

Modeling metamaterials leads to major scientific breakthrough

In their efforts to use metamaterials to construct the world's first working prototype of an **invisibility cloak**, researchers relied on COMSOL Multiphysics to lead them to the materials and designs that would make this sci-fi dream a reality. This work was acknowledged by *Science* magazine as being among the scientific breakthroughs of 2006.

BY STEVEN A. CUMMER, DUKE UNIVERSITY, DURHAM, NC



Steve Cummer (left) and David Schurig adjust some equipment in their experimental set-up for measuring the effects of metamaterials.

Modeling software is generally used to make the invisible visible—to show the fields and flows in a product or process that are impossible to see with the eye or instruments. A group at Duke University, however, has done just the opposite: With the help of COMSOL Multiphysics, we ran simulations that showed it should be possible to fabricate the metamaterials necessary to make objects invisible. Based on the special properties of those materials, we created a computer simulation of an “invisibility cloak” that makes an object invisible to certain frequencies. We then successfully built and tested it.

Modeling every step of the way

Mathematical modeling has accompanied us most of the way down this trail. Our first simulation followed the publication of a paper in which Prof. Sir John Pendry of the Imperial College London and two of my Duke colleagues, David Schurig and David Smith, described the theoretical properties of a material shell that could bend electromagnetic

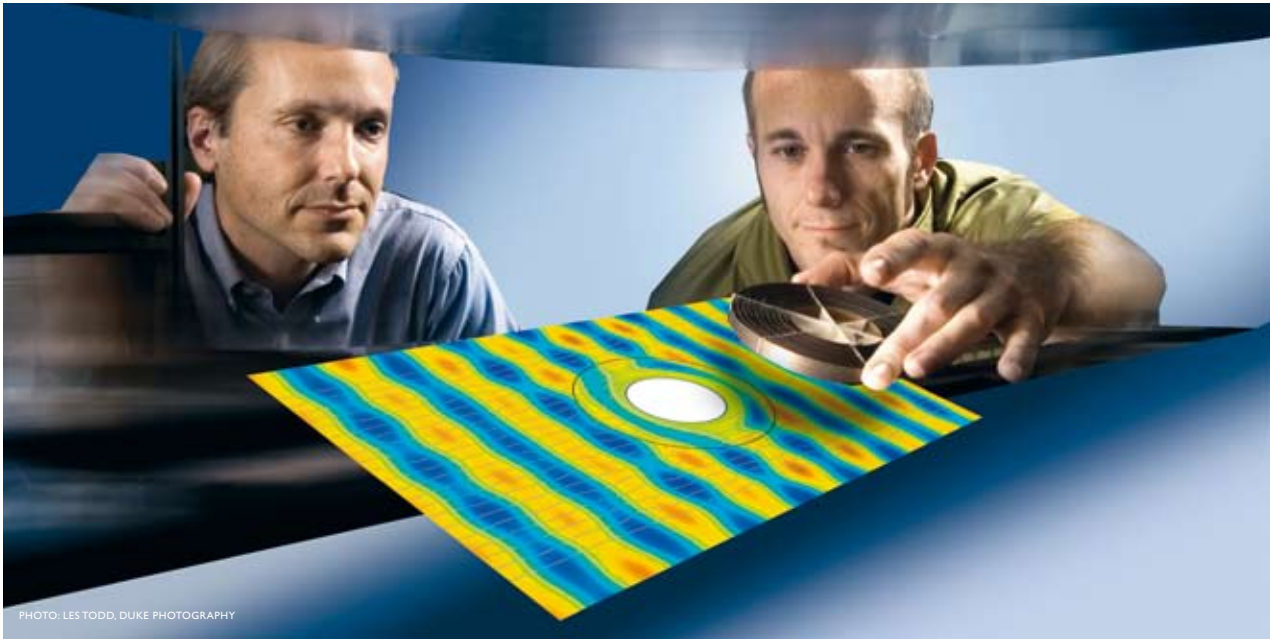


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The author, Steve Cummer (left), and his colleague, David Schurig (right), both from Duke University, Durham, NC.

waves such that the shell and any object placed in the interior would be effectively invisible. The required electromagnetic properties of the shell are not of the sort found in natural materials, and as recently as a decade ago it would not have been feasible to make such a material. But our knowledge of how to engineer materials with specific and complex electromagnetic properties has increased dramatically in that time. We now understand how to create “metamaterials” composed of metallic structures that behave as if they were continuous materials with permittivity, ϵ , and permeability, μ , that can vary with direction and position and can even be negative.

Early efforts at creating these materials, however, were unsuccessful because of the delicate sensitivities involved. If a process did not create a material with exactly the correct properties with almost no variation from the ideal, that material was not useful at all. We started asking ourselves if our approach was similar to “trying to balance on the head of a pin” or was it a bit more forgiving? How difficult is it to actually build the desired material successfully? And finally, if we could not meet specifications for the material in software, was this idea really practical?

Numerical simulations are an excellent tool for exploring these questions because material imperfections, like those that are unavoidable in any real experiment, can easily be included. If we could simulate the ideal and non-ideal conditions success-

fully in COMSOL Multiphysics, then we would have some hope of being able to demonstrate cloaking in an experiment.

The geometry of the COMSOL Multiphysics simulation is simple (Figure 1). Using the RF Module, we solved the 2D cylindrical problem in which a perfect electrical conductor (PEC) infinite circular cylinder is wrapped by a cloaking shell. The PEC shell is a strong reflector of electromagnetic energy, and we wish to mask

this scattering in all directions. On the left and right sides are regions of perfectly matched layers (PMLs), which simulate the infinite domain in which the system resides. A uniform plane wave is launched by a sheet of uniform current density near the left edge of the domain. The top and bottom boundaries are perfect magnetic conductors (PMCs) so that a uniform plane wave with its electric field pointed out of the page can terminate without reflection on these edges. The model uses the RF Module’s In Plane Hybrid-Mode Waves application mode so that all possible reflected fields are accounted for.

Note that this model does not simulate the metamaterial’s fine structure. Instead we simulate

We chose COMSOL because it is likely the only commercial simulation tool that enables the user to specify the shell’s unusual electromagnetic properties.

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Steve Cummer is an Associate Professor in the Department of Electrical and Computer Engineering at Duke University’s Pratt School of Engineering. His research focuses on electromagnetic wave propagation in complex materials and presently includes design and measurement of engineered electromagnetic materials and geophysical remote sensing with low-frequency radio waves.

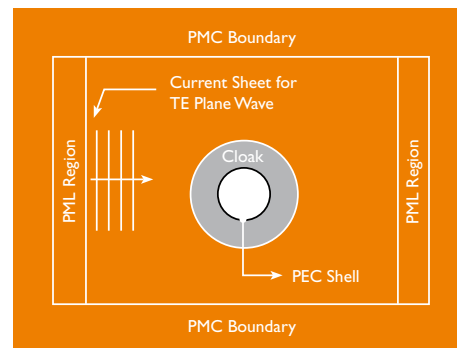


Figure 1: Computational domain and boundary conditions for the full-wave cloaking simulation. The PEC (perfect electrical conductor) has a diameter of 0.2 m, which is 1.33 wavelengths of the incident 2-GHz transverse electric (TE) polarized time-harmonic uniform plane wave.

continuous materials that for this application are anisotropic and smoothly inhomogeneous. The next step is determining how to design the structures like SRRs (split-ring resonators) that approximate the desired continuous material properties. Once we get the desired properties from one unit cell, we fabricate many of them and hopefully get the right bulk properties.

Figure 2a shows the resulting fields for the ideal cloaking shell that has continuously variable permittivity and permeability prescribed by the original theory as modeled in COMSOL Multiphysics. As it travels from left to right, the plane wave is smoothly deformed by the cloaking shell much like river water flowing around a rock. The wave exits the shell looking exactly as it would if there were no object at all. An observer on the right side would thus see only the undisturbed wave, rendering the scattering object transparent and effectively invisible.

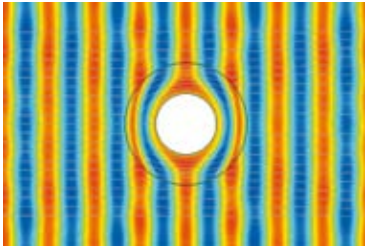


Figure 2a: Ideal parameters

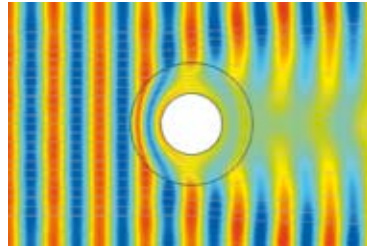


Figure 2b: Ideal parameters with loss

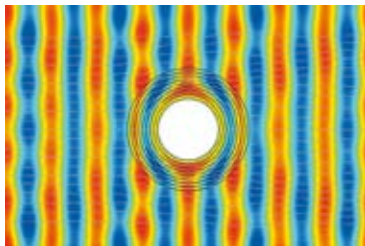


Figure 2c: 8-layer stepwise approximation

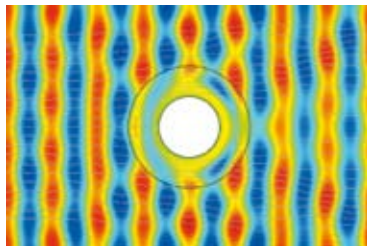


Figure 2d: Reduced material parameters

A continuous anisotropic material

For this simulation we chose COMSOL because it is likely the only commercial simulation tool that enables the user to specify the unusual electromagnetic properties of the shell. Specifically, the shell in our theoretical electromagnetic cloak has highly anisotropic properties that vary smoothly and continuously. Implementing this was straightforward using COMSOL, and to our knowledge, no other commercial products offer this flexibility in specifying a material.

A first simulation (Figure 2a) confirmed that an ideal material would work, so our next step was to see the effects of adding energy absorption as is expected in real-world materials. The use of such



Figure 3: The 2D cloaking structure where the electromagnetic radiation is limited to the x-y plane. An object located in the center of this structure is almost invisible to microwave radiation in a narrow range of frequencies. (photo: Smith, Schurig, Pendry, and Cummer, *Science*)

absorption had made previous attempts to simulate or realize other metamaterial applications fail. We added substantial energy absorption to the shell's permittivity and permeability, and the resulting simulation (Figure 2b) shows that the cloaking effect does not fall apart in the face of losses. The object would now cast a shadow because the incident electromagnetic power is partially absorbed before it can exit the shell, but the wave is otherwise undisturbed and thus the object does not reflect in any other direction.

Our next challenge addresses our present inability to build continuously variable metamaterials. Instead, we must approximate one with discrete layers. What happens if we approximate the material with eight discrete homogeneous cylindrical layers? A simulation (Figure 2c) shows that the cloaking effect, while not perfect, is still evident. Finally, it is difficult to control all three of the key electromagnetic parameters in a fabricated metamaterial at one time. Would it be possible to hold one or two constant, vary only one, and still get reasonable results? Figure 2d shows the field distribution when the cloaking shell is composed of a simplified material in which only the radial component of permeability is spatially varying. Although there is considerable scattering, the smooth deformation of the wave fronts still shows the cloaking principle at work.

We next fabricated an 8-layer metamaterial structure with the simplified cloaking shell parameters described earlier (Figure 3). We simulated exactly what we built, and the experimentally measured fields were in almost exact agreement with the COMSOL-simulated fields. ■

VISIT THE RESEARCH WEBSITE AT:

www.ee.duke.edu/~drsmith

To find out more about metamaterials and the emerging field of plasmonics read:

"The Promise of Plasmonics", by Harry A. Atwater; *Scientific American*, April 2007