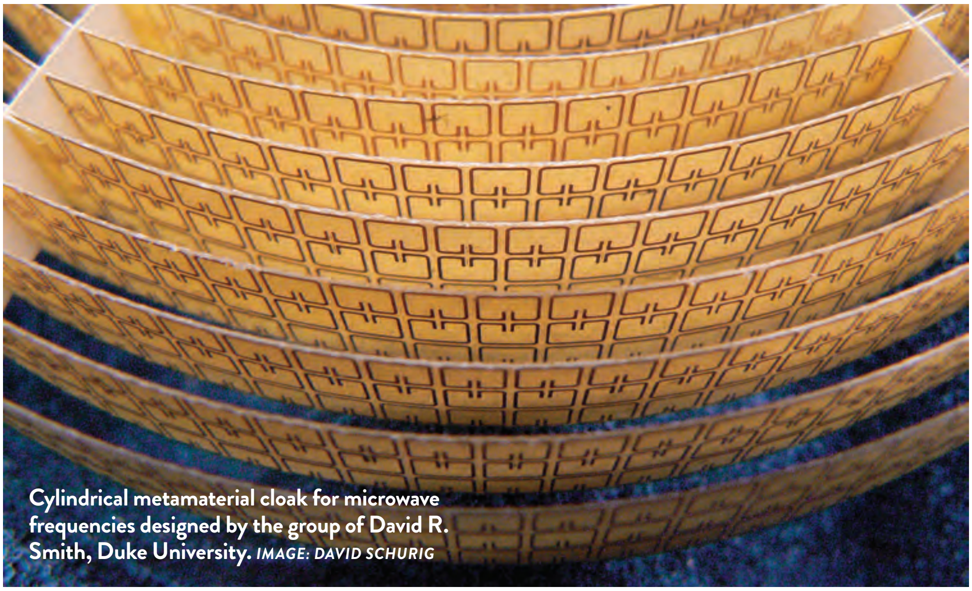

Cylindrical metamaterial cloak for microwave frequencies designed by the group of David R. Smith, Duke University. *IMAGE: DAVID SCHURIG*

METAMATERIALS MAKE PHYSICS SEEM LIKE MAGIC

To achieve this magical effect, one must have simultaneous control over multiple physical phenomena

By **DEXTER JOHNSON, PROGRAM DIRECTOR, CIENTIFICA & BLOGGER, IEEE SPECTRUM ONLINE**

THE FAMED SCIENCE fiction author Arthur C. Clarke once remarked, "Any sufficiently advanced technology is indistinguishable from magic."

If this idea indeed holds true, then the emerging field of metamaterials would have to be classified as a "sufficiently advanced technology." Metamaterials have been stunning both the layman and the scientist in recent years with their ability to render objects invisible (see the cloak image above), leaving many to comment only half in jest that they must be magic.

Metamaterials are not magic, however. Instead, they are the result of a science that requires an enormous amount of knowledge and control over electromagnetic phenomena and other physical attributes of materials.

A metamaterial can be broadly defined as an artificially structured material fabricated by assembling different objects so as to replace the atoms and molecules that one would see in a conventional material. The resulting material has very different electromagnetic properties than those found in naturally occurring or chemically synthesized materials.

Manipulating the structure of the metamaterial allows it to interact with and control electromagnetic waves. Just what an impact this has comes into stark relief when we take into account the fact that electromagnetic radiation can have wavelengths that range from thousands of kilometers to billionths of a meter.

Controlling electromagnetic waves lets us control whether objects can be seen. For instance, the wavelength of the electromagnetic waves that make up visible light ranges from 400 to 750 nanometers. But because the spacing between atoms is much smaller than that—on the order of one-tenth of a nanometer (an angstrom)—we cannot resolve an image of atoms from visible light. This leads to the exciting prospect of using metamaterials to make invisible objects visible and visible objects invisible.

All the fine details of the medium are blurred on the spatial scale of about one wavelength, which allows physicists to use an averaged description known as effective medium theory. The idea of metamaterials stems from this simple concept of field averaging.

The many orders of magnitude difference between the wavelength of visible, infrared, or microwave radiation and the atomic

David R. Smith (above), Yaroslav Urzhumov, Duke University.

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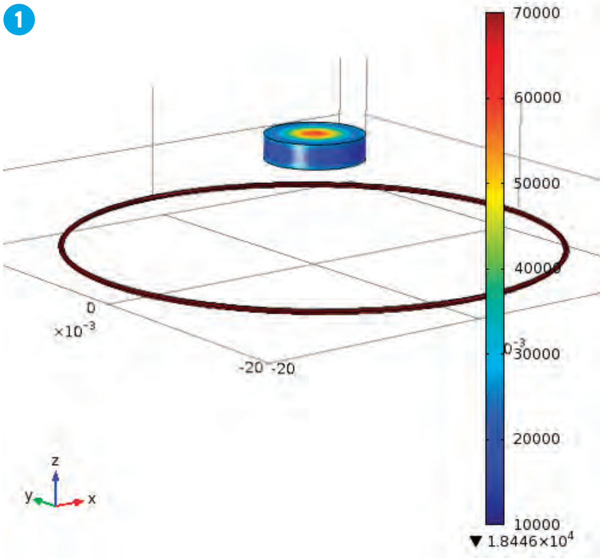

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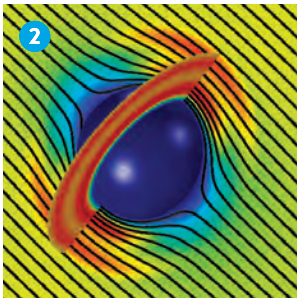

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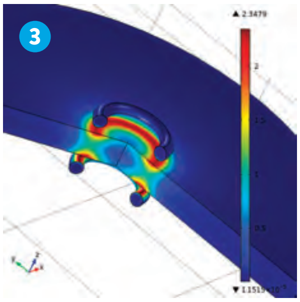

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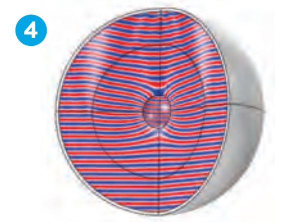

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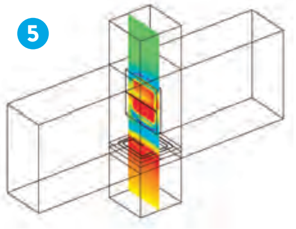


FIGURE 1: Full-wave simulation of a magnetic metamaterial disk levitating above a current-carrying coil.

FIGURE 2: Hydrodynamical cloak: a porous metamaterial shell that eliminates wake. Designed and modeled with COMSOL Subsurface Flow and Optimization Modules.

FIGURE 3: A pair of coils tightly coupled through a negative-permeability metamaterial slab.

FIGURE 4: Unidirectional acoustic cloak based on quasi-conformal transformation optics, modeled using COMSOL's axisymmetric pressure acoustics.

FIGURE 5: A composite Split Ring Resonator Thin Wire Array metamaterial exhibiting negative index of refraction in the microwave X-band; COMSOL simulation. Note the additional blocks of free space that facilitate multi-directional S-parameter simulations.

IMAGES: YAROSLAV URZHUMOV (DUKE UNIVERSITY)

[redacted]

scale creates a window of opportunity for an effective medium consisting of artificial "atoms" that are much larger than real atoms but still significantly smaller than the wavelength of the radiation. Such a medium is what scientists call a metamaterial.

» NEGATIVE REFRACTIVE INDEX

AN IMPORTANT PROPERTY of metamaterials is the phenomenon of negative refraction. Of course, we're all aware from an early age that refraction is the bending of light at the intersection of two materials.

The most common example of refraction at work is the observation of underwater objects from above the water. In this case, refraction makes those objects appear closer to the surface than they actually are. So refraction provides the basic optical principle for the manufacturing of lenses or any other optical device that bends or manipulates light.

All materials in nature have a refractive index, or a measurement of the speed of light through that material. But some metamaterials are capable of achieving what is known as a negative refractive index, resulting in metamaterials' sometimes being referred to as "left-handed" or "negative-index" materials.

A material that has a negative refractive index is capable of bending light in the opposite direction of what we would expect based on typical refraction.

The method by which you make a material that has a negative refraction index requires reversing the electrical component (permittivity) and the magnetic component (permeability) of a material's refractive index. This is accomplished by artificially constructing a material (Figure 5) that possesses structures with dimensions smaller than the wavelengths of the light it is intended to refract. This causes the atoms and the photons in the material to resonate and reverse the material's permittivity and permeability.

These optical capabilities of metamaterials are important for understanding the wide array of applications that exist for them.

» APPLICATIONS FOR METAMATERIALS

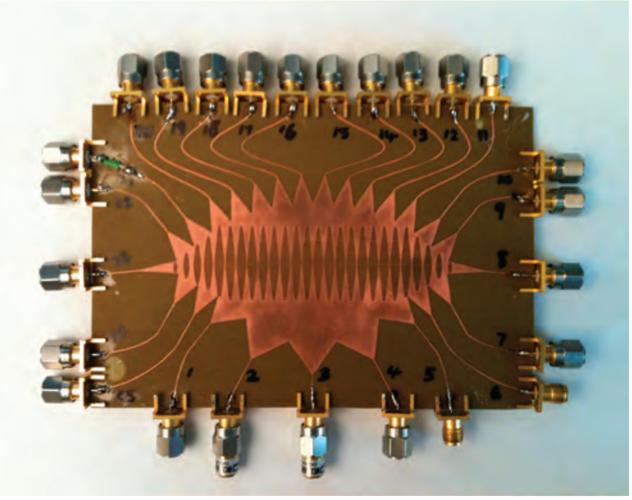
ONE OF THE first potential applications suggested for metamaterials was a "superlens" that would utilize the negative refraction of a metamaterial to provide much higher resolution than is possible with lenses made from natural materials, according to Jeffrey D. Wilson, a physicist at NASA's Glenn Research Center.

Such a lens could enable very high-resolution imaging and lithography, with one application being the fabrication of smaller and faster computer chips. Problems with fabrication and attenuation issues need to be solved, however, before this becomes practical. Attenuation issues that severely limit the performance of negative-index lenses are however less severe in near-field applications, where, instead of negative index, one can use either a negative permittivity or negative permeability. The latter material property - still rarely available in nature - is particularly promising for applications requiring magnetic field enhancement and focusing, such as magnetic levitation (Figures 1, 3).

"The area in which electromagnetic metamaterials have first been used for practical application is antenna technology," explains NASA's Wilson. "Metamaterials have been used in antennas to significantly reduce size, increase frequency bandwidth, and increase gain."

While antenna technology has been the largest application for metamaterials, it is perhaps in the area of "cloaking" that the most excitement and publicity have been generated.

In cloaking, metamaterials are used to divert microwaves or optical waves around an object so that it appears invisible. Most of the applications for this cloaking effect involve the military.



MICROWAVE DEVICE: Microwave Rotman lens whose size is substantially reduced with the aid of magnetic metamaterial filling the tapered transmission lines in the center. *IMAGE: JOHN HUNT (DUKE UNIVERSITY)*

Among the exciting potential future applications being discussed for metamaterials is a seismic metamaterial that could be used to protect structures from earthquakes, according to Wilson.

Another area in which metamaterials are gaining traction is in terahertz (THz) technologies, in particular for imaging applications. THz imaging has aroused interest in the contexts of security and medical imaging because of its ability to penetrate nonmetallic materials and fabrics and do so without damaging tissue or DNA.

"THz waves have frequencies that are higher than those of microwaves but lower than those of optical radiation," explains Wilson. "However, the THz frequency band has been essentially neglected and is referred to as the 'THz gap' of the electromagnetic spectrum. The primary reason for this is that currently available compact THz sources can produce only small amounts of power—on the order of milliwatts."

Some companies have developed airport scanners that make use of THz imaging but achieve their capabilities by means of very expensive and complicated imaging arrangements.

The problem has been that the background thermal energy in the THz range of the electromagnetic spectrum is small compared with infrared, according to Fabio Alves, a researcher from the Sensor Research Lab, led by Professor Gamani Karunasiri, at the Naval Postgraduate School (NPS) in Monterey, Calif. When the THz waves have to travel through open air, as they do in airport imaging technologies, most of the radiation is absorbed before it reaches its target.

Alves and his colleagues at NPS have been developing metafilms (thin films based on metamaterials) that could enable less expensive THz imaging devices and total absorption of the THz waves.

"The metafilm we are developing exhibits properties not found in natural materials," explains Alves. "It is obtained by placing a periodic array of metal cells close to a conducting plane with a dielectric spacer in between to form an artificial structure that exhibits electromagnetic properties such that its impedance matches with the surrounding media (free space in our case) at a specific frequency.

"In this situation, ideally there is no transmission and no reflection, resulting in total absorption. By selecting appropriate materials and geometry, it is possible to design films with near 100 percent absorption in the desired frequency.

> *"Simulation tools enable us to be creative and to quickly test new ideas that would be much more difficult, time-consuming, and expensive to test in the lab."*
>
> **—JEFFREY D. WILSON, NASA GLENN RESEARCH CENTER**

The films can be employed in the fabrication of microbolometers and bimaterial focal plane arrays, where the absorption characteristic can be engineered to match the frequency of the source, significantly improving the efficiency of the imaging system."

One of the leading research organizations in metamaterials—and the one perhaps most closely associated with the cloaking effects of metamaterials—is the Center for Metamaterials and Integrated Plasmonics (CMIP) at Duke University, led by David R. Smith. CMIP is also working on finding ways of compensating near-field decay in free space or open air.

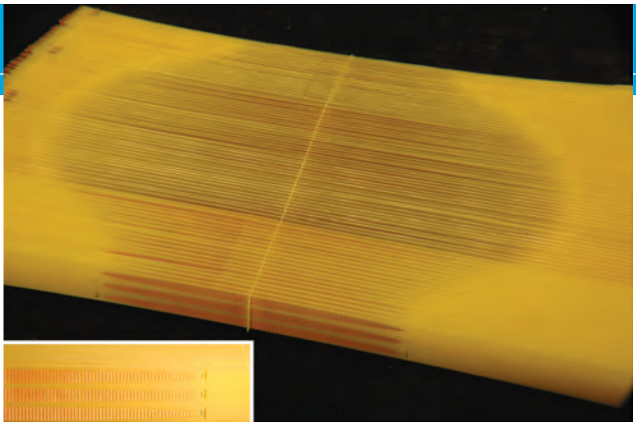
In ongoing work at CMIP, Yaroslav Urzhumov, an assistant research professor, and others are working with Toyota Corporation to fabricate magnetic metamaterials for wireless power transfer for electrical vehicles (EVs).

> *"As for me personally, I discovered entirely in a COMSOL simulation that these cloaks can perform extremely well in the short-wavelength limit."*
>
> **—YAROSLAV URZHUMOV, DUKE UNIVERSITY**

When one imagines how such a wireless transfer of power could be achieved, one usually conjures up devices incorporating microwave or laser technology. Both of these technologies come with the obvious inherent risk of frying the device being charged, however.

Just as Smith and his CMIP colleagues developed metamaterials that made it appear as though an object had disappeared using electromagnetic cloaking, they have now created a lens (Figure 3) made from metamaterials that can focus low-frequency fields in such a way that it makes the distance between the power source and the device being charged disappear.

Making a source appear closer than it really is with the aid of metamaterial-based lenses is just one of the tricks that the novel concept of transformation optics has predicted. Transformation optics is an engineering methodology based on the idea of warping, bending, or squeezing physical space, as electromagnetic waves or fields see it. While cloaks and flattened fish-eye lenses (see the Maxwell fish-eye lens above) are examples of space warping, even more trivial coordinate transformations like space squeezing are of tremendous practical use, as they reduce the device dimensions without deteriorating its performance (See the compressed Rotman lens on the previous page.). Physical implementations of space transformation ideas almost invariably require metamaterials with exotic electromagnetic properties.



A modified Maxwell fish-eye lens with two flattened surfaces for two-dimensional microwave propagation, experimental sample. The flattening of a normally circular Maxwell lens shape is accomplished with quasi-conformal transformation optics theory. *IMAGE: JOHN HUNT (DUKE UNIVERSITY)*

» OBSTACLES IN DESIGNING WITH METAMATERIALS

ONE OF THE key design constraints researchers face when working with metamaterials is the high ohmic loss of metamaterials due to the ohmic losses in the metal. This causes electromagnetic waves that pass through the structure to be strongly attenuated.

Not only are there design constraints in working with metamaterials, but they also require a high level of control over their structure. In fact, a metamaterial derives its properties—such as its electromagnetic cloaking—from its structure rather than its chemical composition. So, as one might imagine, being able to design and then fabricate these complex structures is no easy feat.

"Metamaterials usually have a fairly complex structure, with a large number of design parameters, including architectural parameters as well as electromagnetic properties of the materials from which they are constructed," explains CMIP's Urzhumov.

"Complex structure leads to very complex electromagnetic response. Frequency spectra of metamaterials typically have lots of interesting features, most stemming from electric and magnetic resonances," says Urzhumov.

While analytical models exist for a handful of simple geometries and crude semi-analytical estimates can be made for certain other types of structures by introducing approximations, it is virtually impossible to predict the electromagnetic response of complex structures without simulations, according to Urzhumov.

The impact of modeling and simulation tools in the field of metamaterials is not restricted to the science. It can also extend to business considerations, as well as helping to push the limits of our imagination.

"Simulation tools enable us to be creative and to quickly test new ideas that would be much more difficult, time-consuming, and expensive to test in the lab," explains NASA's Wilson.

“When we find an idea that works, we can optimize the desired effect and thus specify the design to be built.”

But ultimately, science considerations are paramount when working with metamaterials. If one wants metamaterial-based devices to function properly, precise knowledge of the response at each frequency of interest is needed, making accurate frequency-domain simulations a requirement.

It’s become clear that simulation is absolutely necessary in working with structures that have arbitrary, inhomogeneous, time-dependent, and nonlinear electromagnetic properties, as seen in metamaterials. But not all simulation tools have these capabilities—and if they do, they’re quite limited.

According to NPS’s Alves, modeling and simulation tools have been exceptionally helpful in the design and analysis of the metafilms he and his colleagues are developing.

“One of the most significant design constraints in our work is the lack of an analytical model that completely explains the interactions of all involved parameters,” explains Alves. “The numerical simulations fill this gap. The flexibility of COMSOL Multiphysics allows us to deal with several degrees of freedom simultaneously. Furthermore, material properties can be tuned by fitting the measured and simulated data, improving the accuracy of future designs.”

Flexibility and versatility are key requirements for a modeling and simulation tool when working with metamaterials.

“The use of COMSOL Multiphysics allows us to analyze the performance of the sensors in many ways,” (Figure 6) says Alves. “In the specific case of the bimaterial sensor, RF simulations were conducted to obtain the amount of radiated power absorbed by the metafilms. This power is converted into heat that flows through the sensor and is exchanged with the environment. This phenomenon can be studied using heat transfer simulations.”

Ultimately, structural mechanics simulations evaluate the deformation in the bimaterial structures, which is the effect to be probed by the external readout, according to Alves. This is all done in a single run.

“This process would be exceedingly difficult without the help of multiphysics simulations,” says Alves.

“We appreciate the versatility of all boundary conditions and excitation types that can be used in all types of studies in COMSOL,” says Urzhumov. “One feature in particular—the ability to specify a given background field and use it as an excitation—has been truly enabling for many of our projects.”

COMSOL Multiphysics can do much more than just modify all boundary conditions: It allows for changes to the equations themselves.

“I routinely insert additional polarization densities that describe the response of a dispersive medium, such as a metal at optical frequencies, which allows me to model negative-index metamaterials in the time domain,” says Urzhumov. “This extra polarization density is merely an extra term in the main electromagnetics equation that couples it to an extra equation describing the evolution of that polarization density.”

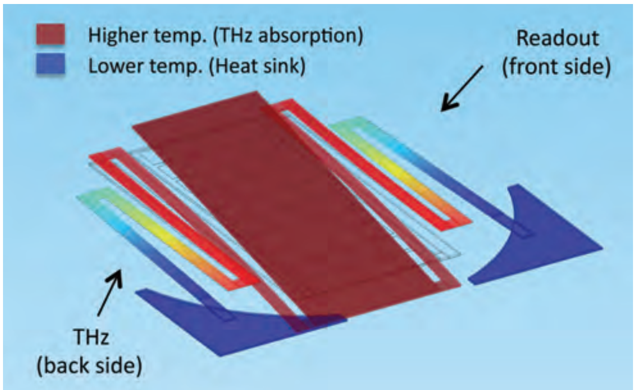


FIGURE 6: COMSOL simulation (deformation analysis) of the Bi-material sensor integrated with the THz sensitive metafilm. The metafilm in the center absorbs THz and transfer the heat to the multifold legs that bend proportionally to the absorbed radiation. The amount of bending can be accessed using optical readouts.

IMAGE: FABIO ALVES (NAVAL POSTGRADUATE SCHOOL (NPS))

In fact, the most noted quality of metamaterials, their ability to cloak objects electromagnetically—the so-called “invisibility” cloak—was predicted entirely by simulation, according to Urzhumov

“As for me personally, I discovered entirely in a COMSOL simulation that these cloaks can perform extremely well in the short-wavelength limit,” says Urzhumov.

» *DISCOVERIES AND APPLICATIONS ENABLED BY MODELING AND SIMULATION*

URZHUMOV CREDITS much of the success of his research to being able to use modeling and simulation tools to open up new avenues of discovery.

According to Urzhumov, one of unique features of COMSOL is its ability to perform a sensitivity analysis semi-analytically, which enables quick gradient-based optimization with a huge number of design parameters.

“With the help of the numerical optimization in COMSOL I could extend my ‘fluid cloak’ solution (Figure 2) into the strongly nonlinear flow regime, where analytical solutions are almost impossible to obtain,” says Urzhumov. ◎