

Metamaterials Allow Manipulation of EM Waves from Low Frequencies to Light

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A short definition of *metamaterials* is provided in the opening statement on DARPA's web page for their metamaterials program:

"Metamaterials are engineered composites that exhibit superior properties not observed in the constituent materials or nature."

Yes, you read it correctly, metamaterials exhibit properties not found in nature. This is somewhat counter-intuitive, but has a legitimate theoretical foundation in Maxwell's equations.

You have probably read news or research papers about this developing family of materials and structures that are involved in all areas of electromagnetics from basic magnets to microwaves to manipulating lightwaves. They exhibit behaviors that are opposite of what is found in natural materials. The particular behaviors of interest are *negative index of refraction* and *negative permittivity and permeability*. The implications of being able to control electromagnetic waves without the limitations found in nature are quite astonishing. Of course, achieving a practical level of control over these non-natural characteristics is the defining goal of metamaterial research.

Metamaterials may be of special interest to the readers of *High Frequency Electronics* because their potential applications span all frequencies of electromagnetism. Key research breakthroughs were done at microwave frequencies, but current work covers the range from near-DC (better electromagnets) to visible light (invisibility cloaking and error-free optics).

Historically, the concept of negative permittivity/negative permeability was described by Russian scientist, V. G. Vesalago in his 1968 paper, "The electrodynamics of substances with simultaneously negative values of ϵ and μ ." Vesalago's work is widely considered to be the first practical study of this area, since he appears to be the first to consider many of the ramifications of such materials for optical phenomena.

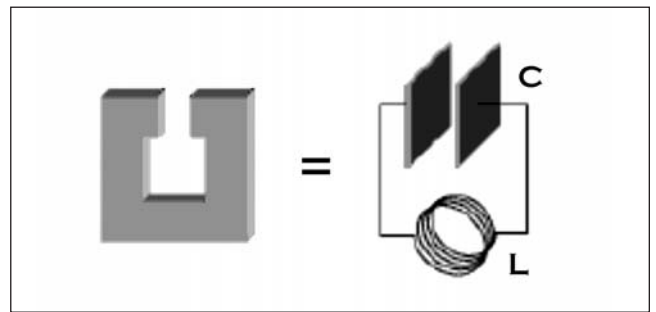


Figure 1 · Resonant loop building block for metamaterial structures.

What Vesalago and others investigated was the fact that the basic equations of electrodynamics are not limited to the classic "right-hand" relationship between electric and magnetic fields. "Left-handed" behavior is also a valid solution for these equations, despite the fact that it is not found in nature.

The first practical metamaterials were microwave structures that exhibited the necessary behavior, but only in a narrow bandwidth. Some practical applications include artificial grounds, EM opaque or transparent surfaces, and microwave lenses. Among this family of narrowband applications are some that have become widely studied, which are logically called *frequency selective surfaces*.

These microwave metamaterials include a large-scale repeating pattern of resonant structures. There are many resonant structures that are appropriate. The most common is a gapped loop that has a resonance determined by the inductance of the loop and the capacitance across the gap (Figure 1). This, or another resonator, is repeated many times to create a two- or three-dimensional lattice. The resonant behavior interacts with an impinging EM wavefront in a manner that has the desired left-handed properties at the frequency of operation. This permits a large number of applications that have previously been impossi-

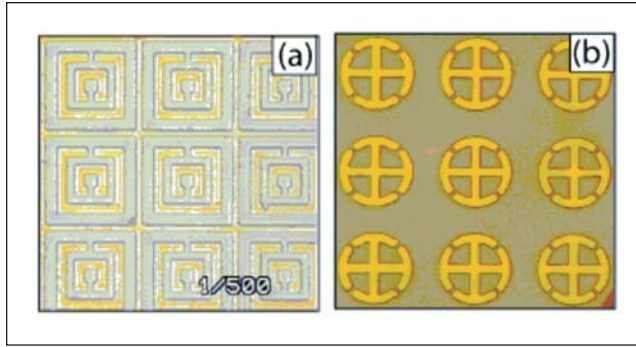


Figure 2 . Magnetic and electric metamaterial structures: (a) nested resonant loops of different sizes, and (b) purely electric resonators (i.e., no loop to reinforce the magnetic lines of force). Each cell has a dimension of $50 \times 50 \mu\text{m}$ for response at terahertz frequencies, which fall in the little-used spectrum between millimeter waves and long infrared light waves. (From *Los Alamos National Laboratory, "Metamaterials for threat reduction applications: imaging, signal processing, and cloaking,"* by R. D. Averitt, A. J. Taylor, and W. J. Padilla.)

ble with typical natural materials.

At optical frequencies, the same types of resonators may be used (see Figure 2), but the operating principles are a bit different, since the structures are large compared to wavelength at lightwave frequencies. Optical metamaterials use the effects of lattice structures to alter light waves, similar to behavior of well-known crystalline lattice structures. These lattices can be fabricated using current optical or electron beam lithography, with self-assembly (akin to crystal or organic growth) being investigated.

Metamaterial Behavior

Some of the behaviors that can be obtained from metamaterials at microwave or optical frequencies include:

- Negative index of refraction, which can correct for dispersion in lenses and allow sub-wavelength resolution in microscopes or telescopes. Near-field “super lenses” for microscopy are of particular interest.
- Precise control of wave propagation over surfaces, which theoretically can make an enclosed object invisible by routing light waves around it. The same behavior at microwaves would create another method for obtaining “stealth” properties for radar.
- Nonlinear behavior can be designed into the material, creating microwave or lightwave diodes, switches and other components. These may become higher-performance replacements for present couplers, isolators and circulators at microwave frequencies.

- Combinations of right-hand and left-hand photons are being explored for quantum-level memory applications. This property is generating research interest among some theoretical physicists.

Since they are presently narrow bandwidth structures, tunability for metamaterials is being actively investigated. Microwave tunable materials such as barium strontium titanate (BST) are already known at microwave frequencies, establishing a starting point for this research. Tunability is being investigated more enthusiastically than broadbanding. At present, it is felt that broadband metamaterials will be extremely difficult to develop.

Metamaterials are also being developed at the lower extreme of frequency: DC, or permanent magnetism. In the case of magnets, the ability to precisely control the magnetic field has the potential for creating extremely powerful magnets for many applications. Power generation and motors for electric vehicles are two areas often mentioned, although there are many other possible applications.

Infrared-wavelength metamaterials are being investigated for thermal management applications, where they may be able to provide superior radiation of heat.

Into the Future

Metamaterials represent a rare family of applications that apply to all frequencies of electromagnetic waves. The usual boundary between “radio waves” and “light waves” is less well defined in this area, although atomic-level interactions still govern the physical realizations of metamaterials at lightwave frequencies.

The technology has passed the period of doubt that inevitably accompanies all new technologies, especially those that are far removed from phenomena that are clearly observed by the naked eye or simple instruments. (A recent example is high-temperature superconductivity, and there is a growing renewal of interest in “tabletop” fusion.)

Practical applications in the microwave realm are coming soon, with a few just now becoming available, such as antennas with artificial ground planes and frequency selective materials applied to walls to control interference or limit the penetration of common wireless signals such as WLAN or cell phones. Millimeter wave antennas and lenses are another potential near-term application.

While this magazine emphasizes practical techniques that can be used immediately by engineers, it is important that we all be aware of research that will eventually become part of our everyday experience. Metamaterials represent an interesting area of current research that may become widely applied.