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Metamaterials Provide Novel EM Capabilities

Metamaterials have been under study for several decades due to their novel electrical characteristics and becoming more practical with the growing use of 3D metal printing.

Metamaterials are engineered materials that are capable of characteristics not found in naturally occurring materials. They can be fabricated with negative refractivity, which causes an electromagnetic (EM) wave to reflect in a direction opposite of what might be expected. Since metamaterials can be structured to affect sound and light waves as well, a great deal of experimentation has been performed with these materials to control audio sound levels and even to control the amount of light reflecting from an object, possibly to the point of invisibility—having all light reflecting away from a viewer. One of the attractions for performing research on metamaterials, which can be produced by three-dimensional (3D) metal printers, is that they can render an object invisible to sound, light, and EM waves, enabling them to be used as a "cloaking" device against radar detection.

Metamaterials are composites formed with an artificial periodic structure (*Fig. 1*). It is the configurations of these periodic structures that result in "unnatural" material characteristics, including the modification of a material's electrical permittivity (ε) and magnetic permeability (μ). By designing the configuration of the periodic structures, the dispersion, refraction, and reflection of an EM wave can be controlled.

1. Compact radar systems have been built around metamaterial electronically scanned array (MESA) antennas and other metamaterial-based components. (Courtesy of Echodyne)

In terms of practical RF/microwave engineering, the use of metamaterials with certain transmission-line structures has enabled the miniaturization of microwave filters in ways that defy the normal impedance/transmission-line/wavelength relationships (*see "Metamaterials Form Miniature Bandstop Filters" on mwrf.com*) http://www.mwrf.com/passive-components/metamaterials-form-miniature-bandstop-filters). The effect of metamaterials on EM waves extends from radio waves to well into the optical region. In the microwave frequency range, the use of metamaterials as the basic for transmission-line structures such as split-ring resonators (SRRs) and complementary split-ring resonators (CSRRs) has led to the development of much-needed components that can be significantly miniaturized by fabricating them on these materials, including antennas, filters, phase shifters, and resonators. Such structures can be combined with conventional microwave transmission-line technologies, such as microstrip, to create circuits that operate at "subwavelengths" of a design frequency, resulting in component sizes a fraction that of conventional circuit designs.

Finite-element three-dimensional (3D) EM simulation software has proven to be an invaluable tool in the design of these "mixed-technology" circuits, since material parameters can be entered and stored to create working models of the metamaterials. When it is time to manufacture a metamaterial microwave circuit, additive manufacturing techniques, in

2. Ground-based radar systems used metamaterial-based flat-panel antennas can provide surveillance of the ground and UAVs simultaneously. (Courtesy of Echodyne)

which different materials are layered on top of each other to create a composite, have proven to be an effective method for producing metamaterial components. Additive manufacturing is becoming more practical with the increasing availability of 3D direct metal printers that can transform the powdered forms of the metals required into the film layers needed for a metamaterial circuit.

CREATING AN ILLUSION

Through manipulation of the period structures of these materials, it is possible to achieve simultaneous negative permittivity and permeability, resulting in what is known as left-handed materials (for having refraction and reflection characteristics that behave in the reverse manner as standard, right-handed materials). The phenomenon of producing materials with negative permittivity and permeability has led to a great deal of the "sensationalism" attached to metamaterials in recent years, including the possibility that metamaterials could be used to achieve optical invisibility by altering the way that light waves reflect and refract from the surface of a metamaterial, essentially by steering the light waves away from the path of a view so that the object covered with the metamaterial is rendered invisible.

These same material capabilities at lower EM frequencies have captured the attention of military systems designers and defense research organizations such as the Defense Advanced Research Projects Agency (DARPA, www.darpa.mil), which see many possibilities for the application of metamaterials beyond just the miniaturization of high-frequency components, including for terahertz (THz) frequency applications and as "cloaking" devices. By using the negative permittivity and permeability characteristics of metamaterials, for example, an aircraft or a ground vehicle covered in the metamaterials could be rendered invisible to an adversary's radar beams and detection.

DARPA recently awarded nearly $8 million (USD) to Penn State University, specifically to Doug Werner, John McCain, and Genevieve McCain, to continue their research into metamaterials. This is actually a combined award from DARPA, the U.S. Navy, and Lockheed Martin (www.lockheedmartin.com), with DARPA "chipping in" more than $5 million. Werner is the director of the Computational Electromagnetics and Antennas Research Lab (CEARL) at the university, and the funding is intended to develop EM cloaking technology, as might be used as a defense against detection by enemy radars. The funding is also expected to deliver advanced software simulation tools for the modeling and design of metamaterials and metamaterial-based components. Penn State will take the lead on the project, and will collaborate with researchers from Purdue University, Rensselaer Polytechnic Institute, and ExH Inc.

INTEREST IS SPREADING

A number of leading universities are involved in metamaterial research, including Duke University and its Center for Metamaterials and Integrated Plasmonics (CMIP, www.metamaterials.duke.edu), the University of Notre Dame, Oregon State University, and Boston University. In addition, a number of new companies are forming to pursue the promise of metamaterials throughout the EM spectrum. At "lower" microwave wavelengths, for example, Echodyne (www.echodyne.com) has developed a series of metamaterial electronically scanned array (MESA) antennas and other metamaterial-based products that are providing unique capabilities to military, industrial, and commercial customers. The patented MESA products are enabling the development of compact, lightweight radar transceivers with electronically scanned radar capabilities for small aircraft and unammed aerial vehicles (UAVs). These metamaterial antennas (*Fig. 1*) and systems show negligible radar cross-sections (RCSs) to an enemy radar and are well suited for integration in UAVs intended for surveillance applications. The company also offers a ground version (MESA-SSR) of the metamaterial-based radar system which can be integrated into any site for surveillance and security applications. This ground-based system operates like a phased-array radar with true beam scanning in both azimuth and elevation. It can track airborne and ground-based targets at the same time (*Fig. 2*), as well as walkers from a distance of about 1.4 km.

Kymeta Corp. (www.kymetacorp.com) has also commercialized metamaterials, into several lines of innovative antennas and antenna modules. The mTenna antenna subsystem modules (ASMs) are compact, lightweight flat-panel antenna assemblies with no moving parts that can be used for transmit and receive functions with a single aperture. The metamaterial-based antenna designs realize the capability of these materials to perform amplitude and phase control of separate antenna elements, to achieve the performance of a phased-array antenna in a fraction of the size. Electronic beam steering is performed by means of software control.

At optical wavelengths, Metamaterial Technologies Inc. (MTI, www.metamaterial.com) has developed metamaterial product lines based on altering the flow of light waves. The company's product lines include Lamda Guard optical filters, to block light and protect vision;

Lamda Lux films, to enhance the efficiency and output of light-emitting-diode (LED) lighting; and Lamda Solar films, to absorb light and increase the efficiency of solar cells. The Lamda Guard filters, for example, can be engineered to block specific wavelengths of light to protect vision, such as for pilots. The materials and light in weight and adhesive, and can be attached to any surface. Since 2014, the company has worked in partnership with Airbus to develop optical filters to protect pilots' vision from laser strikes. MTI recently signed a $5.6 million agreement with Lockheed Martin to develop MTI's metaSOLAR product line. The materials will be used for solar energy harvesting.

Research on metamaterials is ongoing and is sure to lead to wide acceptance of these novel materials in applications throughout the EM spectrum. While efforts are being made to better understand the materials and how to efficiently manufacture them, much research is also focused on the modeling and simulation of the materials, with broad opportunities ahead for suppliers of software simulation tools ready and willing to integrate accurate metamaterial models within their simulation programs.