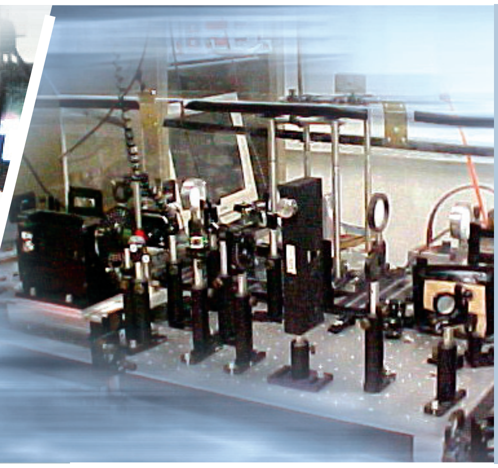
RICE UNIVERSITY RESEARCHERS

EXPLORE THE LAST FRONTIER IN THE ELECTROMAGNETICS SPECTRUM

BY PAUL SCHREIER

Dr. Jason Deibel working with an experimental setup used to characterize the radial photoconductive terahertz antennas designed using COMSOL Multiphysics.



Side view of a free-space terahertz spectroscopy system using multiple mirrors, lenses, and other sensitive optical components. Waveguides and antennas modeled with COMSOL Multiphysics will make it possible to reduce the amount of equipment and system size by 90%.

> The least-explored region of the electromagnetic spectrum consists of terahertz waves, which at 100 GHz to 10 THz fall between microwaves and infrared light. Only in recent years has the development of suitable waveguides for the technical maturation and widespread commercialization of T-ray technology started. Researchers at Rice University have made important discoveries in this regard and are using COMSOL Multiphysics to study how their approach to waveguides works, and how best to connect these waveguides to antennas and other system components.

Promising applications

With the development of efficient and effective waveguides and interfaces, T-ray technology should enjoy wide use due to the unique nature of the radiation. Metals and other electrical conductors are opaque to them, but T-rays can penetrate plastics, paper, dry lumber, and glass just like X-rays. Unlike X-rays, though, they are not hazardous radiation. This combination of attractive traits make T-rays well suited for applications such as the detection of explosives or contraband, defect analysis, moisture monitoring, medical diagnostics, trace-gas detection, and biomedical imaging. In fact, NASA has even used this technology to inspect the foam on the Space Shuttle's external tank, part of the return-to-flight requirement following the Columbia tragedy.

Today's systems, though, are mostly large and stationary due to the lack of suitable waveguides that can carry terahertz waves. Thus, it was a major step forward when a research team at Rice—headed by Prof. Daniel Mittleman with the assistance of Dr. Jason Deibel, graduate students Kanglin Wang and Zhongping Jian, and undergraduate student Mathew Escarra—discovered that a simple cylindrical metal wire can act as a low-loss, low-dispersive waveguide at terahertz frequencies. However, for the development to be fully realized, the team also needed to develop a new type of terahertz antenna, one that better matches to wire waveguides.

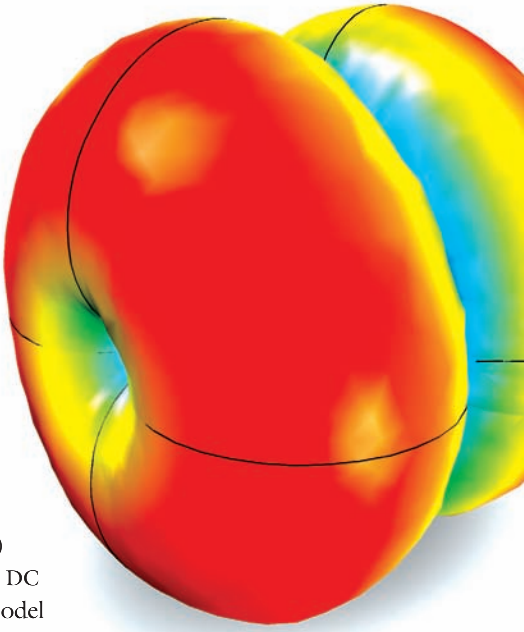
The first terahertz photoconductive antennas were essentially linear dipole emitters that produced primarily linearly polarized radiation. With horizontally polarized terahertz pulses focused onto a 0.9-mm stainless-steel wire waveguide, the team found that they could only couple approximately 1% of the incident power to the waveguide. In an effort to improve performance, they then simulated the coupling efficiency of a configuration of two perpendicular wires with a minute gap between them and found that it was even less at 0.42%.

More recently the team discovered that they could produce radially polarized radiation and couple that radiation very efficiently to a simple metal-wire waveguide. Because the wire's length is many times that of the wavelength, they excite the structure in a small region—then that energy propagates along the wire's surface at the speed of light. When the energy moves, it causes the conduction electrons to oscillate, creating an effect known as a surface-plasmon polariton. At the end of the wire, that polariton radiates its energy into free space as a terahertz wave. With modeling they learned about various effects, and they are currently employing FEA techniques to better understand the loss mechanisms affecting terahertz propagation as well as investigating the effects of curvature and dielectric coatings.

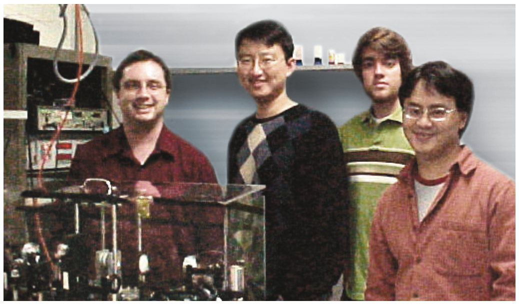
Simulating new antenna concepts

As noted earlier, this breakthrough in waveguides also required a novel antenna. With COMSOL Multiphysics they examined potential designs in the hope that they could produce a radially polarized field. With a multiphysics model that combined the 3D Electromagnetics Wave Propagation application mode (implemented in the Electromagnetics Module) along with an electrostatic analysis of the DC fields in the antenna, they were able to model a proposed photoconductive antenna with radial symmetry.

> "We can take advantage of models with axial symmetry, and use COMSOL Multiphysics to solve models that have more than 14 million DOFs."



In a first model of the radial terahertz antenna, the researchers used an idealized antenna and defined the boundary conditions as being low reflecting. The image shows simulation results for the radiation power.



Several members of the Mittleman Terahertz Research Group at Rice University posing near the terahertz spectroscopy setup. Left to right: Dr. Jason Deibel, Kanglin Wang, Mathew Escarra, and Zhongping Jian.

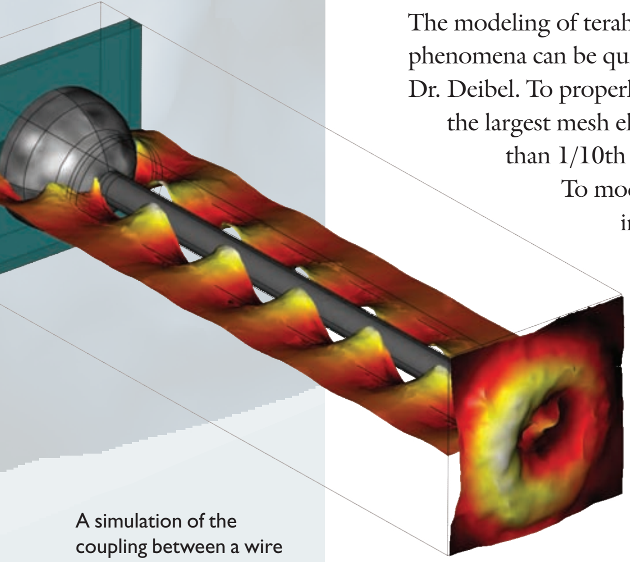
Not only did they show that the proposed design could produce a radially polarized beam, the results agreed perfectly with the analytical model they had developed concurrently. While a simulation showed that the actual radial antenna does not generate a terahertz beam with perfect radial polarization, the beam is largely radially polarized.

They then modeled the coupling of the radial antenna's output to a wire waveguide and found that the coupling efficiency reached approximately 56%, an improvement of more than two orders of magnitude over the dual-wire configuration.

Many millions of DOFs

The modeling of terahertz wave propagation and phenomena can be quite challenging, reports Dr. Deibel. To properly simulate wave propagation, the largest mesh element size must be no larger than 1/10th of the radiation's wavelength. To model an EM wave propagating at a frequency of 100 GHz (wavelength of 3 mm), the largest mesh element can be no larger than 300 microns; for a wave at 1 THz, this critical element size shrinks to 30 microns.

However, a real-world model involves devices and waveguides with feature sizes not only that small but also as large as centimeters. Thus a small critical mesh-element size results in a model with a huge number of mesh elements and subsequently a huge number of DOFs. Comments Dr. Deibel, “While this requirement makes for a difficult model to develop and solve, with proper knowledge of good FEA modeling techniques and the use of its iterative and multigrid solvers, COMSOL Multiphysics can be effectively and efficiently used to model engineering problems and phenomena associated with terahertz wave propagation.”



A simulation of the coupling between a wire terahertz waveguide and a radial antenna fitted with a silicon lens to focus the energy shows that the coupling efficiency of this method exceeds 50%.

More specifically, he reports that “as we learned more about FEA modeling and better utilizing the software, we made a significant upgrade to our computing capacity with a Sun workstation consisting of dual-AMD 64-bit processors with 16 GB of RAM. Using a direct solver, the workstation could solve a 3D electromagnetic wave model consisting of 700,000 mesh elements and 1 million DOFs in 36 hours. Upon switching to the GMRES iterative solver and an SSOR vector preconditioner, a similar model with slightly less than 800,000 mesh elements and 1.1 million DOFs could be solved in 24 hours. Most recently, we learned how to apply the multigrid solver. We now routinely solve very complex and large 3D EM models where the refined mesh consists of 1.5 million mesh elements and 4 million DOFs in less than 12 hours. Further, when we can take advantage of models with axial symmetry, we can solve models that have more than 14 million DOFs, which we are starting to do in our efforts to study propagation of the terahertz pulses along wire waveguides.”

Continues Dr. Deibel, “we've pushed the software into completely new regimes, and the people at COMSOL have been very supportive in these efforts.” Along these lines he says, “in each upgrade I've found something of substantial use.” For instance, the Electromagnetics Module added a transient-propagation application mode. In the past, he's had to work in the frequency domain, but now he can “launch” a time-domain pulse and observe it propagating down the wire.

These results were instrumental in the Rice University group winning an NSF grant to further develop this waveguide technology and to develop a compact and easy-to-use terahertz spectrometer to be used in industry and chemistry labs. “It's our hope,” says Dr. Deibel, “that one day such a spectrometer will be just as common as a FTIR spectrometer in most chemistry labs.”

To read the full paper that Dr. Deibel presented on this topic at the 2005 COMSOL Multiphysics Conference in Boston, order a copy of the Conference CD, which contains this along with more than 200 other papers. ■