wave will change direction as it enters or leaves the material). All known materials had a positive value. After years of searching, Veselago failed to find anything having the electromagnetic properties he sought, and his conjecture faded into obscurity.

A startling advance recently resurrected Veselago's notion. In most materials, the electromagnetic properties arise directly from the characteristics of constituent atoms and molecules. Because these constituents have a limited range of characteristics, the millions of materials that we know of display only a limited palette of electromagnetic properties. But in the mid-1990s one of us (Pendry), in collaboration with scientists at Marconi Materials

Technology in England, realized that a "material" does not have to be a slab of one substance. Rather it could gain its electromagnetic properties from tiny structures, which collectively create effects that are otherwise impossible.

The Marconi team began making these so-called metamaterials and demonstrated several that scattered electromagnetic waves unlike any known materials. In 2000 one of us (Smith), along with colleagues at the University of California, San Diego, found a combination of metamaterials that provided the elusive property of negative refraction.

Light in negative-index materials behaves in such strange ways that theorists have essentially rewritten the book on electromagnetics—a process that has included some heated debate questioning the very existence of such materials. Experimenters, meanwhile, are working on developing technologies that use the weird properties of metamaterials: a superlens, for example, that allows imaging of details finer than the wavelength of light used, which might enable optical lithography of microcircuitry well into the nanoscale and the storage of vastly more data on optical disks. Much remains to be done to turn such visions into reality, but now that Veselago's dream has been conclusively realized, progress is rapid.

Negative Refraction

TO UNDERSTAND HOW negative refraction can arise, one must know how materials affect electromagnetic waves. When an electromagnetic wave (such as a ray of light) travels through a material, the electrons within the material's atoms or molecules feel a force and move in response. This motion uses up some of the wave's energy, affecting the properties of the wave and how it travels. By adjusting the chemical composition of a material, scientists can fine-tune its wave-propagation characteristics for a specific application.

But as metamaterials show, chemistry is not the only path to developing materials with an interesting electromagnetic response. We can also engineer electromagnetic response by creating tiny but macroscopic structures. This possibility arises because the wavelength of a typical electromagnetic wave—the characteristic distance over which it varies—is orders of magnitude larger than the atoms or molecules that make up a material. The wave does not "see" an individual molecule but rather the collective response of millions of molecules. In a metamaterial, the patterned elements are considerably smaller than the wavelength and are thus not seen individually by the electromagnetic wave.

As their name suggests, electromagnetic waves contain both an electric field and a magnetic field. Each component induces a characteristic motion of the electrons in a material—back and forth in response to the electric field and around in circles in response to the magnetic field. Two parameters quantify the extent of these responses in a material: electrical permittivity, ε, or how much its electrons respond to an electric field, and magnetic permeability, μ, the electrons' degree of response to a magnetic field. Most materials have positive ε and μ.

Another important indicator of the optical response of a material is its refractive index, n. The refractive index is simply related to ε and μ: $n = \pm\sqrt{\varepsilon\mu}$. In every known material, the positive value must be chosen for the square root; hence, the refractive index is positive. In 1968 Veselago showed, however, that if ε and μ are both negative, then n must also take the negative sign. Thus, a material with both ε and μ negative is a negative-index material.

A negative ε or μ implies that the electrons within the material move in the opposite direction to the force applied by the electric and magnetic fields. Although this behavior might seem paradoxical, it is actually quite a simple matter to make electrons oppose the "push" of the applied electric and magnetic fields.

Think of a swing: apply a slow, steady push, and the swing obediently moves in the direction of the push—although it does not swing very high. Once set in motion, the swing tends to oscillate back and forth at a particular rate, known technically as its resonant frequency. Push the swing periodically, in time with this swinging, and it starts arcing higher. Now try to push at a faster rate, and the push goes out of phase with respect to the motion of the swing—at some point, your arms might be outstretched with the swing rushing back. If you have been pushing for a while, the swing might have enough momentum to knock you over—it is then pushing back on you. In the same way, electrons in a material with a negative index of refraction go out of phase and resist the "push" of the electromagnetic field.

Metamaterials

RESONANCE, the tendency to oscillate at a particular frequency, is the key to achieving this kind of negative response and is introduced artificially in a metamaterial by building small circuits designed to mimic the magnetic or electrical response of a material. In a split-ring resonator (SRR), for example, a magnetic flux penetrating the metal rings induces rotating currents in the rings, analogous to magnetism in materials

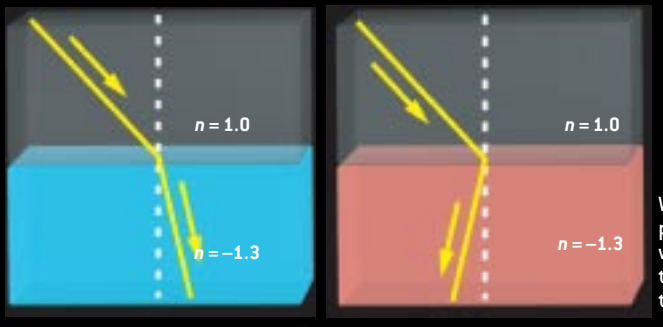
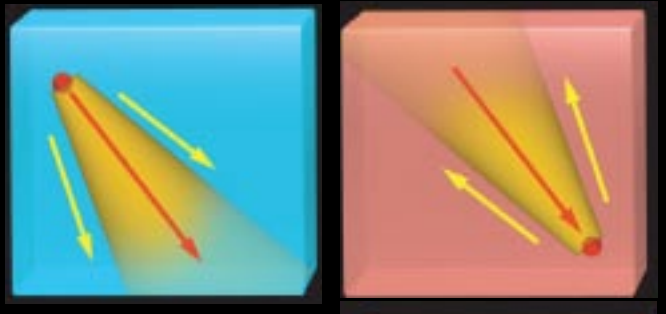
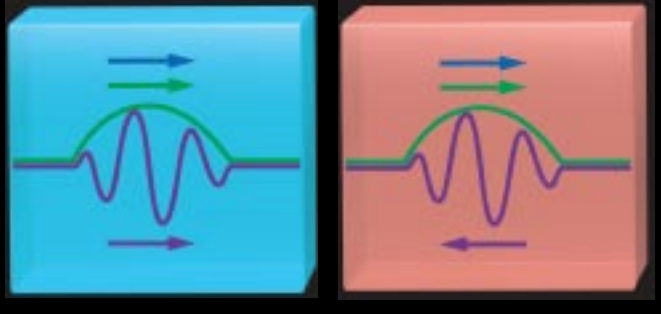
Overview/*Metamaterials*

- Materials made out of carefully fashioned microscopic structures can have electromagnetic properties unlike any naturally occurring substance. In particular, these metamaterials can have a negative index of refraction, which means they refract light in a totally new way.
- A slab of negative-index material could act as a superlens, able to outperform today's lenses, which have a positive index. Such a superlens could create images that include detail finer than that allowed by the diffraction limit, which constrains the performance of all positive-index optical elements.
- Although most experiments with metamaterials are performed with microwaves, they might use shorter infrared and optical wavelengths in the future.

MINAS H. TANIELIAN *Boeing Phantom Works* (*page 60*)

NEGATIVE-INDEX WEIRDNESS

In a medium with a negative index of refraction, light (and all other electromagnetic radiation) behaves differently than in conventional positive-index material. in a number of counterintuitive ways.

POSITIVE-INDEX MEDIUM		NEGATIVE -INDEX MEDIUM
A pencil in a glass of water appears bent because of the water's higher refractive index.		A pencil embedded in a negative-index medium would appear to bend all the way out of the medium.
When light travels from a medium with low refractive index (*n*) to one with higher refractive index, it bends toward the normal (*dashed line at right angles to surface*) .		When light travels from a positive-index medium to one with negative index, it bends all the way back to the same side of the normal.
A receding object appears redder because of the Doppler effect.		A receding object appears bluer.
A charged object (*red*) traveling faster than the speed of light generates a cone of Cherenkov radiation (*yellow*) in the forward direction.		The cone points backward.
In a positive-index medium, the individual ripples of an electromagnetic pulse (*purple*) travel in the same direction as the overall pulse shape (*green*) and the energy (*blue*).		The individual ripples travel in the opposite direction to the pulse shape and the energy.

MELISSA THOMAS

[*see box on page 64*]. In a lattice of straight metal wires, in contrast, an electric field induces back-and-forth currents.

Left to themselves, the electrons in these circuits naturally swing to and fro at the resonant frequency determined by the circuits' structure and dimensions. Apply a field below this frequency, and a normal positive response results. Just above the resonant frequency, however, the response is negative—just as the swing pushed back when pushed faster than its frequency. Wires can thus provide an electric response with negative ε over some range of frequencies, whereas split rings can provide a magnetic response with negative μ over the same frequency band. These wires and split rings are just the building blocks needed to make a wide assortment of interesting metamaterials, including Veselago's long-sought material.

The first experimental evidence that a negative-index material could be achieved came from the experiments by the U.C.S.D. group in 2000. Because the most stringent requirement for a metamaterial is that the elements be significantly smaller than the wavelength, the group used microwaves. Microwaves have wavelengths of several centimeters, so that the metamaterial elements could be several millimeters in size—a convenient scale.

The team designed a metamaterial that had wires and SRRs interlaced together and assembled it into a prism shape. The wires provided negative ε, and SRRs provided negative μ: the two together should, they reasoned, yield a negative refractive index. For comparison, they also fashioned an identically shaped prism out of Teflon, a substance having a positive index with a value of $n = 1.4$. The researchers directed a beam of microwaves onto the face of the prism and detected the amount of microwaves emerging at various angles. As expected, the microwave beam underwent positive refraction from the Teflon prism but was negatively refracted by the metamaterial prism. Veselago's speculation was now reality; a negative-index material had finally been achieved.

Or had it?

Does It Really Work?

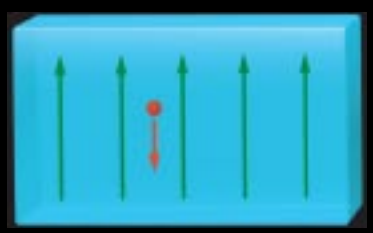
THE U.C.S.D. EXPERIMENTS, along with remarkable new predictions that physicists were making about negative-index materials, created a surge of interest from other researchers. In the absence of metamaterials at the time of Veselago's hypothesis, the scientific community had not closely scrutinized the concept of negative refraction. Now with the potential of metamaterials to realize the madcap ideas implied by this theory, people paid more attention. Skeptics began asking whether negative-index materials violated the fundamental laws of physics. If so, the entire program of research could be invalidated.

One of the fiercest discussions centered on our understanding of a wave's velocity in a complicated material. Light travels in a vacuum at its maximum speed of 300,000 kilometers per second. This speed is given the symbol *c*. The speed of light in a material, however, is

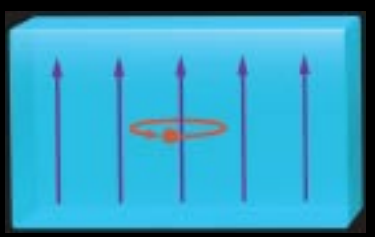
ENGINEERING A RESPONSE

The key to producing a metamaterial is to create an artificial response to electric and magnetic fields.the material.

IN AN ORDINARY MATERIAL

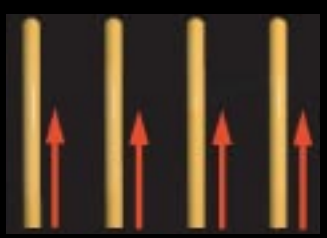


An electric field (*green*) induces linear motion of electrons (*red*).



A magnetic field (*purple*) induces circular motion of electrons.

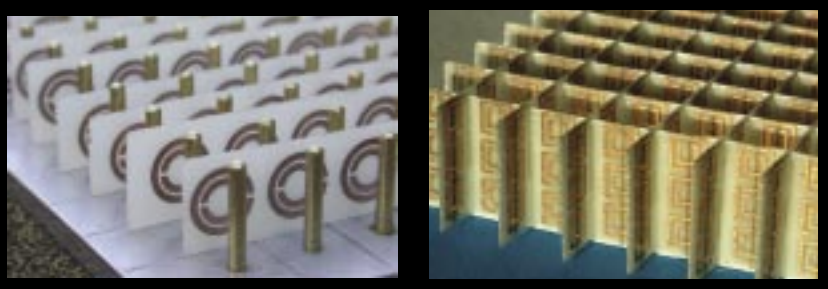
IN A METAMATERIAL



Linear currents (*red arrows*) flow in arrays of wires.

Circular currents flow in split-ring resonators (SRRs).

METAMATERIAL STRUCTURE



A metamaterial is made by creating an array of wires and SRRs that are smaller than the wavelength of the electromagnetic waves to be used with the material.

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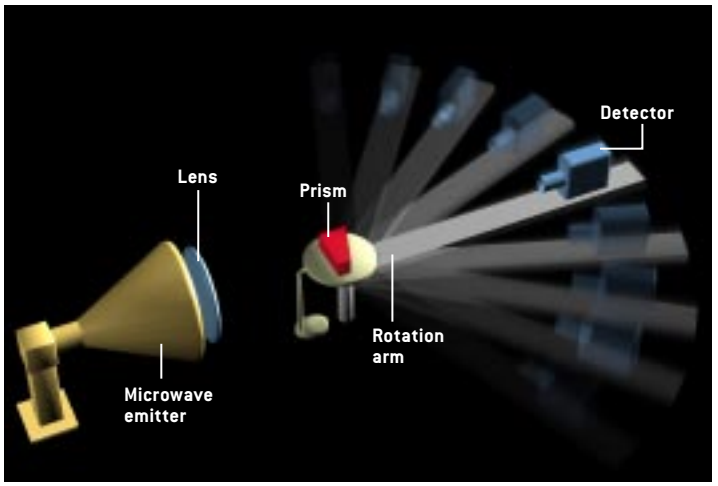
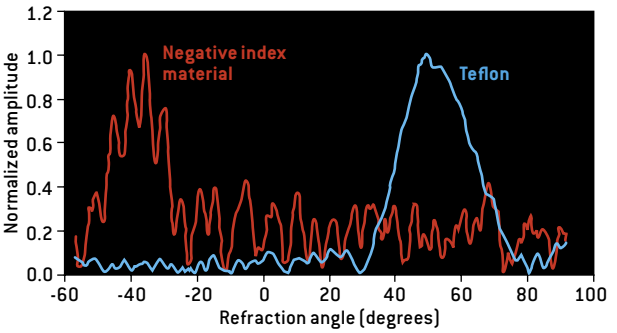




EXPERIMENT CARRIED OUT at Boeing Phantom Works in Seattle using first a metamaterial prism and then a Teflon (positive-index) prism confirmed the phenomenon of negative refraction. The Teflon refracted microwaves by a positive angle (*blue line*); the metamaterial by a negative angle (*red line*).

reduced by a factor of the refractive index—that is, the velocity $v = c/n$. But what if n is negative? The simple interpretation of the formula for the speed of light suggests that the light propagates backward.

A more complete answer takes cognizance that a wave has two velocities, known as the phase velocity and the group velocity. To understand these two velocities, imagine a pulse of light traveling through a medium. The pulse will look something like the one shown in the last illustration in the box on page 63: the ripples of the wave increase to a maximum at the center of the pulse and then die out again. The phase velocity is the speed of the individual ripples. The group velocity is the speed at which the pulse shape travels along. These velocities need not be the same.

In a negative-index material, as Veselago had discovered, the group and phase velocities are in opposite directions. Surprisingly, the individual ripples of the pulse travel backward even as the entire pulse shape travels forward. This fact also has amazing consequences for a continuous beam of light, such as one coming from a flashlight wholly immersed in a negative-index material. If you could watch the individual ripples of the light wave, you would see them emerge from the target of the beam, travel backward along the beam and ultimately disappear into the flashlight, as if you were watching a movie running in reverse. Yet the energy of the light beam travels forward, away from the flashlight, just as one expects. That is the direction the beam is actually traveling, the amazing backward motion of the ripples notwithstanding.

In practice, it is not easy to study the individual ripples of a light wave, and the details of a pulse can be complicated, so physicists often use a trick to illustrate the difference between the phase and group velocities. If we add together two waves of different wavelengths traveling in the same direction, the waves interfere to produce a beat pattern. The beats move at the group velocity.

In applying this concept to the U.C.S.D. refraction experiment in 2002, Prashant M. Valanju and his colleagues at the University of Texas at Austin observed something curious. When two waves of different wavelengths refract at the interface between a negative- and a positive-index material, they refract at slightly different angles. The resulting beat pattern, instead of following the negatively refracting beams, actually appears to exhibit positive refraction. Equating this beat pattern with the group velocity, the Texas researchers concluded that any physically realizable wave would undergo positive refraction. Although a negative-index material could exist, negative refraction was impossible.

Assuming that the Texas physicists' findings were true, how could one explain the results of the U.C.S.D. experiments? Valanju and many other researchers attributed the apparent negative refraction to a variety of other phenomena. Perhaps the sample actually absorbed so much energy that waves could leak out only from the narrow side of the prism, masquerading as negatively refracted waves? After all, the U.C.S.D. sample involved significant absorption, and the measurement had not been taken very far away from the face of the prism, making this absorption theory a possibility.

The conclusions caused great concern, as they might invalidate not only the U.C.S.D. experiments but all the phenomena predicted by Veselago as well. After some thought, however, we realized it was wrong to rely on the beat pattern as an indicator of group velocity.

THE AUTHORS

JOHN B. PENDRY and *DAVID R. SMITH* were members of a team of researchers who shared the 2005 Descartes Research Prize for their contributions to metamaterials. They have collaborated on the development of such materials since 2000, Pendry focusing on the theory and Smith on experimentation. Pendry is professor of physics at Imperial College London, and recently his main interest has been electromagnetic phenomena, along with quantum friction, heat transport between nanostructures, and quantization of thermal conductivity. Smith is professor of electrical and computer engineering at Duke University. He studies electromagnetic-wave propagation in unusual materials and is currently collaborating with several companies to define and develop novel applications for metamaterials and negative-index materials.

MELISSA THOMAS (*left*); MELISSA THOMAS; SOURCE: MINAS H. TANIELIAN *Boeing Phantom Works* (*right*)

We concluded that for two waves traveling in different directions, the resulting interference pattern loses its connection with the group velocity.

As the arguments of the critics began to crumble, further experimental confirmation of negative refraction came. Minas Tanielian's group at Boeing Phantom Works in Seattle repeated the U.C.S.D. experiment with a very low absorption metamaterial prism. The Boeing team also placed the detector much farther from the prism, so that absorption in the metamaterial could be ruled out as the cause of the negatively refracted beam. The exemplary quality of the data from Boeing and other groups finally put an end to any remaining doubts about the existence of negative refraction. We were now free to move forward and exploit the concept, albeit chastened by the subtlety of the new materials.

Beyond Veselago

AFTER THE SMOKE of battle cleared, we began to realize that the remarkable story that Veselago had told was not the final word on how light behaves in negative-index materials. One of his key tools was ray tracing—the process of drawing lines that trace out the path that a ray of light should follow, allowing for reflection and refraction at the interface of different materials.

Ray tracing is a powerful technique and helps us understand, for example, why objects in a swimming pool appear closer to the surface than they actually are and why a half-submerged pencil appears bent. It arises because the refractive index of water (n equals about 1.3) is larger than that of air, and rays of light are bent at the interface between the air and the water. The refractive index is approximately equal to the ratio of the real depth over the apparent depth.

Ray tracing also implies that children swimming in a negative-index pool would appear to float above the surface. (A valuable safety feature!) The entire contents of the pool—and its container—would also appear above the surface.

Veselago used ray tracing to predict that a slab of negatively refracting material, with index $n = -1$, should act as a lens with unprecedented properties. Most of us are familiar with positive-index lenses—in cameras, magnifying glasses, microscopes and telescopes. They have a focal length, and where an image is formed depends on a combination of the focal length and the distance between the object and the lens. Images are typically a different size than the object and the lenses work best for objects along an axis running through the lens. Veselago's lens works in quite a different fashion from those [*see box below*]: it is much simpler, only acting on objects adjacent to it, and it transfers the entire optical field from one side of the lens to the other.

So unusual is the Veselago lens that Pendry was compelled to ask just how perfectly it could be made to perform. Specifically, what would be the ultimate resolution of the Veselago lens? Positive-index optical elements are constrained by the diffraction limit to resolve details that are about the same size or larger than the wavelength of light reflected from an object. Diffraction places the ultimate limit on all imaging systems, such as the smallest object that might be viewed in a microscope or the closest distance that two stars might be resolved by a telescope. Diffraction also determines the smallest feature that can be created by optical lithography processes in the microchip industry. In a similar manner, diffraction limits the amount of information that can be optically stored on or retrieved from a digital video disk (DVD). A way around the diffraction limit could revolutionize optical technologies, allowing optical lithography well into the nanoscale and perhaps permitting hundreds of times more data to be stored on optical disks.

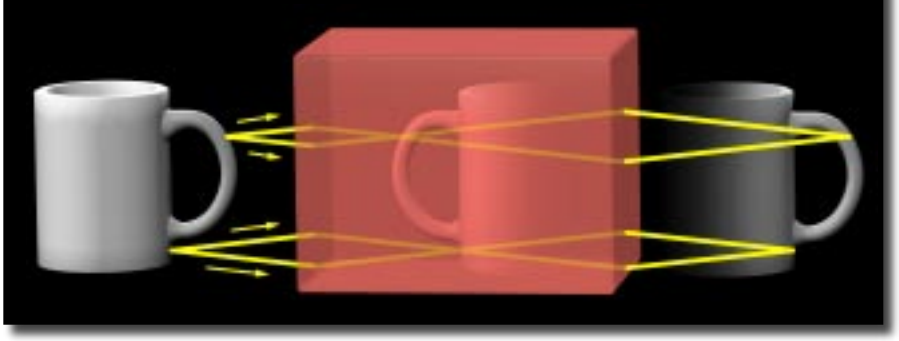
To determine whether or not negative-index optics could surpass the positive version, we needed to move beyond ray tracing. That approach neglects diffraction and thus could not be used to predict the resolution of negative-index lenses. To include diffraction, we had to use a more accurate description of the electromagnetic field.

The Superlens

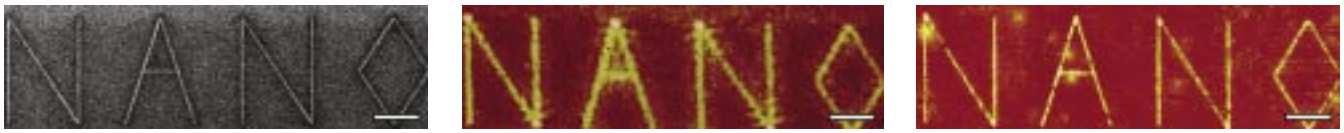
DESCRIBED MORE accurately, all sources of electromagnetic waves—whether radiating atoms, a radio antenna or a beam of light emerging after passing through a small aperture—produce two distinct types of fields: the far field and the near field. As its name implies, the far field is the part that is radiated far from an object and can be captured by a lens to form an image. Unfortunately, it contains only a broad-brush picture of the object, with diffraction limiting the resolution to the size of the wavelength. The near field, on the other hand, contains all the finest details of an object, but its intensity drops off rapid-

THE SUPERLENS

A rectangular slab of negative-index material forms a superlens. Light (*yellow lines*) from an object (*at left*) is refracted at the surface of the lens and comes together again to form a reversed image inside the slab. The light is refracted again on leaving the slab, producing a second image (*at right*). For some metamaterials, the image even includes details finer than the wavelength of light used, which is impossible with positive-index lenses.



MELISSA THOMAS



THIN LAYER OF SILVER acts like a superlens over very short distances. Here the word "NANO" is imaged with a focused ion beam (*left*), optically without a superlens (*middle*) and optically with a 35-nanometer layer of silver in place (*right*). Scale bar is 2,000 nanometers long. With the superlens, the resolution is finer than the 365-nanometer wavelength of the light used.

ly with distance. Positive-index lenses stand no chance of capturing the extremely weak near field and conveying it to the image. The same is not true of negative-index lenses.

By closely examining the manner in which the near and far fields of a source interacted with the Veselago lens, Pendry concluded in 2000—much to everyone's surprise—that the lens could, in principle, refocus both the near and far fields. If this stunning prediction were true, it would mean that the Veselago lens was not subject to the diffraction limit of all other known optics. The planar negative-index slab has consequently been called a superlens.

In subsequent analysis, we and other researchers found that the resolution of the superlens is limited by the quality of its negative-index material. The best performance requires not just that the refractive index $n = -1$, but that both $\varepsilon = -1$ and $\mu = -1$. A lens that falls short of this ideal suffers from drastically degraded resolution. Meeting these conditions simultaneously is a severe requirement. But in 2004 Anthony Grbic and George V. Eleftheriades of the University of Toronto showed experimentally that a metamaterial designed to have $\varepsilon = -1$ and $\mu = -1$ at radio frequencies could indeed resolve objects at a scale smaller than the diffraction limit. Their result proved that a superlens could be built—but could one be built at the still smaller optical wavelengths?

The challenge for scaling metamaterials to optical wavelengths is twofold. First, the metallic conducting elements that form the metamaterial microcircuits, such as wires and SRRs, must be reduced to the nanometer scale so that they are smaller than the wavelength of visible light (400 to 700 nanometers). Second, the short wavelengths correspond to higher frequencies, and metals behave less like conductors at these frequencies, thus damping out the resonances on which metamaterials rely. In 2005 Costas Soukoulis of Iowa State University and Martin Wegener of the University of Karlsruhe in Germany demonstrated experimentally that SRRs can be made that work at wavelengths as small as 1.5 microns. Although the magnetic resonance becomes quite weak at these short wavelengths, interesting metamaterials can still be formed.

But we cannot yet fabricate a material that yields $\mu = -1$ at visible wavelengths. Fortunately, a compromise is possible. When the distance between the object and the image is much smaller than the wavelength, we need only fulfill the condition $\varepsilon = -1$, and then we can disregard μ. Just last year Richard Blaikie's group at the University of Canterbury in New Zealand and Xiang Zhang's group at the University of California, Berkeley, independently followed this prescription and demonstrated superresolution in an optical system. At optical wavelengths, the inherent resonances of a metal can lead to negative permittivity (ε). Thus, a very thin layer of metal can act as a superlens at a wavelength where $\varepsilon = -1$. Both Blaikie and Zhang used a layer of silver about 40 nanometers thick to image 365-nanometer-wavelength light emanating from shaped apertures smaller than the light's wavelength. Although a silver slab is far from the ideal lens, the silver superlens substantially improved the image resolution, proving the underlying principle of superlensing.

Toward the Future

THE DEMONSTRATION of superlensing is just the latest of the many predictions for negative-index materials to be realized—an indication of the rapid progress that has occurred in this emerging field. The prospect of negative refraction has caused physicists to reexamine virtually all of electromagnetics. Once thought to be completely understood, basic optical phenomena—such as refraction and the diffraction limit—now have new twists in the context of negative-index materials.

The hurdle of translating the wizardry of metamaterials and negative-index materials into usable technology remains. That step will involve perfecting the design of metamaterials and manufacturing them to a price. The numerous groups now working in this field are vigorously tackling these challenges. SA

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MORE TO EXPLORE

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Negative-Refraction Metamaterials: Fundamental Principles and Applications. G. V. Eleftheriades and K. Balmain. Wiley-IEEE Press, 2005.

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