Metamaterial

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A **metamaterial** (or **meta material**) is a material that gains its properties from its structure rather than directly from its composition. To distinguish metamaterials from other composite materials, the *metamaterial* label is usually used for a material that has unusual properties. Such unusual properties could be a negative refractive index or infinite inertia (which are not found in naturally occurring materials). The term was coined in 1999 by Rodger M. Walser of the University of Texas at Austin, and he defined metamaterials as :

> Macroscopic composites having a manmade, three-dimensional, periodic cellular architecture designed to produce an optimized combination, not available in nature, of *two or more responses* to specific excitation.

The first metamaterials were developed by W.E. Kock in the late 1940's with metal-lens antennas [1] and metallic delay lenses [2].

Contents

Electromagnetic metamaterials

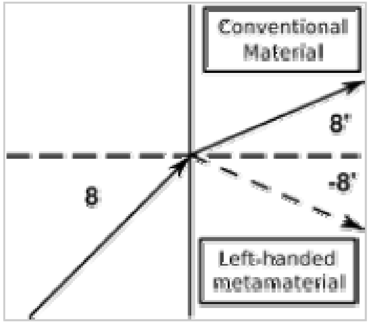
Metamaterials are of particular importance in electromagnetism (especially optics and photonics). They show promise for a variety of optical and microwave applications such as new types of beam steerers, modulators, band-pass filters, lenses, microwave couplers, and antenna radomes.

In order for its structure to affect electromagnetic waves, a metamaterial must have structural features at least as small as the wavelength of the electromagnetic radiation it interacts with. For instance, if a metamaterial is to behave as a homogeneous material accurately described by an effective refractive index, the feature sizes must be much smaller than the wavelength. For visible light, which has wavelengths of less than one micrometre typically (560 nanometers for sunlight), the structures are generally half or less than half this size; i.e., less than 280 nanometres. For microwave radiation, the structures need only be on the order of one decimetre. An example of a visible light metamaterial is opal, which is composed of tiny cristobalite (metastable silica) spheres. Microwave frequency metamaterials are almost always artificial, constructed as arrays of current-conducting elements (such as loops of wire) that have suitable inductive and capacitive characteristics.

Metamaterials usually consist of periodic structures, and thus have many similarities with photonic crystals and frequency selective surfaces. However, these are usually considered to be distinct from metamaterials, as their features are of similar size to the wavelength at which they function, and thus cannot be approximated as a homogeneous material.

Negative refractive index

The main reason researchers have investigated metamaterials is the possibility to create a structure with a negative refractive index, since this property is not found in any naturally occurring material. Almost all materials encountered in optics, such as glass or water, have positive values for both permittivity ε and permeability μ. However, many metals (such as silver and gold) have negative ε at visible wavelengths. A material having either (but not both) ε or μ negative is opaque to electromagnetic radiation (see surface plasmon for more details).



A comparison of refraction in a left-handed metamaterial to that in a normal material

Although the optical properties of a transparent material are fully specified by the parameters ε and μ, in practice the refractive index *N* is often used. *N* may be determined from $N = \pm\sqrt{\epsilon\mu}$. All known transparent materials possess positive values for ε and μ. By convention the positive square root is used for *N*.

However, some engineered metamaterials have ε < 0 and μ < 0; because the product εμ is positive, *N* is real. Under such circumstances, it is necessary to take the negative square root for *N*. Physicist Victor Veselago proved that such substances can transmit light.

Metamaterials with negative *N* have numerous startling properties:

- Snell's law ($N_1 \sin\theta_1 = N_2 \sin\theta_2$) still applies, but as N_2 is negative, the rays will be refracted on the *same* side of the normal on entering the material.
- The Doppler shift is reversed: that is, a light source moving toward an observer appears to reduce its frequency.
- Cherenkov radiation points the other way.
- The time-averaged Poynting vector is antiparallel to phase velocity. This means that unlike a normal right-handed material, the wave fronts are moving in the opposite direction to the flow of energy.

For plane waves propagating in such metamaterials, the electric field, magnetic field and Poynting vector (or group velocity) follow a left-hand rule, thus giving rise to the name left-handed (meta) materials. It should be noted that the terms left-handed and right-handed can also arise in the study of chiral media, but their use in that context is unrelated to this effect.

The effect of negative refraction is analogous to wave propagation in a left-handed transmission line, and such structures have been used to verify some of the effects described here.

Development and applications

The first metamaterials were developed by W.E. Kock in the late 1940's Metal-lens antennas, IRE Proc., 34 November 1946, pp. 828-836 and Metallic delay lenses, Bell. Sys. Tech. Jour.,27, January 1948, pp. 58-82.

The unique properties of metamaterials were verified by full-wave analysis in Caloz *et al.* (2001). [3] However, the LH structures devised up to 2002 were impractical for microwave applications, because they had a too narrow bandwidth and were quite lossy. Eleftheriades *et al.* (2002), and Caloz *et al.* (2002) provided a method to realize left-handed metamaterials using artificial lumped-element loaded transmission lines in microstrip technology.[4][5]

The first superlens with a negative refractive index provided resolution three times better than the diffraction limit and was demonstrated at microwave frequencies at the University of Toronto by A. Grbic and G.V. Eleftheriades[6]. Subsequently, the first optical superlens (an optical lens that exceeds the diffraction limit) was created and demonstrated in 2005 by Xiang Zhang *et al.* of UC Berkeley, as reported that year in the April 22 issue of the journal Science.[7] But their lens didn't rely on negative refraction. Instead, they used a thin silver film to enhance the evanescent modes through surface plasmon coupling. This idea was first suggested by John Pendry in *Physical Review Letters*.

Metamaterials have been proposed as a mechanism for building a cloaking device. These mechanisms typically involve surrounding the object to be cloaked with a shell that affects the passage of light near it.[8] Duke University and Imperial College London are currently researching this use of metamaterials and has managed to use metamaterials to cloak an object (in the microwave spectrum) using special concentric rings; the microwaves were barely affected by the presence of the cloaked object.[9] In early 2007, a metamaterial with a negative index of refraction for visible light wavelengths was announced by a joint team of researchers at the Ames Laboratory of the United States Department of Energy and at Karlsruhe University in Germany. The material had an index of -0.6 at 780 nanometers.[10]

Metamaterials have been also proposed for designing agile antennas [11].

Theoretical models

Left-handed (LH) materials were first introduced theoretically by Victor Veselago in 1967[12].

J. B. Pendry was the first to theorize a practical way to make a left-handed metamaterial (LHM). 'Left-handed' in this context means a material in which the 'right-hand rule' is not obeyed, allowing an electromagnetic wave to convey energy (have a group velocity) in the opposite direction to its phase velocity. Pendry's initial idea was that metallic wires aligned along propagation direction could provide a metamaterial with negative permittivity ($\varepsilon<0$). Note however that natural materials (such as ferroelectrics) were already known to exist with negative permittivity: the challenge was to construct a material that also showed negative permeability ($\mu<0$). In 1999, Pendry demonstrated that an open ring ('C' shape) with axis along the propagation direction could provide a negative permeability. In the same paper, he showed that a periodic array of wires and ring could give rise to a negative refractive index. A related negative permeability particle that was also proposed by Professor Pendry is the Swiss roll.

The analogy is as follows: Natural materials are made of atoms, which are dipoles. These dipoles modify the light velocity by a factor n (the refractive index). The ring and wire units play the role of atomic dipoles: the wire acts as a ferroelectric atom, while the ring acts as an inductor L and the open section as a capacitor C. The ring as a whole therefore acts as a LC circuit. When the electromagnetic field passes through the ring, an induced current is created and the generated field is perpendicular to the magnetic field of the light. The magnetic resonance results in a negative permeability; the index is negative as well. (The lens is not truly flat as the C and its nearby Cs imposes a slope for the electric induction.)

References

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External links

Research groups (*alphabetically*)

1. Allan Boardman's Group (web link) - UK
2. Christophe Caloz' research group — Canada
3. George Eleftheriades's research group — Canada
4. Nader Engheta - US
5. FGAN-FHR — Germany
6. M. Saif Islam's Research Group, University of California at Davis - USA
7. Tatsuo Itoh`s group — USA
8. Akhlesh Lakhtakia - USA
9. Herbert Moser's Group, Singapore Synchrotron Light Source — Singapore
10. Ekmel Özbay`s Research group, Bilkent University - Turkey
11. Sir John Pendry's group — References — Imperial College — UK
12. Vladimir Shalaev's Research Group, Purdue University, USA
13. Shvets Research Group, University of Texas at Austin - USA
14. David Smith's research group — Duke University — USA
15. Costas Soukoulis at IESL, Greece — Photonic, Phononic & MetaMaterials Group
16. Srinivas Sridhar's Group, Northeastern University — USA
17. "Metamorphose" EU Network of Excellence on Metamaterials. Coordinator: Sergei Tretyakov
18. Irina Veretennicoff's research group, Vrije Universiteit Brussel — Belgium
19. Martin Wegener's Metamaterials group — Germany
20. Georgios Zouganelis's Metamaterials Group, NIT — Japan
21. Xiang Zhang's group, Berkeley USA
22. Applied Electromagnetics Laboratory, Lucio Vegni's group, Università "Roma Tre", Rome
23. Yang Hao's research group, Queen Mary, University of London, UK
24. Takuo Tanaka and Satoshi Kawata, Nanophotonics Lab., RIKEN (The Institute of Physical and Chemical Research), Japan
25. Said Zouhdi's group, LGEP at SUPELEC, France

Internet portals

1. MetaMaterials.net Web Group

2. News from "Metamorphose" EU NoE on Metamaterials

More articles and presentations (*newest is first*)

1. Cloaking devices, nihility bandgap, LF magnetic enhancement, perfect radome NIT Japan
2. Left-Handed Flat Lens HFSS Tutorial EM Talk Tutorial
3. Journal of Optics A, February 2005 Special issue on Metamaterials
4. Experimental Verification of a Negative Index of Refraction
5. How To Make an Object Invisible
6. Metamaterials hold key to cloak of invisibility

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