MULTIPHYSICS SIMULATION

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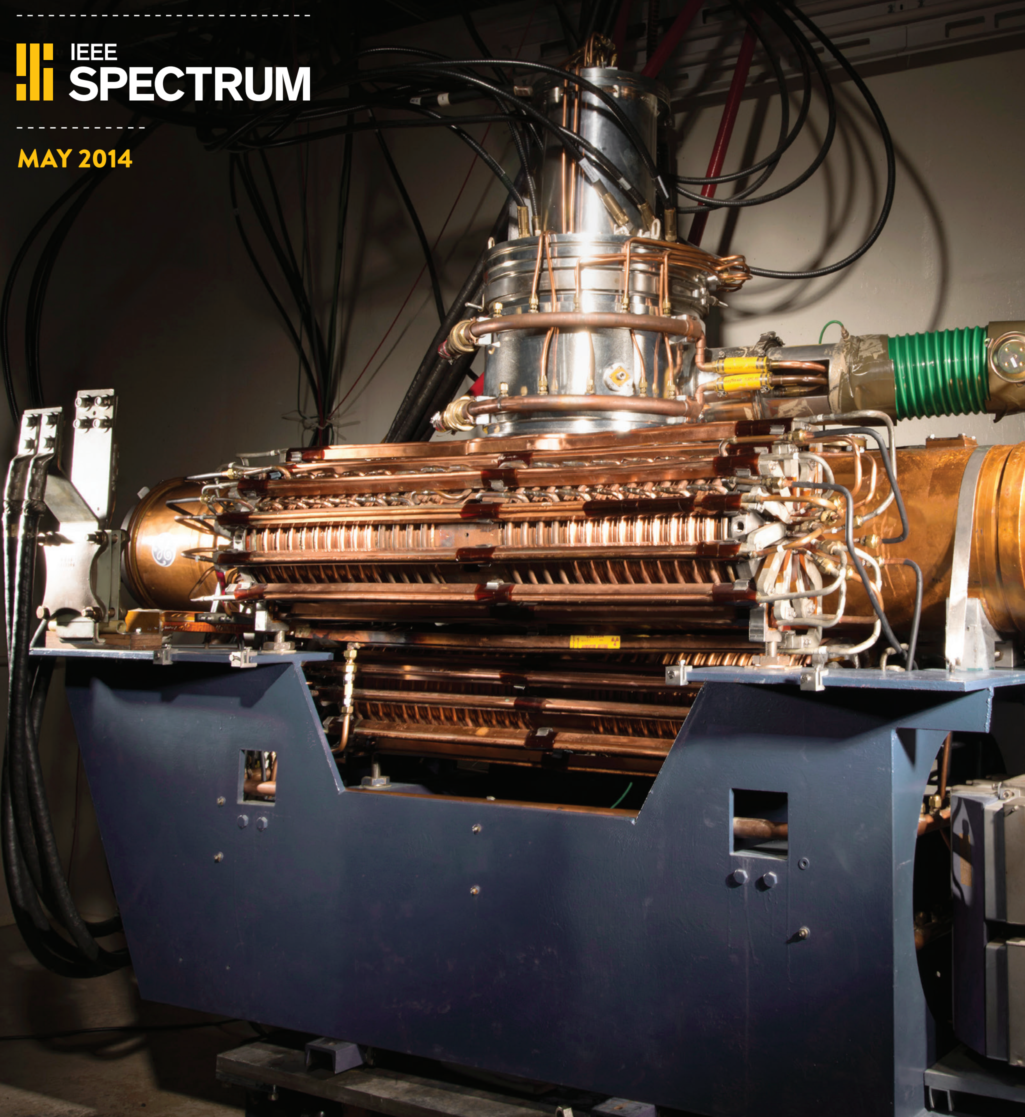

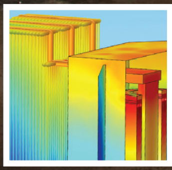

SIEMENS OPTIMIZES POWER TRANSFORMERS

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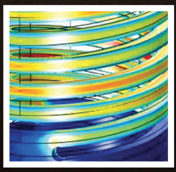

INNOVATIVE ELECTRONICS COOLING DESIGNS FROM BELL LABS

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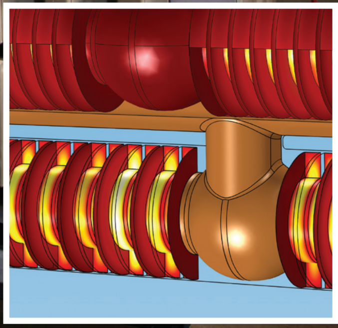

SIMULATION ENSURES DOUBLE BEAM THROUGHPUT AT FERMILAB

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INNOVATIVE DESIGN BEGINS WITH SIMULATION SOFTWARE

By **JAMES A. VICK, SENIOR DIRECTOR, IEEE MEDIA; PUBLISHER, IEEE SPECTRUM**

TODAY'S DESIGN CHALLENGES can't be addressed without simulation software. Take the development of smart grid technologies, for example. Trying to solve the enormous engineering problems that smart grids present through the use of standards, ad hoc design methodologies, or physical testing alone would be prohibitively inefficient and expensive. But accurate simulation software, combined with solid engineering skills, can make cost-effective solutions for challenges like smart grid design realizable.

This year's *Multiphysics Simulation,* sponsored by COMSOL, spotlights engineering thought leaders and their work. The diverse application areas discussed here include optical antennas, power electronics, transformers, high-tech cables, particle accelerators, energy-efficient telecom devices, appliances, semiconductor manufacturing, and smart materials.

One common theme, however, runs through many of the stories that follow: To achieve energy efficiency, you need flexible, powerful thermal management. For example, engineers at Siemens are simulating the mechanical structure of a power transformer to accurately locate and minimize the effect of hotspots caused by inductive heating. At Bell Labs, engineers are designing new microthermoelectric coolers to precisely control laser wavelength in high-speed optical communication systems. Similarly, Whirlpool engineers and designers are establishing simulation protocols to predict the thermal efficiency of heat transfer in household ovens.

The talented engineers and researchers featured in these stories use multiphysics simulation tools to achieve remarkable product design results. We hope you enjoy them. To access the electronic version of *Multiphysics Simulation,* visit www.comsol.com/resources.

Email: jv.ieeemedia@ieee.org

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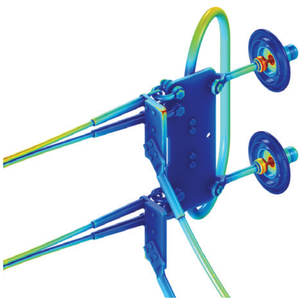

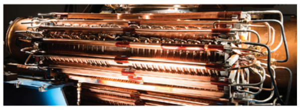

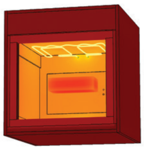

ON THE COVER: An RF cavity with ferrite tuners from the Booster synchrotron at Fermi National Accelerator Laboratory. See Fig. 6 from the full article starting on pg. 12 for more details about the simulation. Photo is by Reidar Hahn and COMSOL simulations by Mohamed Hassan, both of Fermilab.

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ENHANCING TRANSMISSION LINE PERFORMANCE: USING SIMULATION TO OPTIMIZE DESIGN

The design of high-voltage transmission lines involves optimization under a complex series of economic, electrical, mechanical, and environmental constraints. Using simulation, POWER Engineers, Inc. analyzed transmission line corona performance prior to device manufacturing and high-voltage testing, saving both time and money.

By **ALEXANDRA FOLEY**

LEVERAGING HIGHLY accurate simulation technology and knowledge gained from decades of analyzing in-service equipment, today's engineers are able to investigate, model, and neutralize subtle effects that were impossible to assess without expensive and rigorous testing even just a few years ago. One area in which simulation is successfully being applied is in the analysis of the adverse effects of corona discharge in bulk power transmission lines and their associated equipment.

While analyses of this sort are usually conducted through testing in high-voltage labs or by evaluating in-service equipment, POWER Engineers, Inc. (POWER), a global consulting engineering firm, found that finite element simulation software was an effective tool for analyzing the corona performance of transmission lines. As an example, under contract to a Midwestern utility company, POWER performed detailed studies of corona performance for special 345-kilovolt transmission line equipment proposed to mitigate mechanical stress due to wind and ice loads. These studies provided a better understanding of the device's electrical performance prior to high-voltage testing in the laboratory.

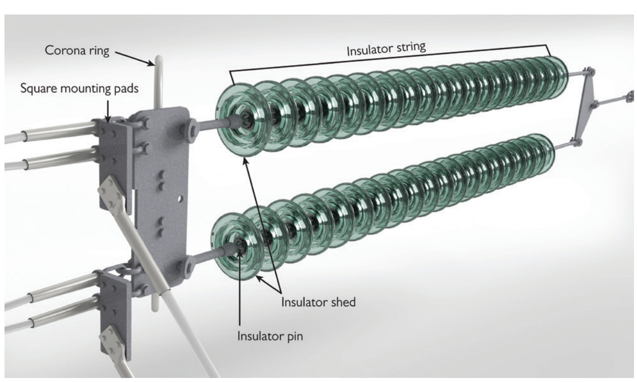


FIGURE 1: Top: A dead-end structure. Bottom: CAD representation of the dead-end insulator assembly.

IMAGES COURTESY OF DANNY FREDERICK AND CHARLIE KOENIG, POWER ENGINEERS, INC.

» CALCULATING ELECTRIC FIELDS FOR COMPLEX GEOMETRIES

TRANSMISSION STRUCTURES designed to support significant lateral forces from conductor tension are called dead-end structures. Insulator assemblies mounted on these structures provide an electrically isolated connection between the structure and the energized conductor (see Figure 1). Electric fields near the surface of these high-voltage conductors and dead-end assemblies can ionize the surrounding air molecules, resulting in corona discharge. The effects of this phenomenon include energy losses, electromagnetic (AM radio) interference, audible noise, visible light, and possible erosion of materials.

"If you've ever stood near a transmission line, you've probably heard the buzzing noise it makes," says Jon Leman, Senior Project Engineer at POWER. "Above a certain voltage, the

> *"The COMSOL software combines the tools necessary for us to provide our customers with an accurate analysis of how the proposed transmission hardware will perform."*
>
> **—JON LEMAN, SENIOR PROJECT ENGINEER AT POWER**

electric field ionizes air molecules and creates corona discharge. Usually that's what causes the noise you hear. Minimizing this noise and other negative effects requires reducing corona discharge." A certain level of corona activity and associated effects are tolerable for transmission line conductors, but attachment hardware is typically supposed to be free of noticeable corona activity. Leman used COMSOL Multiphysics® to determine the electric field strength near the surface of the energized hardware and to estimate the probability of corona discharge at locations with high electric fields.

"In order to set up a lean simulation, we modeled the insulator assembly for one of the three transmission line phases and only included the first unit of the insulator string," says Leman. POWER then used a 2-D axisymmetric model of the complete

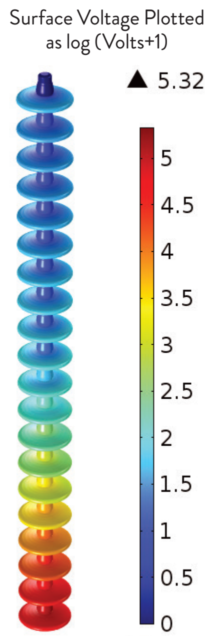


FIGURE 2: A 2-D axisymmetric model showing the electric potential distribution along the insulator string.

insulator string to determine the floating potential on the last insulator unit's cap (see Figure 2). Knowing this boundary voltage allowed POWER to build a reasonably accurate 3-D model without having to include the repetitive geometric complexity and computational burden of the whole insulator string.

» *PREDICTING DEVICE CORONA PERFORMANCE*

CORONA DISCHARGE IS a complex physical phenomenon affected by a combination of electric field strength, device geometry, atmospheric conditions, and the surface condition of the conductor. Leman performed custom postprocessing of the electric field results by entering empirical, space-dependent equations into COMSOL to estimate the net number of air ionizations near regions with high electric fields. This allowed him to estimate the probability of corona activity. Results showed that there were two areas with electric fields strong enough to result in corona discharge: The energized pins of the insulator units and the corner of the upper square mounting pads (shown as red areas in Figure 3).

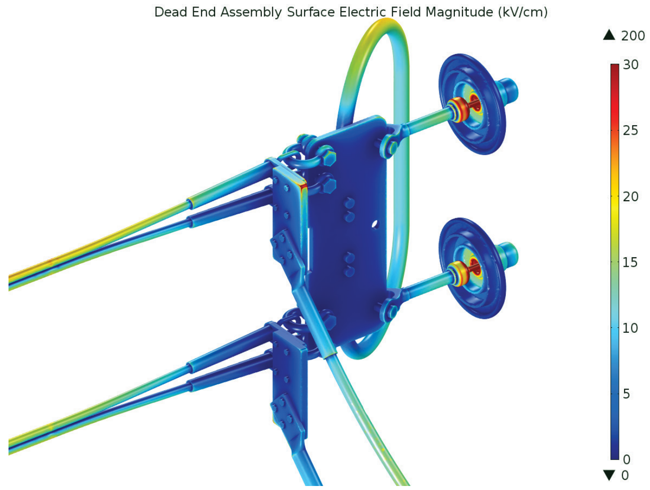


FIGURE 3: Electric field strength at the surface of the dead-end insulator assembly. Areas with high electrical fields occur at the pins of the insulator units and at the square mounting pads.

"Our results demonstrated that the outside corners of the square mounting pads are likely susceptible to corona discharge, but only marginally so," explains Leman. "The insulator pins, however, may experience significant corona discharge." Detailed views of the electric fields present at the insulator pins are shown in Figure 4.

In addition to audible noise and radio interference, severe corona discharge can deteriorate the insulator unit over time, possibly resulting in loss of strength and insulating capability. "Now that we have identified where the issues are likely to occur on the hardware, it will provide an opportunity to modify the design prior to testing," says Leman. Rob Schaerer, a project engineer at POWER who also participated in the project, coordinates procedures and witnesses high-voltage corona testing for clients. He says, "Laboratory testing is an important part of new hardware design, but there are costs that can be saved by up-front analysis, particularly if retesting is required. Scheduling time in high-voltage labs can be difficult on short notice, so by having a reasonably vetted design prior to testing,

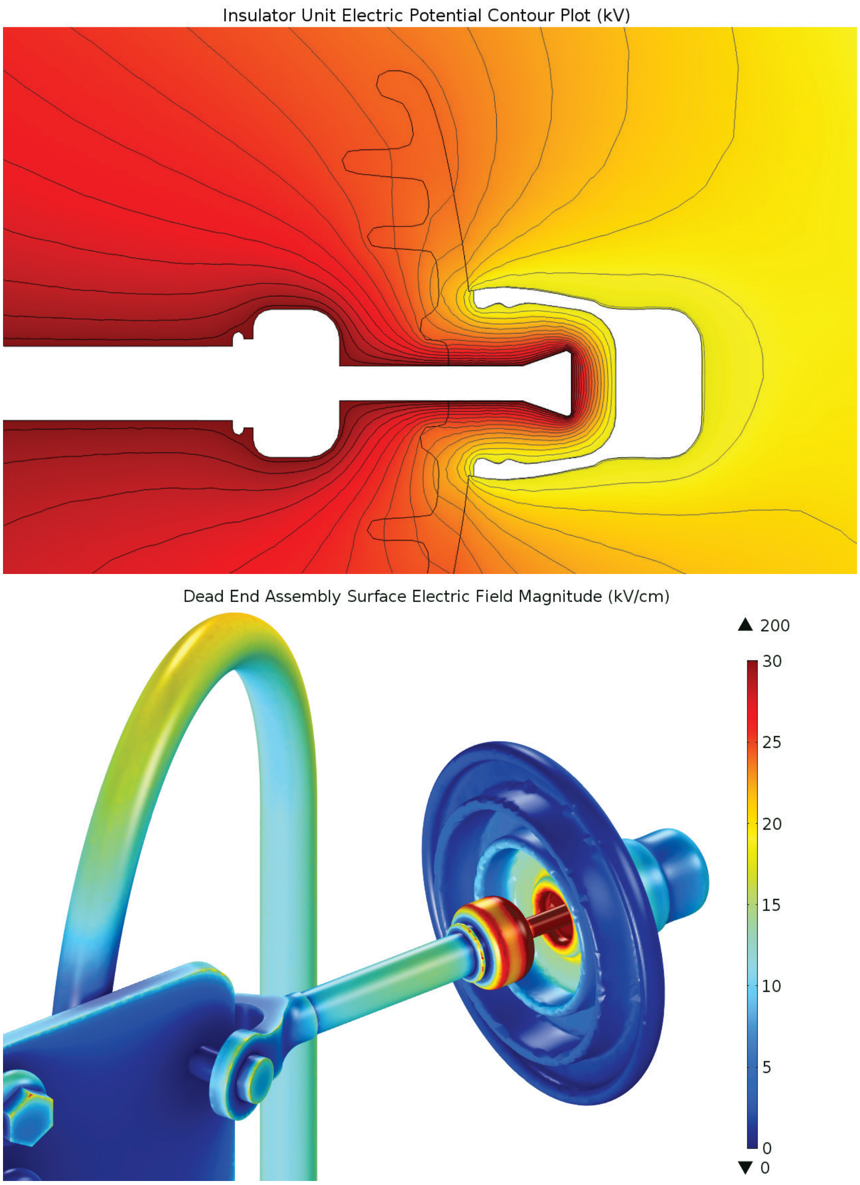


FIGURE 4: Top: Electric potential cross-section of the air surrounding the insulator pin. Bottom: Electric field results for the insulator pin.

Jon Leman, Senior Project Engineer at POWER

Rob Schaerer, project engineer at POWER

Charlie Koenig, Visualization/ Animation Specialist at POWER

a project is less likely to be impacted by a design that's found to be insufficient in the first round of testing."

» ACCURATE SIMULATIONS DRIVE REAL-WORLD RESULTS

SIMULATION CAN BE used to provide information about how a device will perform prior to its construction. When combined with results from empirical testing, engineers can arrive at a reasonable prediction of how a new device design will perform. "I have great respect for the engineers who built the electric grid without the use of modern computing. It's important that we combine that ingenuity with the use of advanced tools to efficiently design tomorrow's grid," says Leman. "The COMSOL software combines the tools necessary for us to provide our customers with an accurate analysis of how the proposed transmission hardware will perform, allowing opportunities to reduce design iterations that would otherwise take place after high-voltage testing." Examples such as this show how simulation can change the process by which devices are designed in order to reduce costs and more quickly optimize solutions. ◎

SIMULATION ENABLES THE NEXT GENERATION OF POWER TRANSFORMERS AND SHUNT REACTORS

Transformers are the workhorses of the electrical grid, and now they are getting assistance from computer modeling in order to meet today's power demands.

By **DEXTER JOHNSON**

DESIGNERS AT SIEMENS BRAZIL, located in Jundiaí, São Paulo, are employing simulation to guarantee the safety of power transformer and shunt reactor operation. By performing these simulations in addition to using their internal tools, members of the design team at the company are now better able to control overheating despite the increasing power demands placed on this equipment.

Shunt reactors are used to absorb reactive power and increase the energy efficiency of transmission systems (see Figure 1). Power transformers are designed to efficiently transfer power from one voltage to another. Both devices are used in all stages of the electrical grid, from power generation to distribution to end users. The increasing demand for more power from constantly growing cities is translating into a need for larger devices. But sometimes conditions limit their size: Transportation and space to place the devices at the customer's plant are some examples of these limitations.

The need to produce more power without increasing the device size adds additional load and increases thermal losses, eventually leading to higher temperatures. While methods for the design of active parts (the cores and windings) of these devices are well-established, the design of their inactive components (structural parts) is still not straightforward and requires further investigation. If the equipment is not carefully designed, there is a risk of overheating, potentially leading to the degradation of the material properties of the transformer's insulating oil.

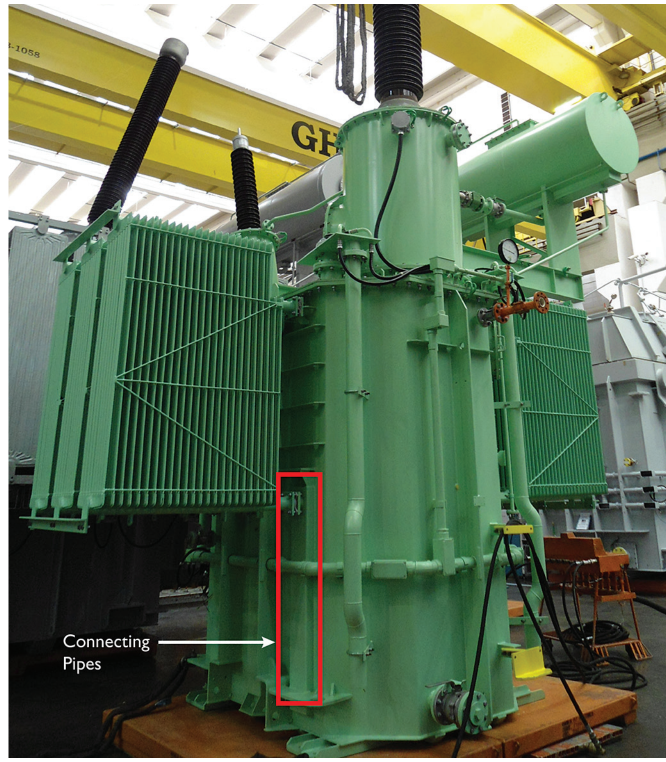


FIGURE 1: Shunt reactor. In the original design of the oil circuit the radiator is connected to the tank by pipes enclosed in rectangular boxes welded to the exterior of the reactor.

» OVERCOMING INDUCTIVE HEATING ISSUES

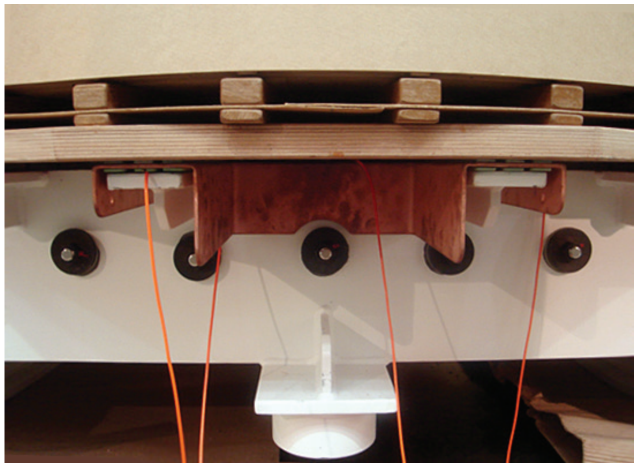
SIEMENS HAS EMPLOYED COMSOL® simulation software to address these design constraints and control the inductive heating of metal parts. Induction heating is the phenomenon of heating a conductive body subjected to a varying electromagnetic field, where eddy currents lead to the Joule heating of the material due to electrical resistance.

The modeling of inductive heating has helped designers at Siemens avoid "hotspots"—small regions with high induced current density and, consequently, high temperatures. With the geometric and material complexity of these transformers, it is very difficult to avoid these hotspots completely. The oil in immersed transformers is a powerful electrical insulator and also works as a coolant fluid. However, these hotspots can overheat the oil and bubbles of gas can be generated. These bubbles have a smaller dielectric strength than the insulating oil and may cause an electrical discharge in the oil, potentially damaging the transformer.

"With COMSOL, we can simulate this behavior and propose changes to transformer design to reduce inductive heating of structural parts," says Luiz Jovelli, Senior Product Developer at Siemens.

In their inductive heating work, Siemens used COMSOL Multiphysics® and the AC/DC Module. The first change that was made as a result of the simulation was to alter the design of the metal structure. For example, by changing the original clamping frame structure of the shunt reactor (see Figure 2, top), the design team was able to reduce induction heating and improve cooling with better oil circulation through that region. As a result, the temperatures of the hottest points were reduced by about 40°C. This change eliminated the need for installing copper shielding over the clamping frame, thus saving material costs (see Figure 2, bottom, and Figure 3).

Because of the simulation work Jovelli and his colleagues have done with COMSOL, they have been able to suggest several improvements to the design of these devices. "Sometimes the cooling accessories of the equipment may be over dimensioned to fit some hotspots in the whole design," says Jovelli. "With COMSOL, we're able to control these spots." Jovelli noted that even a slight change can solve the problem and lead to a reduction in the costs associated with cooling accessories.



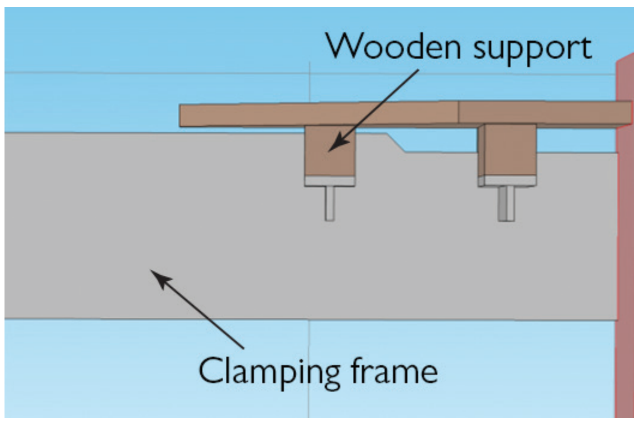


FIGURE 2: Top: Original clamping frame design with copper shielding. Bottom: Optimized clamping frame design using less materials.

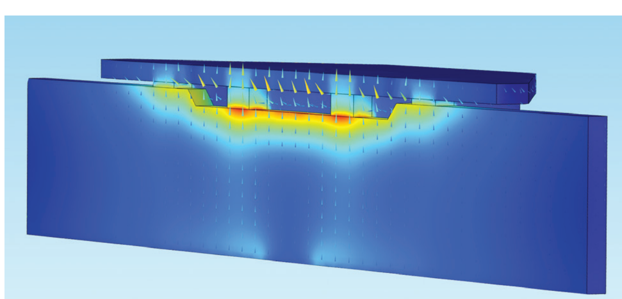


FIGURE 3: Optimized design of the clamping frame (back view). Temperature (surface plot) and oil flow fields (arrows) are shown.

"COMSOL is a powerful modeling and simulation software," says Jovelli. "We can improve the accuracy of our calculations by performing numerical experiments with it. It is also an ally against failure. Design checks can be quickly done to guarantee equipment quality for the entire service life."

» COOLING THE CORE MORE EFFICIENTLY

FROM A THERMAL point of view, a shunt reactor's core has higher heat loss relative to its winding than power transformers, i.e., the ratio of core loss to winding loss in a reactor is higher than in a transformer, and overheating may occur. Therefore, the design must guarantee the efficient cooling of the reactor's core (see Figure 4).

In this case, Siemens simulated the oil circulation and heat transfer in a shunt reactor to understand the oil's behavior and propose an optimized design. A small change in design improved the core cooling, is cleaner than previous designs, reduced man-hours of maintenance, as well as saved material.

Another change that was made involved the piping welded in the tank of the reactor (see Figure 1). Changing this design to the one shown in Figure 5 has reduced material and manufacturing costs and improved oil distribution at the bottom of the reactor tank.

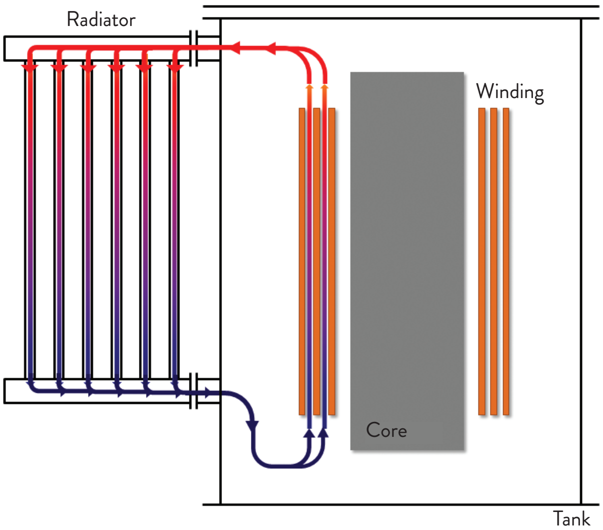
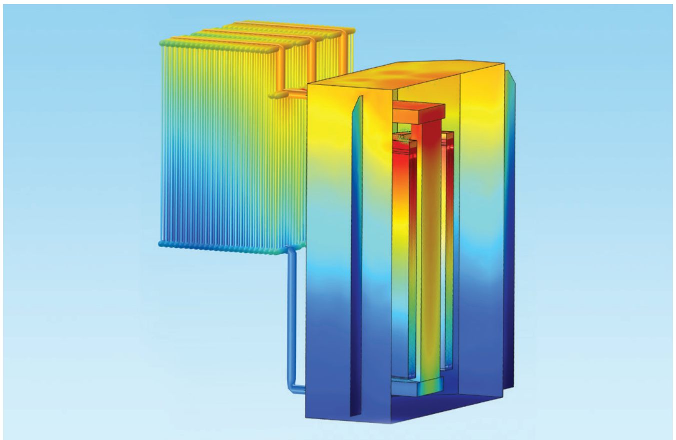


FIGURE 4: Schematic of the new oil circuit design used in shunt reactors and power transformers.



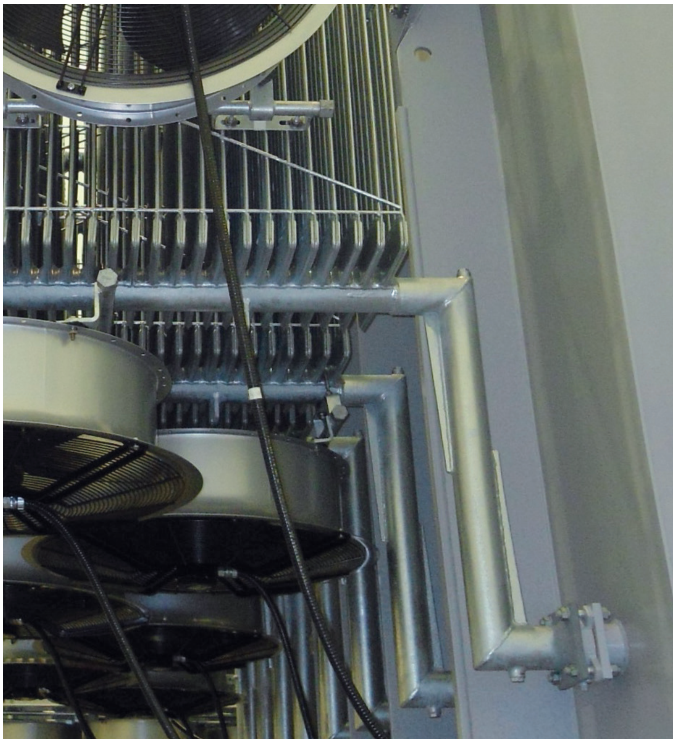


FIGURE 5: Top: The thermo–fluid dynamics simulation of the new design. Bottom: New collecting pipes design. In the new design, the pipes have been removed from their previous position circling exterior of the reactor. Instead, the pipes travel directly from the cooling fan and into the reactor itself.

» *COUPLING 1-D, 2-D, AND 3-D MODELS INTO ONE FULL OIL CIRCUIT SIMULATION*

JOVELLI AND HIS colleagues are also modeling the 3-D thermohydraulic behavior of free convection of oil inside a power transformer (see Figure 4). It is typically quite computationally demanding to perform computational fluid dynamics (CFD) simulations of transformers by representing all parts in 3-D.

COMSOL offers the ability to take a pipe or channel of a transformer and simulate it efficiently in 1-D. A particular strength of the software is that the pipe and channel models seamlessly combine with larger entities modeled in 2-D and 3-D.

"In order to perform a realistic 3-D CFD simulation of an entire transformer oil circuit with this amount of detail, a large amount of computer resources are required," explains Jovelli. "Sometimes simplifications have to be made, and, depending on the objective, you don't get reliable results. With COMSOL Multiphysics, we can easily couple 1-D, 2-D, 2-D axisymmetric, and 3-D models for any physics and perform this simulation on a single workstation with desired reliability."

> *By using COMSOL and its multiphysics coupling capabilities, we're the first Siemens Transformer unit in the world to make a real 3-D model of this equipment."*
>
> —**LUIZ JOVELLI, SENIOR PRODUCT DEVELOPER, AND GLAUCO CANGANE, R&D MANAGER AT SIEMENS**

Using the unique ability of COMSOL to map data from edges (1-D) to surfaces (2-D and 2-D axisymmetric) and volumes (3-D), Jovelli was able to model the windings of transformers using a 2-D axisymmetric model. Additionally, the tank and inlet and outlet pipes were modeled in 3-D, and the heat exchangers were modeled using 1-D elements. The silicon steel core is also a heat source and was modeled in 3-D. Since thin sheets of silicon steel make up the core of the transformer, their anisotropic thermal properties have also been taken into account.

» *THE MULTIPHYSICS APPROACH DELIVERS REALISTIC RESULTS*

FOR JOVELLI AND his colleagues, COMSOL makes it possible to perform more realistic simulations of equipment due to its multiphysics capabilities.

"The ability to couple physics allows us to accurately model real-world physics in a manner that is computationally efficient," say Jovelli and Glauco Cangane, R&D Manager at Siemens. "By using COMSOL and its multiphysics coupling capabilities, we're the first Siemens Transformer unit in the world to make a real 3-D model of this equipment. Maybe we're even the first transformer manufacturer to do it." ◎

MODELING TIPS: INDUCTION HEATING

BY VALERIO MARRA

THE ABILITY TO create multiphysics models is one of the more powerful capabilities of COMSOL Multiphysics®. Several predefined couplings are available where the settings and physics interfaces required for a chosen multiphysics effect are already included in the software. The user interested in modeling induction heating can select the Induction Heating multiphysics interface (Figure 1) that automatically adds a Magnetic Fields interface and a Heat Transfer in Solids interface. In addition, the necessary multiphysics couplings are defined where electromagnetic power dissipation is added as a heat source (Figure 2, Added physics section) and the electromagnetic material properties depend on the temperature. The next step is to select study types such as Stationary, Time Dependent, Frequency Domain, or a combination. Combined frequency-domain modeling for the Magnetic Fields interface and stationary modeling for the Heat Transfer in Solids interface is referred to as a Frequency-Stationary study and, similarly, Frequency-Transient modeling is also available (Figure 2, Added study section). The Magnetic Fields interface is used to compute magnetic field and induced current distributions in and around coils, conductors, and magnets. The Heat Transfer interfaces provide features for modeling phenomena such as phase change and heat transfer by conduction, convection, and radiation.

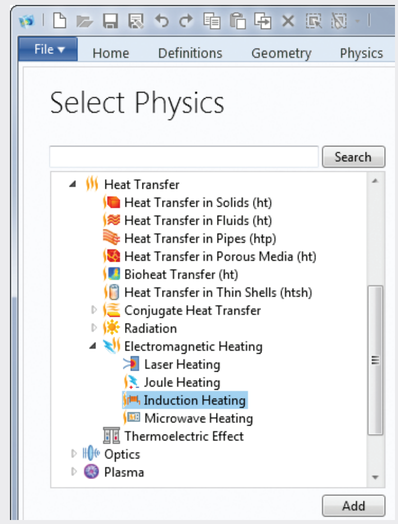


FIGURE 1: A multiphysics coupling is automatically created by selecting the predefined Induction Heating interface.

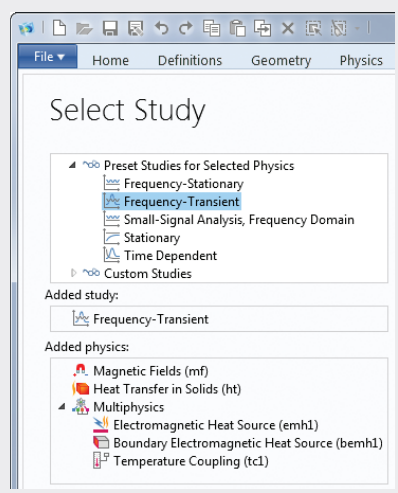


FIGURE 2: The Frequency-Transient study is used to compute temperature changes over time together with the electromagnetic field distribution in the frequency domain.

SIMULATION SOFTWARE BRINGS BIG CHANGES TO CABLE INDUSTRY

Multiphysics simulation has helped Prysmian generate new business and increase profits by delivering high-technology cables.

By **DEXTER JOHNSON**

PRYSMIAN GROUP IS a world leader in energy and telecom cables. The company's energy sector alone is made up of a wide range of products such as high-voltage cables for terrestrial and submarine applications; these include both alternating-current (HVAC) and direct-current (HVDC) systems.

Back in 2010, the R&D group at Prysmian made a big change in how it designs and tests new cables and systems. This shift is already producing dividends in terms of new revenues and increased profits. By fully adopting multiphysics simulation software, the group is able to optimize cable and systems designs for a wide range of harsh environments.

» MOVING BEYOND APPROXIMATIONS TO THERMAL SIMULATION

ONE IMPORTANT ASPECT to consider when designing a power transmission system is its ability to deliver the prescribed amount of current in steady-state conditions without exceeding the maximum permissible operating temperature. To address this point, a detailed thermal model of the system must be built that takes into account many variables: the structure of the cables and internal sources of electric losses (see Figure 1); the geometry of the installation; the installation environment (e.g., soil, water, forced or buoyant air); the ambient temperature; external loads due to solar radiation; and the system's proximity to other infrastructures.

Prior to using multiphysics simulation, Prysmian and others in the cable industry employed formulas or calculation methods provided by international standards. The standards work pretty well for those installations in which the cables are in an undisturbed thermal condition (typically, underground). But nowadays it is becoming common to have such systems installed in or crossing regions characterized by a so-called unfavorable thermal environment where, for example, the new cable system is in the vicinity of existing infrastructures such as other cables that cross the cable route.

Prysmian selected COMSOL Multiphysics® simulation software to build computer models that combine the structure of each cable, that of the power transmission system, the load conditions, and the conditions in the external environment to obtain realistic and reliable simulations (see Figure 2).

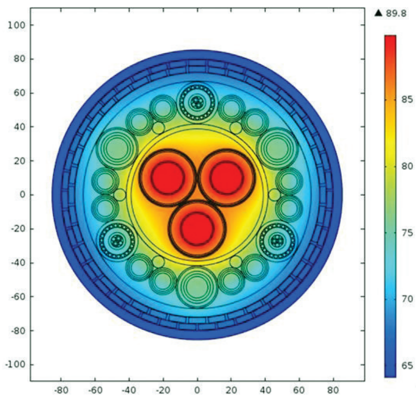


FIGURE 1: Cross-sectional view of the temperature distribution in a double-armored umbilical cable.

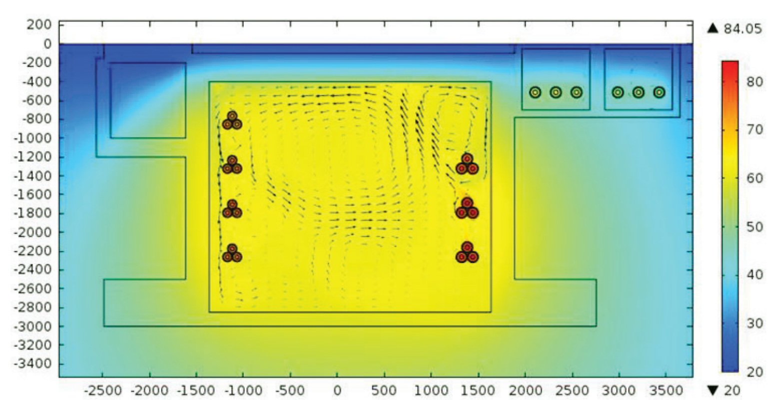


FIGURE 2: Using COMSOL Multiphysics, Prysmian combined thermal and computational fluid dynamics (CFD) analyses of high-voltage cable systems placed inside a horizontal tunnel with natural ventilation only.

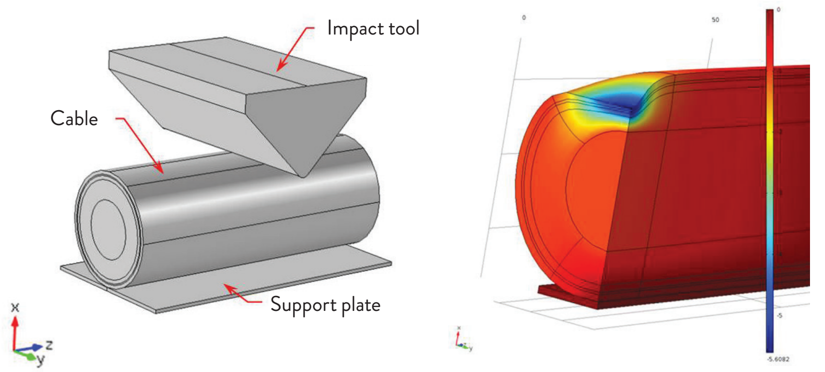


FIGURE 3: Simulation of an impact test on a medium-voltage cable.

"COMSOL is able to solve these kinds of problems because we can build a parametric model to optimize the geometry, the laying of the cables, and we can include the physics needed to account for the convection with the air," explains Massimo Bechis, Modeling and Simulation Specialist at Prysmian. "We can do extensive transient analyses to account for daily variations in solar irradiation and ambient temperature conditions. We can account for current load changes instead of considering constant operating conditions. This allows us to satisfy requests to consider transient conditions due to load changes. So multiphysics simulation really solves these kinds of problems that were very difficult or even impossible to do before."

» *OPTIMIZING THE PROCESS OF MAINTAINING PERFECTION*

NUMERICAL SIMULATIONS have already improved the way Bechis and his colleagues design some of Prysmian's most high-tech products. For example, parametric studies can be conducted to optimize the geometric dimensions or positioning of components in composite cables that may be made up of power conductors, cables for signal transmission, and hoses for delivery of fluid—all in the same structure. Bechis expects that progressive implementation of these methodologies will soon result in improved manufacturing processes as well.

Prior to using multiphysics simulation, many studies were done using mathematical tools developed internally by the company using commercial products such as Microsoft® Excel® or Visual Basic® and based on simplified models. By leveraging the know-how gained from the internally developed code when transitioning to new tools, Bechis is able to model at a much higher level of detail and with much greater accuracy for this kind of system. With COMSOL Multiphysics, Bechis says the company has taken a big step forward and improved the level of the services it can provide to both designers and customers.

"Now we have a lot of requests from colleagues because, for example, they know COMSOL is available to help them analyze and solve many thermal, electromagnetic, and structural problems," Bechis says.

Of course, prior to using simulation tools, Prysmian never had a cable fail. But in order to achieve that perfect record, a large design margin was built into every cable and system because of the calculation procedures adopted.

> *"Multiphysics simulation really solves these kinds of problems that were very difficult or even impossible to do before."*
>
> **—MASSIMO BECHIS, MODELING AND SIMULATION SPECIALIST, PRYSMIAN**

"Now we are able to optimize, among other things, the structure of our cables and still meet the specifications," says Bechis. "We can also explain why we use a certain amount of material in a certain layer and show how we came to our decisions based on the modeling."

With simulation, it is possible to perform the analysis of a test impact on a medium-voltage cable (see Figure 3). The ability to simulate this kind of test on a computer makes it possible to optimize the thickness and the kind of materials used in building the external layers of cables.

"We don't need to perform a lot of tests inside our laboratory," says Bechis. "Instead, we can do a lot of virtual tests on our computer. Then, when we are confident that we have found the optimum design for our cable, we can manufacture it and perform routine field tests in our laboratory."

Physical tests of actual prototypes are still performed, but the prototypes are much closer to the final design, and overall development time is therefore considerably shortened. These tests verify the mechanical behavior of the cables and systems so that the Prysmian team knows they can rely on their models.

» *INCREASING PROFITS AND GENERATING NEW REVENUE*

ONE OF THE clearest indications of the success of the new modeling tools is that Bechis and his colleagues have been able to respond to a lot of customer requests that specifically ask that there be simulation in addition to the standards that are normally used.

"We are now able to provide a better service," says Bechis. "We are saving money. We have improved procedures for designing our cables and power transmission systems. We have an additional and powerful way to respond to requests from clients." ◎

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DOUBLING BEAM INTENSITY UNLOCKS RARE OPPORTUNITIES FOR DISCOVERY AT FERMI NATIONAL ACCELERATOR LABORATORY

At Fermi National Accelerator Laboratory, upgrading the 40-year-old RF cavities in the Booster synchrotron will provide a twofold improvement in proton throughput for high-intensity particle physics experiments that could lead to breakthrough discoveries about the universe.

By **JENNIFER A. SEGUI**

PARTICLE ACCELERATORS SUCH as the Booster synchrotron at the Fermi National Accelerator Laboratory (FNAL) produce high-intensity proton beams for particle physics experiments that can ultimately reveal the secrets of the universe. High-intensity proton beams are required by experiments at the "intensity frontier" of particle physics research, where the availability of more particles improves the chances of observing extremely rare physical processes. In addition to their central role in particle physics experiments, particle accelerators have found widespread use in industrial, nuclear, environmental, and medical applications.

Radio frequency (RF) cavities are essential components of particle accelerators that, depending on the design, can perform multiple functions, including bunching, focusing, decelerating, and accelerating a beam of charged particles. Engineers Mohamed Awida Hassan and Timergali Khabiboulline, both from the Superconductivity and Radiofrequency Development Department of FNAL's Technical Division, are working in collaboration with John Reid from the Accelerator Division to model the RF cavities required for upgrading the 40-year old Booster synchrotron. Reid leads the rather complicated process to refurbish, test, and qualify the upgraded RF cavities.

"In our work, we demonstrate the early-stage feasibility of the upgraded RF cavities to sustain an increased repetition rate of the RF field required to produce proton beams at double the current intensity," says Hassan. "We are using both multiphysics simulation and physical measurements, provided by our colleagues in the Accelerator Division, to evaluate the RF, thermal, and mechanical properties of the Booster RF cavities."

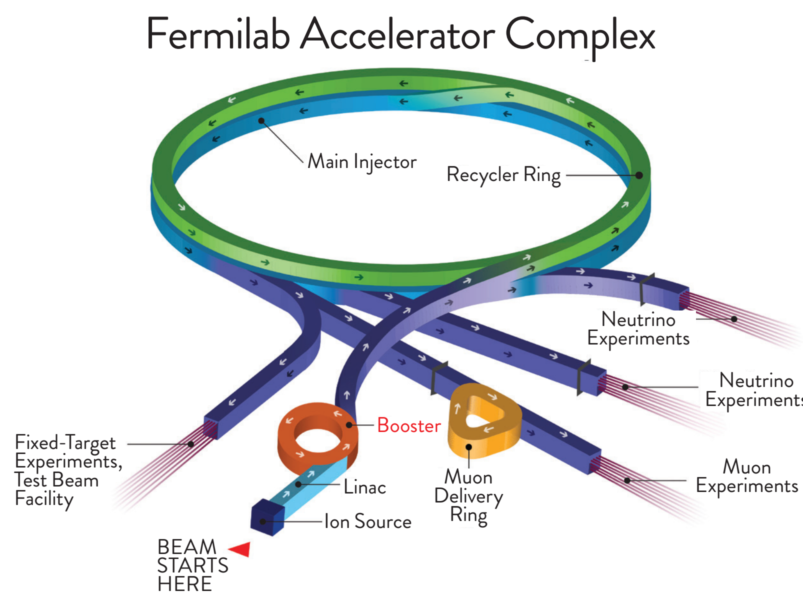

FIGURE 1: The FNAL accelerator chain showing the location of the Booster synchrotron.
IMAGES COURTESY OF FERMI NATIONAL ACCELERATOR LABORATORY

» *POWERING PARTICLE PHYSICS RESEARCH*

FNAL IS CURRENTLY enacting its Proton Improvement Plan (PIP), under the leadership of William Pellico and Robert Zwaska. The plan calls for facility upgrades in order to double the beam throughput and modernize the particle accelerators. A schematic of the accelerator

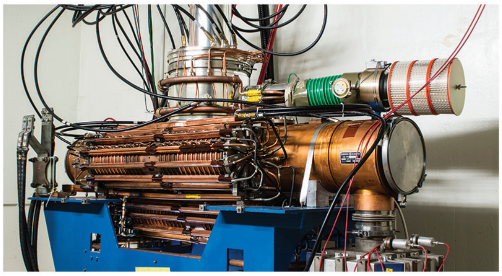


FIGURE 2: At left, a photograph of a copper ferrite-tuned RF cavity from FNAL's Booster synchrotron. At right, a ferrite tuner.

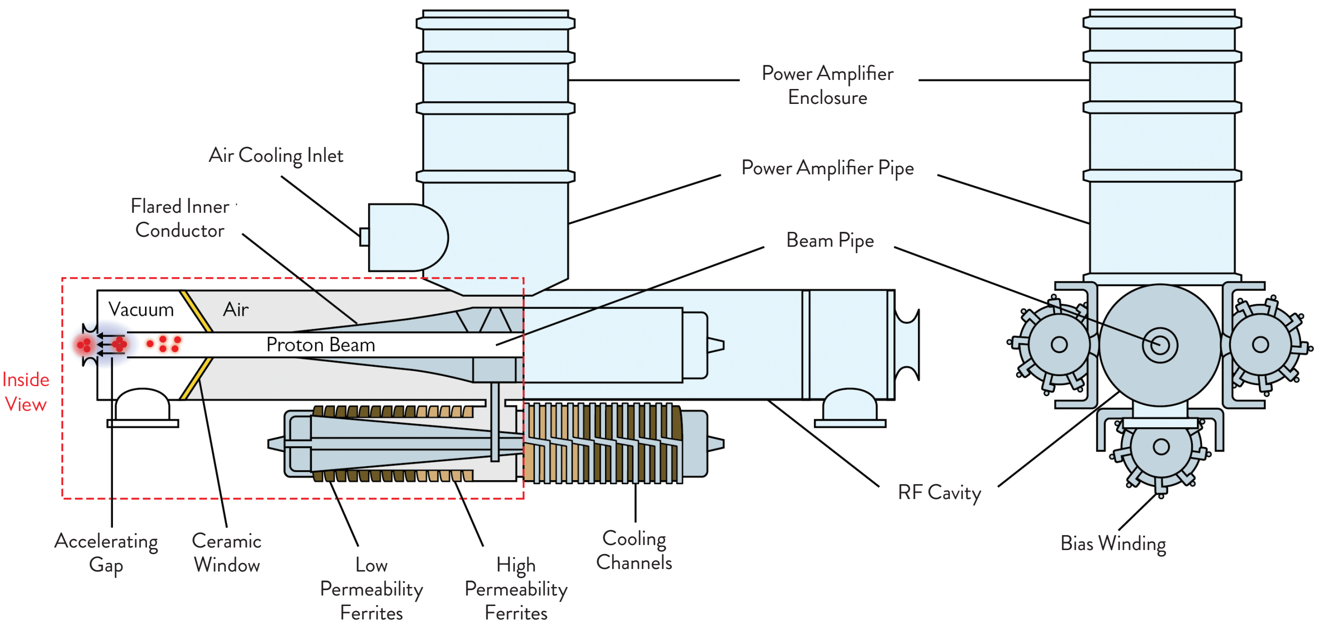

FIGURE 3: Front- and side-view drawings of a Booster RF cavity with three ferrite tuners and a tetrode power amplifier. The side-view drawing shows the high- and low-permeability ferrites, including the cooling channels required to prevent overheating. The ferrites are enclosed in a copper tube that has been eliminated in this drawing in order to expose more detail.

chain at FNAL is shown in Figure 1. The Booster synchrotron, a cyclic particle accelerator and intermediate stage in the particle accelerator chain, is shown in red in the figure. Located about 20 feet below ground, the Booster uses magnetic fields to bend the proton beam in a circular path while 19 ferrite-tuned RF cavities accelerate the protons to 20 times their initial energy when first arriving at the Booster. The protons are transferred to the Main Injector synchrotron, where they are further accelerated, and then directed to multiple underground beam lines. Protons in the underground beam lines interact with neutrino production targets, experimental target materials, or detectors as part of testing.

» THE WORKHORSE OF THE BOOSTER SYNCHROTRON

ONE OF THE remaining challenges of the PIP is upgrading the RF cavities of the Booster synchrotron so they can handle the higher-intensity beams. A photograph of a Booster RF cavity is shown in Figure 2. The Booster RF cavities are half-wave resonators that generate an oscillating electromagnetic field to accelerate protons along the central beam pipe. Each RF cavity is loaded with three coaxial ferrite tuners placed at 90-degree intervals to achieve sufficiently low power loss density per tuner. In the fourth position, a tetrode power amplifier

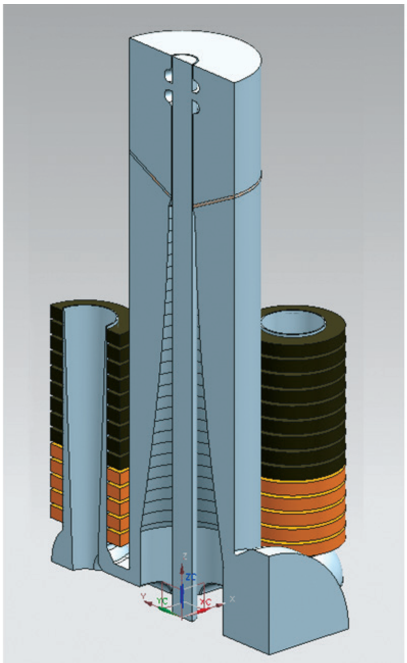

FIGURE 4: RF model geometry for the Booster RF cavity with ferrite tuners. One-quarter of the symmetric cavity design was modeled and imported into COMSOL.

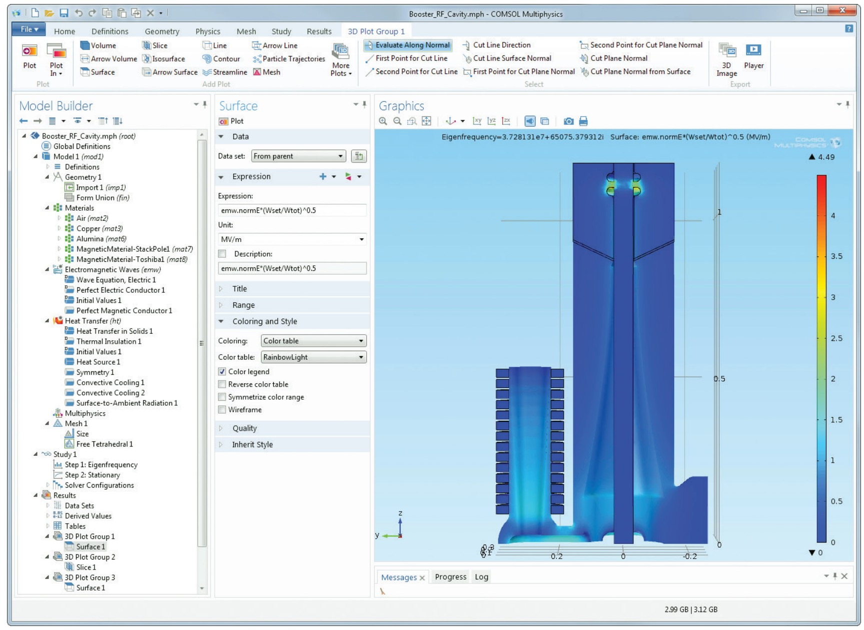

FIGURE 5: This COMSOL Desktop® image shows model setup and analysis for a multiphysics model of an RF cavity. The geometry, materials, physics, and study are defined in the Model Builder window at left. A surface plot of the electric field on the RF cavity and tuner is displayed in the Graphics window. RF analysis is initially conducted to capture the electric and magnetic fields that will be used later as sources of heating in the thermal analysis. The electric field distribution was also investigated to ensure that breakdown will not occur near the high-field regions in air or under vacuum.

supplies the RF signal. Side- and front-view drawings of the Booster RF cavity are shown in Figure 3.

The RF cavities are designed with a specific size and shape in order to allow tuning of the resonant frequency from 37 MHz to 53 MHz. As protons cycle through the Booster, the frequency is gradually increased by varying the bias on the ferrite tuners to accelerate the particles up to the target energy. The operating frequency range of the RF cavities will not change as part of the PIP. Parameters such as the accelerating voltage and beam repetition rate, which governs how often particle beams are produced and sent through the accelerator chain, do need to increase, however.

» SIMULATION QUANTIFIES RF HEATING

OPERATING THE BOOSTER RF cavities at the higher repetition rate and accelerating voltage is necessary in order to increase the overall efficiency of the particle accelerators and double the hourly proton yield. An increase in the power dissipated in the RF cavities is projected, however, which could lead to overheating. Additional thermal stress in the cavity and tuners could potentially reduce their lifetime and produce an unreliable proton yield. Better cooling may be required to ensure stable long-term proton production at the desired rate. The current cooling mechanism uses water circulating in pipes surrounding the cavities in addition to fans that generate a cooling air flow.

Hassan and Khabiboulline are evaluating the Booster RF cavities to estimate the cooling requirements at the increased repetition rate and accelerating voltage. Physical measurements of temperature in the RF cavity and tuner can be difficult to acquire and are often inaccurate. Multiphysics simulations were used in conjunction with experiments to develop a model of the RF cavity that could be used to evaluate its RF, mechanical, and thermal properties. The model was set up in COMSOL Multiphysics®, where one-quarter of the actual geometry was imported from an SAT® file that was created in a separate CAD program. The imported model geometry is shown in Figure 4 and includes the cavity and tuners. “We chose to simulate only part of the symmetric design to reduce the computational complexity and time required to solve the model,” says Hassan. “Perfect magnetic conductor (PMC) boundary conditions were enforced along the symmetry planes while the perfect electric conductor (PEC) boundary condition was enforced on all other boundaries in the RF model.”

The materials, physics, and study were set up as shown in the model tree in Figure 5. The copper material for the walls was defined using the built-in material properties available in the Material Library. The properties of the ferrite mate-

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From left to right, the engineers behind the Proton Improvement Plan and RF cavity simulations: Robert Zwaska, PIP deputy leader; William Pellico, PIP leader; Mohamed Hassan, senior RF engineer; and Timergali Khabiboulline, RF Group leader. They are pictured in the Booster synchrotron tunnel at FNAL, next to a ferrite-tuned RF cavity. John Reid, not pictured, is the RF Group Leader from the Accelerator Division.

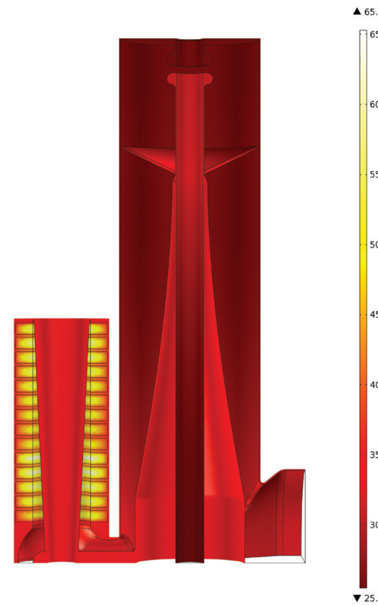


FIGURE 6: A surface plot of temperature is shown from the thermal analysis of an FNAL Booster RF cavity at 55 kV accelerating voltage and 7 Hz repetition rate.

rial for the tuners were custom-defined. Initially, the electromagnetic problem was evaluated to solve for the electric and magnetic fields. Electromagnetic losses in the ferrite and resistive losses along the cavity surface were used as heat sources for solving the heat transfer problem. The cooling mechanism was incorporated into the model by applying the convective cooling boundary condition to the outer walls of the tuner. The model was validated by comparing the measured quality factor (Q) of the RF cavity with the quality factor computed in the COMSOL® environment.

Thermal analysis was performed to show the effect of increasing the repetition rate and accelerating voltage on the operating temperature of the tuners. The results shown in Figure 6 are for an accelerating voltage of 55 kV and repetition rate of 7 Hz where a temperature maximum of 65°C was observed in the tuners. The accelerating voltage was held constant at 55 kV, while the repetition rate was increased from 7 to 15 Hz. The analysis showed that this approximate doubling of the repetition rate could cause the operating temperature of the tuners to increase by more than 30°C. A further increase in the accelerating voltage to 60 kV while operating at the 15 Hz repetition rate could cause the operating temperature to increase by another 10°C. The power dissipated in the RF cavity and tuners increased from 16.6 kW at 55 kV and 7 Hz repetition rate to 39.1 kW at 60 kV and 15 Hz repetition rate.

» *ENSURING SMOOTH OPERATION THROUGH 2025*

BASED ON THE simulation results, Hassan confirms that "the cooling mechanism will need to be upgraded along with the cavities to handle the increased repetition rate and accelerating voltage through 2025 as called for in the Proton Improvement Plan." Increasing the airflow will be one of the first adjustments made, although adding more pipes, further reducing the water temperature, and experimenting with the water flow rate are all possibilities. The RF cavity model will be expanded in the future to include air and pipe flow so that the geometry and cooling mechanism more closely represents that of the actual RF cavity.

In the extreme environment of the Booster synchrotron, radiation hazards and high temperatures make upgrading the RF cavities a challenge. Simulation results are being used to facilitate design decisions with regard to the cooling mechanism to help reduce the time, risks, and expense associated with the upgrade and continued use of the RF cavities. Successfully implementing the improved cooling system will aid in keeping the unique RF cavities of the Booster synchrotron operational through their 55th year and accelerating even more high-energy protons. ◎

MODELING OF COMPLEX PHYSICS SPEEDS CHIP DEVELOPMENT

The symbiotic relationship between computer chips and computational modeling helps keep Moore's Law on pace at Lam Research Corporation.

By **GARY DAGASTINE**

IN 1965, Gordon Moore predicted that ongoing technological advances would lead to a doubling of the number of transistors on computer chips about every two years, slashing the computing cost per calculation and exponentially increasing computing power.

But while more powerful chips are driving advances in computational modeling, the reverse is also true: Computational modeling is in turn driving progressively higher transistor densities and better architectures, reliability, and processing speeds. This virtuous circle is helping the semiconductor industry stay on pace with Moore's Law.

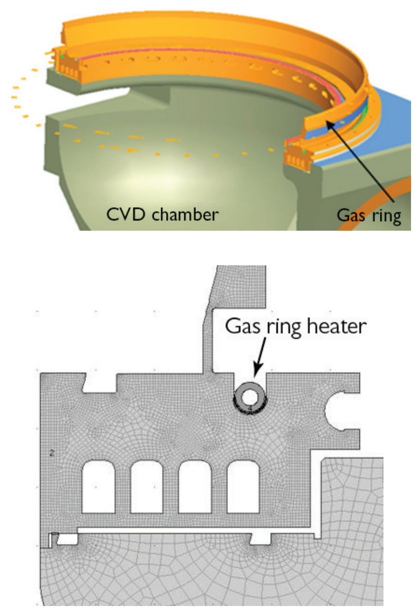


FIGURE 1: Gas is introduced into a chemical vapor deposition (CVD) chamber via a gas ring. The challenge is to keep the temperature of the ring uniform throughout the entire processing sequence.

Lam Research Corporation is one of the world's leading suppliers of semiconductor manufacturing equipment and services. Its products are used to etch, deposit, and clean the ultrathin material layers from which semiconductors are built.

To meet the demands of the fast-paced semiconductor industry, Lam continually increases the performance, reliability, and availability of its products while also keeping their capital costs as low as possible. Many departments at Lam use computational modeling for the detailed analyses of nanoscale transistor features, to assess the performance of equipment, and for continuous product improvement involving many different scale levels.

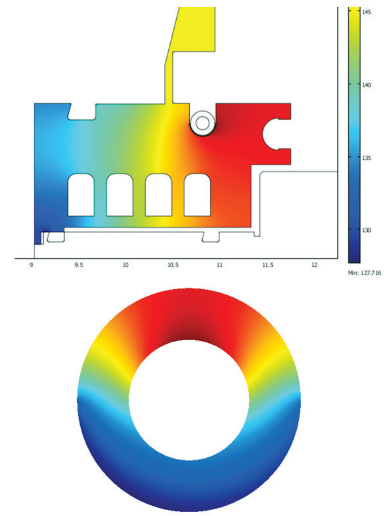


FIGURE 2: Lam is using the Heat Transfer Module in COMSOL Multiphysics® to help predict temperature uniformity under various operating conditions for CVD chamber gas ring heaters.

The company's Computational Modeling and Reliability Group, headed by Peter Woytowitz, serves as a centralized internal resource for product research, development, and support. "Lam's goal is to be first to market with the best technology, but because our customers' processes and needs are constantly changing it's imperative for us to be fast and efficient. COMSOL Multiphysics helps us do that," he noted.

» *SIMULATION LEADS TO BETTER CONTROL OF TEMPERATURE UNIFORMITY*

IN SEMICONDUCTOR manufacturing, integrated circuits are fabricated on a wafer of semiconducting material. The circuits are built from multiple layers of different conducting and insulating materials that must follow an extremely precise design. These layers—some now only a few nanometers thick—are created via a series of many different processes that involve multiple aspects of material deposition, patterning, and selective removal.

Among the equipment used to deposit these layers, or thin films, of material onto a wafer are chemical vapor deposition (CVD) tools. A wafer is placed into a sealed CVD chamber for processing, and gas containing the material to be deposited is introduced to the chamber. In one design, this is done via a gas ring that distributes the gas uniformly throughout the chamber (see Figure 1). The gas is energized to its plasma state to help drive the material onto the wafer and is then exhausted from the chamber.

It's imperative that the temperature of the gas ring be both uniform and hot enough throughout the entire process to minimize the amount of material deposited on it. If the desired temperature control is not achieved, then repeated thermal cycling can cause microscopic particles to break off the ring and fall onto a wafer, creating defects that could ruin the wafer. Particles are one of the leading causes of defects on otherwise good—and expensive—wafers in progress.

Using simulation, engineers design the heating and cooling channels within the gas ring, as well as an external heater to control gas ring temperature accurately during all phases of the CVD process. This entails both cooling the ring during plasma heating and heating it appropriately at other times (see Figure 2).

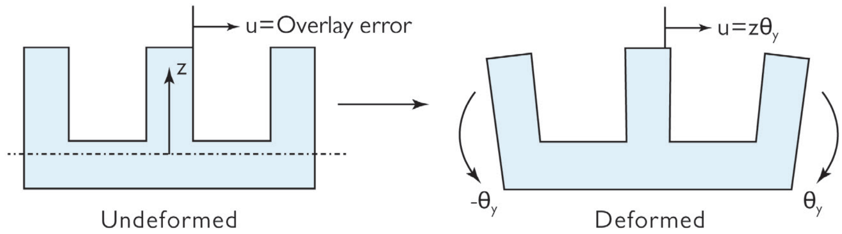


FIGURE 3: The cross-section at left shows an undeformed structure that introduces no photolithographic overlay error. On the right, a semiconductor wafer deformed by various stresses tilts, thereby introducing overlay error.

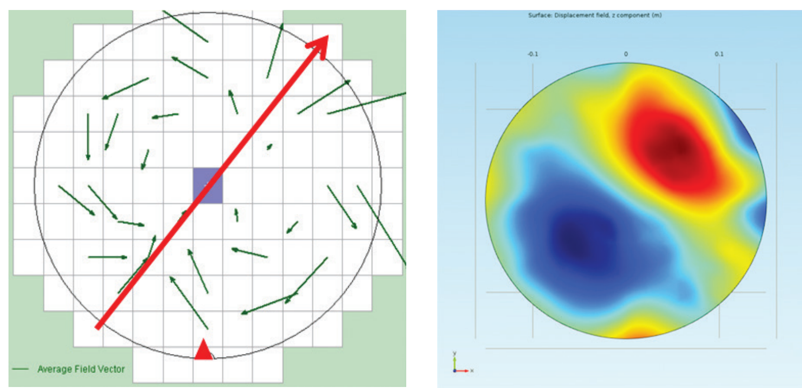


FIGURE 4: At left is a map of vectors contributing to wafer bow. The software resolved them into wafer displacement contour maps. On the right is a view in the x-y plane.

» *MAJOR INSIGHTS GAINED INTO WAFER DEFORMATION IMPACTS*

ANOTHER PROJECT at Lam was to study the effects of wafer deformations on photolithography, a key chip-manufacturing process similar to the process by which a photograph is developed on photosensitive paper.

During photolithography, light shines through a pattern known as a mask onto a photosensitive semiconductor wafer surface, and a layer of material is deposited onto and/or etched into the wafer according to the mask pattern. A series of masks are used to successively pattern layers until the integrated circuit is complete.

With the feature sizes on advanced chips now measuring 22 nanometers or less, many seemingly minor wafer distortions can have major deleterious effects on patterning accuracy. "Minute distortions of the wafer can cause misalignment and can distort features," describes Woytowitz. "This can then affect the ability of the photolithography process to accurately align and pattern the wafer."

Using COMSOL, analysts can identify any deviations from the desired pattern, called overlay error (see Figure 3), to determine if these defects were caused during the manufactur-

> *Lam's goal is to be first to market with the best technology, but because our customers' processes and needs are constantly changing it's imperative for us to be fast and efficient. COMSOL Multiphysics helps us do that."*
>
> **—PETER WOYTOWITZ, DIRECTOR OF ENGINEERING, LAM RESEARCH CORP.**

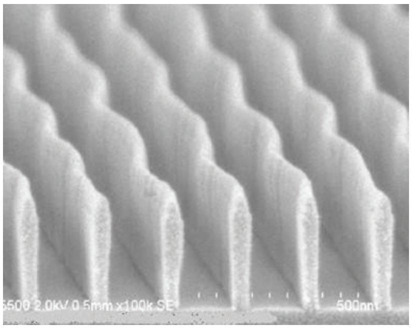


FIGURE 5: Photomicrograph showing the buckling of dummy structures used as building blocks to fabricate high aspect ratio interconnect for advanced computer chips.

ing process. If so, the performance of those tools can be optimized.

Woytowitz's group uses simulation to study how Lam's tools affect wafer deformation and then to determine if these deformations would impact photolithography. Plate theory, in conjunction with plate elements, is used to help characterize and correlate these distortions with measurable overlay errors.

For example, physical displacement from the horizontal plane, or wafer bow, is a significant contributor to overlay error. Before photolithographic processing, semiconductor wafers typically exhibit a bow of as much as 100 µm. Even when electrostatically bound to a tool's chuck for processing, or "clamped," they still may displace about 1 µm (see Figure 4).

Through simulation, Lam has determined that 1 µm of wafer bow generates overlay errors of about 10 nm. Since allowable overlay errors on today's advanced chips are generally about 10 nm (although they can be less), that is right at the allowable limit. Instead of a difficult and time-consuming trial-and-error testing process, simulation helped to quickly and precisely correlate the degree of wafer bow with overlay error.

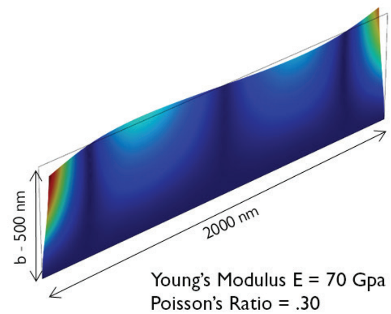


FIGURE 6: The Structural Mechanics Module in COMSOL Multiphysics can predict how buckling will occur in high aspect ratio chip interconnect.

» SUSCEPTIBILITY TO BUCKLING CAN NOW BE PREDICTED

THE USE OF high aspect ratio structures and features on today's chips is growing in order to save space, particularly for the metal lines known as interconnects that connect a chip's transistors.

The fabrication of interconnect is a multistep process. First, temporary lines are built from a film such as amorphous carbon by first depositing the material, then etching a series of closely spaced trenches into the film. Next, the trenches are filled with a dielectric (insulating) material, the temporary structures are etched away, and metal is deposited into the now-vacant spaces, forming tall, thin lines of metal interconnect.

However, manufacturers found that sometimes the temporary structures would buckle (see Figure 5). This buckling was not well understood, but if it could be predicted, then Lam could determine which high aspect ratio geometries would be successful in a production environment.

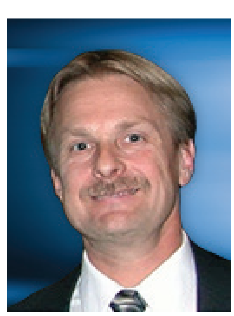
Woytowitz's group theorized that the buckling resulted from intrinsic compressive stress or possibly from mismatching coefficients of thermal expansion.

To investigate, they built COMSOL models, taking into account Young's modulus, for measuring the stiffness of an elastic material, and Poisson's ratio, the ratio of transverse to lateral strain. They compared these results with experimental values.

Analysis to date confirms that it is largely a buckling problem, and with an appropriate adjustment factor to correlate theory to experimental data, simulation can be used to predict when and how buckling will occur (see Figure 6).

» MODELING IS AN INCREASINGLY IMPORTANT TOOL

"**COMPUTATIONAL MODELING** is playing an increasingly important role at Lam, and we rely heavily on it," Woytowitz concludes. "COMSOL isn't the only tool we use, but its accuracy, ease of use, and the common look and feel of its user interface for many different physics domains allow us to become productive with it much more quickly and deeply than with other tools. These projects are just a few examples of how we are putting it to use." ◎



In addition to the individuals named in this article, thanks and acknowledgment go to all the technologists, engineers, and managers at Lam Research Corporation for their involvement and support in computational modeling. In particular, thanks go to Lam engineers **RAVI PATIL**, *for work associated with the gas ring (Figures 1 and 2), and to* **KEERTHI GOWDARU**, *for work associated with line-bending analysis (Figures 5 and 6).*

Peter Woytowitz, Director of Engineering, Lam Research Corp.

MEETING HIGH-SPEED COMMUNICATIONS ENERGY DEMANDS THROUGH SIMULATION

Simulation-driven design is employed at Bell Labs Research to meet the energy demands of exponentially growing data networks and reduce the operational energy costs of the telecommunications network.

By **DEXTER JOHNSON**

ENERGY DEMANDS ARE becoming a bottleneck across multiple industries. From reducing the energy costs associated with operating a building to maintaining the exponential growth of high-speed networks, energy considerations are critical to success. Significantly improved energy efficiency is driving researchers at Bell Labs to design and implement new technologies in a scalable and energy-efficient way.

Bell Labs is the research arm of Alcatel-Lucent and is one of the world's foremost technology research institutes. Bell Labs Alcatel-Lucent founded the GreenTouch consortium, a leading organization for researchers dedicated to reducing the carbon footprint of information and communications technology (ICT) devices, platforms, and networks. The goal of GreenTouch is to deliver and demonstrate key components needed to increase network energy efficiency by a factor of 1000 compared with 2010 levels.

The Thermal Management and Energy Harvesting Research Group at Bell Labs (Dublin, Ireland) leads Alcatel-Lucent's longer-term research into electronics cooling and energy-harvesting technology development. It has developed two new energy-saving approaches that promise significant savings.

One research project is targeting between 50 and 70 percent energy reduction by improving the thermal management surrounding the photonic systems by means of which laser light transmits data through our networks. Meanwhile, another team has developed an entirely new approach to the harvesting of energy from ambient vibrations that generates up to 11 times more power than current approaches and is used to power wireless sensors for monitoring the energy usage of large facilities.

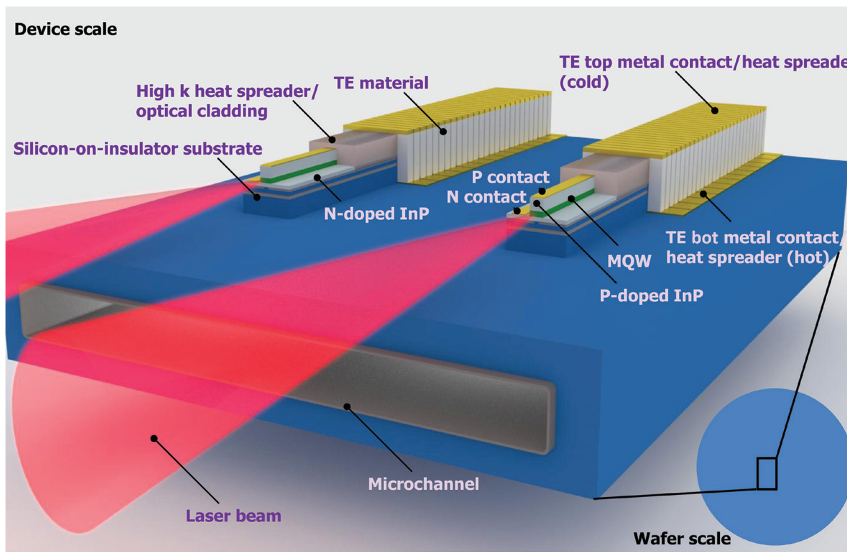


FIGURE 1: Schematic of the thermally integrated photonics system (TIPS) architecture, which includes microthermoelectric and microfluidic components.

» *USING SIMULATION TO MEET DATA TRAFFIC DEMAND WITH PHOTONICS COOLING*

THE EXPLOSION IN data traffic in the last few years is causing an immense strain on the current network, which was designed for low cost and coverage rather than energy efficiency. Energy management is becoming a major obstacle to the deployment of next-generation telecommunication products.

To address this issue, the Thermal Management team investigates all aspects of electronics and photonics cooling. The research team is realizing benefits that affect product performance by employing multiphysics simulation at multiple length scales—from the micrometer scale to the macro level.

To find efficiencies at the micrometer scale, Bell Labs has turned to COMSOL Multiphysics® to model potential approaches for cooling photonic devices that rely on the thermoelectric effect. Thermoelectric

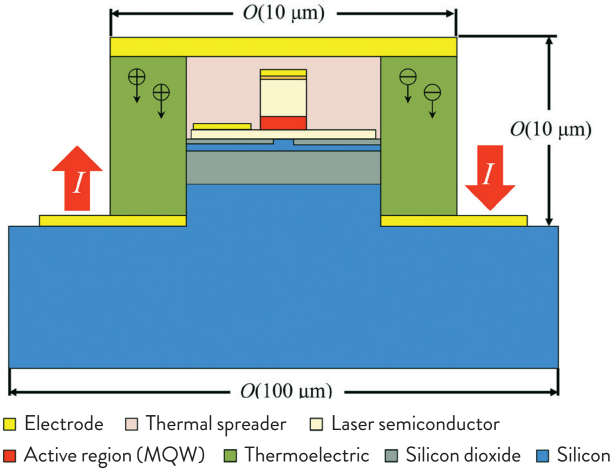


FIGURE 2: Cross-section schematic of laser architecture with integrated µTEC (not to scale).

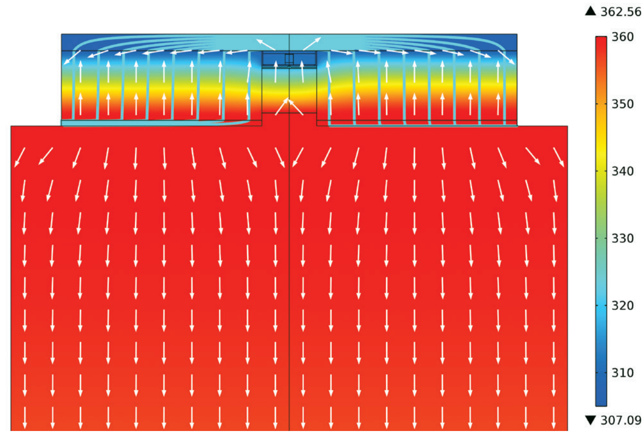


FIGURE 3: Multiphysics simulation of a laser with an integrated µTEC where temperature (surface plot), current density (streamlines), and heat flux (surface arrows) are shown.

materials are those in which a temperature difference is created when an electric current is supplied to the material, resulting in one side of the material heating up and the other side cooling down to provide heat pumping against an adverse temperature gradient. This effect can be employed to provide high-precision temperature control of photonics devices and forms one of the core building blocks within a novel architecture called a thermally integrated photonics system (TIPS), as depicted conceptually in Figure 1. Using the TIPS architecture, the team has simulated the electrical, optical, and thermal performance of new laser devices with the integrated microthermoelectric coolers (µTECs), as shown in Figure 2. Such µTECs have the potential to be applied in telecommunication laser devices that require cooling to maintain their design output wavelength, output optical power, and data transmission rates. Simulation results from COMSOL Multiphysics are shown in Figure 3 and help optimize the system design. The challenges in cooling photonics devices include precise temperature control, extremely high local heat fluxes, and micrometer-size features that need to be cooled. In particular, the research team investigated how precise temperature control and refrigeration are maintained in these systems through µTECs that are integrated with semiconductor laser architectures.

"COMSOL is the best simulation software solution for simultaneously solving all the physical processes associated with advanced photonic integrated circuits," says Shenghui Lei, one of the Bell Labs team members looking at photonics cooling. "The reason for this is that thermoelectric effects—Peltier, Thomson, and Seebeck—and the resulting temperature and electrical fields are all coupled within the same simulation environment, COMSOL. This provides deeper physical insight into the problem."

Another key COMSOL functionality is the link between COMSOL and MATLAB® through the LiveLink™ interface. This link lets the team accelerate the design phase by accurately modeling different parts of the package with design rules in MATLAB®.

> *"COMSOL is the best simulation software solution for simultaneously solving all the physical processes associated with advanced photonic integrated circuits."*
> **—SHENGHUI LEI, BELL LABS**

"If we look at the length scales of typical lasers used in photonics devices, you are talking about micrometers to tens of micrometers," says Ryan Enright, TIPS technical lead at Bell Labs. "However, laser performance is coupled from that scale all the way up the thermal chain until you get to the ambient air on the board. Solving complicated multiphysics problems across multiple length scales is computationally expensive. So we value the functionality of being able to use COMSOL and MATLAB® together to provide insight into the role of system design on laser performance in a computationally efficient way."

Domhnaill Hernon, Research Activity Lead at Alcatel-Lucent, further explains that, beyond just capturing the thermal behavior of integrated thermoelectrics, by carefully validating simulations against experimental device performance data it's also possible to more precisely determine the region of

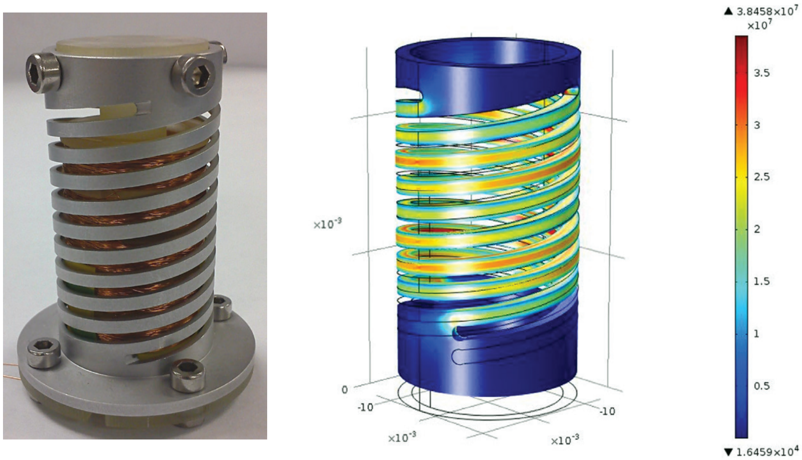


FIGURE 4: Left: Prototype of novel machined-spring energy harvester. Right: Simulation of the energy harvester, showing von Mises stress.

the laser device that caused the heat generation in the first place.

"It's the capability of accurately modeling the heat generation source and then coupling that to the device- and system-level cooling solutions where we see the power of COMSOL," says Hernon.

» *OPTIMIZING A NEW ENERGY-HARVESTING DEVICE*

PHOTONICS COOLING IS not the only way that Bell Labs is addressing energy concerns. Simulation is also enabling wireless sensors to be powered autonomously, reducing the need to frequently replace batteries in a network. Large-scale commercial deployments of wireless sensors have been hindered by costs associated with battery replacements.

The Bell Labs Energy Harvesting team developed a solution that efficiently converts ambient vibrations from motors, AC, HVAC, and so on to useful energy. In this way, a wireless sensor can potentially be powered indefinitely. Energy-harvesting technology can be employed in many different ways with low-power wireless sensors in applications ranging from monitoring energy usage in large facilities to enabling the large-scale sensor deployments of the future Internet of Things (IoT).

The energy-harvesting devices designed at Bell Labs operate by converting vibrations into electricity thanks to electromagnetic induction. Traditionally, energy harvesters consist of a single magnet that moves inside a coil, thus inducing a current.

The team employed simple physical principles: the conservation of momentum and velocity amplification. The design they developed uses multiple masses, or what is called multiple degrees of freedom, and can significantly amplify the velocity of the smallest mass in the system. This novel energy-harvesting device is now being investigated, as it is more efficient at converting ambient vibrations into electrical current than similar technology that does not employ the multiple-degree-of-freedom approach.

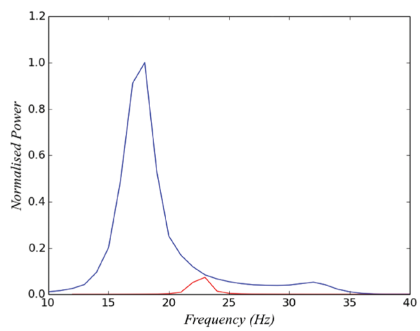


FIGURE 5: The figure compares the Bell Labs design (blue line) with a similar state-of-the-art single-mass system (red line). The multiple-mass system designed by Bell Labs has 11 times greater peak energy.

COMSOL is used for modeling the magnetic, electrical, and structural behavior of this system. See Figure 4, left for a picture of the energy harvester prototype and Figure 4, right for simulation results.

"We are using COMSOL to examine the electromagnetic coupling and the magnetic field distribution," says Ronan Frizzell, the lead researcher on this topic. "We've used the parametric sweep capabilities of COMSOL to optimize the system configuration and better understand the system dynamics."

A parametric sweep allows for the understanding of how the performance of the system is affected if you change one of its components, such as a spring or a magnet orientation. Figure 5 shows experimental results for the novel energy-harvesting device whose design process made use of COMSOL to achieve an enhanced understanding of the system dynamics involved.

"Reasonably quickly we can go through a parametric sweep, and by that I mean looking at structural, electrical, and magnetic parameters that are important to the system and how they couple together and affect each other," says Hernon. "That's very important. We don't look at them separately, but we use COMSOL to look at them in a coupled way. It's important for optimizing the system for real-life deployment."

While these technologies are not yet in commercial use, Hernon and his colleagues are confident they are getting a level of accuracy in the models for these new technologies that could only have been reached before by using much more time-consuming and laborious methods. At this pace of development, Hernon believes that the new thermoelectric cooling methods and innovative energy-harvesting devices should see commercial use in as little as five years. ◎

NANORESONATORS GET NEW TOOLS FOR THEIR CHARACTERIZATION

Nanoresonators offer optical science a new subwavelength tool to control light, and at Institut d'Optique d'Aquitaine, we have developed a method to gain new insights into their properties.

By **JIANJI YANG,** post doctorate at Laboratoire Photonique, Numérique et Nanosciences (LP2N), **MATHIAS PERRIN,** CNRS scientist at Laboratoire Ondes et Matière d'Aquitaine (LOMA) and **PHILIPPE LALANNE,** Directeur de Recherche at LP2N

AT THE LABORATOIRE PHOTONIQUE, Numérique, et Nanosciences of the Université de Bordeaux in France, we have been working to develop a method for understanding and predicting the interaction of light with matter at the subwavelength scale.

We have implemented a numerical tool based on electrodynamics equations using COMSOL Multiphysics®, its RF Module, and MATLAB®. Simulation is particularly useful for developing and operating the emerging technology known as nanoresonators, or optical nanoantennas. Theory, analytical solutions, and simulation provide great insights into how these devices operate and shorten their development time. This will favor the use of nanoresonators in applications ranging from photovoltaics to spectroscopy.

» *WHY ARE NANORESONATORS USEFUL?*

THE INTRODUCTION OF nanoresonators has been a relatively recent event in optics. These devices manage the concentration, absorption, and radiation of light at the nanometer scale in much the same way as it is accomplished with microwaves at much larger scales. An example of an optical nanoantenna is given in Figure 1, where a source, placed in between two gold nanospheres, is coupled to the far field more strongly than if it were alone in vacuum. Typically, the shape of the antenna can control the radiation. For example, Figure 2 shows how a silver sphere illuminated by a plane wave influences the scattered near-field.

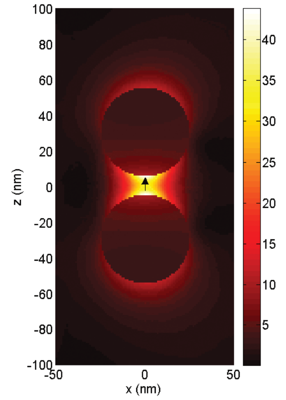


FIGURE 1: Example of nanoantenna: Intensity of electric field radiated by a gold sphere doublet coupled to a dipolar source (represented with a black arrow). The sphere radii are only 25 nanometers, and the distance between the spheres is 10 nm. The power radiated by the source is much larger than the power that would be radiated by the same source in the absence of the spheres. The radiation diagram in the far field can be controlled by tailoring the shape of the antenna. All dimensions are much smaller than the emission wavelength of 505 nm.

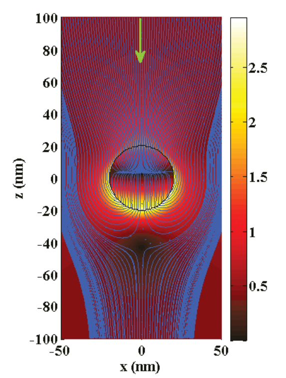


FIGURE 2: Intensity of the electric field around a single silver sphere with a radius of 20 nm illuminated by a plane wave incident from the top (the green arrow indicates the direction of propagation). The flux lines are represented in blue.

» *MODELING ELECTRODYNAMICS IN NANORESONATORS*

SINCE NANORESONATORS are essentially made of metal and can have different shapes, their simulation should rely on a software that can represent their geometry and model their electromagnetic properties accurately.

However, the electromagnetic properties of metal are not so easy to model, especially when you are solving for problems in the time domain and with complicated shapes like small, oddly shaped objects with curves and sharp corners that are also very close together. To model such complex nanoresonators, we rely on the finite element method (FEM) to achieve accurate predictions. And with COMSOL, one can get very good numerical representations of the curved surfaces and corners and of the volume involved in the computation, so it's quite convenient and appropriate.

Until very recently, the state of the art was to solve Maxwell's equations for a particular excitation, i.e., for a given incidence, wavelength, and polarization of a light beam impinging on a resonator.

However, when using such an approach, the whole numerical simulation has to be redone each time the excitation field changes. The numerical load may then be too heavy to fully characterize the nanoresonator, and above all, the computed results obtained with brute-force calculations may still hide a great deal of knowledge about the physical mechanisms at play.

» A NEW ANALYTICAL-NUMERICAL METHOD FOR CHARACTERIZING NANORESONATORS

USING THE STRIKING of a bell as an analogy for light excitation of a nanoresonator, it is possible to understand that any hammer stroke will more or less excite the same vibration modes of a bell. The latter represents an intrinsic characteristic of the resonator that does not depend on the excitation. If one is able to find these modes and understand how they are excited, then it is possible to describe the interactions between the resonator and its environment much more easily and intuitively and without the need to rely on brute-force calculations. Very rapidly, we realized how helpful it was to have a modal theory to describe our resonators.

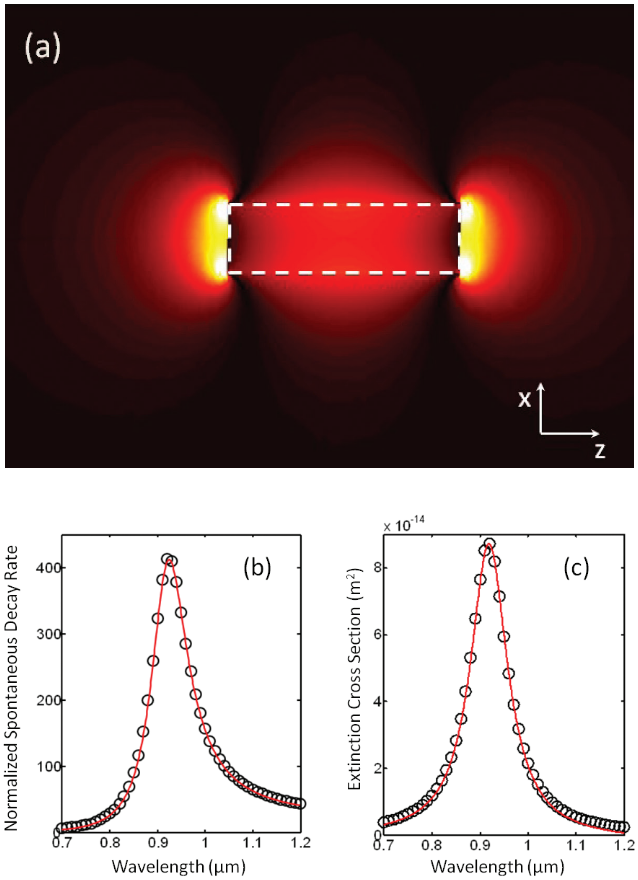


FIGURE 3: (a) Distribution of z-component of the electrical field |Ez| for the normalized quasinormal mode of a cylindrical gold nanorod with a diameter of 30 nm and a length of 100 nm. The white dashed line represents the rod contour. (b) Spontaneous decay rate of a cold molecule located on the rod axis at a 10 nm distance from the rod. (c) Attenuation cross section of the rod under illumination by a plane wave polarized along its axis. In (b) and (c), black circles are fully vectorial computational results obtained with COMSOL. Each point requires an independent calculation. Simulation results are in good agreement with the predictions of the analytical model represented by the solid red curves.

Our initial contributions were more theoretical. We knew that if you hit a nanoresonator with light, you are going to excite its resonance modes, which is obvious. Defining what the excitation strength is analytically, however, was not obvious. Using COMSOL, we created a tool that calculates the modes and their excitations quite easily and solved this long-standing problem.

We were able to use COMSOL both to compute the response of the system to a particular excitation and to compute the modes of the nanoresonator. The fact that COMSOL can easily be interfaced with MATLAB® was an essential point for us, as our COMSOL simulation could be integrated as the field-computing engine of a theoretical procedure.

When we adapted our mathematical theory to COMSOL, it permitted the normalization of the modes and allowed us to compute their excitation coefficients simply by evaluating a volume integral. This part was crucial, as it further resulted in a rapid and analytical method to calculate the electromagnetic field scattered by the resonator along with all the associated physical quantities, such as the scattering and absorption cross sections and the radiation diagram, as depicted in Figure 3.

Now that a method has been developed to understand how light is scattered by nanoresonators, we expect that this will assist in the spread of nanoresonators in a number of optical applications, ranging from sensors and defense applications to computers and electronics. A new breed of devices called nanoelectromechanical systems (NEMS) will soon see the light, thanks to simulation. ◎

SIMULATION TURNS UP THE HEAT AND ENERGY EFFICIENCY AT WHIRLPOOL CORPORATION

Researchers at Whirlpool Corporation are using simulation to test innovative and sustainable technologies for new oven designs.

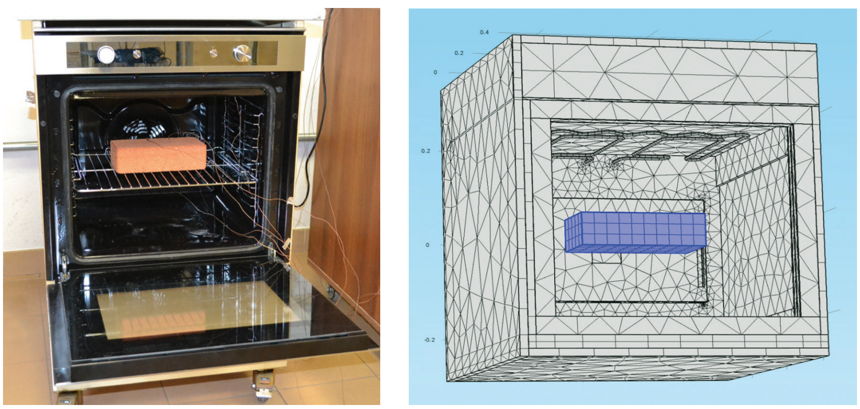


FIGURE 1: Left: Whirlpool's Minerva oven set up for the "brick test." Right: The meshed geometry.

By **ALEXANDRA FOLEY**

IN TERMS OF energy consumption, ovens have the most room for improvement of any appliance in the kitchen, with only 10 to 12 percent of the total energy expended used to heat the food being prepared. This is one of the reasons why Whirlpool Corporation, the world's largest home appliance manufacturer, is exploring new solutions for enhancing the resource efficiency of their domestic ovens. Using a combination of experimental testing and finite element analysis (FEA), Whirlpool engineers are seeking solutions to improve energy efficiency by exploring new options for materials, manufacturing, and thermal element design.

In partnership with the GREENKITCHEN project, a European initiative that supports the development of energy-efficient home appliances with reduced environmental impact, researchers at Whirlpool R&D (Italy) are studying the energy consumption of their ovens by exploring the heat transfer processes of convection, conduction, and radiation. "Multiphysics analysis allows us to better understand the heat transfer process that occurs within a domestic oven, as well as test innovative strategies for increasing energy efficiency," says Nelson Garcia-Polanco, Research and Thermal Engineer at Whirlpool R&D working on the GREENKITCHEN project. "Our goal is to reduce the energy consumption of Whirlpool's ovens by 20 percent." Even if only one electric oven is installed in every three households in Europe, the resulting increase in efficiency would reduce the annual electricity usage of European residential homes by around 850 terawatt-hours. This would lead to a reduction of about 50 million tons in CO_2 emissions per year.

» LIGHT AS A FEATHER, NOT THICK AS A BRICK

A LOAF OF bread should be as light as a feather, not, as they say, as thick as a brick. Ironically, the standard test for energy consumption in the European Union, known as the "brick test," involves heating a water-soaked brick and measuring temperature distribution and evaporation during the process. "A brick is used since it offers a standard test for all ovens. The brick is created to have similar thermal properties and porosity as that of many foods, making it a good substitute," says Garcia-Polanco.

During the experiment, a wet brick with an initial temperature of 5°C is placed in the oven's center and is heated until the brick reaches a previously defined "delta" temperature (in this case, 55°C). The temperature and amount of water evaporated from the brick are recorded throughout the experiment. Using simulation, Garcia-Polanco and the team created a model of Whirlpool's Minerva oven to explore its thermal performance during this test (see Figure 1).

» ACCURATE SIMULATIONS PROVIDE THE RIGHT SOLUTION IN LESS TIME

THE SECRET TO efficient cooking lies in the heat transfer rate, which describes the rate at which heat moves from one point to another. Inside an oven, food is heated by a combination of conduction, convec-

> *"Our goal is to reduce the energy consumption of Whirlpool's ovens by 20 percent."*
> —**NELSON GARCIA-POLANCO, RESEARCH AND THERMAL ENGINEER AT WHIRLPOOL R&D**

GREENKITCHEN is a European Union funded research project where Whirlpool R&D is a partner.

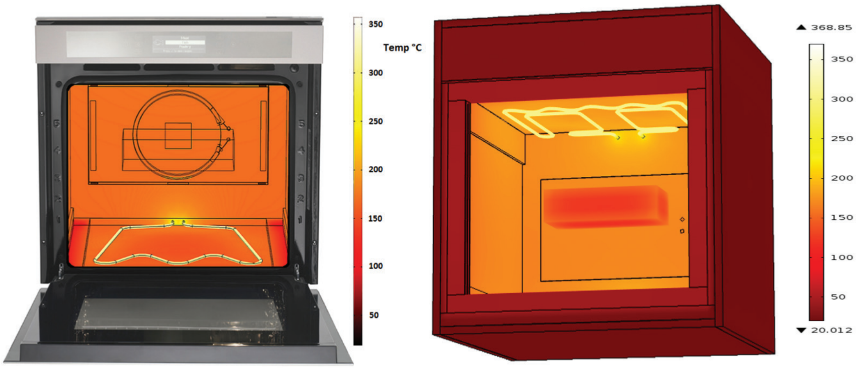
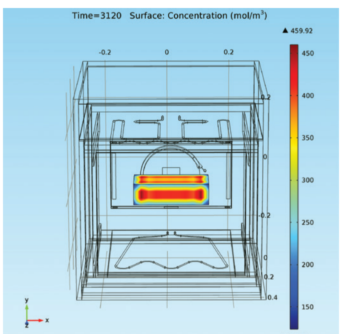


FIGURE 2: Predicted temperatures of the oven surfaces (color scale in °C) after 50 minutes in a broil cycle (right) and a bake cycle (left).



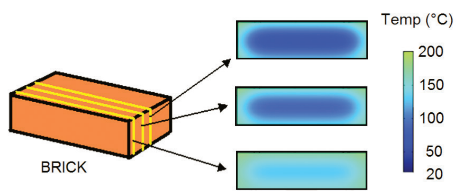
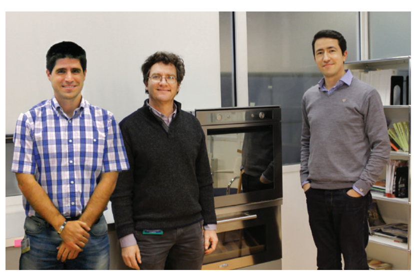


FIGURE 3: Left: Brick surface moisture concentration (in moles per cubic meter) at the end of the simulated test. Right: Predicted temperature profiles at different slices of the brick after 50 minutes at 200°C.

tion, and radiation. "The static cycle heats the oven from the bottom (bake) and the top of the cavity (broil) using the corresponding heating elements, while the forced convection cycle uses the same configuration along with an internal fan," says Garcia-Polanco. "Therefore, radiation is most important during a static cycle, and convection dominates during the forced convection cycle." The simulation took into account the different heat transfer rates of the various heating methods (see Figure 2) as well as a combination of different elements including material properties, oven shape, and the type of food being prepared.

There are several factors that proved especially important when considering the transient behavior of the oven model. "We considered the emissivity of the glass door, the thickness of the walls, and the material properties of the walls," says Garcia-Polanco. "We made a detailed comparison of the results of both the simulation and actual



From left to right: Joaquin Capablo, Energy Engineer; John Doyle, Principal Engineer, Energy & Environment; and Nelson Garcia-Polanco, Thermal Engineer.

experiment throughout the heating cycle, which helped verify that our simulation was accurate."

In addition to predictions of the temperature of the oven surfaces, detailed information about the temperature profiles and moisture concentrations within the brick were acquired. "We looked at the temperature behavior within the brick," says Garcia-Polanco (see Figure 3). "When we compared data from our simulation with the experimental data, we found that our predictions about the internal temperature of the brick closely matched that of our experimental data." Knowing that the simulation is accurate will allow Whirlpool's team to probe the oven and brick at any point in space and time with confidence in the results they obtain. "For our future experiments, this knowledge will help us to save both time and money by reducing the number of prototypes and design iterations we go through before settling on a final oven design."

The team also looked at the water concentration in the brick throughout the experiment. The experimental results were very close to the simulation, with an average predicted value of 166 grams of evaporated water after 50 minutes and an actual value of 171 grams. "Knowing the rate at which water evaporates from the brick will help us to conduct further studies into different strategies for reducing energy consumption without decreasing the final quality of the product," says Garcia-Polanco.

» *A RECIPE FOR HIGH-QUALITY, HIGH-EFFICIENCY COOKING*

THE RESULTS FROM this verification study will help further the mission of GREENKITCHEN project to empower innovative households to reduce national energy consumption and improve energy efficiency in Europe. A proven, reliable model simplifies the verification of new design ideas and product alterations, helping designers to find the right solution in less time. "This study confirmed that our model is accurate, allowing us to be confident in the results when we test future design ideas," concludes Garcia-Polanco. "Our next steps will be to use this model to optimize the use of energy resources in the oven and to deliver a robust, energy-efficient design to the European market." ◎

INNOVATIVE PACKAGING DESIGN FOR ELECTRONICS IN EXTREME ENVIRONMENTS

Extreme environments and high currents pose challenges for designers in the power electronics industry. Using multiphysics simulation, Arkansas Power Electronics International has developed new packaging to improve the performance and thermal management of power electronics devices.

By **LEXI CARVER**

EVERY TIME YOU start your car, use your phone, or turn on a modern lamp, you're relying on a product from the power electronics industry. In addition to supplying products used by billions of people on a daily basis, this industry concerns itself with energy density, power density, customer safety, and cost per watt. Consequently, there is an obvious need for ways to analyze and refine designs for these devices while increasing efficiency and lowering cost.

» PUSHING LIMITS WHILE PREVENTING FAILURE

MECHANICAL, THERMAL, and electrical properties influence the performance and thermal management of power electronics devices; a temperature increase outside the specified operating conditions may cause failure or produce increased resistance, threshold drifts, and lower switching frequencies, all of which reduce efficiency and controllability. Parasitic inductances in device packaging create voltage spikes that shorten the lifetime of a device. Arkansas Power Electronics International, Inc. (APEI), a company that designs and manufactures high-efficiency power electronics, has addressed this problem by designing new packaging systems and power modules. Brice McPherson, a lead engineer at APEI, and his colleagues are developing power modules and discrete packages with better thermal management capabilities than the industry standard (see Figure 1). One of their designs has 25 percent reduced thermal resistance and half the inductance of the widely used transistor outline (TO) package.

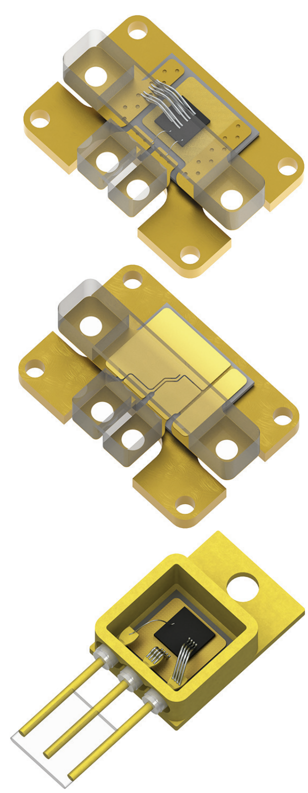


FIGURE 1: The custom SiC (top), custom GaN (middle), and TO (bottom) power modules.

Their goal is to create power modules with a packaging robust and flexible enough for use in many applications—one that is small and easy to configure, with good thermal conductivity and low inductance.

» SEMICONDUCTORS FOR EXTREME ENVIRONMENTS

A CLASS OF materials known as wide-bandgap semiconductors can operate stably at high temperatures and frequencies, and these materials therefore have an advantage over typical silicon-based power electronics. Systems based on wide-bandgap semiconductors may be more usable in extreme conditions—for example, in drilling equipment used at depths with higher pressures and temperatures than are currently reachable. It may even be possible to improve the survivability of equipment in environments as harsh as that on the surface of Venus.

Two materials have become the cornerstones for APEI's new designs: gallium nitride (GaN) and silicon carbide (SiC). For medium currents and thermal loads where extremely fast and efficient switching is required, GaN is optimal. For very high currents and thermal loading where large amounts of energy need to be processed in a small area—such as in a vehicular motor drive—SiC is the best choice. APEI worked with GaN Systems in Ottawa, Canada, a leading provider of high-performance GaN devices, to design the GaN power package. McPherson and his colleagues exploited the materials'

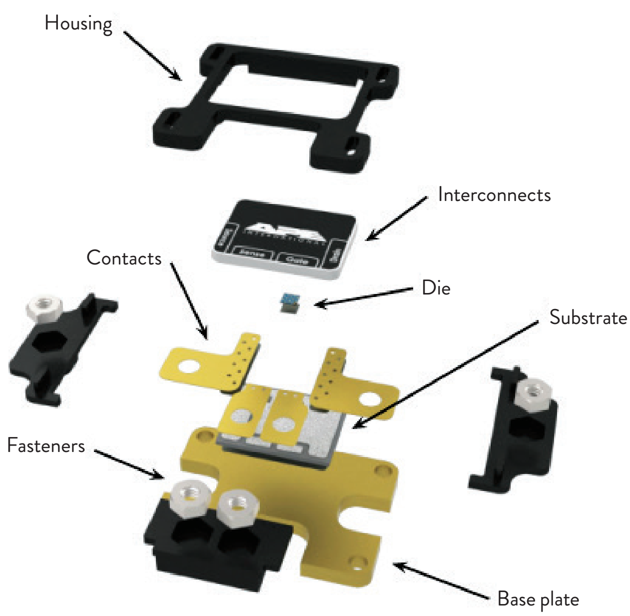


FIGURE 2: Power module components (above) and the assembled power module (bottom). Fully assembled, the entire device is a little larger than a quarter.

SiC Power Package	
Inductance	7.83 nH
Thermal Resistance	0.38°C/Watt
Operating Temp	225°C

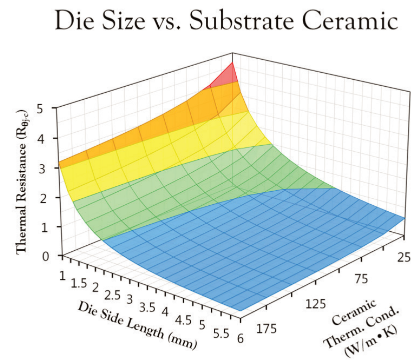


FIGURE 3: Parametric sweep showing how thermal resistance varies with changes in device size and thermal conductivity of the substrate.

properties to develop breakthrough power-packaging technology.

» IMPROVING PERFORMANCE THROUGH REDUCED THERMAL RESISTANCE AND INDUCTANCE

TO ACCOMPLISH THIS, they embarked on a search for the right combination of geometry and thermal and electrical properties to effectively optimize power density, weight, and switching frequency. They wanted a design that offered the ease of use and capabilities of a larger, higher-power module but was no larger than the TO option. Their new power module includes the die (the device), a copper base plate, contacts, interconnects, fasteners, a housing, and a metal substrate between the contacts and the base plate (see Figure 2).

McPherson combined his packaging and systems expertise with the simulation tools of COMSOL Multiphysics®. The LiveLink™ *for* SolidWorks® add-on let him directly import his geometry from SolidWorks® and run a parametric sweep analysis in COMSOL. He compared his designs, applied temperatures and voltage boundary conditions, and analyzed their electrical and thermal performances. He tested the effects of changing device dimensions, base plate thickness, substrate thickness, and material properties.

> *"It's very valuable to be able to simulate something before you invest money and time into prototyping and building it."*
>
> **—BRICE McPHERSON, LEAD ENGINEER, APEI**

One major benefit of the multiphysics modeling process was being able to model Joule heating and analyze the amount of heat generated in the conductors. "APEI specializes in high power density products, which need a lot of precise testing before they're perfected. It's very valuable to be able to simulate something before you invest money and time into prototyping and building it," McPherson says. The majority of the parametric sweeps he performed (one is shown in Figure 3) aimed to optimize thermal resistance, current-carrying capacity, and footprint.

"Designing for low thermal resistance involves selecting materials with high thermal conductivity, reducing the distance heat travels to leave the layers, and optimizing layer thickness to take advantage of thermal spreading," McPherson explains. "That's where parametric modeling is your best friend: You can set up parametric sweeps to find out exactly what's influencing

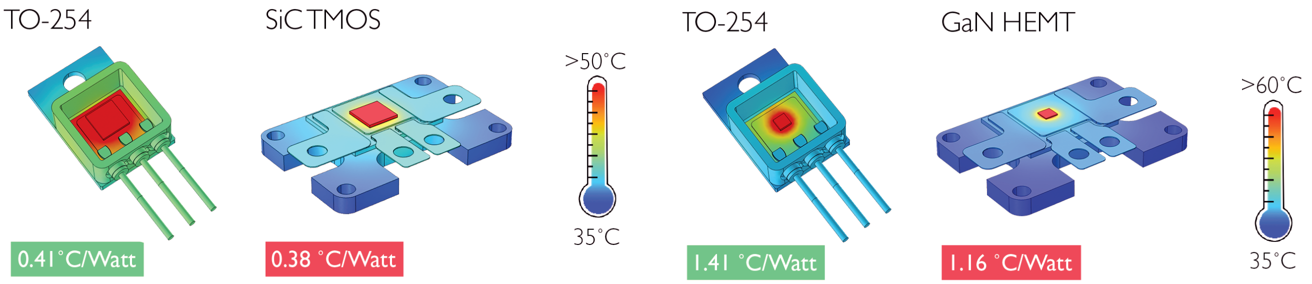


FIGURE 4: Thermal resistance results when comparing TO-254 to SiC (left) and TO-254 to GaN (right).

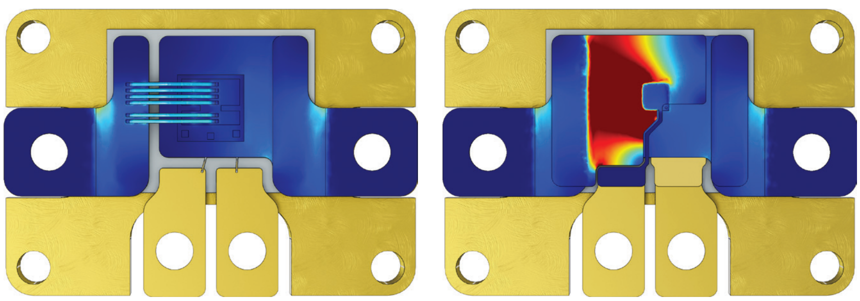


FIGURE 5: Current density gradients in the SiC (left) and GaN (right) geometries. In the SiC package, the current shows a relatively low density (preferred for higher currents), with the major concentrations found in the wire bonds. The GaN package has a higher average density, but more area available for conduction (ideal for low inductance).

the system the most and get the best compromise among performance, complexity, and cost." McPherson modeled a TO-254, a common TO transistor, to see how his designs (see Figure 4) compared.

Figure 5 gives a detailed view of current density in both packages. According to the simulations, APEI's power modules had lower thermal resistance than the TO-254 (see Figure 4). Even better, they both showed significantly lower inductance. The parameter with the greatest influence on the inductance turned out to be the device size, followed by the thickness of the base plate. To reduce inductance, it was critical to maximize the cross-sectional area of the device and minimize the current path length, while maintaining an acceptable thermal performance. The GaN module shows the least inductance, and the TO-254 exhibits the highest (12.98 nanohenries for the TO-254 vs. 7.5 nH and 7.83 nH for GaN and SiC, respectively). The current path length and conductor geometry drive the inductance trends, while the die size and material are less influential than in the thermal simulations.

> *"You can set up parametric sweeps to find out exactly what's influencing the system the most and get the best compromise among performance, complexity, and cost."*
>
> —BRICE McPHERSON

APEI's new packaging is flexible enough to be used with either material, according to the needs of the customer. It operates well with GaN and SiC, which both allow for rapid, clean switching.

» APEI DELIVERS THE NEW PACKAGING STANDARD USING MULTIPHYSICS SIMULATION

MCPHERSON SUCCESSFULLY created a power module that improves on industry standards, with a packaging that ensures low inductance, good thermal management, and can be operated at temperatures over 225°C. His work demonstrates the potential of improving packaging to enhance current electronics technology and the use of a powerful simulation tool such as COMSOL to aid the design process. McPherson hopes that this design, with its strong thermal performance, will improve existing options but also open doors to new applications. His remarkable results are an encouraging move toward more efficient power modules, paving the way for power electronics to deliver higher currents and be used in more extreme conditions. Perhaps Venus is not so far away after all.

MAKING SMART MATERIALS SMARTER WITH MULTIPHYSICS SIMULATION

What if a material could be designed to transform in response to external stimuli, exhibiting certain characteristics only when exposed to a specific environment?

By **ALEXANDRA FOLEY**

MATERIALS THAT DEMONSTRATE different responses to varying external stimuli are known as "smart materials," and their discovery has led to the creation of products that perform on a whole new level. These engineered materials are developed to perform smarter and more efficiently than their predecessors, allowing materials to be designed based on the products and environments in which they will be used. Magnetostrictive materials are engineered smart materials that change shape when exposed to a magnetic field and they have proven crucial for the production of transducers, sensors, and other high-powered electrical devices.

Engineers at ETREMA Products, Inc. design devices using magnetostrictive materials for defense and other industry applications including sensors, loudspeakers, actuators, SONAR, and energy harvesting devices. The unique properties of magnetostrictive materials—their ability to mechanically respond to magnetic fields and their characteristic nonlinearity—make designing these devices a challenge.

Researchers at ETREMA have found that multiphysics simulation can be used to accurately represent the material properties and complex physics interactions within such devices, facilitating the production of the next generation of smart products.

» DESIGN AND SIMULATION OF MAGNETOSTRICTIVE TRANSDUCERS

MAGNETOSTRICTION OCCURS AT the magnetic domain level as magnetic regions realign in response to variation in either magnetic or mechanical energy, causing a change in a material's shape or magnetic state (see Figure 1).

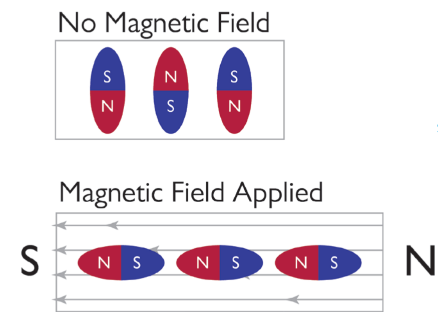


FIGURE 1: Magnetostrictive materials change their physical shape in response to an applied magnetic field and vice versa.

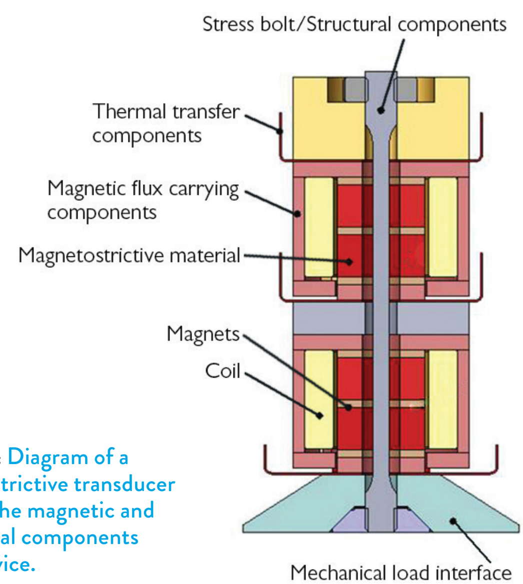


FIGURE 2: Diagram of a magnetostrictive transducer showing the magnetic and mechanical components of the device.

For example, the magnetostrictive material iron elongates by 0.002 percent when exposed to a strong magnetic field, and nickel contracts by 0.007 percent under that same field. Terfenol-D, a "giant magnetostrictive material," demonstrates deformations 100 times that of iron and was first developed by the U.S. Navy in the 1970s. ETREMA is currently its sole commercial producer.

ETREMA designs magnetostrictive transducers (see Figure 2) using Terfenol-D—devices that convert magnetic energy into mechanical energy and that are critical components of many larger, more complex systems. To accurately model these complex devices, ETREMA uses COMSOL Multiphysics® . Their simulations include permanent magnets and coils, the magnetic fields created by these coils, stress and modal analyses of structural mechanics components, as well as heat transfer in the device to mitigate heat generated by eddy currents and hysteresis. Fully coupled models are used to evaluate the overall electro-mechanical characteristics of these transducers.

"When we first began to expand our engineering process to model such devices, our modeling techniques consisted of a system of disjointed methods that included hand calculations, equivalent circuits, and single-physics modeling," says Julie Slaughter, Senior Engineer at ETREMA. "However, our decision to move toward a devices and systems approach coincided with the advent of multiphysics finite element analysis and we adopted COMSOL as our modeling tool for systems-based modeling. This greatly improved our understanding of transducers and their design."

ETREMA's modeling approach demonstrates the unique flexibility of COMSOL Multiphysics. First, models are created to analyze individual physics; then, multiphysics simulations are built to determine how the physics interact with one another. This approach allows for both a targeted look as well as a complete picture of the physics interactions taking place within their devices.

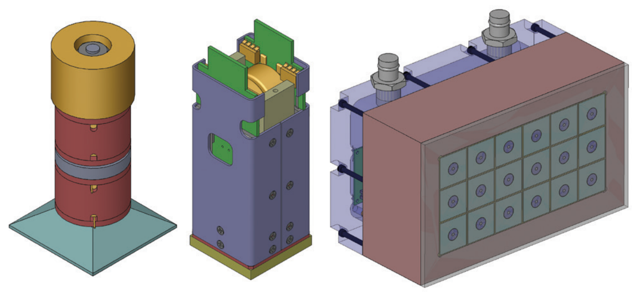


FIGURE 3: Closely packed SONAR array, which includes a magnetostrictive transducer at its core. From left to right: a single magnetostrictive SONAR transducer; the transducer packaged with power electronics; and the full array, made up of 18 transducer elements.

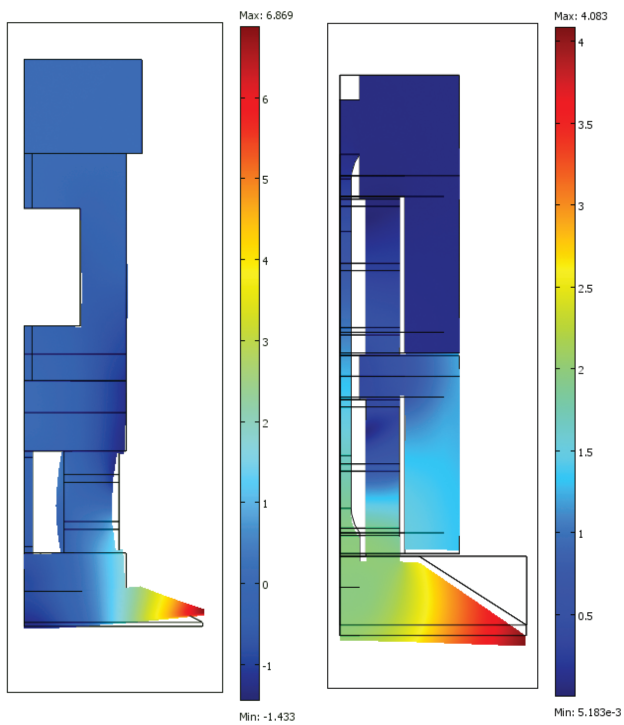


FIGURE 4: Left: The initial transducer design shows severe bending in the mechanical interface to the load. Right: The redesigned model demonstrates reduced deformation.

» *DESIGN DIAGNOSIS*

AN OVERVIEW OF this design process can be seen in the design of a close-packed SONAR source array, which includes a magnetostrictive transducer at its core (see Figure 3). Not only are there many different material properties that need to be analyzed and optimized, but the transducer also contains a combination of electrical, magnetic, and structural physics that interact within the device.

Deformation within the transducer was analyzed using a single-physics model in which static loads were used to estimate fatigue and determine if the prestressed bolts and Terfenol-D core would hold up against the system's strain. The initial transducer design demonstrated severe bending at the mechanical interface between the transducer and the load, however further load analysis and structural optimizations allowed the transducer to be redesigned with reduced deformation and stress (see Figure 4). The model was also used to detect undesirable modes of vibration in the operating bandwidth that could affect overall performance.

Single-physics models were developed to evaluate the DC and AC magnetics separately. "We matched the electrical requirements of the transducer with the available power amplifiers, and evaluated electrical losses due to eddy currents and air gaps within the device," says Slaughter. Permanent magnets were integrated into the transducer design to magnetically bias the material to enable bidirectional motion and minimize nonlinear behavior and frequency-doubling effects. "Stray magnetic fields in close proximity with the electron-

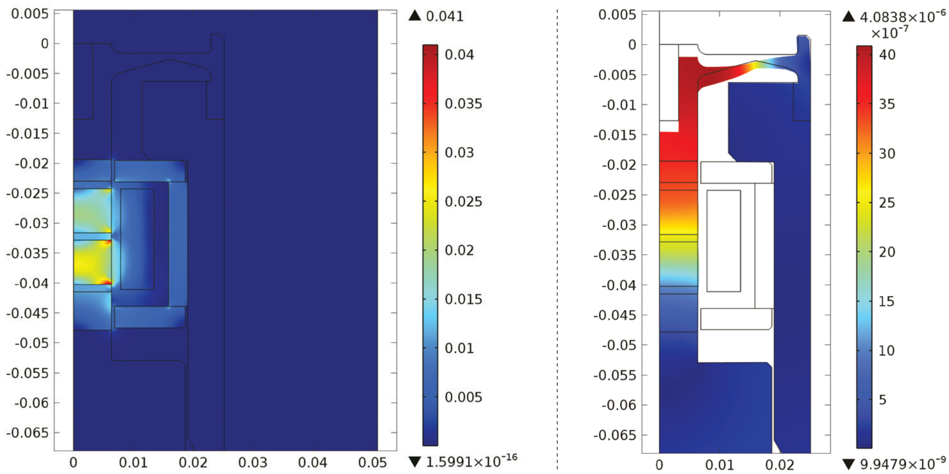


FIGURE 5: Magnetic fields generated from a 1-ampere input to the coil. Displacements are calculated using the maximum current input.

ics can cause problems with noise and corrupted signals," Slaughter explains. "We had to carefully consider the design of the transducer's magnetic circuit as well as the placement of key electrical components to avoid stray magnetic flux that can interfere with the electronics."

Using COMSOL, ETREMA researchers were able to find a design that was optimized for the competing requirements of both the AC and DC magnetics. The models for this design demonstrated that the magnetic fields mainly stay confined to the magnetic components, thereby reducing the exposure of the electronics to the magnetic fields.

> *"When setting up our multiphysics models, we use coupled equations, where strain is a function of stress and also of the magnetic field."*
>
> —**JULIE SLAUGHTER, SENIOR ENGINEER, ETREMA PRODUCTS, INC.**

» DESIGN VALIDATION

THE NEXT STEP in ETREMA's design process was to create fully coupled multiphysics models. "When setting up our multiphysics models, we use coupled equations, where strain is a function of stress and also of the magnetic field," says Slaughter. "This is the basis of implementing coupled magnetostriction in COMSOL." Using this process, Slaughter and her team determined how the magnetic and mechanical domains would interact within the device and ultimately predicted how the magnetostrictive material would behave (see Figure 5).

"For the coupled linear magnetostrictive model, our simulations showed that the device would perform largely as expected, with few adjustments needed in either the mechanical or magnetic aspects of the design," she continues. "The magnetic fields remained confined to the magnetic circuit, and deformations remained minimal."

These multiphysics models were further validated using experimental data. "The models of impedance and displacement were very similar to experimental results," says Slaughter.

» A MULTIPHYSICS APPROACH TO MODELING

AT ETREMA, BOTH single-physics models and fully coupled multiphysics simulations have proven to be powerful tools for transducer design, evaluation, and optimization. The construction of single-physics models allows for design diagnosis prior to the development of multiphysics models, where attributing an undesired interaction to a certain physics type is more straightforward. Coupled models then further describe the way the individual physics will interact in the real world. Although ETREMA focuses on magnetostrictive materials, all transducer technologies involve coupled multiphysics interactions, including piezoelectric, electrostatic, and electromagnetic effects, and each can benefit from the use of multiphysics simulations. Finite element models can be used at different stages of product development: During design development, for the evaluation of existing products, and when it is necessary to troubleshoot performance issues. ◎

FROM CONCEPT TO MARKET: SIMULATION NARROWS THE ODDS IN PRODUCT INNOVATION

By **CHRIS BROWN**

IN TODAY'S ELECTRONICS industry, innovation is essential for growth, while a short time from idea to market is the key to realizing maximum value. The argument that huge gains are possible by improving decision-making processes at an early stage of R&D—known for good reason as the "fuzzy front end"—is undoubtedly sound. In my experience, however, it is the quality of an idea and, crucially, the quality of the evidence supporting that idea that can really make the difference. Even the best processes cannot produce decisive outcomes when dealing with potentially ground-breaking technologies backed up by scant evidence. A quick, cost-effective way of narrowing the odds is needed.

Sharp Laboratories of Europe (SLE) in Oxford, UK is part of a global network of Sharp R&D sites responsible for delivering new technologies to the corporation. Our role is not only to support the continuous improvement of Sharp's current product portfolio but to secure the future success of Sharp in the longer term through more radical innovation to create entirely new product lineups.

A distinct change in the lab since I joined SLE almost 15 years ago is the move to a more multidisciplinary way of working. There has been a shift in focus to systems or products as a whole, such as health systems and energy systems. The multidisciplinary nature of our work brings with it an increased complexity, as our researchers must understand how all the parts fit together and the complicated relationships that exist at the boundary between two physical systems.

Fortunately, as the complexity of the problems we face in the lab has increased, advances in computer modeling provide a helping hand in the form of powerful finite element simulation tools such as COMSOL Multiphysics®. For us, a key advantage of COMSOL is that it enables virtual experiments to be carried out that cross the boundaries of different physical mechanisms and that would be difficult, time-consuming, and costly to try out in the real world.

One example of where COMSOL has been a valuable tool is in our project to develop a lab-on-a-chip device for medical diagnostic applications. The project leverages Sharp's LCD manufacturing expertise and is based on a technology, known as digital microfluidics, that enables precise control and manipulation of sub-millimeter-scale fluid droplets on top of an electronic sensor array. A key challenge in the development of the device lay in designing the fluid input ports to allow biological fluids and test reagents to flow onto the array under electronic control. Critically, the multiphysics capability of COMSOL enabled us to model interactions between the solid-liquid interface, electric field distribution, and fluid flow simultaneously. The result was an initial design for a fluid input structure that provided a more accurate starting point for experimental work when compared with simple hand calculations. The consequent reduction in the number of physical design iterations helped us reduce the R&D prototyping time and cost and will help bring the device to market more quickly than could otherwise have been achieved.

As electronics continue to proliferate into yet more facets of modern life, the boundaries between what were once distinct scientific and engineering disciplines will become ever more blurred. In research organizations such as SLE, where scientists and engineers are faced with increasingly complex problems and where speed of development is increasingly vital, COMSOL Multiphysics is well placed to become a truly indispensable tool. Those of us working in the fuzziness appreciate the guiding hand it provides. ◎

CHRIS BROWN *is manager of the Health & Medical Devices group at Sharp Laboratories of Europe. He holds B.A. and M.Eng. degrees in Electrical and Information Sciences from Cambridge University. After spending 10 years developing display technology for Sharp, including three years in Japan, he now leads a multidisciplinary research initiative combining electronics and biology to create new devices for the health care market. He is glad he can still find the time to work with COMSOL.*