Novel Composite Medium Exhibits Reversed Electromagnetic Properties

According to Maxwell's equations, lossless propagation of electromagnetic waves requires the index of refraction n, given by $(\varepsilon\mu)^{1/2}$, to be real, where ε is the electrical permittivity or dielectric constant and μ is the magnetic permeability. All familiar materials have a positive μ and, for the most part, positive ε. But at the March Meeting of the American Physical Society, held in Minneapolis, a group of researchers from the University of California, San Diego, led by David Smith and Sheldon Schultz, reported having built a composite medium with an effective μ that is negative. By combining that medium with one that has a negative ε, they have created a composite material that allows transmission of microwaves that would be blocked by either medium alone.[1] But the propagation inside the composite is predicted to have unusual properties, such as a negative index of refraction.

The San Diego team used only ordinary metal (copper) and some fiberglass to create their medium, but the overall properties, at least at microwave frequencies, are not governed by the behavior of the raw materials. Instead, they are determined by the interactions among the building blocks that constitute the composite material (see photo at right). Because the microwave wavelength is much longer than the lattice constant, the radiation effectively averages over many unit cells.

In classical electrodynamics, the response (typically frequency-dependent) of a material at the microscopic or atomic scale to electric and magnetic fields is bundled into two macroscopic parameters, the permittivity ε and the permeability μ. (The permittivity relates the electric displacement field $\mathbf{D}$ to the electric field $\mathbf{E}$ through $\mathbf{D} = \varepsilon\mathbf{E}$. The permeability relates the magnetic fields $\mathbf{B}$ and $\mathbf{H}$ by $\mathbf{B} = \mu\mathbf{H}$.) Similarly, with these composite materials, or "metamaterials," one can define effective parameters ε_{eff} and μ_{eff} that characterize the average response of the materials to long-wavelength electromagnetic fields.

> In a material with a negative dielectric constant and negative permeability, convex lenses are diverging and Čerenkov radiation is emitted backward.

John Pendry (Imperial College, London) and his colleagues at Marconi PLC have examined schemes for composite materials that allow the tailoring of the dielectric[2] and magnetic[3] responses and, in particular, permit each of these parameters to be made negative. The San Diego experimenters have combined such schemes to produce a novel type of material with both ε_{eff} and μ_{eff} negative simultaneously. In this new regime, not found in nature, many familiar electromagnetic effects—such as Snell's law and the Doppler effect—are expected to be reversed.

COMPOSITE MEDIUM consisting of intercalated two-dimensional arrays of split-ring copper resonators and wires. The resonators, illustrated in the inset, have a negative effective magnetic permeability μ over a certain frequency range. The wire array has a negative electric permittivity ε over an overlapping frequency interval. The lattice constant is 8 mm. Having simultaneously negative μ and ε permits radiation to propagate, but with unusual effects. (Photo by Willie Padilla, UCSD.)

Negative ε and μ

Consider a two-dimensional coordinate system, with ε along the horizontal axis and μ along the vertical. The four quadrants characterize the four qualitative responses to electromagnetic radiation. Dissipation will add imaginary components to ε and μ, but for a qualitative picture, one can ignore losses and treat ε and μ as real numbers. (Also, strictly speaking, ε and μ are second-rank tensors, but they reduce to scalars for isotropic materials.)

The first quadrant, where both ε and μ are positive, contains all our everyday transparent media. The second quadrant ($\mu > 0$, $\varepsilon < 0$) also holds familiar materials, including metals and Earth's ionosphere.

Metals and the ionosphere have free electrons that have a natural resonant frequency—the plasma frequency—which is on the order of 10 MHz in the ionosphere and falls at or above visible frequencies for most metals. At frequencies above the plasma frequency, ε is positive and electromagnetic waves are transmitted. For lower frequencies, ε becomes negative and the index of refraction becomes imaginary. Consequently, radiation doesn't propagate through, but is, instead, reflected: Thus, metals are transparent in the ultraviolet but make good mirrors in the visible. And microwaves from the ground can reach satellites and interplanetary probes, whereas shortwave radio signals bounce off the ionosphere, which allows them to be heard up to halfway around the world.

The other two quadrants of ε–μ space have negative μ, which, except for the case of some anisotropic antiferromagnets, is not found in nature. But Pendry and company have proposed schemes to produce, using only nonmagnetic materials, a composite medium with values of μ_{eff} not found naturally, including negative values.[3]

One of the suggested methods for creating an effective μ is an array of split-ring resonators (SRRs), illustrated above. The capacitance between the two rings, combined with the self-inductance, produces a resonance. In a periodic arrangement, the rings couple together, and, for an electromagnetic wave oriented with its magnetic field threading the rings, the sign of the permeability changes when the wave's frequency crosses the SRR resonance. Another method for tailoring μ_{eff} that is being explored by Pendry and his colleagues is a spiral or "Swiss roll" structure.

The UCSD team built a two-dimensional periodic array of SRRs (photo, page 17) and measured its transmission spectrum (see figure at right) with the magnetic field oriented along the resonator axis. The spectrum revealed a notch, or stop band, in the vicinity of the SRR resonance. Although simulations showed that the notch was due to negative μ_{eff} in that frequency range, the experimental transmission spectrum by itself cannot establish whether such a stop band is indeed due to negative μ_{eff} or arises from negative ε_{eff}.

To verify that the stop band is due to crossing a resonance in μ_{eff}, the experimenters combined the SRR array with an array of wires—a medium known to have negative ε_{eff} at these frequencies[2] and, therefore, a stop band covering the entire range of the figure at right. If the observed SRR stop band were due to negative ε_{eff}, the negative contribution of the wire array to ε_{eff} would only increase the stop band. Instead, the intercalated arrays, with **H** along the resonator axis and **E** parallel to the wires, showed a transmission window. This window must therefore correspond to the spectral region where both ε_{eff} and μ_{eff} are negative.

"Left-handed" material

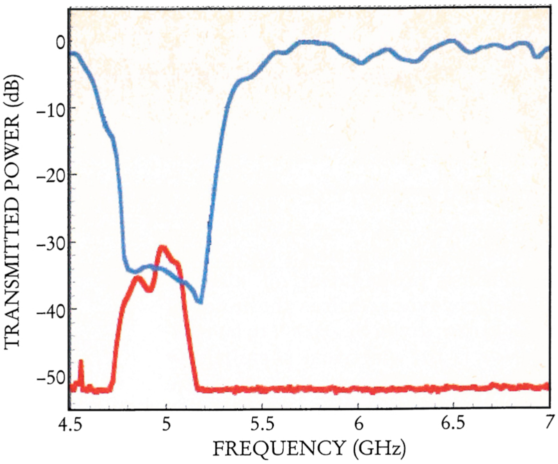
In a medium with ε_{eff} and μ_{eff} both negative, the index of refraction is real and radiation can propagate. But that's not the end of the story. Over 30 years ago—when no material with simultaneously negative ε and μ was known—Victor Veselago (Lebedev Physics Institute, Moscow) realized that such a medium should give rise to several peculiar properties.[4]

The cross product of **E** and **H** for a plane wave in regular media gives the direction of propagation and of energy flow; in a medium with negative ε and μ, $\mathbf{E} \times \mathbf{H}$ for a plane wave still gives the direction of energy flow, but the wave itself (that is, the phase velocity) propagates in the opposite direction. Veselago therefore termed such a medium "left handed." As one immediate consequence of this behavior, because the group velocity is in the same direction as the energy flow, a pulse traveling to the right in a left-handed material can be decomposed into plane waves traveling to the left.

Snell's law gets a twist, too, with left-handed media: When a wave in a right-handed material hits an interface with a left-handed medium, it will have a *negative* angle of refraction—the refracted wave will be on the same side of the normal as the incident wave. In other words, the index of refraction, as used in Snell's law, is negative, too, with left-handed media. Thus, lenses of left-handed material will behave oppositely from their right-handed counterparts: Convex lenses will be diverging and concave lenses converging.

The Doppler and Čerenkov effects will also be reversed in a left-handed medium: An approaching source will appear to radiate at a lower frequency, and charged particles moving faster than the speed of light in the medium will radiate in a backward cone, not a forward cone.

Although these counterintuitive properties follow directly from Maxwell's equations—which still hold in these unusual materials—they have yet to be demonstrated experimentally. That's a high priority of the UCSD researchers. Part of that work will be making the medium more isotropic: Currently it is only left-handed for one direction and one polarization of propagation. Also, the demonstration of negative μ has only been done at microwave frequencies. "It will be a challenge to get to the optical," says Schultz, "and the important step right now is for us to get a better understanding of all the implications of negative ε and negative μ and the dependencies on the material and geometrical properties."



TRANSMISSION SPECTRA of the split-ring resonator array by itself (blue) and combined with an array of thin wires (red). The resonators by themselves produce a stop band in the vicinity of 5 GHz, which corresponds to the region where the effective permeability μ_{eff} is negative. The wire array alone produces an effective permittivity ε_{eff} that is negative below the array's 12 GHz plasma frequency. When the arrays are combined, microwaves are transmitted in a pass band near 5 GHz where *both* μ and ε are negative. (Adapted from ref. 1.)

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References

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Chandra Probes Deeper into the Mystery of the X-Ray Background

Thanks to its superb sensitivity, angular resolution, and positional accuracy, NASA's Chandra x-ray observatory has detected nearly all the individual sources that collectively make up the cosmic x-ray background.

One minute before midnight on 18 June 1962, an Aerobee rocket was launched from White Sands Missile Range in New Mexico. Packed into its nose cone were three Geiger counters, which Riccardo Giacconi, Herbert Gursky, Frank Paolini, and Bruno Rossi hoped would detect solar x rays fluorescing off the moon. But when the four researchers analyzed the data, they instead found something more remarkable: x rays from a point source in the constellation of Scorpio and a background signal from the sky.