IEEE SPECTRUM

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Power Play

B. JAYANT BALIGA INVENTED A NEW KIND OF TRANSISTOR AND LAUNCHED **A SEMICONDUCTOR REVOLUTION** P. 44

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On the Cover **Photograph for *IEEE Spectrum* by D.L. Anderson. Illustration by Mark Montgomery**

PHOTOGRAPH BY D.L. Anderson

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Quantum Controversy
With a series of high-profile sales, quantum-computing company D-Wave has been riding high. The company's CEO, Vern Brownell [above right], spoke with Rachel Courtland for a *Techwise Conversations* podcast about the debate over how D-Wave's machines operate, and if they can really beat conventional computers.

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LEVEL UP IEEE gaming experts say that in the next few years, some companies will implement a gaming system in which employees earn points for good performance. If they earn a certain number of points, they could get a promotion or a corner office.

REVAMP YOUR RÉSUMÉ Looking for a new job? Recruiters share tips on how to make your résumé stand out from the rest.

EMPOWERING WOMEN To mark the 20th anniversary of the IEEE Women in Engineering committee, we profiled one of its founders, Senior Member Jan Brown.

FROM LEFT: STEFFEN RICHTER/HARVARD UNIVERSITY; DAVID YELLEN; D-WAVE SYSTEMS

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BACK STORY_

Ghost Lusters

IN SHOOTING THE portrait of this year's IEEE Medal of Honor recipient, B. Jayant Baliga, photographer D.L. Anderson applied a technique that dates to the 19th century, when "spirit photographers" produced images of people alongside ghostly replicas of their deceased loved ones. Those renderings were fabricated by some less-than-scrupulous photographers who realized the effect was easy to produce using double exposure–something apparently lost on the gullible folks who viewed and purchased the pictures. (The ghost in Anderson's double-exposure self-portrait above is nothing more than a compact fluorescent bulb.)

Combining multiple exposures has remained a popular technique, especially because photographers can easily superimpose images these days using Adobe Photoshop or similar software. Anderson has long been using actual double exposures in his film photography and recently began applying the technique to create intriguing digital images as well. He does that not with Photoshop but "in camera," using a Canon 5D Mark III, which allows a photographer to combine multiple exposures into a single frame.

"It's a bit like painting," says Anderson, who spotted a semiconductor wafer when he visited Baliga's office and decided that a close-up of the patterns it contained would make an intriguing overlay on a portrait of his subject. By using gels and controlling the color temperature of the lighting, he was able to bring out pleasantly matching hues in the melded images. (You can see the result in "The Power Broker," in this issue.)

It turns out that the technology for controlling the color temperature and flash duration of Anderson's high-end strobe lights depends on the very device that Baliga pioneered in the 1980s: the integrated-gate bipolar transistor, or IGBT. Baliga and Anderson understood this subtle connection between their professions, which made their considerable efforts to get just the right picture that much easier for both. ■

CITING ARTICLES IN IEEE SPECTRUM *IEEE Spectrum* publishes an international and a North American edition, as indicated at the bottom of each page. Both have the same editorial content, but because of differences in advertising, page numbers may differ. In citations, you should include the issue designation. For example, Dataflow is in *IEEE Spectrum*, Vol. 51, no. 5 (INT), May 2014, p. 52, or in *IEEE Spectrum*, Vol. 51, no. 5 (NA), May 2014, p. 64.

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PHOTOGRAPH BY D.L. Anderson

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John Capp & Bakhtiar Litkouhi

Capp [left] and Litkouhi, authors of "The Rise of the Crash-Proof Car" [p. 24], are both with General Motors Research and Development. Capp is director of electrical- and control-systems research and strategic lead for automated driving technologies. Litkouhi runs research on vehicle control systems and is also program manager of the GM–Carnegie Mellon University Autonomous Driving Collaborative Research Lab. A childhood fan of the futuristic TV cartoon "The Jetsons," Capp marvels at how much progress has been made toward creating the kind of vehicle the show's George Jetson would recognize.

Dan Saelinger

To illustrate "The Rise of the Crash-Proof Car" [p. 24], Saelinger built mini danger zones for his tiny, bubble-protected cars to navigate. The sets included fallen trees, wandering deer, ominous rockslides, and even a multicar accident complete with engine fire (using dabs of rubber cement as the flammable material). Staging smart-car scenarios was fun, he says, "but I'd only be interested in having my car take more control if I could take a nap."

Susumu Sasaki

Sasaki, a professor emeritus at the Japan Aerospace Exploration Agency, spent much of his 41-year JAXA career researching space-based solar power systems, the subject of his article "It's Always Sunny in Space" [p. 38]. The best-case scenario for this technology, he says, is a global "paradigm shift" in which nations stop competing for energy resources on the ground, and instead work together to build grand orbital power stations that beam clean energy down to Earth. He remains optimistic.

Katherine Tweed

Brooklyn-based Tweed regularly contributes to *IEEE Spectrum*'s Energywise blog. She's been digging into power grid issues for years, but investigating their vulnerability to physical attack—by bullets instead of hackers—was new to her. "Cybersecurity has been the focus for so long," she says. Through reporting in Europe and Washington, D.C., for "Bulletproofing the Grid" [p. 9], she was relieved to learn that it's getting easier for grid operators to plan for assaults in both the virtual and real worlds.

Paul Wallich

Wallich, a *Spectrum* contributing editor, wrote this month's Hands On column [p. 20]. In it he describes using wireless technology and 3-D printing to add some remote control to his home and office without altering existing wiring. But there were hiccups: The first version of a system to buzz visitors in at his office proved "even more annoying than having to answer the door, because it only worked about half the time," says Wallich.

PHOTO-ILLUSTRATIONS BY **Gluekit**

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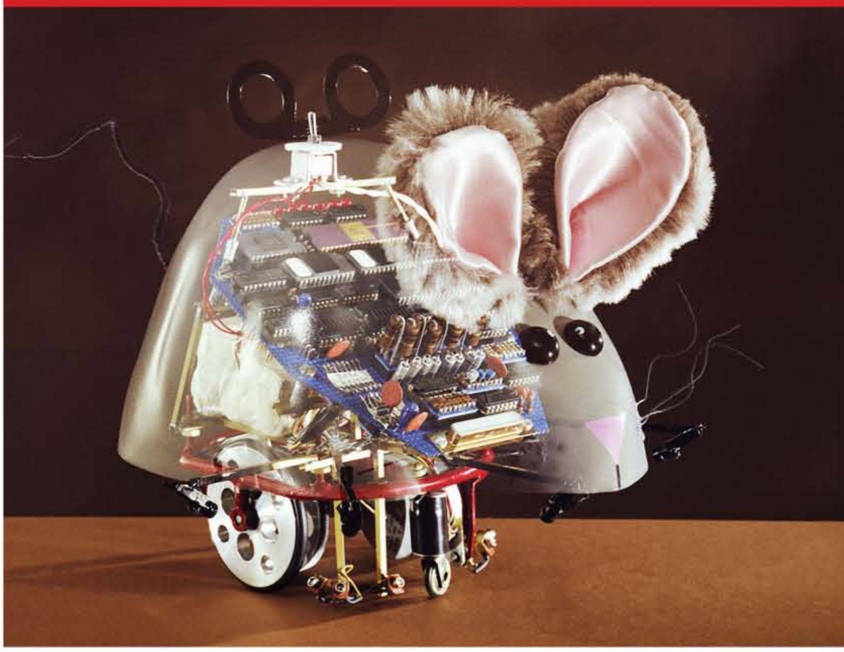

MOONLIGHT SPECIAL came in fourth in the 1979 championship, held in New York City.

BATTELLE

The Amazing MicroMouse Roars On

IEEE SPECTRUM was just entering its teenage years when, 37 years ago in this column, I challenged its readers to design and build a maze-solving "micromouse." It would have its own self-contained logic and memory and would successfully navigate a maze that *Spectrum*'s own engineer-editors would design. The configuration of the maze would be held secret until race time. Each mouse would be given an opportunity to probe the maze in test runs, learn from its mistakes, and thereby improve its time in the final run.

We called our event the Amazing MicroMouse Maze Contest. Thousands of entrants signed on in that inaugural year of 1977, but at the first time trials only five contestants had entries ready, and only two of the mice got through the maze. As designers and their mice sharpened their skills, however, 15 mice successfully competed in the *Spectrum* finals at the 1979 National Computer Conference.

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The finals were covered by CBS, NBC, and ABC television and were reported in the evening newscasts of Walter Cronkite, John Chancellor, and David Brinkley. Press clippings piled up from a broad range of newspapers, from the *International Herald Tribune* to the *Booneville Daily News*, of Missouri. One winning mouse was pictured on the front page of *The Wall Street Journal.*

In just a few years the micromouse challenge had become a worldwide event. In 1980 the first European competition was held in London, followed a year later by one in Paris. Japan announced the first World Micromouse Contest in 1985. I was invited to judge the first Singapore Micromouse Contest in 1987. That same year the IEE (now the Institution of Engineering and Technology, or IET) hosted an international competition in London.

Micromouse mania has continued to spread up to now, when it's estimated that more than 100 contests are held annually. Many are sponsored by universities and by IEEE Regions. The 28th annual micromouse contest hosted by the Applied Power Electronics Conference and Exposition was held in Fort Worth, Texas, in March, and this year marks the 35th running of the All-Japan Micromouse Robot contest. Other long-running competitions continue in Mumbai and in Birmingham, England.

The standard micromouse maze is 8 feet square and consists of a 16 by 16 matrix. Each micromouse is permitted a number of search runs to determine the shortest path to the goal, located at the center of the maze. Scoring is based on both the fastest run and the total time consumed for all runs. Contestants may not communicate with their mice in any way. Parts for a micromouse include a chassis, wheels, stepper motors and motor drivers, onboard wall sensors, microcontrollers, and batteries.

The first micromice were scratch built and thus not uniform in appearance. Some were so tall they teetered at the turns. Monty Mouse, from Britain, appeared to be an aluminum sandwich on wheels. Charlotte, "The Belle of Philadelphia," sported long, seductive black eyelashes. Today, micromouse aficionados no longer need build their mice from scratch. Parts, kits, and complete ready-to-program micromice are now commercially available. Maze walls and posts as well as parts for a complete maze can also be purchased. Many online sites provide advice and tutorials on building micromice, plus schedules and rules for particular contests.

Today's micromice are smaller, lighter, and faster, and they can turn more quickly, evoking frequent comments of "Amazing!" from audiences and affirming *Spectrum*'s propitious choice of that adjective to describe its introductory mouse and maze competition. Participants commend the contests not only for the fun they accord but because the micromice can be seen as a compact system involving many interdisciplinary design challenges. The *Spectrum* staffers who helped launch the Amazing MicroMouse contest should take great pride in what one writer has called "an international phenomenon."

—DONALD CHRISTIANSEN

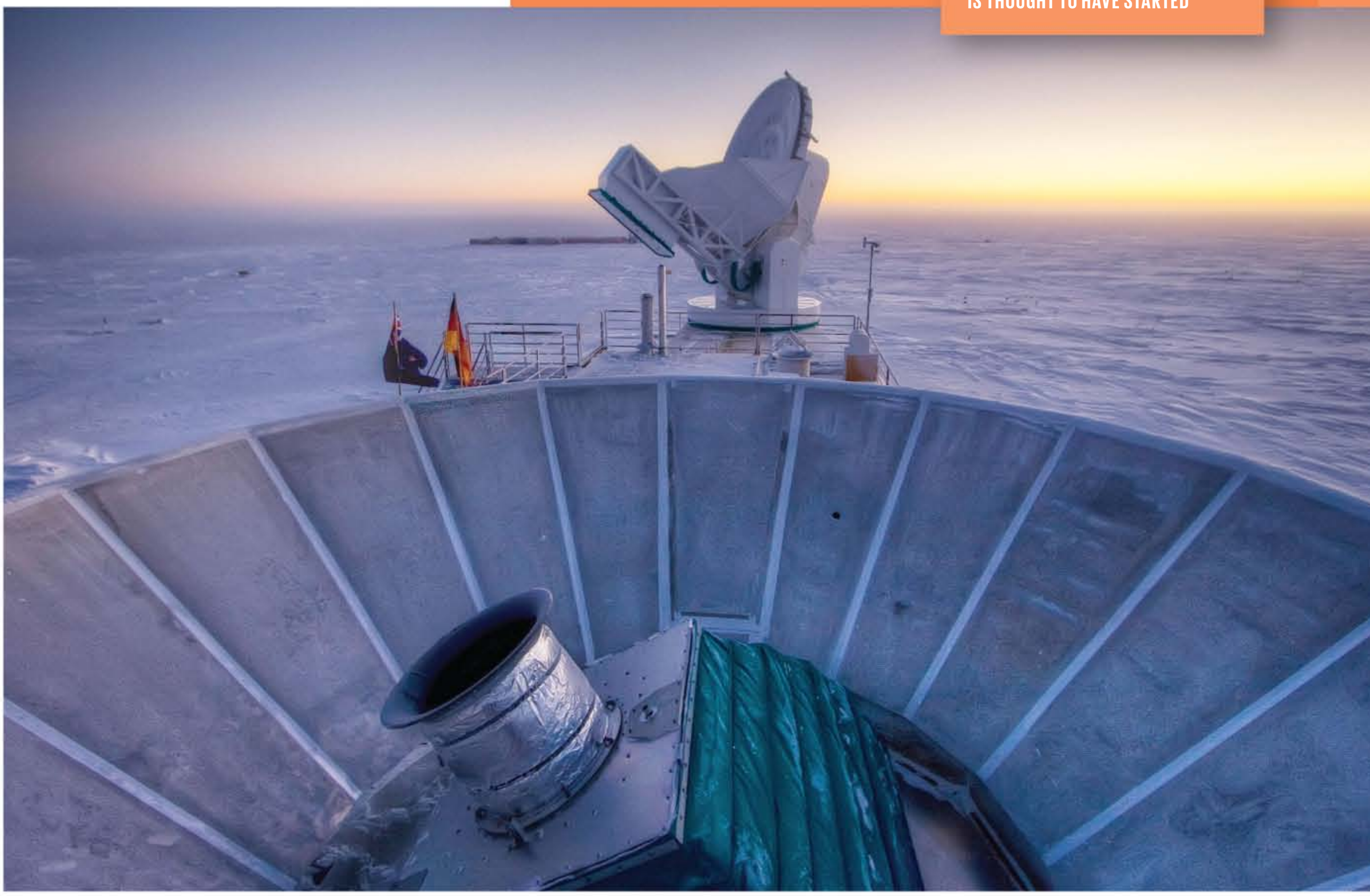
CORRECTION: For the bar charts in "The Age of the Zettabyte" [Dataflow, March], we incorrectly gave the unit of measurement as petabytes. The correct unit is exabytes.

Editor's note: In this 50th-anniversary year of IEEE Spectrum, *we are using each month's Spectral Lines column to describe some pivotal moments in the magazine's history. Here, the Amazing MicroMouse Contest is recalled by the man who conceived it, former* Spectrum *Editor in Chief Donald Christiansen.*

NEWS

10^{-37} SECONDS

THE APPROXIMATE AGE OF THE UNIVERSE WHEN COSMIC INFLATION IS THOUGHT TO HAVE STARTED



ANTARCTIC EYES: The BICEP2 telescope and its sister, the South Pole Telescope, scan for ancient radiation.

STEFFEN RICHTER/HARVARD UNIVERSITY

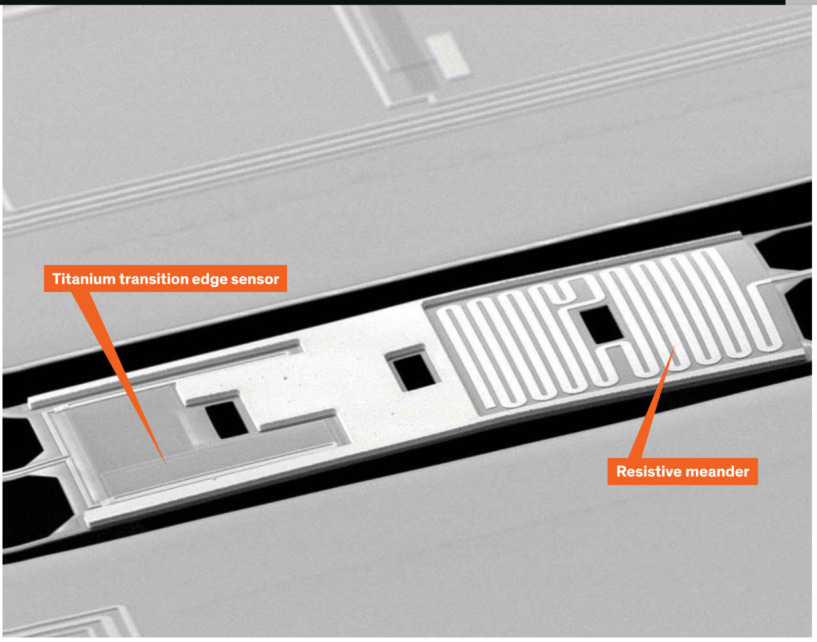
THE CHIPS THAT SAW THE BIG BANG'S FINGERPRINTS

The Antarctic telescope, BICEP2, used a new kind of superconducting detector circuit to find evidence for inflation

In March, a team of astronomers announced some very big, potentially Nobel Prize-winning news: the first sighting of gravitational waves that filled the very early universe. The waves could be an echo of "inflation"–a brief but explosive period just after the big bang when the universe is thought to have ballooned enormously in size. If confirmed, the discovery opens a window back to that time, practically the beginning of time itself.

And we never would have been able to peer through that window without a host of new, highly sensitive superconducting circuitry. "New generations of hardware have totally enabled this measurement," says Kent Irwin, a member of the team that runs the BICEP2 Antarctic telescope, which saw the gravity waves. Irwin is also a professor at Stanford University and at the SLAC National Accelerator Laboratory.

BICEP2 is the first of several experiments to find evidence of gravitational waves that stretched and compressed space in the early »



universe. Like its competitors, BICEP2 did not look for the gravitational waves themselves. Instead, it hunted for the imprint these waves left on the cosmic microwave background (CMB), a haze of 13.8-billion-year-old light that can be seen all across the sky.

Ancient gravitational waves show up as a slight "twist" or "swirl" in the polarization of photons in the CMB. This kind of polarization pattern is called the B-mode, and it is faint. Physicists equate the intensity of light of a particular wavelength with temperature. By that measure, the B-mode signal amounts to roughly one 10-millionth of a degree against the much brighter, 2.73-kelvin CMB radiation, says cosmologist Andrew Jaffe of Imperial College London. To add to the difficulty, confounding sources from the Milky Way and other galaxies can produce polarization patterns that look like those created by primordial gravitational waves.

BICEP2's detectors, which were developed and fabricated by a team at NASA's Jet Propulsion Laboratory (JPL), in Pasadena, Calif., employ a few key technologies that weren't present in the previous generation of B-mode hunters.

BICEP's first incarnation, which ran from 2006 to 2008, contained pixels that functioned like individual cameras. Incoming light passed through feed horns, filters, and polarization-sensitive components before finally reaching semiconductor-based bolometers. These bolometers heat up when hit with radiation, and this heating shows up as a change in resistance that can then be sensed by read-out circuitry and processed. Although the system worked, the pixels proved difficult to manufacture into large arrays, which astronomers need. "Every component in the pixel has its own personality and has to be thoroughly tested before hand assembly, which makes it hard to make a large focal plane," says Jamie Bock, an experimental cosmologist at Caltech and JPL. Another key issue was the wiring. To keep the noise down, the bolometers were cooled to less than a degree above absolute zero. But at some point, the signals must move out of the chilled telescope to room-temperature electronics. The more sensors you have, the more wires and thus more heat-conducting elements that can counteract the cooling power of your cryogenic equipment.

For BICEP2, Bock's team found a way to perform many of the same pixel functions using flat printed antennas that can be mass-produced by lithography. Much of the processing electronics were made from superconducting circuitry and moved into the same cryogenic stage as the bolometers, which were also made from superconducting devices. To cut down on the wiring, the pixels were made to share wires and were read out one at a time. With this setup, the team was able to construct a system containing 512 superconducting sensors, compared with BICEP's 98 semiconducting ones.

To map the CMB with this array, each of BICEP2's pixels collects incoming microwaves through interleaved antennas. One set picks up the signal from photons with an *x* component to their polarization, and the other is sensitive to the *y* component. The resulting electromagnetic signals are then sent down two superconducting transmission lines. Each line terminates in a small resistive device containing what's called a transition edge sensor. The signal's current produces heat, and the heat alters the conductivity of the circuitry. The result is read out and processed by a superconducting integrated circuit.

COSMIC THERMOMETER: Ancient microwave radiation pushes current through a "resistive meander" [right], heating it up. This heat is picked up by a titanium-based superconducting transition edge sensor [left].

JPL-CALTECH/NASA

The transition edge sensors are so named because they operate right at the transition zone where a material goes from being normally conducting (resistive) to superconducting (lacking resistance). Transition edge sensors ride this edge, self-regulating along the way. When their temperature goes down, their resistance also decreases. This lets more electricity flow across them, which raises the temperature and thus the resistance. A voltage is applied across them in such a way that the increase in resistance actually reduces the power dissipated, lowering the temperature.

"It's an exquisitely sensitive instrument," says Irwin, who worked to develop it while he was a graduate student at Stanford some 20 years ago. For these measurements, he says, "you can't actually get more sensitive." At this point, the sensitivity of such detectors is limited by the shot noise of the incoming photons: Even if the temperature of a spot on the sky stays perfectly stable, the number of photons hitting the detector will fluctuate over time simply because there's a finite number of them.

Nowadays, most of the competing B-mode hunting experiments, which include Polarbear in Chile and the South Pole Telescope (just meters from BICEP2), incorporate similar superconducting detectors. The Planck space telescope launched less than a year before BICEP2 started operations, but it carries semiconductor-based polarization sensors because space-bound engineering specs have to be locked in quite early.

If the signal holds up, scientists will likely be able to extract even more information from it in the not-too-distant future.

The next step for these kinds of detectors will be to adjust the electronics so that they're sensitive to more colors, says Matt Dobbs of McGill University, in Montreal, who has worked on the South Pole Telescope's B-mode detector. BICEP2 looked at light of just a single microwave frequency: 150 gigahertz. But more colors can be detected by splitting up the signal picked up by each antenna, or pixel, among several wires. Lumped element filters—simple capacitors and inductors made from traces on a silicon wafer—can be constructed to filter out all but one color along each line and pass the signal on to a bolometer for detection.

Next year, the South Pole Telescope and Polarbear are slated to get detectors sensitive to three different wavelengths of CMB light. Picking up otherwise discarded photons will mean a "gigantic jump" in sensitivity, Dobbs says.

But adding color sensitivity is a challenge for telescope optical systems, says Bock. Because the BICEP team uses smaller, less expensive telescopes, he says, it is easier for them to simply build more of them and make each one sensitive to a different single frequency. Indeed, the team plans to ship BICEP3, a single-color detector containing 2560 bolometers sensitive to 95-GHz light, to the South Pole later this year.

With either approach, astronomers hope to use the added color sensitivity to perform some basic spectral analysis. As they explore more of the sky, this could allow them to separate "foreground" sources of polarized light from CMB signals and learn even more about the universe's first moments.
—RACHEL COURTLAND

A version of this article appeared online in March.

NEWS

BULLETPROOFING THE GRID

A gun attack on a Silicon Valley substation has utilities looking to boost physical security

In the early hours of 16 April 2013, one or more gunmen opened fire on the Pacific Gas & Electric (PG&E) Metcalf substation for nearly 20 minutes. They took out 17 transformers at the Silicon Valley location and then slipped away into the night before police arrived.

The attack caused significant damage but did not result in a power outage. It did, however, reignite a conversation about the physical security of the electricity grid in the United States and elsewhere, shifting the focus somewhat away from cybersecurity. *The Wall Street Journal* later reported that the Federal Energy Regulatory Commission (FERC) had done a study that same year assessing grid weaknesses. According to the newspaper, it found that a coordinated attack on a small, specific set of the 55 000 transmission substations in the United States could plunge the entire nation into darkness.

Some experts question the findings that the entire U.S. power grid could be taken down by an attack on fewer than 10 substations, as some news reports claimed, although these experts all noted they had not seen the FERC study. "Maybe if you made that 50 or 60, but 10?" says Clark Gellings, a fellow at the Electric Power Research Institute (EPRI). "Sure, you could do some damage, but I just don't buy it."

Whether or not the substation number is true, work is under way to avoid such an alarming outcome. Government agencies and electric utilities are reassessing critical equipment, evaluating how to build and deploy critical assets faster in an emergency, and developing cutting-edge software tools to help utilities plan more broadly for storms, terrorism, or any other calamity.

In the United States, FERC is refocusing on physical security requirements by asking the North American Electric Reliability Corporation to develop reliability standards for grid »

SUSCEPTIBLE SUBSTATIONS: New software should help utilities figure out which of their substations are critical to the grid.

HAL BERGMAN/GETTY IMAGES

operators that address physical security threats. The standards are still being drafted, but they will require that utilities and grid operators identify critical facilities, evaluate potential threats, and develop a security plan to address the threats. That's no simple task, given that the country is host to some 3000 utilities.

Europe got a jump start on that task with the Directive on European Critical Infrastructures in 2008, a set of procedures for identifying and assessing protection for critical infrastructure, including the electricity grid.

No matter how far in advance utilities may plan for outages, evaluating threats is a dynamic, complex procedure, and not a one-time endeavor. "What's critical does change from time to time," says Jeffery Dagle, chief electrical engineer at the U.S. Department of Energy's Pacific Northwest National Laboratory (PNNL). "It can be a function of what else is knocked out."

Help is on the way in the form of advanced algorithms that will let utilities model different scenarios to come up with flexible security plans that can react to changing grid conditions. PNNL's Future Power Grid Initiative includes tools that take advantage of real-time, high-performance computing and parallel algorithms to simulate the U.S. grid and its millions of customers. The tools are still being crafted but could be widely available in a few years.

In the meantime, experts say there is more focus on beefing up security and making operational changes, such as ensuring that backup components don't sit within the same substation as the assets they would need to replace.

Among those components considered critical in both physical and cybersecurity threats are large, difficult-to-replace, extra-high-voltage (EHV) transmission transformers. Weighing hundreds of metric tons, filled with oil, and capable of handling more than 345 kilovolts, EHVs can take months to manufacture. Orders are usually placed far in advance, according to a leading maker of EHV transformers, ABB. After a long lead time, they can also take weeks to install, sometimes requiring specialized rail cars to transport the hulking pieces of power equipment. There are about 2000 in the United States alone, and 90 percent of consumed power passes through EHVs, says ABB.

Concerned that the loss of such transformers from a cyberattack could cripple the grid, the U.S. Department of Homeland Security decided to prototype a fast-turnaround transformer. ABB, EPRI, and CenterPoint Energy, in Texas, worked together on the Rapid Recovery Transformer (RecX) program to see how quickly a replacement transformer could be built and deployed in an emergency.

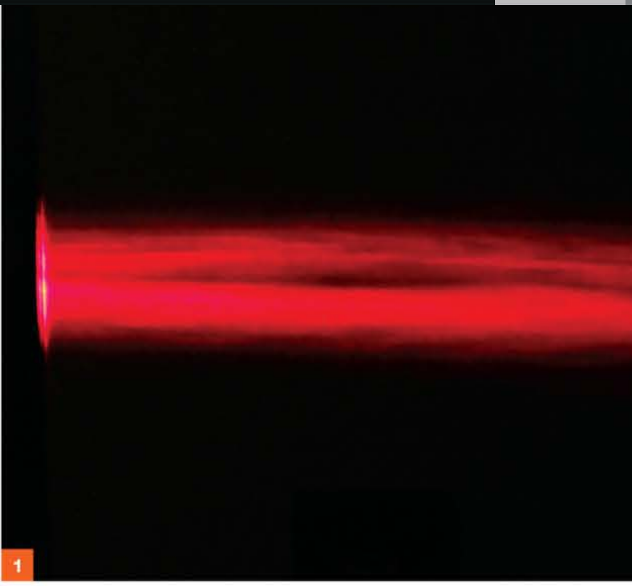
"It took two weeks start to finish," says Barry Dillon, spokesperson for the North American branch of ABB. The Swiss power electronics giant has 3 factories in North America and 10 more globally that could add extra shifts or change priorities to produce EHV transformers faster if there was a sudden need. Other manufacturers, such as Mitsubishi, have also expanded their North American factories in recent years.

Focusing on physical security can be an opportunity to add more sensors and software that not only alert grid operators in the case of attack or failure but also monitor the health of critical assets, says EPRI's Gellings. As more IT is brought on line to monitor critical assets, cybersecurity must be evaluated in conjunction with physical security. "I worry more about the combination of the physical and cyber done in a very intelligent way," he says.

Says PNNL's Dagle: "The trick is not letting the crisis du jour trump all the things we need to keep an eye on."

—KATHERINE TWEED

Could destroying a handful of critical substations bring down the whole U.S. grid? Some experts doubt it, but utilities are beefing up security.



1

THREE WEIRD WAYS TO MAKE THINGS DISAPPEAR

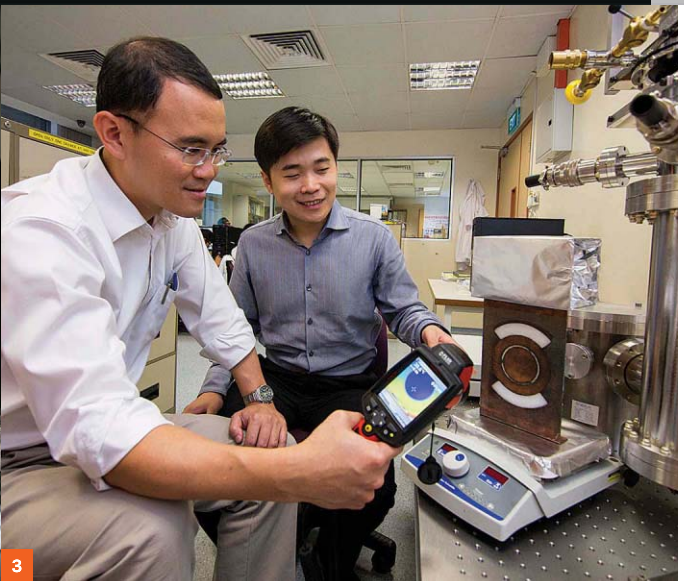
With these tricks, objects can go undetected by sight, sound, or heat

In 2006, scientists at Duke University captured the world's imagination by announcing they had created an invisibility cloak. It could hide an object only from a particular wavelength in the microwave region, and only when viewed from certain directions, but it sparked waves of research along with countless cracks about boy wizards and Romulan warbirds. You still can't hide a spaceship, but that hasn't stopped scientists from coming up with new and strange ways to make small objects undetectable, and the past few months have produced particularly unusual innovations.

Invisibility is accomplished using metamaterials, which feature structures that are substantially smaller than the wavelengths of light. For instance, an early metamaterial, described in 2008 by Xiang Zhang, a professor of mechanical engineering at the University of California, Berkeley, consisted of 30-nanometer-thick layers of silver interwoven in a fishnet pattern with 50-nm-thick layers of magnesium fluoride. The right arrangement of structures gives the material a negative index of refraction, allowing it to bend light

UNIVERSITY OF BUFFALO


2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of a particular wavelength in directions it would not normally bend. With careful engineering, the idea goes, you could route the light around an object and let it continue on as if the object weren't there.

Since the original work, researchers have found methods to cover wider bands of wavelengths and make objects invisible from a wider field of view. They've even developed cloaks to hide things at visible wavelengths, although the hidden objects tend to be just a few millimeters wide. Zhang says that in theory it's possible to build cloaks for any sort of wave, including sound waves and heat waves. In practice, while there have been plenty of advancements in the last half dozen years, there are still a lot of problems to be solved. "You can make cloaks. The question is, can you scale them up?" Zhang says. He believes invisibility will eventually be possible, but, he says, "I wouldn't say how long it will take. It's not an easy task." Here are three new ways that researchers are using to make objects invisible. —NEIL SAVAGE

1. HIDING IN A HOLE

While most approaches to making an object invisible entail building something to hide the object, Natalia Litchinitser, associate professor of electrical engineering at the State University of New York at Buffalo, proposes structuring the light itself in such a way that it misses the object and then continues on unchanged. In her experiment, she shot a beam of light from a laser and expanded it so it had a diameter of 10 millimeters. Then she passed it through a spiral phase plate, which wound the beam into a helical structure, like the coils of a spring. She passed the beam over a thin metal rod, as if she were slipping the spring over a nail, and then through another phase plate, which returned the beam to its original shape. Because the rod rested in the empty space in the middle of the beam, it wasn't visible. Of course, the object to be hidden has to fit into the relatively small hole in the light beam, and it works only if the beam passes in the right direction. But Litchinitser says her approach might be combined with more conventional metamaterial approaches to improve the performance of both.

2. CONE OF SILENCE

Instead of light, Steven Cummer, a professor of electrical and computer engineering at Duke University, designs his metamaterials to manipulate sound waves. Sonar "sees" an object by measuring distortions in the reflected sound waves that bounce off it. To hide an object from sonar, the metamaterial must be designed so that sound bounces off it in the same pattern it would if it were being reflected by the surface beneath it. In his experiment, Cummer wanted to hide a small plastic pyramid, so he built a cloaking pyramid to cover it. He built this undetectable pyramid out of air-filled cubes of acrylic and used a laser cutter to perforate acrylic plates within each cube with 850-micrometer-wide holes. Each unit of this periodic structure is about 1/20th the size of the wavelength of the 3-kilohertz sound used by the detector. The researchers pinged their cloak from many different angles to make sure it worked in 3-D space. Though the experimental results weren't perfect, the cloak did manage to mostly mask the plastic pyramid beneath it.

3. HIDDEN HEAT

One way to camouflage an object is to hide its heat signature. Cheng-Wei Qiu, assistant professor of electrical and computer engineering, and his colleagues at the National University of Singapore have come up with a thermal cloak that masks how heat scatters off an object. They use a bilayer cloak with different levels of conductivity in each layer. The inner layer in this case is silicone, which is an insulator. The outer layer is copper, which of course is highly conductive. The combination causes heat to flow differently around the hidden object than it normally would. Instead of producing one thermal signature where the object is, there are now scattered signatures at different locations. To complete the illusion, Qiu places other objects at the locations of these "ghost" heat signatures, so the scene appears ordinary. Qiu calls the hidden object—really a copper cylinder—a "man" and the ghost objects, which are insulators, "women." With the cloak in place, the man vanishes among the women.

LEFT: DUKE UNIVERSITY; RIGHT: NATIONAL UNIVERSITY OF SINGAPORE

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NEWS

CENTIMETER-SCALE GPS COMING TO JAPAN

A $1.2 billion system would give unprecedented accuracy

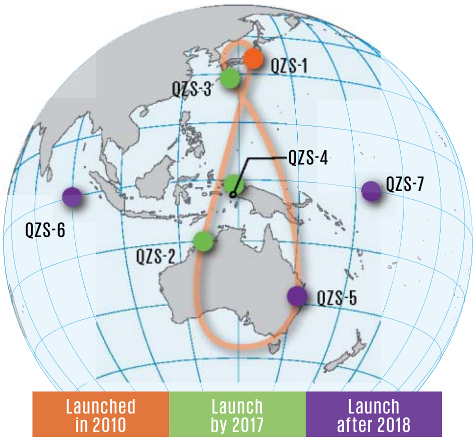
A stranger to Tokyo could easily get lost in its urban canyons. And GPS navigation, stymied by low resolution and a blocked view of the sky, might not be much help. But that won't be the case after 2018. Engineers at Tokyo-based Mitsubishi Electric Corp. report that they're on track to start up the first commercial, nationwide, centimeter-scale satellite positioning technology. As well as spot-on navigation, the technology will also usher in a variety of innovative new applications, its proponents say.

Named Quazi-Zenith Satellite System (QZSS), it is designed to augment Japan's use of the U.S.-operated Global Positioning System (GPS) satellite service. By precisely correcting GPS signal errors, QZSS can provide more accurate and reliable positioning, navigation, and timing services.

Today's GPS receivers track the distance to four or more GPS satellites to calculate the receiver's position. But because of the various errors inherent in the GPS system, location can be off by several meters. In using the data from QZSS to correct the measured distance from each satellite, the accuracy of the calculated position is narrowed down to the centimeter scale.

"GPS positioning can be off by as much as 10 meters due to various kinds of errors," says Yuki Sato, a research engineer in Mitsubishi Electric's Advanced Technology R&D Center, the prime contractor for the space portion of the project. "And in Japan, with all its mountains and skyscrapers blocking out GPS signals, positioning is not possible in some city and country locations," he adds.

The Japan Aerospace Exploration Agency (JAXA) got the project under way with the launch of QZS-1 in September 2010. Three additional satellites are slated to be in place by the end of 2017, with a further three launches expected sometime later to form a constellation of seven satellites—enough for sustainable operation and some redundancy. The government has budgeted about US $500 million for the three new satellites, which are to be supplied by Mitsubishi. It also apportioned an additional $1.2 billion for the ground component of the project, which is made up of 1200 precisely surveyed reference stations. That part's being developed and operated by Quazi-Zenith Satellite System Services, a private company established for this purpose.



PACIFIC CONSTELLATION: Four QZSS satellites will orbit in such a way that at least one is always directly over Japan. Three reserves will hang at the equator.

The four satellites will follow an orbit that, from the perspective of a person in Japan, traces an asymmetrical figure eight in the sky. While the orbit extends as far south as Australia at its widest arc, it is designed to narrow its path over Japan so that at least one satellite is always in view high in the sky—hence the name quasi-zenith. This will enable users in even the shadowed urban canyons of Tokyo to receive the system's error-correcting signals.

"Errors can be caused, for example, by the satellite's atomic clock, orbital shift, and by Earth's atmosphere, especially the ionosphere, which can bend the signal, reducing its speed," says Sato.

To correct the errors, a master control center compares the satellite's signals received by the reference stations with the distance between the stations and the satellite's predicted location. These corrected components are compressed from an overall 2-megabit-per-second data rate to 2 kilobits per second and transmitted to the satellite, which then broadcasts them to users' receivers.

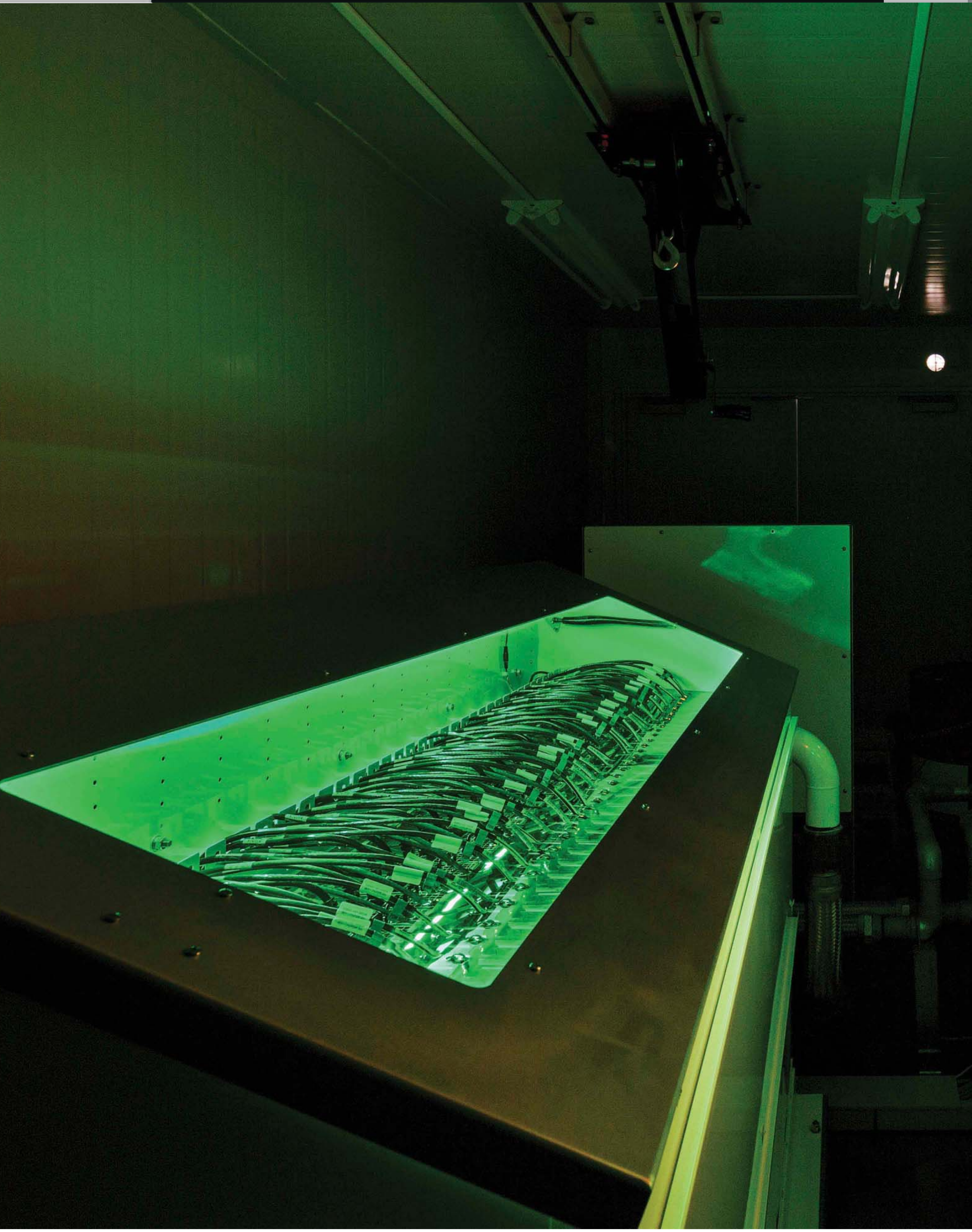
"This is all done in real time, so compression is really important," says Ryoichiro Yasumitsu, a deputy chief manager in Mitsubishi's Space Systems Division. "It would take too long to transmit the original data." Compression also means a practical-size antenna can be employed in the user's receiver. In QZS-1 trial tests, Yasumitsu notes that the average accuracy is about 1.3 centimeters horizontally and 2.9 cm vertically.

This centimeter-scale precision promises to usher in a number of creative, or at least greatly improved, applications beyond car and personal navigation. Besides pointing out obvious uses like mapping and land surveying, Sam Pullen, a senior research engineer in the department of aeronautics and astronautics at Stanford, says precision farming and autonomous tractor operations will be big applications.

"Unmanned aerial vehicles and autonomous vehicles in general," he adds, "will also find centimeter-level positioning valuable in maintaining and assuring separation from other vehicles and fixed obstacles."

In addition, the Japanese government plans to use the service to broadcast short warning messages in times of disaster, when ground-based communication systems may be damaged. As instructed by the government, the control center will transmit a brief warning message to the QZSS satellite, which will then broadcast it to users on the same frequency.

Given the range of promised applications and relatively low cost of the Japanese system compared with the €5 billion ($6.9 billion) budgeted for the EU's Galileo, for instance, other nations will be watching and waiting to see if QZSS achieves its goals. —JOHN BOYD



PHOTOGRAPH BY Jeremie Souteyrat/The New York Times/Redux

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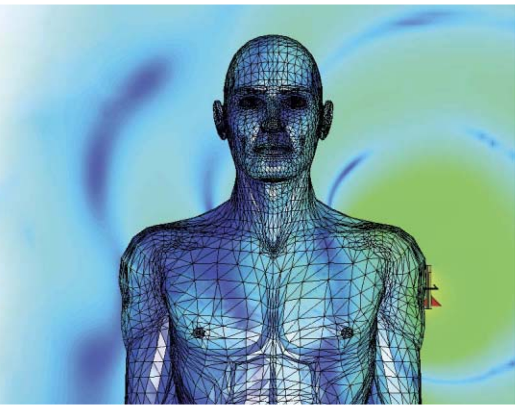
MORE OIL, LESS ENERGY

THE TSUBAME KFC supercomputer, developed by researchers at the Tokyo Institute of Technology's Global Scientific Information and Computing Center, is a prototype meant to demonstrate the effectiveness of submersion cooling for greatly improving energy efficiency. In tests late last year, the oil-cooled machine (yes, it's called KFC and it sits in grease) delivered more than 4500 megaflops per watt. That was more than enough to vault it to the top of the latest Green500 supercomputers list. The system, whose theoretical peak operating performance is 217 teraflops, has 40 superefficient computing nodes, each comprising two Intel Xeon E5-2620 v2 processors (Ivy Bridge EP) and four Nvidia Tesla K20X GPUs. The compact setup and the liquid cooling scheme cut to the bone the amount of energy used for computing as well as for cooling.



RESOURCES

100 MILLIVOLTS: THE CHANGE IN VOLTAGE INSIDE A NEURON WHEN IT FIRES, BRIEFLY SWINGING FROM –70 mV TO +30 mV

RESOURCES_GEEK LIFE

BRAIN HACKING

SELF-EXPERIMENTERS ARE ZAPPING THEIR HEADS

SELF-MADE MAN: Anthony Lee believes his home-brew equipment for electrically stimulating the brain helps him with a range of cognitive tasks.

PHOTOGRAPH BY David Yellen

OFF THE SHELF: In addition to DIY solutions, home tDCS experimenters can also buy commercially manufactured headsets, such as this one from Foc.us.

FOC.US

ANTHONY LEE HAD JUST BEGUN TRYING to hack his brain when his girlfriend caught him at it. He was sitting in the living room of his Alabama home with electrodes attached to his head, fiddling with the device he'd built to send a current through his gray matter, when she strolled in. "It was that awkward moment when your family walks in on you while you're doing science," he says with a laugh. ● Lee was an early member of a DIY community that's sprung up around a technology called transcranial direct current stimulation (tDCS). This noninvasive way to jolt brain cells is being studied in labs and clinics for its potential to reveal how our brains function—and perhaps to augment abilities or treat disorders. (How tDCS works is not well understood, but it is believed to act through making neurons either more or less likely to fire, depending on the polarity of the closest electrode.) Unlike most other brain-tweaking technologies, tDCS doesn't require expensive equipment; all it takes is a 9-volt battery, some simple circuits, and a couple of electrodes. Consequently, it didn't take long for so-called biohackers to band together and come up with schematics for devices. ● Lee isn't an engineer, but once he heard about tDCS he decided to build his own rig. He discovered a few websites and a subreddit forum where people were exchanging information, and found techies there who could answer his questions. Once he got his tDCS system working, he made a YouTube video to pass on his knowledge. That was a few years ago, and the community has grown dramatically since then. Now, several commercial tDCS headsets are on the market, raising questions about whether brain hacking should be made so easy.

Many self-experimenters got interested because of research studies that have shown tDCS to have a variety of fascinating effects, depending on electrode location and the amount of stimulation. Faster learning, better math skills, improved memory, more creativity: All these enhancements have been observed in one study or another. Lee's first plan was to use tDCS to learn German, but when he realized that language-learning would still be a huge time commitment, he shifted his focus and decided to test the technology's cognitive effects with as much scientific rigor as one amateur could pull off. Granted, that's not all that much; as the user can usually physically feel when a device is turned on, there's no easy way to control for the placebo effect.

But now the community is taking a turn from enhancing healthy people to helping the sick. With word of tDCS spreading, more people are trying it to treat disorders such as depression, ADHD, and chronic pain. Lee says he and other pioneers are fielding lots of questions from such patients. "Most of us try to help as much as we can, but we're not working in a lab doing the real experiments, nor are we psychiatrists," he says.

Brent Williams, who is the director of a children's-education technology program at Kennesaw State University, in Georgia, and an electrical engineer by training, is another pioneer who's fielding requests. He started his own experiments with tDCS in August 2012 and regularly uses it for a creativity boost; he typically does a 20-minute session of 2 milliamps and says he can feel the effects within 5 minutes. Williams keeps a blog about the technology and how to use it safely, and he says he always advises newbies to do plenty of reading before they start their own experiments. But enthusiastic people don't always take his advice. "tDCS is becoming more widely known to the general public, so there are more people doing dumb things that they shouldn't be doing," he says.

Williams argues, though, that these beginners can't do much damage to themselves. He says that only minor side effects have been reported in the DIY community, such as skin irritation under the electrodes, flashes of light, and headaches. "It's relatively risk-free," he says. "Hundreds of thousands of people have been treated by tDCS, and there's not one report of someone being injured."

That confident attitude troubles Marom Bikson, a biomedical engineering professor at the City University of New York who has done extensive research on tDCS technology and who has warned of its misuse. He says that the technology's excellent safety record is based on lab experiments, which use fault-resistant devices and careful medical protocols.

Bikson says that at-home experimenters shouldn't assume tDCS is risk-free, especially if they're using rigs they built themselves. "Anybody who has ever tinkered with something at home knows the first time it doesn't work, then it does work, then the battery blows out or the IC has a fault. That's fine if you made an automatic door opener," he says. "But it's different if you made something that connects to your head."

The recent emergence of commercial headsets could give would-be experimenters an alternative to cobbling together their own devices, but such products may not be on the market for long. For example, one buzzed-about company, Foc.us, advertises a US $250 headset as a tool to boost performance on video games while claiming that its product is not a medical device and so not regulated by the U.S. Food and Drug Administration. If the FDA disagrees with that assessment, the Foc.us headset and others will be pulled from the market and subjected to the FDA's onerous approval process.

In such a situation tDCS would once again be left to the mercies of the DIY community—where, Lee says, it will be in pretty good hands. "I don't think I would have been able to do the experiments I did, and get the results I did, without the community," he says. "Now I have a pretty good body of knowledge, and I just want to share it with people who are interested."
—ELIZA STRICKLAND

A version of this article appeared online in March.

AKILI: DIAGNOSING ALZHEIMER'S WITH A GAME
A FUN AND FRIENDLY APP COULD IDENTIFY PATIENTS

A HEALTHY TOUCH: The simple interface of this iPad game masks sophisticated diagnostic technology that aims to spot cognitive problems.

***Project: Evo* is a brightly colored** iPad game that doesn't look different from any app you might use to while away the time. Yet it's intended for a much more serious endeavor: The game's creators believe it can be used to both diagnose and ultimately treat mental disorders.

The start-up behind this game is Akili Interactive Labs, and they've gotten the attention of the pharmaceutical industry. Pfizer, of New York City, is partnering with Akili on a clinical trial that began in March, which will determine whether *Project: Evo* can identify people with a high risk for developing Alzheimer's disease.

"There would be a lot of utility in detecting patients early," says Eddie Martucci, Akili's vice president of R&D. "Then physicians could enroll them in drug trials early and could try other interventions." Currently, expensive PET scans are used to spot people at risk of Alzheimer's by estimating the amount of amyloid plaque in their brains. In the clinical trial, researchers will enroll people with high and low amyloid levels to see if the two groups have different degrees of success with Akili's game. "If we can match amyloid measurements to our game-play results, then you have a quick, easy way to find those patients," Martucci says.

Users play by tilting the iPad or iPhone to steer a cheerful alien down a river while keeping an eye out for fish or birds and tapping the screen when a specified animal appears. This multitasking is surprisingly challenging, and success is tied to a player's abilities in what neuroscientists call interference processing.

The game is based on work by Adam Gazzaley, a neuroscientist at the University of California, San Francisco. Gazzaley, one of the cofounders of Akili, has shown that people's interference processing capacities decline with age. He has also built a rudimentary game called *NeuroRacer*, says Eric Elenko, the company's chief business officer. "We've taken that under-

PHOTO: ISTOCKPHOTO; SCREENSHOT: AKILI INTERACTIVE LABS lying science and...prototype, and we've created a mobile product that has the look and feel of an entertaining game," he explains. Akili also built out a back end for the game that harvests data 30 times per second during game play for remote monitoring and analysis.

In addition to the Alzheimer's study, Akili is conducting clinical trials researching ADHD, autism, and depression. While it may seem unlikely that one game could be used to identify such a broad range of disorders, Martucci explains that interference processing is a key component of executive functioning—essentially, goal-directed behavior and the faculties necessary to reach those goals. "If you're overcome by interference, if you're highly distractible, many of your other faculties under executive function start to degrade," Martucci says. "We're targeting the weak link in the system." While the Alzheimer's study will attempt to identify patients, other clinical trials will determine whether a regimen of game play can provide cognitive benefits.

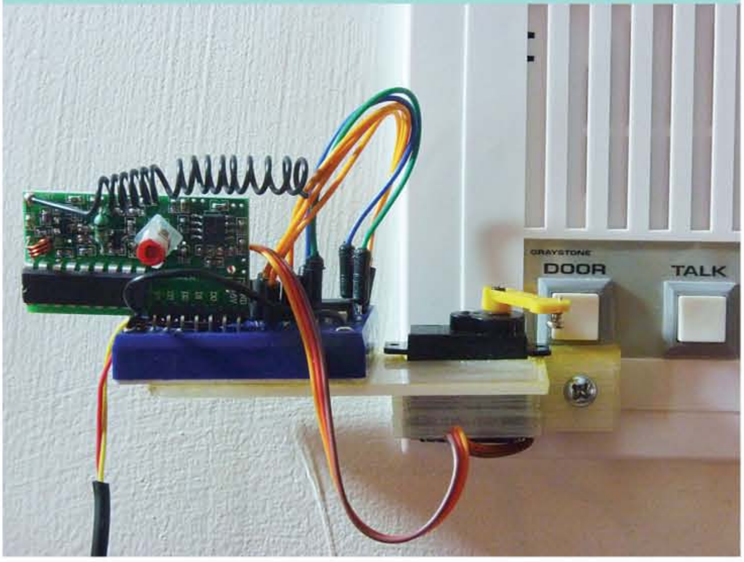
Akili is one of a dozen high-tech health start-ups nurtured by PureTech, which operates out of a sleek office in downtown Boston and focuses on health-care challenges. Akili hopes to begin seeking approval this year from the U.S. Food and Drug Administration to sell *Project: Evo* as a medical product. Elenko says such approval would encourage doctors to take the game seriously. "There would be nothing to prevent us from taking it and putting it on the App Store today," he says, "but we want it to be viewed in the realm of medicine."

Experts in the booming mobile health market say Akili's game could provide great cost savings and medical benefits. But Corey Ackerman, president of Happtique, a company based in New York City that's establishing a certification system for mobile health apps, says the key to success will be establishing Akili's scientific credibility. "We speak to hospitals and other types of providers and clinicians, and we get asked a lot about the efficacy of apps," he says. "Doctors are scientists, and they want proof before they do something new and extra."
—ELIZA STRICKLAND

Founded: December 2011 **Headquarters:** Boston **Founders:** PureTech **Funding:** US $7 million **Employees:** 5.5 **Website:** http://www.akiliinteractive.com

AUTOMATE YOUR HOME WITHOUT REWIRING

FLIP SWITCHES WITH RADIO-CONTROLLED SERVOS



PAUL WALLICH

I DON'T LIKE WORKING IN THE DARK. BUT I ALSO DON'T like mains current. Maybe it's the smoke and flames, maybe it's the flying droplets of molten metal, maybe it's the chance of sudden death, but I just like to make my mistakes at lower voltages and amperages. So years ago, when I found out that all the light fixtures and most of the sockets in my basement (where I have my workbench) were on the same circuit, I put my plans for converting everything to remote control on indefinite hold. ● But lately I've been exploring more mechanical solutions: If I can't play with the power lines, why not just use microcontrollers and servos to push buttons, pull lightbulb chains, and flip switches directly? ● It started at the office space in downtown Montpelier, Vt., that I share with a couple of dozen other freelancers and small entrepreneurs. There's an intercom-buzzer setup for letting people in, but no one likes interrupting a coding spree or a conference call to walk over to answer the door. So I thought it would be easy and fun to build a widget that would push the door button remotely while avoiding any landlord trouble that could come from monkeying around with the intercom system itself. ● Several prototypes later, I'd learned some valuable lessons. First, solenoids are expensive and power hungry and can push a button effectively only if they're mounted to within a fraction of a millimeter of their ideal position—too close in and you risk crushing the button into its housing; too far out and the button

PUSHING 2.0

won't depress far enough to register. And a solenoid completely blocks the button, so you can't push it with your finger either. Then I thought of using a servo to swing a button-pushing arm in and out of the way, but getting stand-alone 555-timer-based circuits to control a servo's motion reliably is harder than I first imagined.

So I decided to replace the simple timer-based circuit with an ATtiny84 microcontroller in a 16-pin package (well under US $1 if you order 25 or more). This controls a $5 microservo mounted on a little 3-D-printed housing attached to the intercom, and the controller and servo are powered via a DC adapter plugged into a wall socket.

I designed the housing using OpenSCAD, an open-source, text-based, solid-geometry program that's particularly suited for people like me, who can't draw but can still type a precise description of what they want. Add a rectangle here, cut out a cylinder there, and voilà. Then I sent the design to the little PrintrBot Jr sitting next to my desk using Repetier, a free controller program. I use PLA (the somewhat incorrectly named polylactic acid) plastic at the office because the molten ABS that's commonly used for 3-D printing smells really unpleasant.

Then I used the Arduino IDE to program the controller, thanks to the community of hackers who have made definition files and libraries for the ATtiny series in addition to the ATmegas that grace regulation Arduino boards. (There is one minor factor-of-8 error in the microsecond delay code in the core library for the ATtiny, but that was easily fixed.) When I push a button on a radio-transmitter key fob, a matching receiver (about $12 for the set) changes the signal on one pin of the controller. In response, the ATtiny84 sends a series of pulses to the servo, which commands the servo to swing its arm into the button, wait 3 seconds, and then swing back out of the way.

I didn't have to be as precise in mounting the arm as with a solenoid, because I made it easy to adjust the swing of the servo arm after installation. My code, which uses only about 1200 bytes of the 8 kilobytes available in the ATtiny84, can precisely tweak the swing based on which of the microcontroller's spare I/O pins

My first attempt to build a remote-controlled button pusher for an intercom used a solenoid [top], but mounting it was problematic, so I 3-D-printed servo mounts [second from top] to push the button. I used a similar approach to flick light switches and pull chains on and off in my basement, printing a special servo arm for the latter [bottom].

PAUL WALLICH (4)

are connected to the supply voltage and which are connected to ground.

To flip light switches in my basement, I've used a similar servo arm but have taken a slightly different approach with the remote control, because I don't have a convenient wall socket and must rely on battery power. The transmitter-receiver devices I used at the office are out of the question, as the receiver draws close to 5 milliwatts and takes too long to wake from sleep mode and register a signal for a snappy response. At 5 mW, without sleeping, a typical stack of four 2000-milliampere-hour AA batteries would last only a few weeks.

Instead, I'm stuck, so to speak, with the Nordic Semiconductor nRF24L01+, a mesh-network transceiver with way more features than I need. But it can wake up, do its business in a few milliseconds, and go back to sleep. (It's $20 a unit from Sparkfun, but from a Shenzhen, China, supplier in the backwaters of the Internet, it's a fifth that price if you order enough items to justify the terrifying shipping charge.) Once again, hackers have built and made available RF24-series libraries for the ATTiny84 as well as for regulation Arduinos. Power consumption in standby mode is a few dozen microamperes, which matches well with the similar amount used by the microcontroller in deep-sleep mode. Consequently, I expect to get six months out of the batteries, maybe more. Once I get a bunch of units built, say one for each light fixture, I'm going to test different power-saving strategies with the nRF24L01+, such as whether it's thriftier to have the device sleep deeply and take more time waking up, or to have it sleep lightly and wake up—and thus go back to sleep—more quickly.

Oh, and if you've been wondering about the power consumed by the servos, don't bother. Even drawing a whole ampere—considerably more than a microservo actually draws—for 3.6 seconds is all of 1 mAh. Another idea would be to charge a battery from the light source: I've discovered that if I cram a small solar cell right next to the tube of a fluorescent light fixture, I can get a couple milliamperes of charging current, but I'm not sure I want to bother with that. **—PAUL WALLICH**

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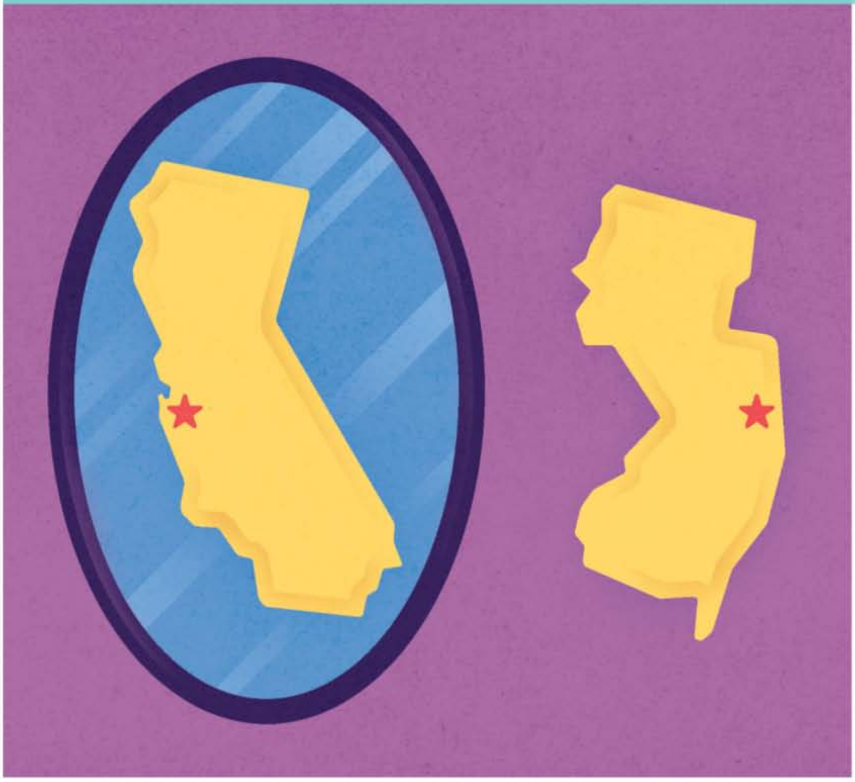

CLONING SILICON VALLEY

A place's spirit comes from hard-to-reproduce historical circumstances

THE SPEAKER WAS TALKING ABOUT HOW NEW JERSEY could become the next Silicon Valley. I was skeptical, but the audience was enthusiastic. "We could be *Silicon Valley*!" they were thinking. • Through the years I've been a number of places that people thought could become Silicon Valley. Some have done well enough–Boston; Research Triangle Park, in North Carolina; Austin, Texas; and Cambridge, England, to name a few. Many more places have had their hopes and aspirations bear little fruit. But Silicon Valley is still the only Silicon Valley. • While the speaker was lauding the potential of New Jersey, I was remembering a time in the 1960s when I had just started my career at Bell Labs. Back then some executives started the original effort to make New Jersey into a Silicon Valley. They had put together a consortium of New Jersey research organizations and hired Fred Terman, the Stanford University dean given credit for creating Silicon Valley, to do something similar for New Jersey. • I vividly remember attending meetings where Terman outlined his vision for a New Jersey Silicon Valley. The state had the greatest concentration of engineers and scientists in the country, but he said that what New Jersey lacked was a Stanford. None of the existing universities had the necessary culture of engineering innovation. But we could create a Stanford! Terman proposed a new graduate university, making use of all the talent the state had. He said that the new university would have immediate credibility and that universities were like cathedrals in small towns; when seen from a distance only the high spires were apparent, and New Jersey already had those high spires in its famous engineers and scientists. I was thrilled. "We could be *Silicon Valley*!" I thought.

Needless to say, it never happened. The consortium fell apart, and there was no new university. However, even if the consortium had succeeded in establishing a new campus, I seriously doubt that it would have led to a Silicon Valley. New Jersey R&D was a set of noncommunicating islands, of which the largest was Bell Labs. The geography kept engineers apart; there were no watering holes where they met up (and perhaps Cambridge, Mass., lost more than it knew when the F&T Restaurant beside MIT was demolished in the 1980s to make way for a new subway entrance). The culture on the East Coast favored academic publication instead of entrepreneurship. And though I believe New Jersey's attractiveness as a place to live is underappreciated, the San Francisco Bay Area is justly famed. Moreover, New Jersey's proximity to New York City is both a blessing and a curse. All roads lead to Manhattan (or, these days, Brooklyn), like a giant black hole sucking matter from its surroundings.

Even if an area had all the necessary ingredients in its environment to duplicate Silicon Valley, it would be unlikely to happen. I think of it as a tipping-point phenomenon–winner takes all. Silicon Valley became *the* place to be, and so game over.

It has now been about a half century since Terman tried to clone Silicon Valley in New Jersey. During that time many other unlikely places have aspired to create their own Valley, and I still hear of ongoing attempts. Perhaps it's time to find another model. Some people have suggested a distributed model in which each geographic area focuses on a particular area of competence. Such a horizontal segmentation already exists to some degree with design, fabrication, software, and assembly taking place among a global community.

Still, there is some magic in having companies clustered face-to-face across the street. All these years, and I'm still envious. ■

ILLUSTRATION BY Jesse Lefkowitz

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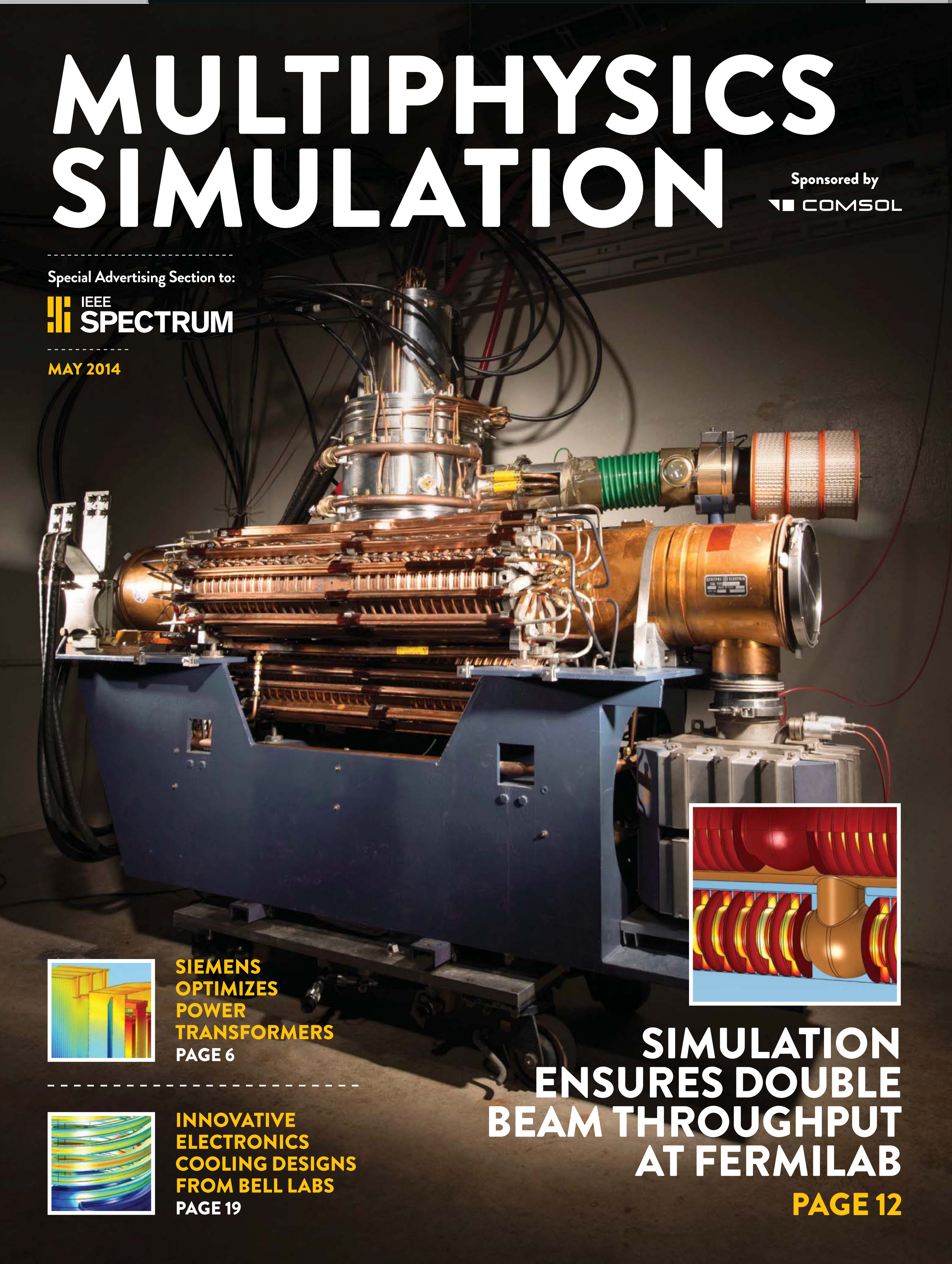

SIMULATION ENSURES DOUBLE BEAM THROUGHPUT AT FERMILAB

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SIEMENS OPTIMIZES POWER TRANSFORMERS

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INNOVATIVE ELECTRONICS COOLING DESIGNS FROM BELL LABS

PAGE 19

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.

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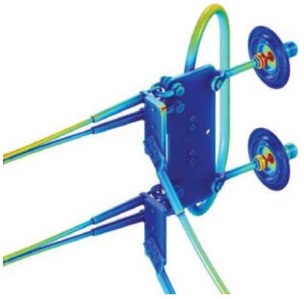

ON THE COVER: An RF cavity with ferrite tuners from the Booster synchrotron at Fermi National Accelerator Laboratory. See Fig. 6 from the full article starting on pg. 12 for more details about the simulation. Photo is by Reidar Hahn and COMSOL simulations by Mohamed Hassan, both of Fermilab.

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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.

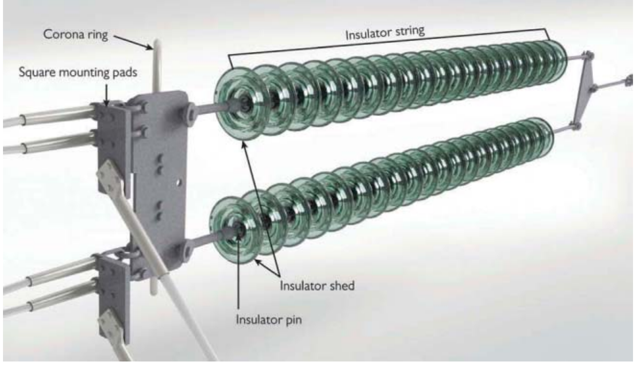


FIGURE 1: Top: A dead-end structure. Bottom: CAD representation of the dead-end insulator assembly.

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

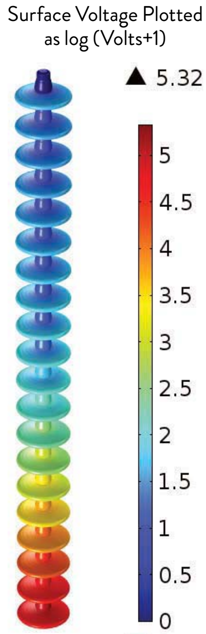


FIGURE 2: A 2-D axisymmetric model showing the electric potential distribution along the insulator string.

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).

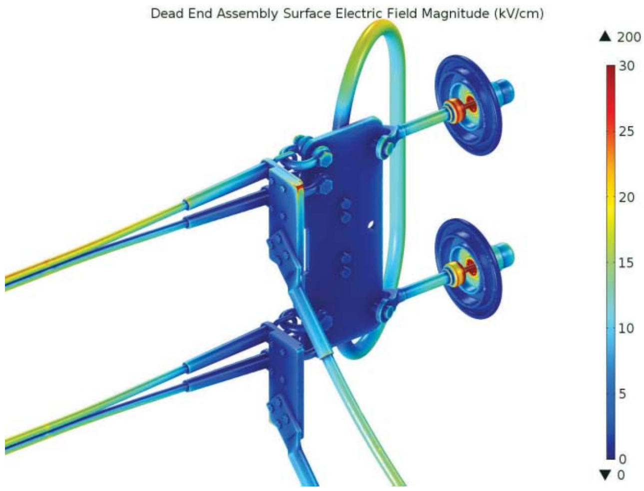


FIGURE 3: Electric field strength at the surface of the dead-end insulator assembly. Areas with high electrical fields occur at the pins of the insulator units and at the square mounting pads.

“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,

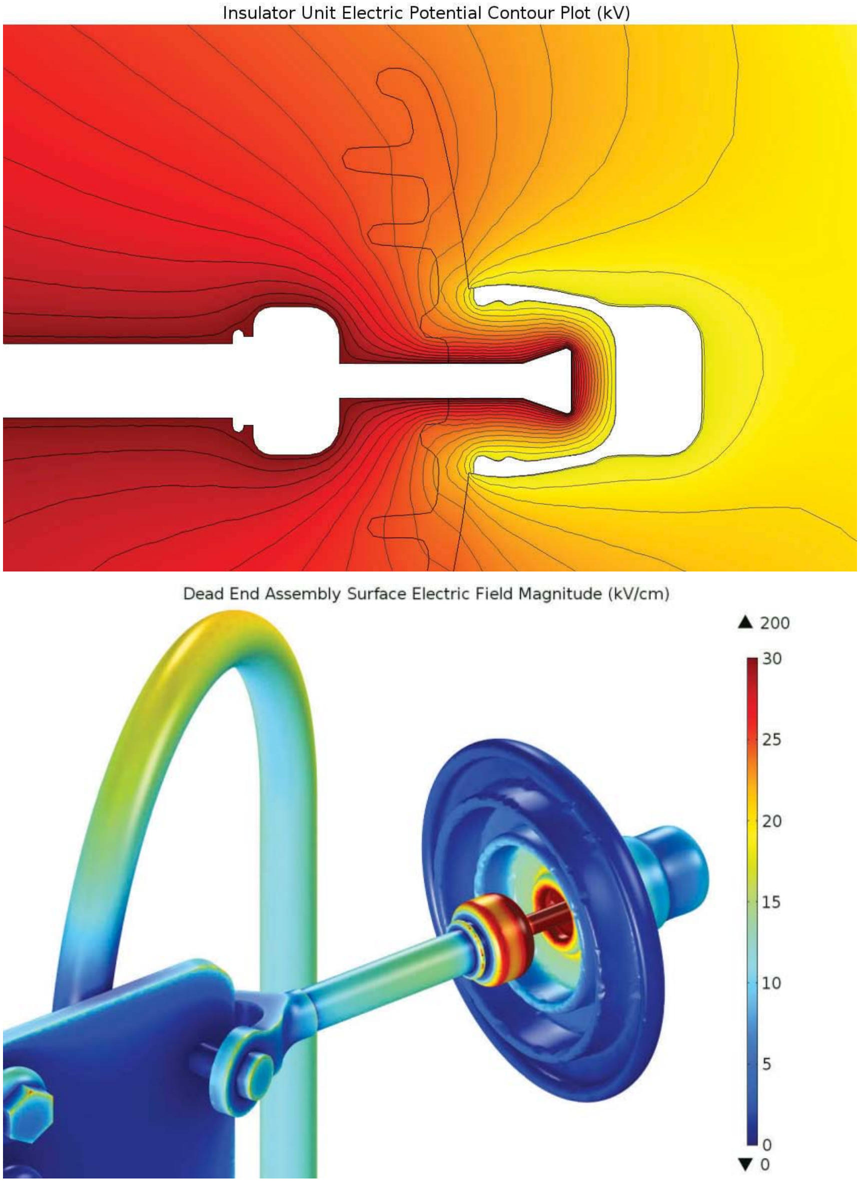


FIGURE 4: Top: Electric potential cross-section of the air surrounding the insulator pin. Bottom: Electric field results for the insulator pin.

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**

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.

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.

» OVERCOMING INDUCTIVE HEATING ISSUES

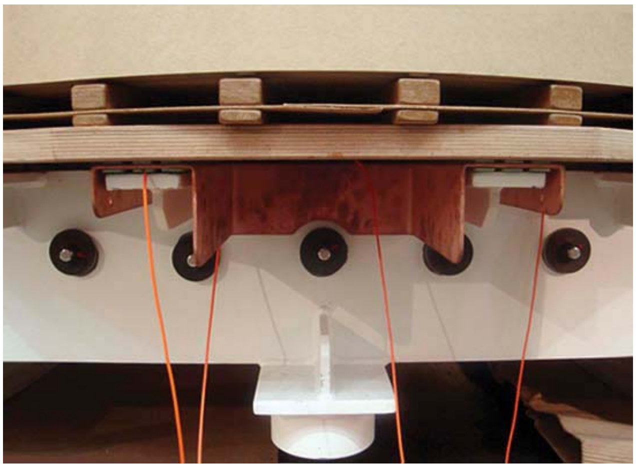
SIEMENS HAS EMPLOYED COMSOL® simulation software to address these design constraints and control the inductive heating of metal parts. Induction heating is the phenomenon of heating a conductive body subjected to a varying electromagnetic field, where eddy currents lead to the Joule heating of the material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



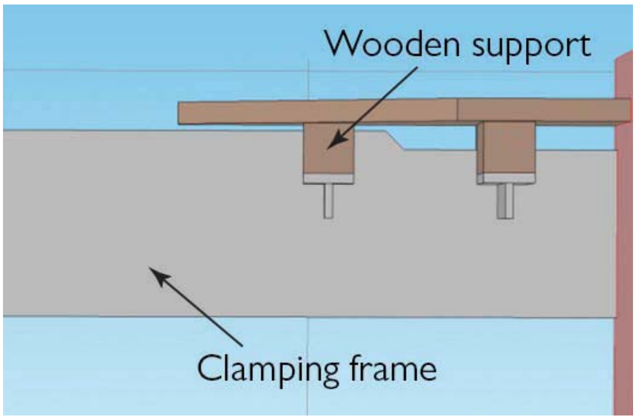


FIGURE 2: Top: Original clamping frame design with copper shielding. Bottom: Optimized clamping frame design using less materials.

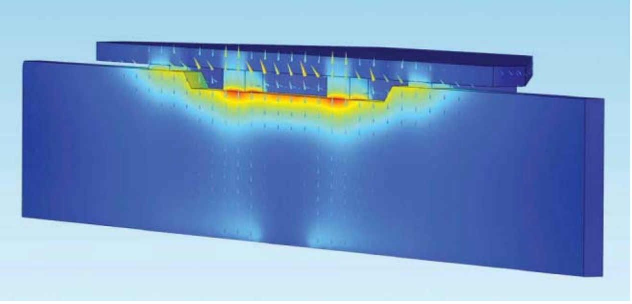


FIGURE 3: Optimized design of the clamping frame (back view). Temperature (surface plot) and oil flow fields (arrows) are shown.

"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.

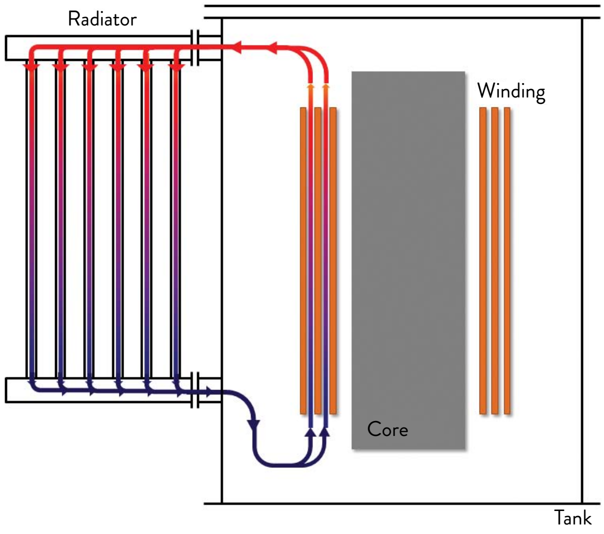


FIGURE 4: Schematic of the new oil circuit design used in shunt reactors and power transformers.

» 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."

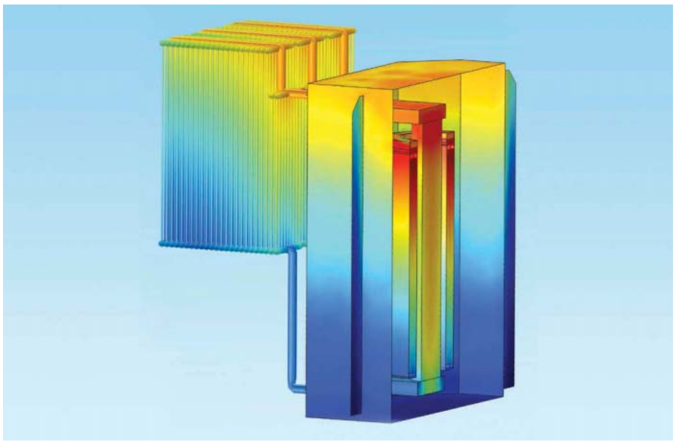


FIGURE 5: Top: The thermo–fluid dynamics simulation of the new design. Bottom: New collecting pipes design. In the new design, the pipes have been removed from their previous position circling exterior of the reactor. Instead, the pipes travel directly from the cooling fan and into the reactor itself.

> *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.

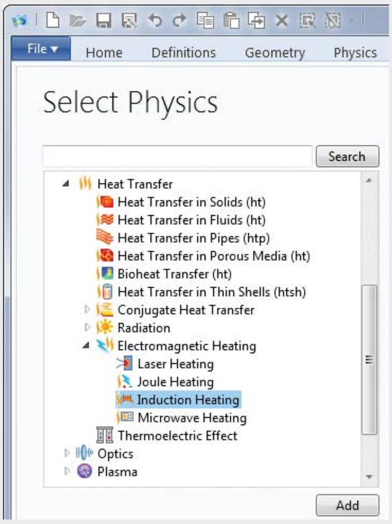


FIGURE 1: A multiphysics coupling is automatically created by selecting the predefined Induction Heating interface.

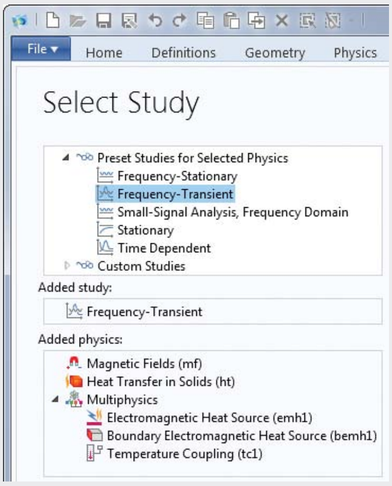


FIGURE 2: The Frequency-Transient study is used to compute temperature changes over time together with the electromagnetic field distribution in the frequency domain.

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).

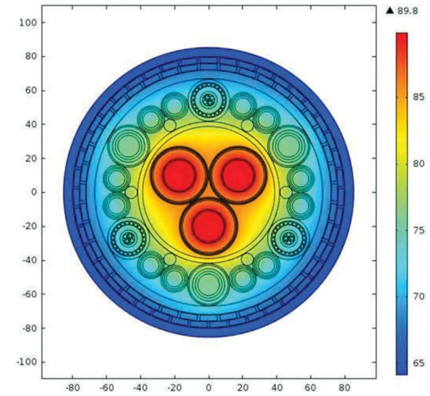


FIGURE 1: Cross-sectional view of the temperature distribution in a double-armored umbilical cable.

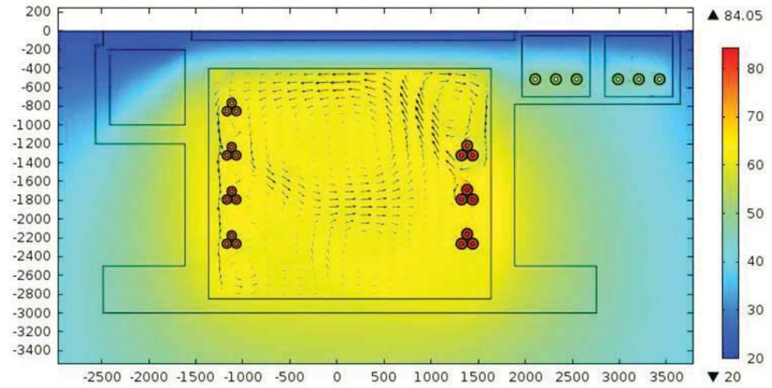


FIGURE 2: Using COMSOL Multiphysics, Prysmian combined thermal and computational fluid dynamics (CFD) analyses of high-voltage cable systems placed inside a horizontal tunnel with natural ventilation only.

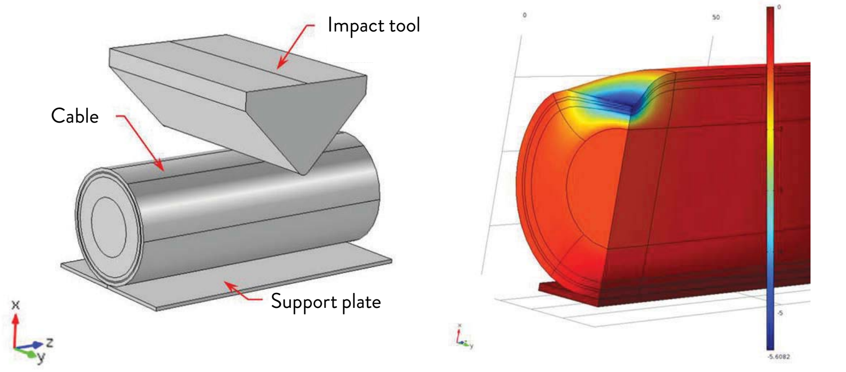


FIGURE 3: Simulation of an impact test on a medium-voltage cable.

"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."

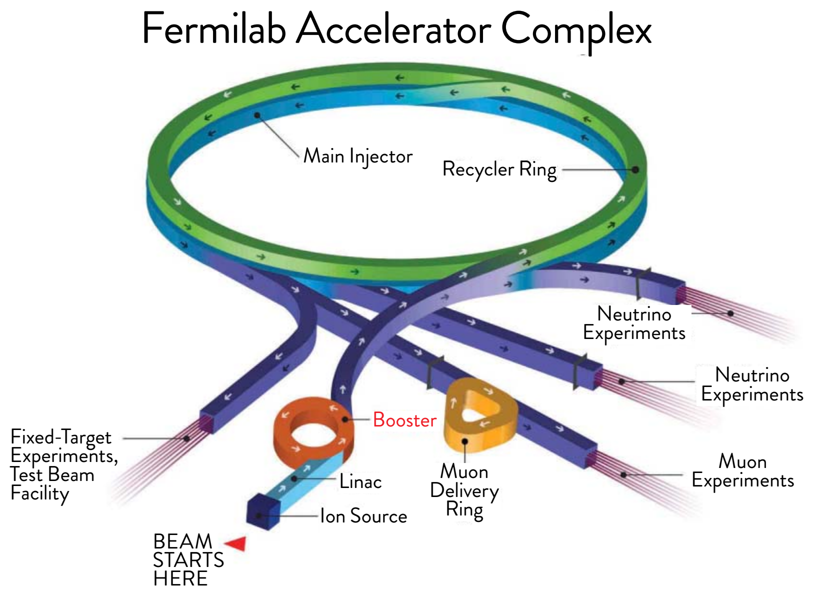

FIGURE 1: The FNAL accelerator chain showing the location of the Booster synchrotron.
IMAGES COURTESY OF FERMI NATIONAL ACCELERATOR LABORATORY

» 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.

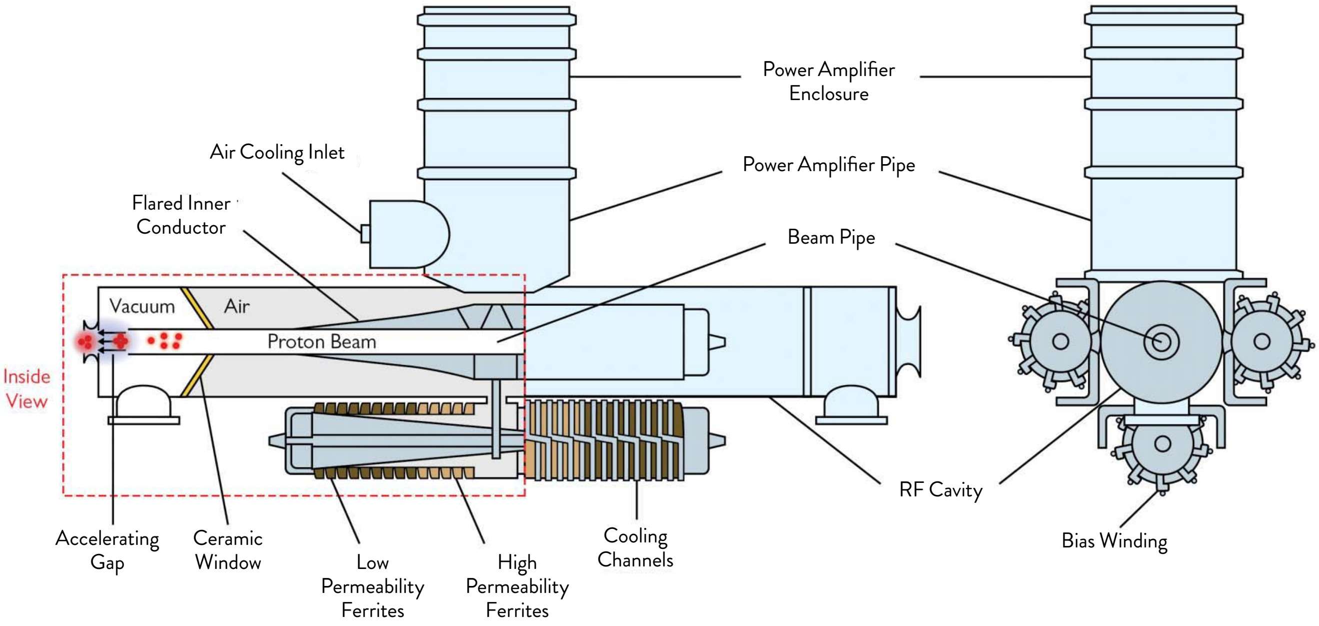

FIGURE 3: Front- and side-view drawings of a Booster RF cavity with three ferrite tuners and a tetrode power amplifier. The side-view drawing shows the high- and low-permeability ferrites, including the cooling channels required to prevent overheating. The ferrites are enclosed in a copper tube that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

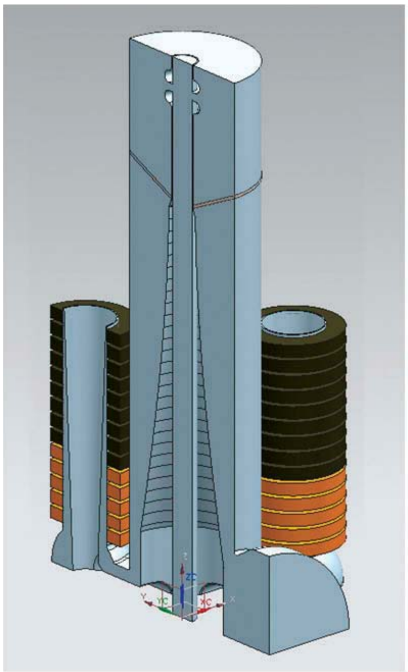

FIGURE 4: RF model geometry for the Booster RF cavity with ferrite tuners. One-quarter of the symmetric cavity design was modeled and imported into COMSOL.

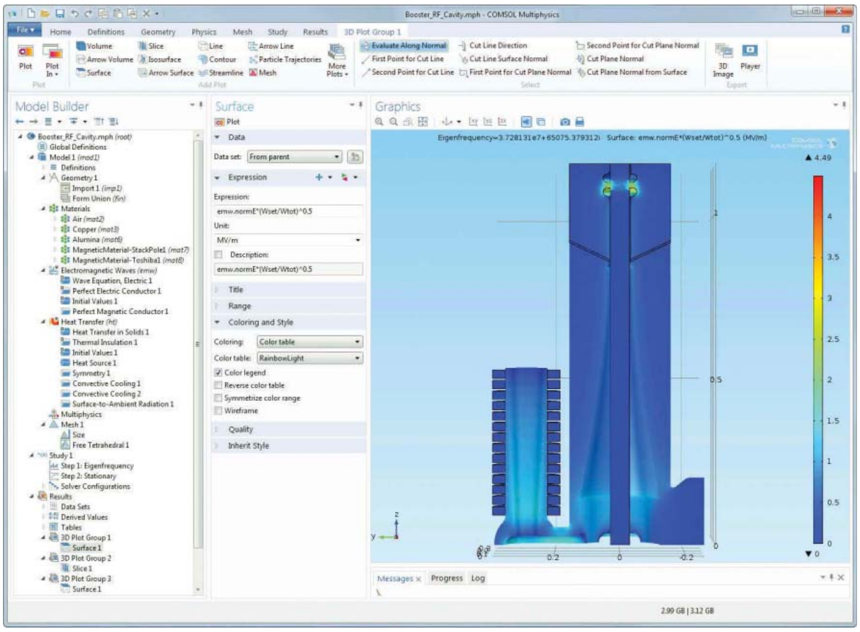

FIGURE 5: This COMSOL Desktop® image shows model setup and analysis for a multiphysics model of an RF cavity. The geometry, materials, physics, and study are defined in the Model Builder window at left. A surface plot of the electric field on the RF cavity and tuner is displayed in the Graphics window. 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.

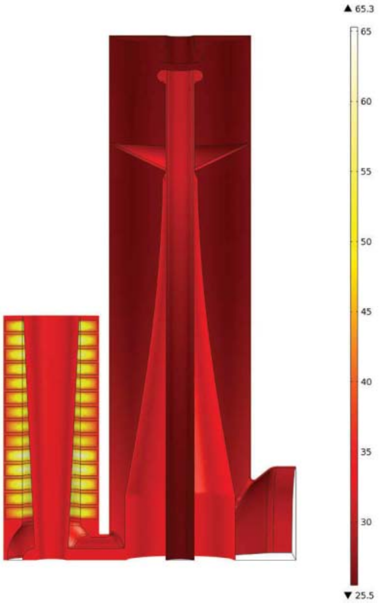


FIGURE 6: A surface plot of temperature is shown from the thermal analysis of an FNAL Booster RF cavity at 55 kV accelerating voltage and 7 Hz repetition rate.

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.

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

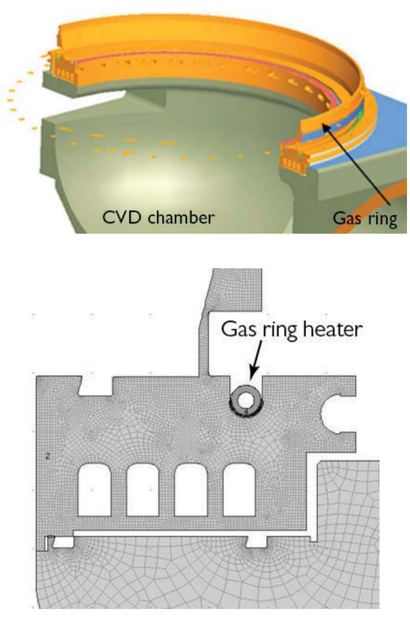


FIGURE 1: Gas is introduced into a chemical vapor deposition (CVD) chamber via a gas ring. The challenge is to keep the temperature of the ring uniform throughout the entire processing sequence.

involving many different scale levels.

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

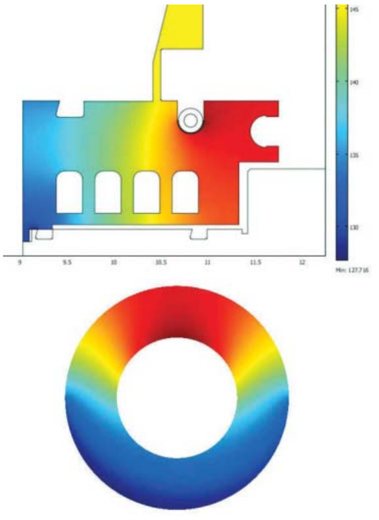


FIGURE 2: Lam is using the Heat Transfer Module in COMSOL Multiphysics® to help predict temperature uniformity under various operating conditions for CVD chamber gas ring heaters.

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).

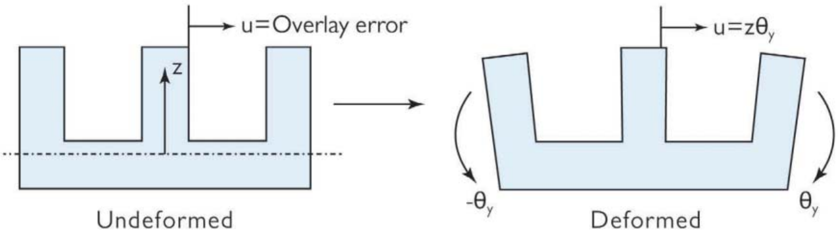


FIGURE 3: The cross-section at left shows an undeformed structure that introduces no photolithographic overlay error. On the right, a semiconductor wafer deformed by various stresses tilts, thereby introducing overlay error.

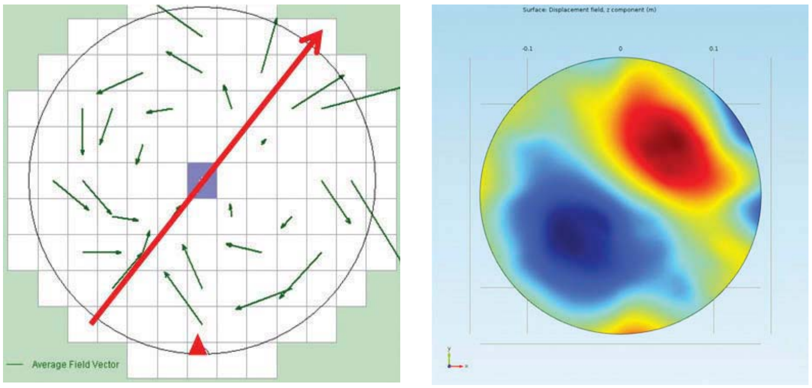


FIGURE 4: At left is a map of vectors contributing to wafer bow. The software resolved them into wafer displacement contour maps. On the right is a view in the x-y plane.

» 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.**

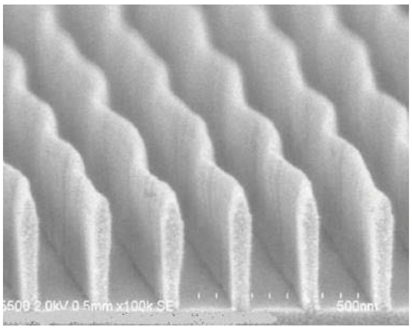


FIGURE 5: Photomicrograph showing the buckling of dummy structures used as building blocks to fabricate high aspect ratio interconnect for advanced computer chips.

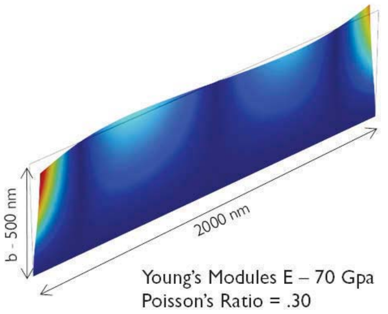


FIGURE 6: The Structural Mechanics Module in COMSOL Multiphysics can predict how buckling will occur in high aspect ratio chip interconnect.

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.

» 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.

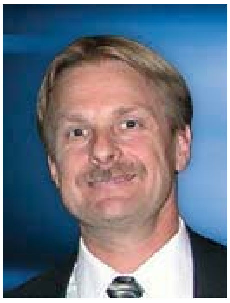
Woytowitz's group theorized that the buckling resulted from intrinsic compressive stress or possibly from mismatching coefficients of thermal expansion.

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.

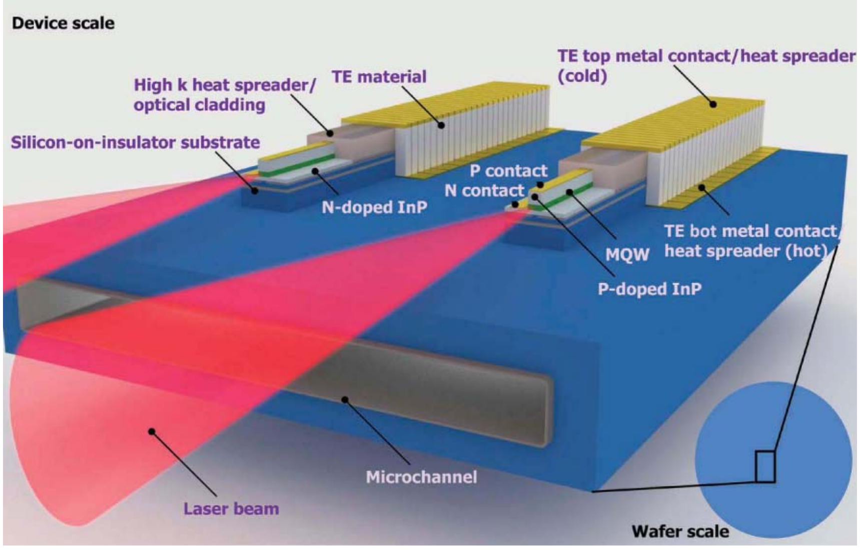


FIGURE 1: Schematic of the thermally integrated photonics system (TIPS) architecture, which includes microthermoelectric and microfluidic components.

» 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

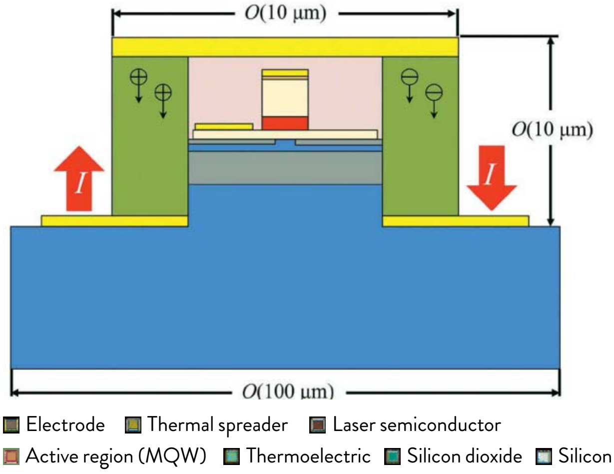


FIGURE 2: Cross-section schematic of laser architecture with integrated µTEC (not to scale).

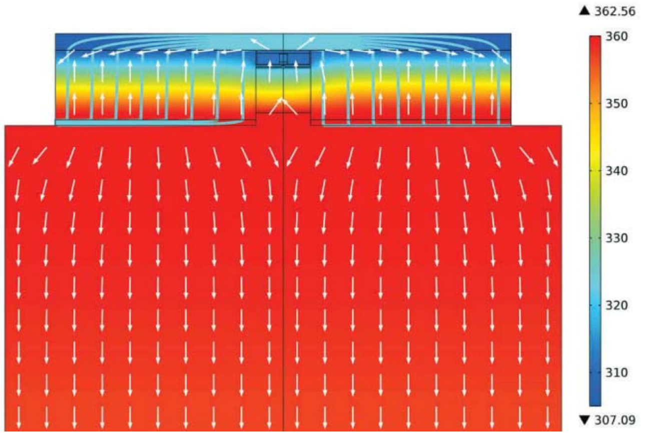


FIGURE 3: Multiphysics simulation of a laser with an integrated µTEC where temperature (surface plot), current density (streamlines), and heat flux (surface arrows) are shown.

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®.

"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

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

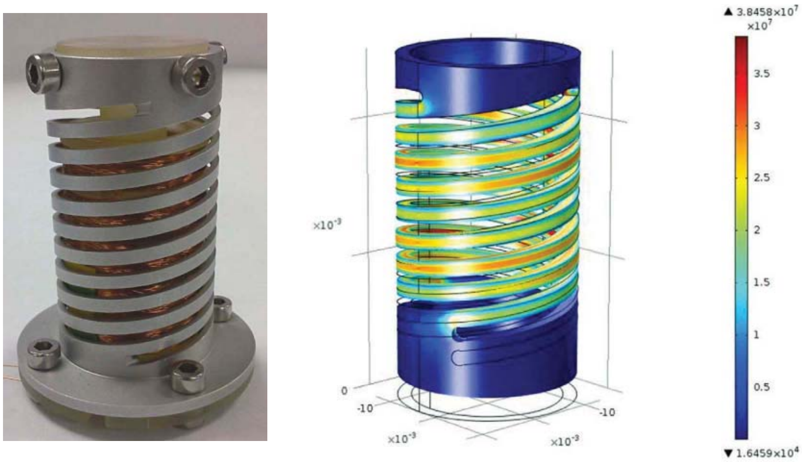


FIGURE 4: Left: Prototype of novel machined-spring energy harvester. Right: Simulation of the energy harvester, showing von Mises stress.

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

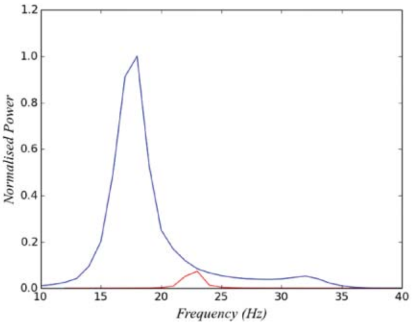


FIGURE 5: The figure compares the Bell Labs design (blue line) with a similar state-of-the-art single-mass system (red line). The multiple-mass system designed by Bell Labs has 11 times greater peak energy.

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.

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,

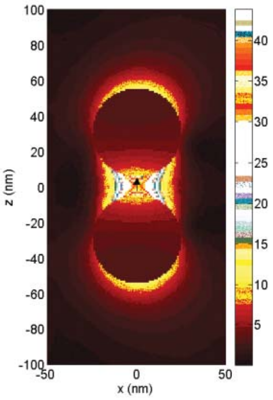


FIGURE 1: Example of nanoantenna: Intensity of electric field radiated by a gold sphere doublet coupled to a dipolar source (represented with a black arrow). The sphere radii are only 25 nanometers, and the distance between the spheres is 10 nm. The power radiated by the source is much larger than the 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.

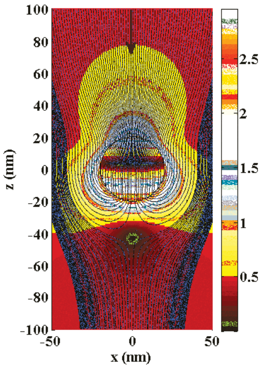


FIGURE 2: Intensity of the electric field around a single silver sphere with a radius of 20 nm illuminated by a plane wave incident from the top (the green arrow indicates the direction of propagation). The flux lines are represented in blue.

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.

» 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

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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.

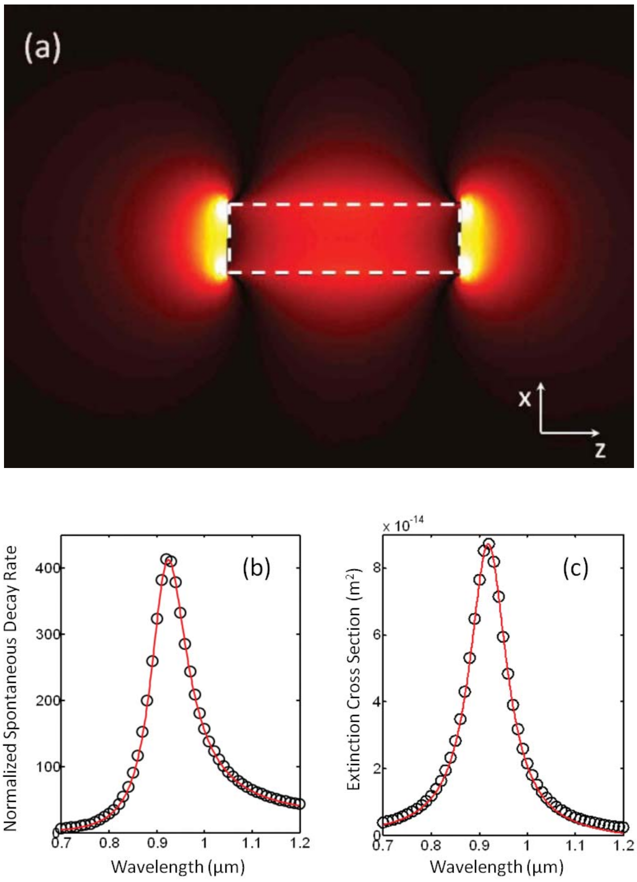


FIGURE 3: (a) Distribution of z-component of the electrical field |Ez| for the normalized quasinormal mode of a cylindrical gold nanorod with a diameter of 30 nm and a length of 100 nm. The white dashed line represents the rod contour. (b) Spontaneous decay rate of a cold molecule located on the rod 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 (NEMSs) 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.

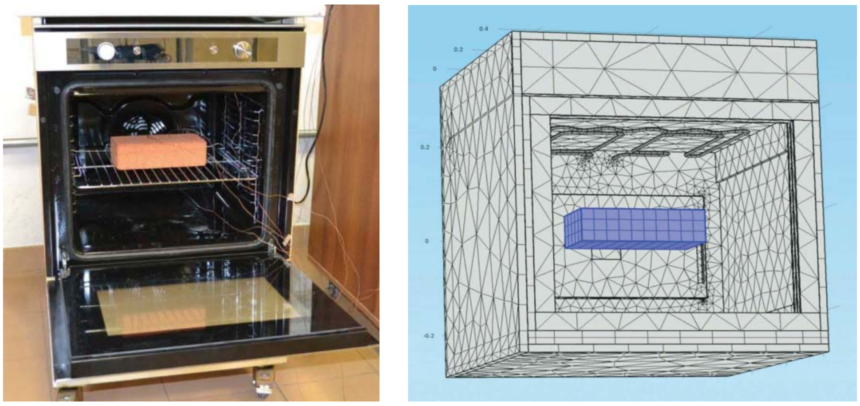


FIGURE 1: Left: Whirlpool's Minerva oven set up for the "brick test." Right: The meshed geometry.

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.

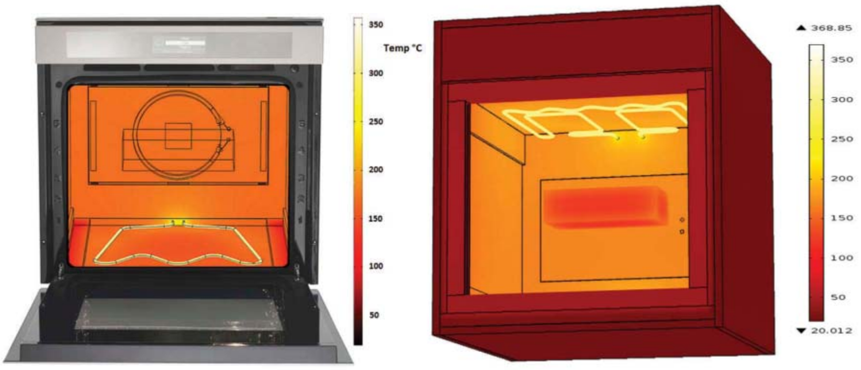
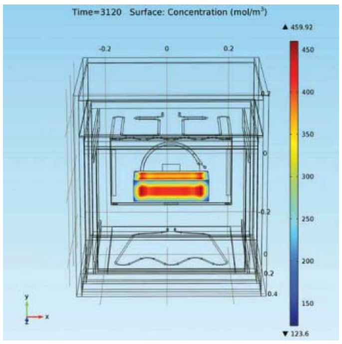


FIGURE 2: Predicted temperatures of the oven surfaces (color scale in °C) after 50 minutes in a broil cycle (right) and a bake cycle (left).



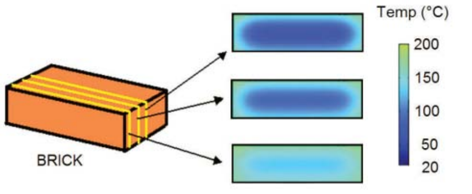


FIGURE 3: Left: Brick surface moisture concentration (in moles per cubic meter) at the end of the simulated test. Right: Predicted temperature profiles at different slices of the brick after 50 minutes at 200°C.

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.

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.

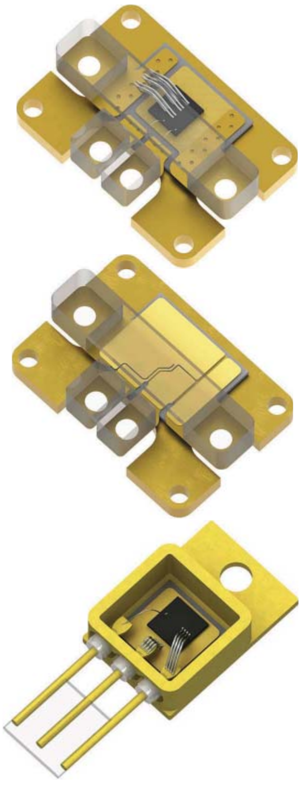


FIGURE 1: The custom SiC (top), custom GaN (middle), and TO (bottom) power modules.

» 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'

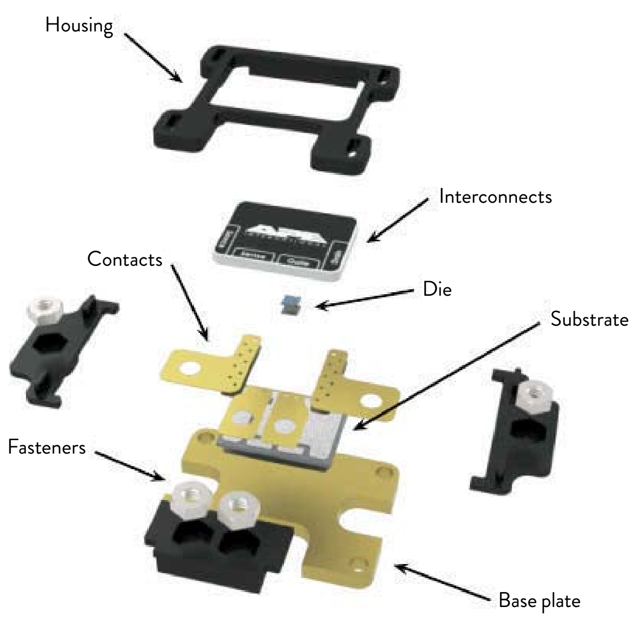


FIGURE 2: Power module components (above) and the assembled power module (bottom). Fully assembled, the entire device is a little larger than a quarter.

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

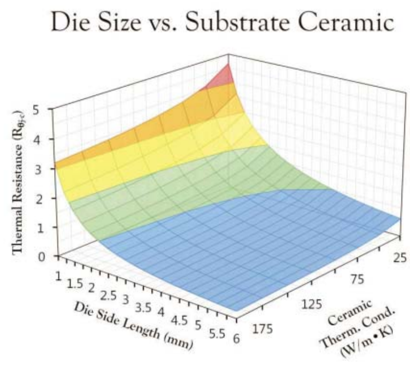


FIGURE 3: Parametric sweep showing how thermal resistance varies with changes in device size and thermal conductivity of the substrate.

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

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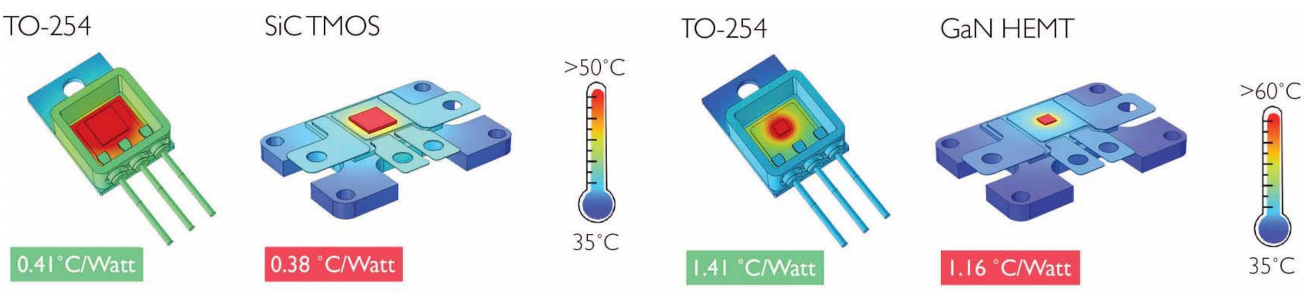


FIGURE 4: Thermal resistance results when comparing TO-254 to SiC (left) and TO-254 to GaN (right).

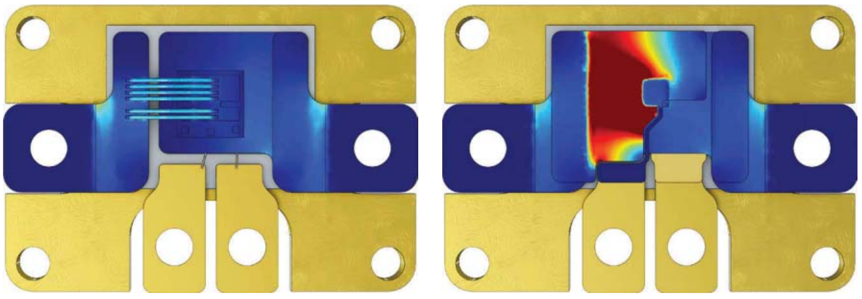


FIGURE 5: Current density gradients in the SiC (left) and GaN (right) geometries. In the SiC package, the current shows a relatively low density (preferred for higher currents), with the major concentrations found in the wire bonds. The GaN package has a higher average density, but more area available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

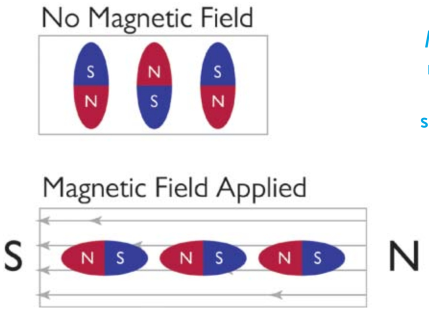


FIGURE 1: Magnetostrictive materials change their physical shape in response to an applied magnetic field and vice versa.

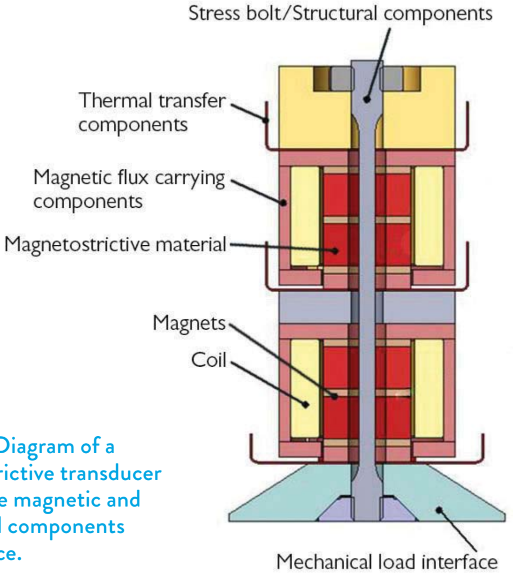


FIGURE 2: Diagram of a magnetostrictive transducer showing the magnetic and mechanical components of the device.

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.

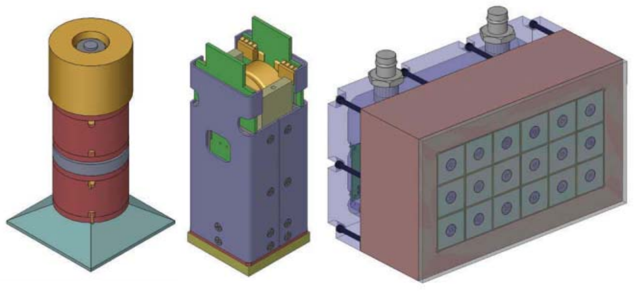


FIGURE 3: Closely packed SONAR array, which includes a magnetostrictive transducer at its core. From left to right: a single magnetostrictive SONAR transducer; the transducer packaged with power electronics; and the full array, made up of 18 transducer elements.

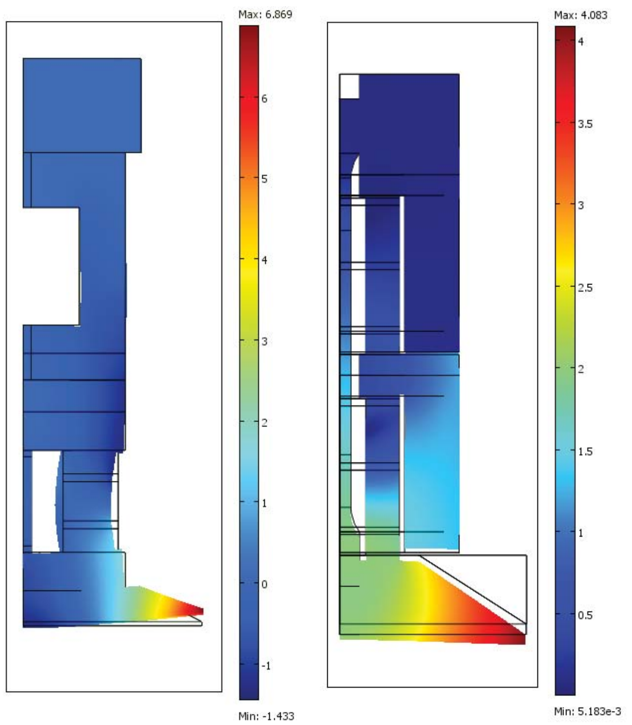


FIGURE 4: Left: The initial transducer design shows severe bending in the mechanical interface to the load. Right: The redesigned model demonstrates reduced deformation.

» 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-

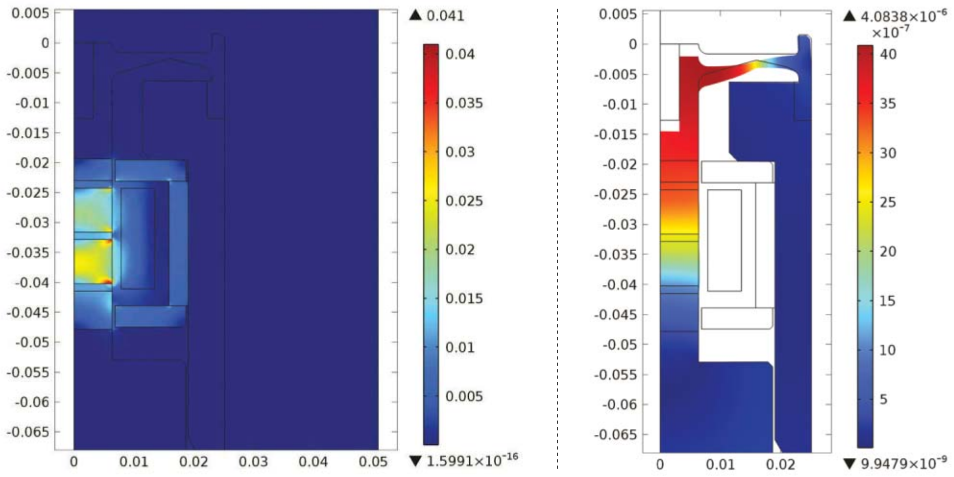


FIGURE 5: Magnetic fields generated from a 1-ampere input to the coil. Displacements are calculated using the maximum current input.

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.*

By John Capp & Bakhtiar Litkouhi

THE RISE OF THE CRASH-PROOF CAR

WHEN CARS WON'T LET DRIVERS MAKE MISTAKES, CRASHES MAY BECOME A THING OF THE PAST

Photography by Dan Saelinger

YOU'RE SITTING BEHIND THE WHEEL OF your car, but instead of looking at the road, you've been staring at your phone, perhaps reading a new e-mail message or texting a friend. Suddenly, the driver in the car ahead of you slams on the brakes. Rather than becoming a victim of distracted driving, you feel a gentle deceleration as your car comes to a stop on its own, easily avoiding a collision. You might look up to see what the holdup is, but that's the extent of your concern. And your car starts itself up again as soon as the road is clear.

While this isn't a realistic portrayal of your commute just yet, this future is coming–and some of the technology that will make it possible is already present in today's cars. The more advanced models can warn of obstacles, adjust the distance to a car ahead, and activate the brakes when a distracted driver doesn't. And this is just the beginning. According to research firm IHS, by 2055 roughly 90 percent of the cars in the United States will be able to drive themselves in some, if not most, circumstances.

Ironically, while technology will ultimately protect us from accidents on the road, sometimes it does the opposite. That's because so many people make phone calls, text, manipulate GPS units, and fiddle with infotainment systems when they should be concentrating on their driving. And even the most diligent drivers can choose the wrong moment to glance at a navigation screen. According to the National Highway Traffic Safety Administration, driver distraction is a factor in almost 20 percent of crashes in which someone is injured.

But a class of technological aids called active-safety systems is beginning to address this problem by raising drivers' awareness of crash threats that may exist in the surrounding traffic. Virtually every car sold in developed countries today uses passive-safety features, like seat belts, air bags, and car frames that absorb impact to protect occupants during a crash. Active safety goes further by using loud sounds, visual alerts, and vibrations to direct the driver's attention to imminent danger. Some systems can even operate the brakes to help avert disaster. These active-safety systems are the building blocks for the crash-avoiding cars of the future.

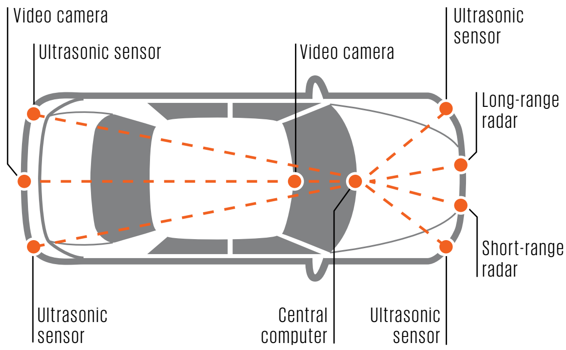
Consider Cadillac's Driver Assist package, which our company (General Motors) introduced in 2012. This group of safety systems detects road hazards and draws your attention to them. It adjusts your speed and the distance from the car or truck in front of you based on levels you set, and it can even bring you to a full stop when the vehicle ahead does the same. It also helps when you're backing out of a parking spot, using visual alerts, sounds, and seat vibrations to warn of approaching cross traffic. The system sets off similar alarms if you start drifting out of a lane without the turn signal activated.

A car equipped with this package can avoid many low-speed crashes, such as those in parking lots or in stop-and-go traffic, with a low-speed emergency automatic braking system that kicks in when it senses an object ahead and notices that the driver is not reacting appropriately. And at higher speeds, this same system automatically brakes to help avoid–or at least reduce the severity of–an impending rear-ender.

Smarts like these require some high-tech sensors. A long-range radar, positioned in the grille behind the Cadillac logo, scans for objects as far ahead as 150 meters. Short-range radars, which can sense cars a few dozen meters away, hide behind the plastic that covers the bumpers–two radars in the front and three in the rear. A video camera attached to the windshield behind the rearview mirror registers lane markings and vehicles ahead. Another camera near the rear license plate surveys the scene behind the car. Eight ultrasonic sensors, four on the front bumper and four on the rear, detect objects at very close range, which is helpful when you're trying to parallel park.

The data from all these sensors go to a central computer, which uses the information to figure out what kinds of objects are around the car, recognizing that in certain situations some sensors are more reliable than others. For example, when you're traveling at highway speeds, the readings from the ultrasonic sensors aren't helpful, whereas they are nearly essential when you're navigating your car into a tight parking space. The central computer then decides what kind of alert needs to be activated or what level of automatic braking needs to be applied.

A TYPICAL ACTIVE-SAFETY SYSTEM uses a central computer to collect information from a variety of sensors—including long- and short-range radars, video cameras, and ultrasonic distance detectors. The computer activates alerts or brakes automatically based on its analysis of the sensor inputs.



These active-safety systems are enormously helpful, but they aren't enough to make a car truly crash proof or able to take over the driving. They can't grab the wheel from you and take evasive action when braking alone won't do, for example, and they can't stop you from steering out of your lane into danger if you ignore all the alerts.

While fully autonomous vehicles are a ways off yet, we believe cars that can pilot themselves briefly under certain conditions should be in showrooms before the end of the decade.

Actually, self-driving vehicles are already here, although you can't yet buy one at your local dealer. In November 2007, a Chevrolet Tahoe modified by researchers at Carnegie Mellon University and GM along with other partners won the Defense Advanced Research Projects Agency (DARPA) Urban Challenge, a closed-course competition that tested the ability of autonomous cars to drive in traffic. Since then, companies and universities have built upon the technology showcased in the challenge. Google, for example, has a fleet of driverless Toyota Priuses, which have reportedly traveled an aggregate of 500 000 kilometers.

To drive itself, a car requires four basic things. It needs a satellite-navigation system and digital maps to know where it is. It needs to be able to see 360 degrees around itself under all sorts of conditions. It needs to be able to communicate with other vehicles and with certain parts of the road infrastructure, like traffic lights, school zones, and tollbooths. Finally, it needs software intelligent enough to determine what the car should do and electronic controls and actuators to make the car do it. All these technologies exist on some level today, and many of them are already on vehicles, as in Cadillac's Driver Assist package. But these systems need to be more capable before they usher in the era of fully self-driving cars.

Satellite navigation and digital maps are old news: GM incorporated GPS, digital maps,

ILLUSTRATION BY mckibillo

and wireless communications into its OnStar system more than 17 years ago. Add-on GPS systems from Garmin, TomTom, and others have been around for years, and today people consult digital maps on smartphones even when walking down the street. For the most part, the basic "Where am I?" part of the equation is solved, at least in the United States and most other developed countries, although fully self-driving cars will require greater precision.

To have a 360-degree sensing capability, self-driving cars will need a combination of cameras, radar, lidar, or perhaps other sensors, because each has its strengths and weaknesses. Cameras require visible light–a weakness–but they can readily be used to identify objects. Radar and lidar can send signals in the dark but are more limited in determining shapes around them; they do better than cameras at gauging relative velocity and estimating distance, however. Lidar can give a more detailed look in a focused direction, whereas radar provides broader coverage.

Communicating with other vehicles and the road infrastructure will also be immensely important, adding capabilities beyond those of today's drivers. For example, if you're an attentive driver, you immediately notice when the brake lights illuminate on the car ahead, but typically you don't know whether the driver of a vehicle two or three cars ahead applied the brakes. Wireless communications systems could soon change that.

T**his area is a hotbed** of development right now. Automakers are working on technologies for both vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication. Both use a special form of Wi-Fi called Dedicated Short-Range Communications, which operates on a band near 5.9 gigahertz. V2V communication allows similarly equipped vehicles within a few hundred meters of each other to trade information about location, speed, and direction of travel. V2I communication can share information about traffic-signal timing, the number of lanes a highway has, whether a curve is coming up, surface conditions, and so forth, when such data are available.

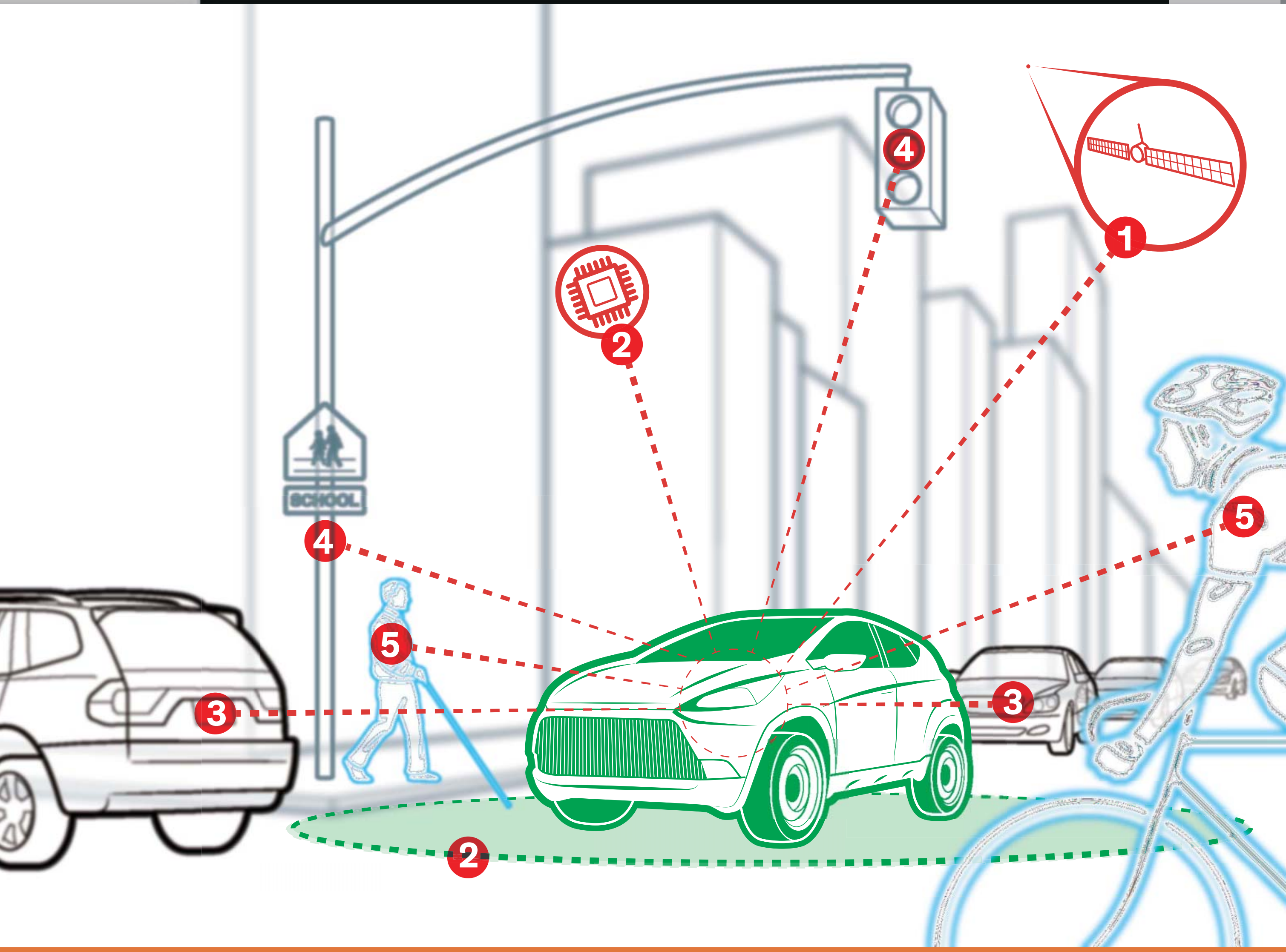
GM pioneered V2V technology eight years ago and has demonstrated many V2V and V2I features using real vehicles. Nine U.S. car companies, in an effort led by the U.S. Department of Transportation (USDOT), have been working for several years as part of a research consortium, the Crash Avoidance Metrics Partnership, to develop standard communications protocols and security mechanisms for this technology. Automakers have started a similar project in Europe: the Car-2-Car Communication Consortium.

To help understand the safety benefit of V2V technologies, the USDOT and a team of public agencies, universities, and major auto manufacturers began a pilot program in Ann Arbor, Mich., in August 2012 and are still collecting data. The test involves about 3000 cars, trucks, and transit vehicles equipped with communications devices. The group also used V2I, equipping some parts of the infrastructure to communicate with the fleet, such as traffic signals at busy intersections, road edges along sharp curves, and several spots along highways. This combination of technologies is known as V2X. Similar collaborative programs have been under way in Japan, led by the Japanese government in cooperation with several of that nation's auto companies.

Of course, having V2X communications on your car doesn't help you much unless other vehicles and parts of the road infrastructure are able to talk back. So this technology will need to spread over time. And as it is built into more and more vehicles, the benefits will grow.

PROP STYLIST: DOMINIQUE BAYNES

PHOTOGRAPH BY Dan Saelinger



In February, U.S. Secretary of Transportation Anthony Foxx attempted to shift the V2V rollout into high gear with an announcement that the USDOT would, before President Obama leaves office, develop a proposal to require V2V communications on all new vehicles. There's no word on exactly when that requirement will kick in, but just knowing it's coming is likely to speed adoption of the technology.

The infrastructure piece will take longer to evolve, but with cars on the road having communication abilities, it will make sense for local and regional governments to update equipment when they replace various bits of road infrastructure, like traffic lights and in-road sensors, so V2I will also grow gradually.

And your car may soon be communicating with pedestrians as well. In 2009, GM demonstrated a V2X capability that can alert drivers to pedestrians and cyclists. It relies on Wi-Fi Direct, the peer-to-peer wireless standard that allows devices like smartphones to communicate directly with one another rather than through a shared access point. An app on a pedestrian's phone would transmit location information using Wi-Fi Direct, and a receiver in a nearby vehicle would note the signal and send an alert to the driver—for example, by flashing a light on the dashboard.

V2V systems will, of course, have to be extremely robust to ensure that the messages traded are accurate. Investigators involved with the Ann Arbor test of V2V systems are currently evaluating the quality of the messages sent and received under various conditions. Intervehicle signaling is, fortunately, easier than using traditional cellular or Wi-Fi communications, because the messages need only be exchanged when vehicles are close together, and the vehicles talk directly to one another rather than through an external wireless network.

In discussing the future of V2V communications, transportation secretary Foxx made it clear that while vehicles will be broadcasting their locations and speeds, they will not identify their owners. Regulators will also need to make it clear how the information will be used. Part of the remaining technical work is to define a security system that will ensure that no malefactors can access the messages and that this information can be used only for its intended purpose.

Although automated-driving technologies have only recently started making the news, cars have actually been intervening in the driving process in limited ways for some time. One of the earliest examples was electronic stability control: systems

ILLUSTRATION BY mckibillo

A CAR THAT KEEPS ITS "EYES" ON THE ROAD

A car can be a safer driver than the typical human, but it needs to gather and analyze a lot of information about the world around it. [1] Satellite navigation systems can help the car know where it is. [2] A variety of sensors, analyzed by a central computer, can provide a 360-degree view of the car's surroundings. [3] Other vehicles can communicate their behavior and intentions wirelessly. [4] Signs, roads, and other parts of the transportation infrastructure can alert the car to local conditions. [5] Pedestrians and bicyclists can alert the car to their presence.

that incorporate antilock brakes, traction control, and differential braking to apply the necessary brake pressures at each wheel automatically, thus helping a driver maintain steering control during a skid. Similarly, today's electronic power-steering systems, which use inputs from steering, speed, and other sensors, help prevent drivers from overcorrecting in skids. Such technologies are common on vehicles today.

Coming soon is lane-following technology, which is one component of automated highway driving. This equipment mainly relies on cameras to detect lane markings but can also use GPS data to anticipate upcoming curves and other road characteristics. But even the best such systems face certain operational limitations. For example, when snow or poor visibility obscures lane markings, the driver will still need to steer manually.

Lane following will be the centerpiece of the first systems capable of maintaining speed and lane position under certain highway driving conditions. GM calls the concept Super Cruise, having first demonstrated it in 2012, and other car companies have since demonstrated similar technology. Super Cruise works on freeways in both bumper-to-bumper traffic and on long road trips in light traffic. It works well in either situation, but the driver must still pay attention to the road and be ready to take over in an instant.

The next frontier will be more-complicated driving conditions. Staying centered in a lane on a highway, for example, is much less demanding than staying centered on a road in a crowded city, where markings can be less visible to begin with, if they exist at all, and other vehicles may block a camera's view of road markings. So in urban settings, a car will likely have to rely on additional sensors and approaches. Urban driving gets even more complex when the movement of cars, motorcycles, bicyclists, pedestrians, and trains are considered. So it will take longer to develop the sensing systems and software needed to automate driving in these more-challenging situations.

Not only will automated driving systems have to manage the ever-changing conditions around the car, they will also have to monitor the health of all the various controls, sensors, and processors within the vehicle. This will add considerable complexity, especially if the software involved includes algorithms that attempt to identify impending failures. And like all computerized systems that handle important information, automated driving systems will have to be protected from hackers, to prevent an unauthorized command of a vehicle's control systems, such as braking and steering.

Regulators are of course interested in the safety benefits these technologies can provide, but they must also minimize the risks of unproved technologies. So they will move cautiously. The recent announcement of the upcoming mandate for V2V communications is an important step forward, at least for the United States.

We look forward to similar moves elsewhere in the world. As they happen, harmonizing standards will become a significant issue. Although auto manufacturing is global, standards affecting the industry are often local. Radar frequencies allocated for public use often vary by country, for example. Countries could also differ in the communications protocols they select for use in V2V systems or in performance standards for collision-warning systems. None of these obstacles is insurmountable, but adopting standardized approaches for things like radars, digital maps, markings, and roadway signs and markers should speed the deployment of active-safety and automated-driving technologies around the world.

While many of us just long for the day we can surf the Internet on our commutes to work, the automation of the passenger automobile stands to benefit drivers who are older or disabled in more significant ways.

And for every driver, active-safety systems and automated-driving tech will provide not only assistance and support but also the valuable gift of time—time to reach for something in the glove compartment, to turn around and fix a child's jacket, to put on makeup, or to chat on the phone. Drivers are already doing these things, but in the future they could do them without being a hazard to themselves or others.

But until these technologies evolve into fully fledged robotic chauffeurs, the automated systems will need to be able to communicate clearly to the driver about when they are—and are not—capable of handling the vehicle. And when they are not, they must alert the driver with plenty of time to take over. Much research will be required to understand the safe limits of automated-driving systems and how to manage them.

As the auto industry works to develop and implement these automated technologies, it has an opportunity to completely reinvent the automobile. When cars no longer really crash, their frames—designed now to protect occupants during a collision—could be built lighter, making the vehicle more efficient. If automated systems fully replace the driver, the entire cockpit design could be reimagined to provide greater comfort. Thanks to automated systems, the cars of 2100 may look nothing like the cars of the past 100 years. ■

POST YOUR COMMENTS at http://spectrum.ieee.org/crashproofcar0514

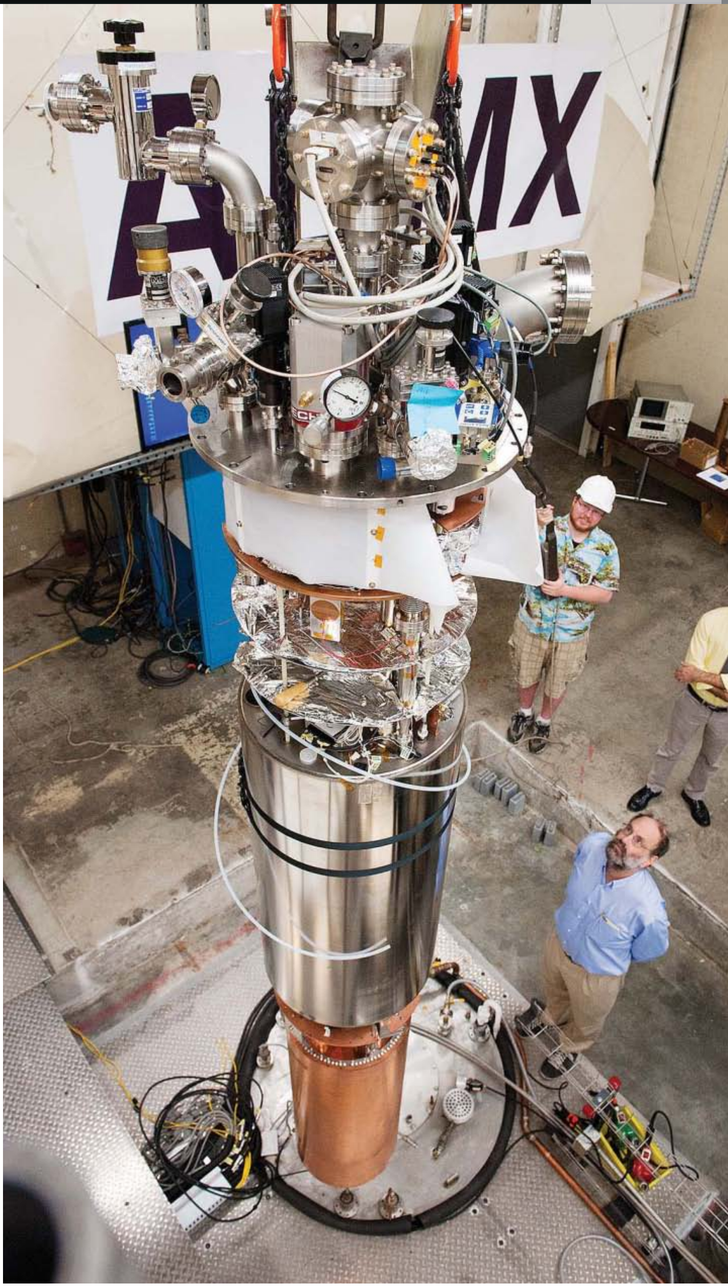
LIGHTS, CAMERA, AXION: Physicists Leslie Rosenberg [left] and Gray Rybka examine the Axion Dark Matter eXperiment insert in October 2013.

ONE TEAM GOES IT ALONE IN THE HUNT FOR THE DARK HORSE IN THE DARK MATTER RACE

GETTING ON DARK MATTER'S WAVELENGTH

BY RACHEL COURTLAND

DARK MATTER, the most abundant form of matter in the universe, is invisible and intangible. But that doesn't keep Leslie Rosenberg from seeing it nearly everywhere he looks. Like most physicists, he finds ample evidence of it written on the sky. It's there in the swirling of galaxies, the aftermath of cosmic collisions, and the vast, weblike scaffolding that the universe's luminous matter seems to hang upon. ● It's also, he hopes, near at hand. Dark matter almost certainly sweeps through Earth like water through cheesecloth. But Rosenberg, a professor at the University of Washington, in Seattle, thinks he might have just the thing to coax it out of hiding. ● Tucked into the concrete floor of a large warehouselike laboratory at the edge of campus, the Axion Dark Matter eXperiment (ADMX) contains the world's most sensitive radio receiver in its frequency range. Its builders are fond of boasting that if the detector were placed on Mars, it could pick up a cellphone signal sent from Earth, assuming there were no interference.



It'll need that kind of sensitivity to have any chance of detecting dark matter. Based on a wide range of observations going back to the 1930s, astronomers estimate that for every kilogram of ordinary matter in the universe–be it hydrogen, silicon, concrete, or feathers–there are some 5 kilograms of dark matter. But for all its ubiquity, no one knows what the dark stuff is made of. They only know that, with the exception of exerting a gravitational pull, it interacts very little with ordinary matter.

ADMX is designed to hunt for one of the leading dark matter candidates: the axion. And now, after some 25 years of development, Rosenberg and his colleagues may be on the verge of finally seeing the elusive particle–if it does in fact exist. Later this year, a new cryogenic cooling system will chill the ADMX detector down to just a tenth of a degree above absolute zero, bringing the experiment to its peak sensitivity. Over the coming months and years, the detector will scan radio bands in the hopes of literally tuning into dark matter's wavelength, converting axions into electromagnetic radiation that can be picked up and amplified through sensitive quantum electronics. Any day now, finding dark matter could just be a matter of hitting the right frequency, says collaborator Gianpaolo Carosi, a research scientist at Lawrence Livermore National Laboratory, in Livermore, Calif. "We're trying to look for that little tone above the hiss."

Nowadays, thanks to a range of complementary observations of the universe, a consensus has emerged over its composition. Astrophysicists estimate that if you count all the mass and energy contained in the cosmos, ordinary matter–all the gas, dust, stars, and planets–makes up only 5 percent of the total. The rest is divided between two unknown entities: dark energy and dark matter.

Dark energy–which seems to be some sort of vacuum-filling field that forces space apart–is the more recent discovery. The first hint of it was detected in 1998, when astronomers used the brightness of exploding stars to gauge cosmic distances and, by extension, the universe's recent expansion history. They found that today the universe is not only expanding, it is expanding at an accelerating rate.

Dark matter is a much older puzzle. Its presence was first revealed in the 1930s, when astronomer Fritz Zwicky measured the speeds of eight galaxies in the nearby Coma cluster and found that they were moving far too quickly to be bound by the gravity of the cluster's luminous matter. Zwicky concluded that some extra, unseen mass must be present to keep the galaxies in tow.

Since then, evidence of dark matter has cropped up in many other places. Some astronomers contend that what seems to be extra mass is actually evidence of a breakdown of gravitational laws on large scales. But for many researchers, the observations clearly point toward an entirely new particle. Finding it would be a major milestone in our effort to understand the fundamental physics of the universe.

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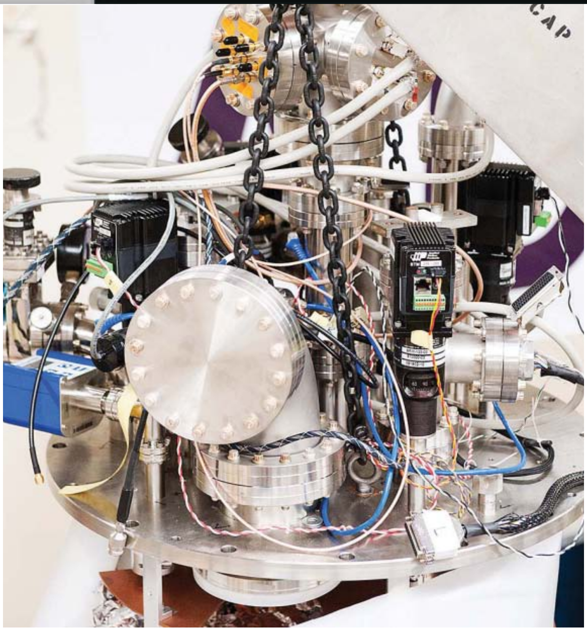


TOP TO BOTTOM: When in operation, the Axion Dark Matter eXperiment insert **[far left]** sits in a hole in the concrete floor of an experiment hall at the University of Washington's Center for Experimental Nuclear Physics and Astrophysics. When the insert is in place, only the room-temperature electronics **[top right]** are accessible, and the copper cavity at the bottom of the insert rests inside a superconducting coil [not shown]. Two tuning rods, two antennas, and a thermal link **[bottom right]** go into the cavity, which is slated to be cooled to a tenth of a degree above absolute zero later this year.

The axion is just one of a host of dark matter candidates that have been proposed over the years, including very small black holes, formed moments after the big bang. Nowadays, many consider the leading candidate—and the axion's main rival—to be the weakly interacting massive particle, or WIMP, a hypothetical heavyweight that could have a mass hundreds of times that of the proton. WIMPs aren't like ordinary matter; they don't respond to electromagnetic fields or give off light. Instead, they interact only through gravity and the feeble weak force, most famous for causing some atoms' neutrons to decay into protons.

The WIMP most heavily favored today is tied to the theory of supersymmetry, a potential extension of the standard model of particle physics that could explain why ordinary particles have the range of masses they do. Supersymmetry predicts a new family of particles more massive than those we see around us. The lightest of those could have been created in large enough quantities in the early universe to account for dark matter. Such a particle could also act as its own antiparticle, so that when two collide, they annihilate, releasing particles such as photons in the process.

The WIMP hunt is wide. Some researchers look for evidence of the particle's creation in data from the Large Hadron Collider. Others scrutinize the Milky Way's gamma-ray glow for light that would be produced when WIMP pairs annihilate. Year after year, ever-larger and more-sensitive detectors are built in the hopes of capturing WIMPs as they pass through Earth. To isolate these detectors from confounding signals produced by particles zipping through Earth's atmosphere, the experiments are hidden inside mountains and former mines and down boreholes in Antarctic ice.

There, like enormous catcher's mitts, the detectors lie in wait for extremely rare collisions between one of these lumbering phantasms and an ordinary atom. Such a collision would cause the atom to recoil, raising a small vibration. In some cases, electrons and photons would be released. These sorts of effects can be picked up with light- and charge-sensitive detectors. The hope is that, over time, the infinitesimal energy released by that occasional bump might just add up to a signal that's consistent with an entirely new particle. In this hunt, seasonal variation will be key, as the flux of dark matter particles will change depending on where Earth is in its orbit.

"We have something like 20 different experiments out there that are designed to look for WIMPs," says Dan Hooper, a physicist at the Fermi National Accelerator Laboratory, in Batavia, Ill. Recently, astrophysicists looking toward the center of the Milky Way have found a peculiar spike in intensity at a particular frequency in the gamma-ray part of the spectrum. The signal looks more and more WIMP-like year after year, Hooper says, but terrestrial detectors have yet to turn up any hard evidence of WIMPs, and recent results have "dampened enthusiasm."

Last year, for example, physicists put the finishing touches on the most sensitive such detector yet built, the Large Underground Xenon experiment, which contains some 350 kg of liquid xenon. In the first three months of its hunt beneath the Black Hills of South Dakota, the detector turned up no evidence of WIMPs, knocking down a few models and contradicting hints seen in prior experiments.

Against all this effort, there is ADMX, the only experiment looking for the other leading dark matter candidate: the axion. Compared with the WIMP, the dark matter axion is staggeringly ethereal. At most it would be just a trillionth the mass of the proton, much too light to register in the recoil of atoms, as WIMPs are supposed to. To provide the same gravitational heft, dark matter axions would have to be present in much higher numbers than WIMPs would. Trillions of them would occupy each cubic centimeter of our corner of the galaxy. But detecting even a few of those particles will be a challenge, requiring highly sensitive electronics that generate very little noise of their own.

Over the years, Rosenberg says, he has encountered sometimes strong resistance to the idea that ADMX could ever be sensitive enough to see an axion signal. Now, with the WIMP still elusive and ADMX's hunt under way, he sees the tide turning. On a visit to Seattle, I ask him over sandwiches what the WIMP community thinks of ADMX. He grins. "They're thinking, 'Are those pigs going to find a truffle?' "

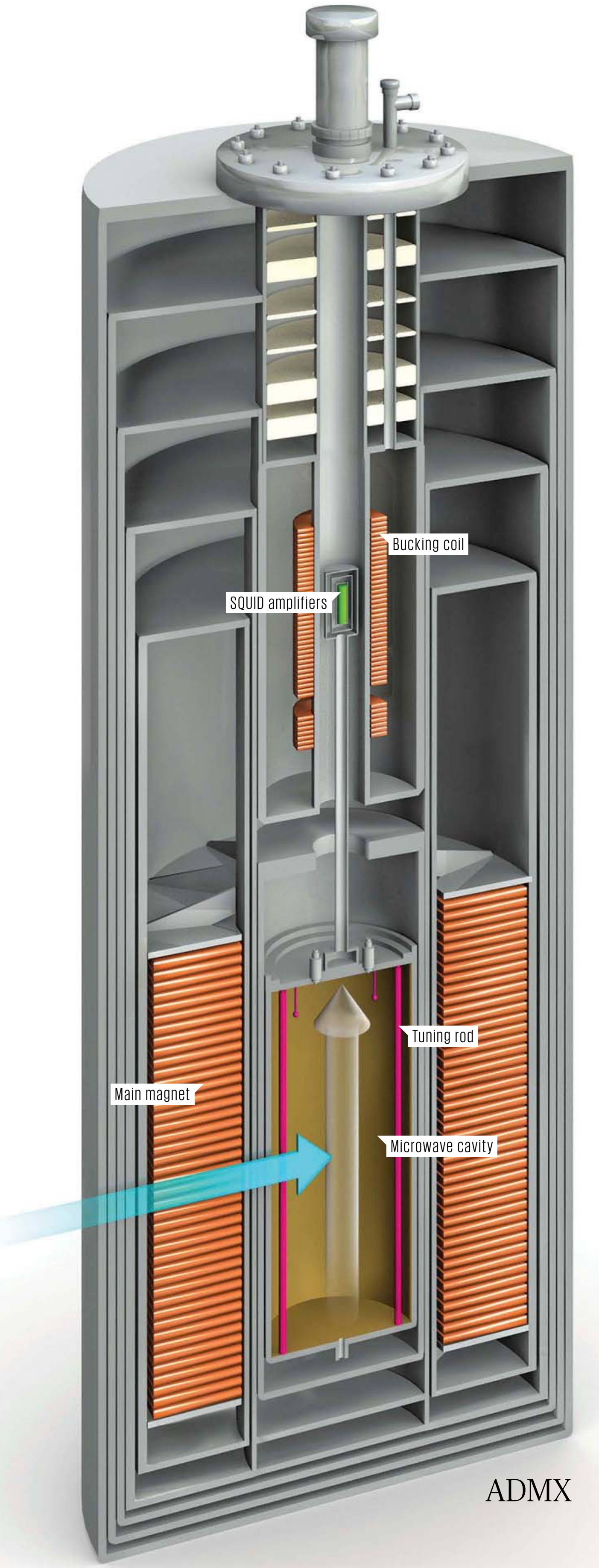
T**he axion was not devised** with dark matter in mind. The idea for the particle first emerged in the late 1970s, in an effort to solve a different puzzle relating to quarks and gluons. According to the standard model of particle physics, every proton and neutron consists of three quarks, which are held together by gluons. Quarks and gluons behave extraordinarily symmetrically: Swap a particle for its antiparticle and reverse the spatial coordinates and you'll get the same behavior. This is surprising because the theory that describes how quarks and gluons interact–quantum chromodynamics–could easily violate these symmetries. These violations should be apparent in the neutron's electric dipole moment–a measure of the electric field that would arise if the positive charge inside the neutron resided closer to one end of the particle and the negative charge closer to the other. But to the limit of their experiments, physicists detected no evidence of such a moment, suggesting a high degree of symmetry, one that was quite unlikely to occur by chance.

In 1977, two physicists at Stanford University, Roberto Peccei and Helen Quinn, published a paper proposing a solution: an additional field that would pervade space and, like a kind of gravity, provide a mechanism for the universe to essentially "tilt" naturally into a symmetrical state. Hot on their heels, physicists Steven Weinberg and Frank Wilczek each published a paper pointing out that the existence of a field implied a corresponding particle. Wilczek, thinking of a once-popular brand of detergent, already had the perfect name in mind for something that could clean things up so nicely: the axion.

When the axion was first proposed, particle physicists looked for it in particle colliders. But the axion did not emerge, and theorists concluded that if the particle did exist, it must be too light and interact too rarely with matter to appear in such collisions. Around the same time, Wilczek and others realized that this new, more ethereal version of the particle could have been created in large enough numbers in the early universe to account for dark matter.

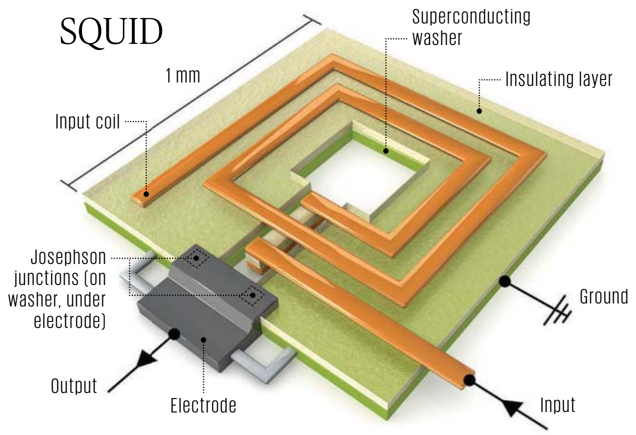
How to find it? Wait long enough and an axion will naturally decay into two photons. But that process would take 10^{50} seconds or more. That's about 10^{32} times as long as dark matter axions (and the rest of the universe, for that matter) have been around.

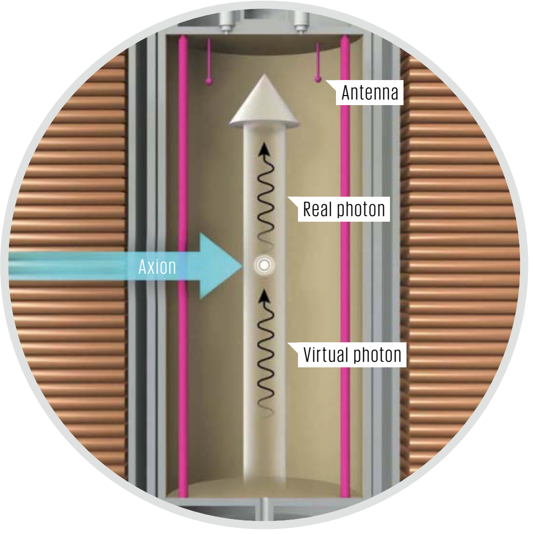
"The axion had been declared invisible," says theorist Pierre Sikivie. "[I said], let me just calculate how invisible they truly are." A newly minted professor at the University of Florida in the early 1980s, Sikivie had just finished teaching his first graduate-level



ADMX

ILLUSTRATION BY Emily Cooper





The Cosmic Tuning Fork

A strong magnetic field and a sensitive, low-noise amplifier could turn "unseeable" axion dark matter particles into microwave radiation

THE CORE OF THE AXION DARK MATTER EXPERIMENT, or ADMX **[left]**, is a microwave cavity, a copper cylinder that contains two tuning rods to adjust the resonant frequency. The superconducting coil wrapped around this cylinder creates an 8-tesla magnetic field, which produces a large population of virtual photons at the resonant frequency of the cavity. As Earth sweeps through its orbit, axion particles enter the cavity. If their frequency matches those of the virtual photons, some will convert into microwave photons **[above]**. Two small wire antennas in the cavity pick up signals and carry them to two superconducting quantum interference device (SQUID) amplifiers specially designed for high-frequency operation. A bucking coil isolates the amplifiers from the magnetic field of the main coil. Signals from the ADMX cavity enter each SQUID **[top]** through a superconducting coil. In these SQUIDs, the far end of the coil is left unattached instead of going on to complete a circuit. A signal with the right frequency will create a resonance between the coil and the underlying magnetic-field-sensitive washer. This minor change in wiring allows the SQUID to amplify signals at much higher frequencies.

electromagnetism course and was hunting for a juicy physics problem to work on.

Producing an axion in a collider was already a low-probability event. Detecting that axion would be another low-probability event, compounding the problem. But Sikivie found there was a reasonable hope of finding axions that already exist. In a 1983 paper, he outlined a scheme that might work: exposing the particles to a very strong magnetic field. This field would create a sea of "virtual photons"—packets of electromagnetic energy that flit in and out of existence due to quantum mechanical variations in vacuum. By the same rules that cause an axion to decay into two photons, a virtual photon could be used to trigger the conversion of an axion into another photon.

The trick would be to create virtual photons with the axion's frequency: Axions, like all other particles in quantum mechanics, are also waves and so have a corresponding wavelength and frequency.

"If the dark matter is axions, then we are surrounded by this field that is oscillating at a frequency given by the axion mass," Sikivie explains. On its own, a strong magnetic field creates a host of virtual photons, but with a range of different frequencies. Because only a small number of those photons would match the axion frequency, few would trigger an axion conversion. But Sikivie reckoned he could boost the chance of conversion using an electromagnetic cavity with a high quality factor. In such a cavity, electromagnetic radiation at a particular resonant frequency bounces back and forth with little loss, like sound waves in an organ pipe.

Thanks to some quantum mechanical magic, this setting would create a high population of virtual photons with frequencies that matched the cavity's resonant frequency. If an oscillating axion field matched this frequency, an axion could be converted into microwave radiation with that same frequency. The cavity could then amplify that signal.

"All of us were smitten, I think, by the elegance of that idea," says Karl van Bibber of the University of California, Berkeley. Within a few years, two teams—one based at Brookhaven National Laboratory, in Upton, N.Y., and the other at the University of Florida, in Gainesville—had built small, tabletop-class metal cavities to test the concept. One thing the researchers had to prove is that such cavities could tune their resonant frequency. Because the mass—and thus the frequency—of the axion was unknown, the detectors would have to sweep through a large swath of the radio spectrum until they hit upon the frequency that would call axions out of hiding.

The teams showed that you could use rods, moved in from the edge of the cavity or out from the center, to alter the interior of the cavity and so tune its resonant frequency over a fairly wide range. But the experiments fell short of the sensitivity needed to see the axion at even its most optimistic interaction strengths. At the very least, the researchers found, they'd need stronger magnetic fields to boost the probability of converting axions into photons. Bigger cavities, which would expose more axions to the magnetic field at any given moment, would also help.

Flash forward to 1989. Van Bibber, who was then working at Livermore, found he'd been volunteered for the task of building the next axion detector. So ADMX–although it wasn't yet called that–began its earliest incarnation there, in an old hangar with no climate control and temperatures that could top 45 °C in the summer.

To create the magnetic field needed to convert the axions, in 1995 van Bibber and his team purchased a 6-metric-ton, 1-meter-tall superconducting magnetic coil. They designed an insert to go inside this coil–an empty copper-plated stainless steel cylinder about the size of an oil drum. A set of motor-controlled tuning rods would be inserted into the cylinder to control the resonant frequency, along with a simple wire antenna to pick up the microwave signals. A chain of ultralow-noise, transistor-based amplifiers would boost this signal and send it to signal processing equipment: a series of mixers and filters to bring the signal frequency down to audio frequencies. The signal would then be converted into a power spectrum by using a fast Fourier transform. Over time, as the detector moved through frequencies, data showing power as a function of frequency would accumulate. If the axion were found, it would appear as a simple spike in the spectrum, rising above the noise.

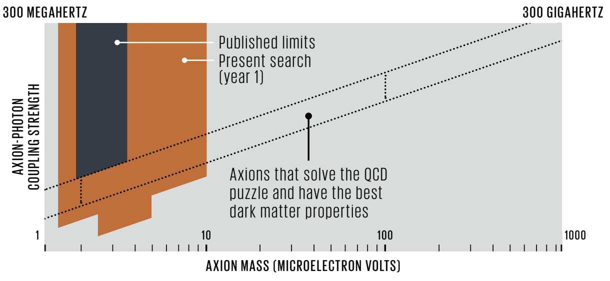
By 1996, construction was well under way. Even then, the team knew that although their detector could see some kind of axion, it wouldn't be sensitive enough to do a thorough search. In a year they could search a small, 100-megahertz chunk of the microwave spectrum. Even within that window, the detector would be sensitive only to an axion that had a relatively strong interaction with electromagnetic fields and thus a high chance of converting into a photon. There was the possibility that the dark matter axion might have a much weaker "coupling" to electromagnetic fields and so a very low chance of converting.

To find an axion with the weakest of couplings in that same range, they'd have to sit on each frequency for much longer. The search might take 50 years, or even more. Physicists beginning the hunt fresh out of graduate school probably wouldn't see the end of it before they retired. To detect the most weakly interacting axions, the system would need to be sensitive to power as low as a yoctowatt, a trillionth of a trillionth of a watt. That's about a thousandth the power of the last signal received on Earth from Pioneer 10, when the spacecraft was some 12 billion kilometers away, long past the orbit of Pluto.

"We were scratching our heads about how to speed things up," Rosenberg says. For the initial signal amplification, the team was already using what might be considered the gold standard: high-mobility, heterojunction field-effect transistor amplifiers. To keep the noise to a minimum, these were cooled to just a few degrees above absolute zero. But they'd need something even quieter to speed up the search.

Fortunately, by the late 1990s, the team had found John Clarke. A physicist at UC Berkeley, Clarke was working on superconducting quantum interference devices, or SQUIDs, which each consist of a loop of superconducting material interrupted by two Josephson junctions. Minute changes in the magnetic field passing through the loop will register as a voltage that can be detected using conventional electronics.

After a workshop at Livermore, Clarke told the ADMX team that a SQUID could, in principle, be used to amplify an axion signal with far lower noise–about a fortieth that of high-electron-mobility transistor amplifiers. That would mean a speedup of about a factor of 1000 in the experiment's scan rate. But there was a catch: To be sensitive to axions, the SQUIDs would have to be made to work at frequencies extending beyond a gigahertz. That was well above the frequency range of a typical SQUID at the time, which topped out at about 100 MHz. The obstacle was parasitic capacitance. Signals enter a typical SQUID as current in a superconducting coil, which is separated by an insulating layer from the SQUID washer–the part of the device that contains the loop and Josephson junctions. In ordinary operation, the washer picks up the magnetic field created by the coil. But at high frequencies, the capacitance between the coil and washer saps a signal's power instead of amplifying it. Michael Mück, a researcher in Clarke's lab, found that an adaptation to the input coil would fix the problem. He made it so the far end of the coil would dangle unattached instead of going on to form a complete circuit. A signal coming into the coil would bounce off this end. If the signal had the right wavelength, a standing electromagnetic wave would arise between the coil and the washer, a resonance that would amplify the signal. "This trick makes a virtue out of what was formerly a parasitic capacitance," Clarke says.



THE AXION WINDOW: Based on astrophysical observations, the dark matter axion could potentially have properties anywhere within a range of about 1000 in mass and frequency. The Axion Dark Matter eXperiment's search is centered on the lower mass range, where axions that best fit astrophysical observations and solve the quantum chromodynamics (QCD) problem would reside.

By 2003, the team had high-frequency SQUIDs in hand, and they had started building a new insert for ADMX that would incorporate one of them to amplify signals from an antenna. But the experiment would have to go a bit slower than expected. To get the most out of a SQUID, the experiment's temperature would have to be lowered to 100 millikelvins–a tenth of a degree above absolute zero. ADMX's previous incarnation had run at 1.3 kelvins at its lowest.

So how much trouble could a measly degree and a quarter kelvin cause? Plenty. The team would need to add new cryogenic equipment to get down to 100 mK. But the U.S. Department of Energy deemed that integrating SQUIDs into the experiment was a "high technical risk" all by itself, Rosenberg says. The team had to ensure they could isolate the exceedingly sensitive device from all external magnetic fields while installing it near the coil of a superconducting

ADMX COLLABORATION

electromagnet with a magnetic field strength of 8 teslas—more than double what's seen in a typical MRI machine. "The SQUID would just get wiped out in the Earth's magnetic field, let alone our field," he says. As a result, the experiment was split into two phases. The first (Phase 1) would integrate the SQUID, and the second (Phase 2) would cool the experiment to its ultimate temperature.

To isolate the SQUID from all external magnetic fields, the team settled on a configuration that put the amplifier about a meter above the magnet's coil. They built an onionlike enclosure with a set of layers designed to block out the magnetic field. The most crucial of these was a pair of counterwound superconducting electromagnets, called a bucking coil, that would cancel out the magnetic field created by the main coil. The design had to be carefully done; because the bucking coil sits in a region where the magnetic field strength is changing dramatically from point to point, there would be tons of force on it. "The mechanical tolerances aren't exquisite, but they can't be pooh-poohed," Rosenberg says. "You make a centimeter error and the bucking coil would rocket out of the experiment."

After a somewhat nail-biting start, the SQUID amplifier was installed, and by 2006 the first phase was complete. The team showed that SQUIDs could work well in the high-magnetic-field environment. By 2010 the experiment had been dismantled, and magnet and cavity were strapped to the back of a flatbed truck. These components followed Rosenberg from Livermore to the University of Washington, where Phase 2 recently got under way.

I**n October of 2013,** when I visit the Seattle team, Rosenberg takes me on a circuitous tour past snaking cables, jumbles of equipment, a small particle accelerator, and an imposing-looking Faraday cage. ADMX, which sits at the far end of a massive gray experiment hall, looks dwarfed by its surroundings. Most of its hardware, including its giant superconducting coil, is tucked down in the floor to give researchers easy access to all the valves and electronics at the top. Billowing clouds of water vapor condense around the area where liquid nitrogen is being piped into the experiment—the first step in bringing temperatures inside the detector down to a hair above absolute zero.

The team has since started scanning for axions, but ADMX is still awaiting one major component: a dilution refrigerator, which will use a mix of helium-3 and -4 to bring the temperature of the experiment down to 100 mK. At that point, Livermore's Carosi says, "the experiment will be at its ultimate sensitivity." The low temperatures will push the noise of the two SQUIDs in ADMX's present incarnation down close to the minimum. It will also lower the amount of radiation created by the cavity itself. Like any object with a temperature, the cavity walls naturally produce some electromagnetic radiation, and here the bulk of it will be at microwave frequencies. That radiation creates noise that, if not minimized, could swamp the signal of a handful of axions-turned-photons.

ADMX is now poised to scan for axions at a speed about 1000 times as fast as when it first started, allowing the team to cover large swaths of the spectrum in a matter of years. "This is what we call the definitive search," Rosenberg says when we sit down in his office for a break after visiting the lab. "If it's there, we'll find it."

But it's not quite as simple as that. There is a lot of ground to cover. Physicists have put upper and lower limits on the possible mass of the dark matter axion based on astrophysical observations. If the hypothesized particle mass is too low, too many of them would have been created in the moments after the big bang, producing more dark matter than we know to exist. On the other hand, if the mass is too high, it would affect the physics of stars, providing supernovae with another channel by which energy could be released. This would cool the explosions and allow particles like neutrinos, which bounce around repeatedly in the expanding stellar remnants, to escape more readily.

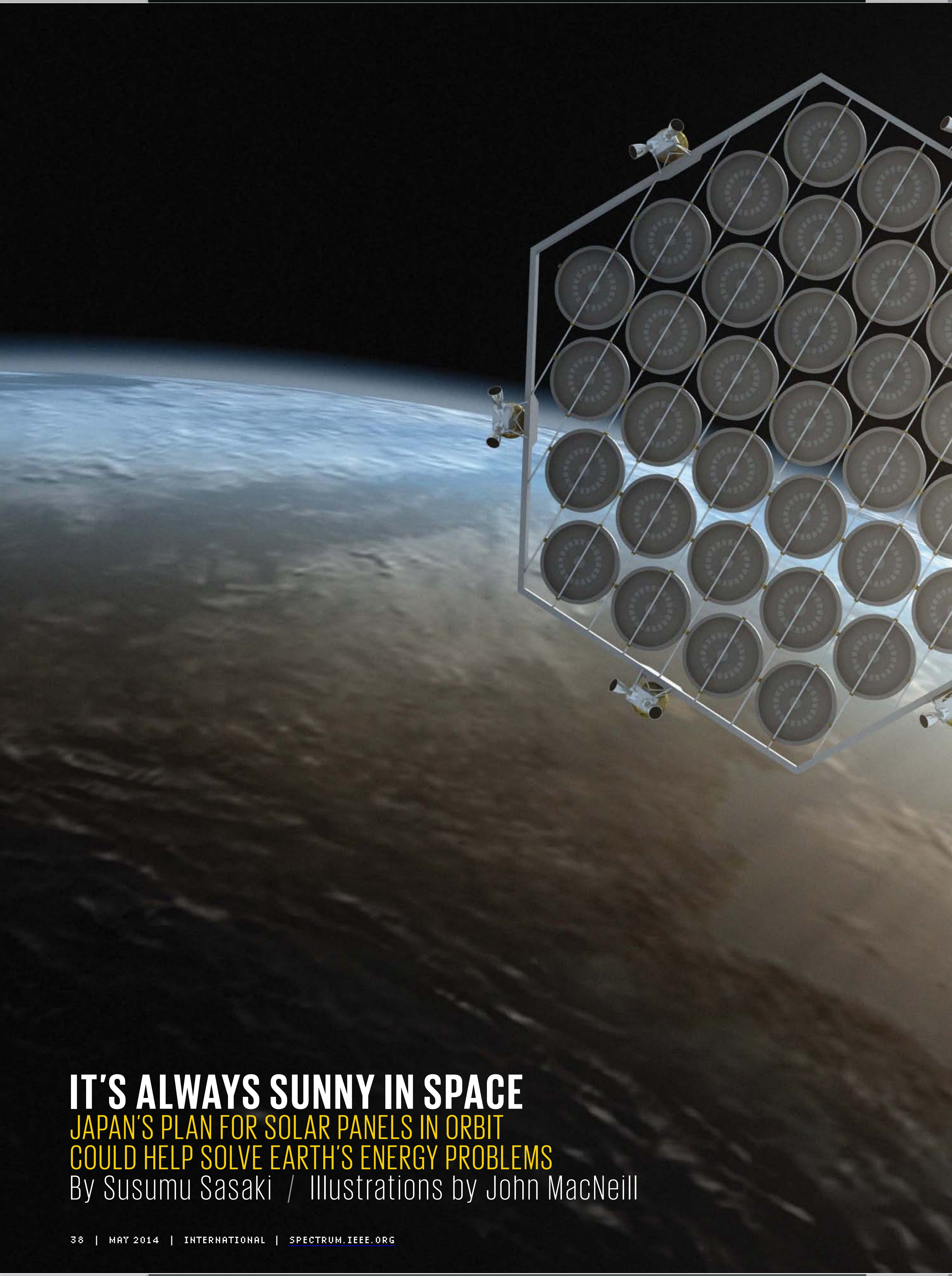
Even with those bounds, there is still a factor of 1000 in mass—and therefore a factor of 1000 in frequency—that the dark matter axion hunt must cover [see illustration, "The Axion Window"]. ADMX will start at the bottom, around 300 megahertz, representing the lowest-possible-mass particle, and work its way up. The team hopes to cover the first "decade," or factor of 10, in frequency in a year or so and then, with some modifications to the cavity size and the electronics, make a good dent in the second decade.

That will allow the team to cover a large chunk of the range occupied by the "best-motivated" axions, those with properties most favored by astrophysical observations and particle physics theory. But covering the complete range of possible dark matter axions will be a challenge, especially when it comes to the last decade in frequency, which spans 30 to 300 gigahertz. When the experiment reaches frequencies of 10 GHz or so, the cavities would have to be quite small, about the size of saltshakers, Carosi says. A smaller cavity will catch fewer axions. To make up for the smaller volumes, the team would have to find ways to create large arrays of these tiny cavities. They'd have to make robotic motors capable of tuning them all to the same frequency at the same time, so they could be used in concert to look for an axion at a given mass. "That can really get quite unwieldy," van Bibber says. Both he and Carosi, in collaboration with a team at Yale University and the University of Colorado, Boulder, are exploring what can be done to extend the experiment to higher frequencies. It won't be easy. "A couple of decades into a venture like this, you get afflicted with these night thoughts about whether there's a there there," says van Bibber. "But I'm optimistic."

But even if ADMX manages to hit every note, from 300 MHz to 300 GHz, there is the possibility that the dark matter axion could be hiding elsewhere. Frank Wilczek, one of the two physicists who first proposed the axion, notes the possibility that dark matter is inhomogeneously distributed in the universe on very large scales and that our particular patch might just have relatively little. If that's the case, axions might have been created in even higher amounts than our observations suggest. That would mean the particle could be quite light, potentially well outside the window in which ADMX—or any other experiment of its ilk—might hope to see it.

Wilczek says he admires the ingenuity of the ADMX team. "It's a brilliant experiment, and I hope they find it. It deserves to be true," he says. "But nature gets the last word." ■

POST YOUR COMMENTS at http://spectrum.ieee.org/axiondetection0514



IT'S ALWAYS SUNNY IN SPACE

JAPAN'S PLAN FOR SOLAR PANELS IN ORBIT COULD HELP SOLVE EARTH'S ENERGY PROBLEMS

By Susumu Sasaki / Illustrations by John MacNeill

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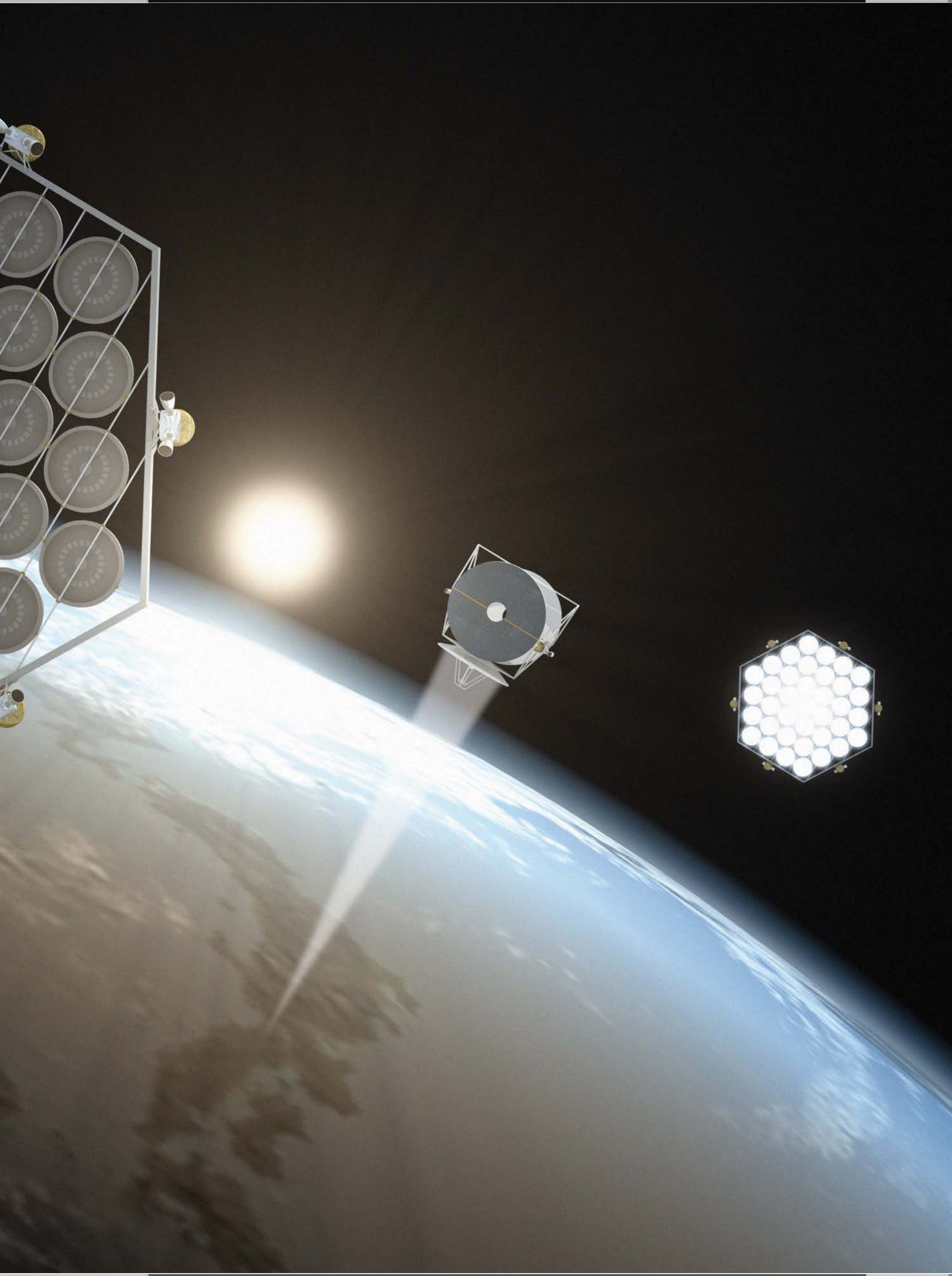


Imagine looking out over Tokyo Bay from high above and seeing a man-made island in the harbor, 3 kilometers long. A massive net is stretched over the island and studded with 5 billion tiny rectifying antennas, which convert microwave energy into DC electricity. Also on the island is a substation that sends that electricity coursing through a submarine cable to Tokyo, to help keep the factories of the Keihin industrial zone humming and the neon lights of Shibuya shining bright. ¶ But you can't even see the most interesting part. Several giant solar collectors in geosynchronous orbit are beaming microwaves down to the island from 36 000 km above Earth.

It's been the subject of many previous studies and the stuff of sci-fi for decades, but space-based solar power could at last become a reality–and within 25 years, according to a proposal from researchers at the Japan Aerospace Exploration Agency (JAXA). The agency, which leads the world in research on space-based solar power systems, now has a technology road map that suggests a series of ground and orbital demonstrations leading to the development in the 2030s of a 1-gigawatt commercial system–about the same output as a typical nuclear power plant.

It's an ambitious plan, to be sure. But a combination of technical and social factors is giving it currency, especially in Japan. On the technical front, recent advances in wireless power transmission allow moving antennas to coordinate in order to send a precise beam across vast distances. At the same time, heightened public concerns about the climatic effects of greenhouse gases produced by the burning of fossil fuels are prompting a look at alternatives. Renewable energy technologies to harvest the sun and the wind are constantly improving, but large-scale solar and wind farms occupy huge swaths of land, and they provide only intermittent power. Space-based solar collectors in geosynchronous orbit, on the other hand, could generate power nearly 24 hours a day. Japan has a particular interest in finding a practical clean energy source: The accident at the Fukushima Daiichi nuclear power plant prompted an exhaustive and systematic search for alternatives, yet Japan lacks both fossil fuel resources and empty land suitable for renewable power installations.

Soon after we humans invented silicon-based photovoltaic cells to convert sunlight directly into electricity, more than 60 years ago, we realized that space would be the best place to perform that conversion. The concept was first proposed formally in 1968 by the American aerospace engineer Peter Glaser. In a seminal paper, he acknowledged the challenges of constructing, launching, and operating these satellites but argued that improved photovoltaics and easier access to space would soon make them achievable. In the 1970s, NASA and the U.S. Department of Energy carried out serious studies on space-based solar power, and over the decades since, various types of solar power satellites (SPSs) have been proposed. No such satellites have been orbited yet because of concerns regarding costs and technical feasibility. The relevant technologies have made great strides in recent years, however. It's time to take another look at space-based solar power.

A COMMERCIAL SPS capable of producing 1 GW would be a magnificent structure weighing more than 10 000 metric tons and measuring several kilometers across. To complete and operate an electricity system based on such satellites, we would have to demonstrate mastery of six different disciplines: wireless power transmission, space transportation, construction of large structures in orbit, satellite attitude and orbit control, power generation, and power management. Of those six challenges, it's the wireless power transmission that remains the most daunting. So that's where JAXA has focused its research.

Wireless power transmission has been the subject of investigation since Nikola Tesla's experiments at the end of the 19th century. Tesla famously began building a 57-meter tower on New York's Long Island in 1901, hoping to use it to beam power to such targets as moving airships, but his funding was canceled before he could realize his dream.

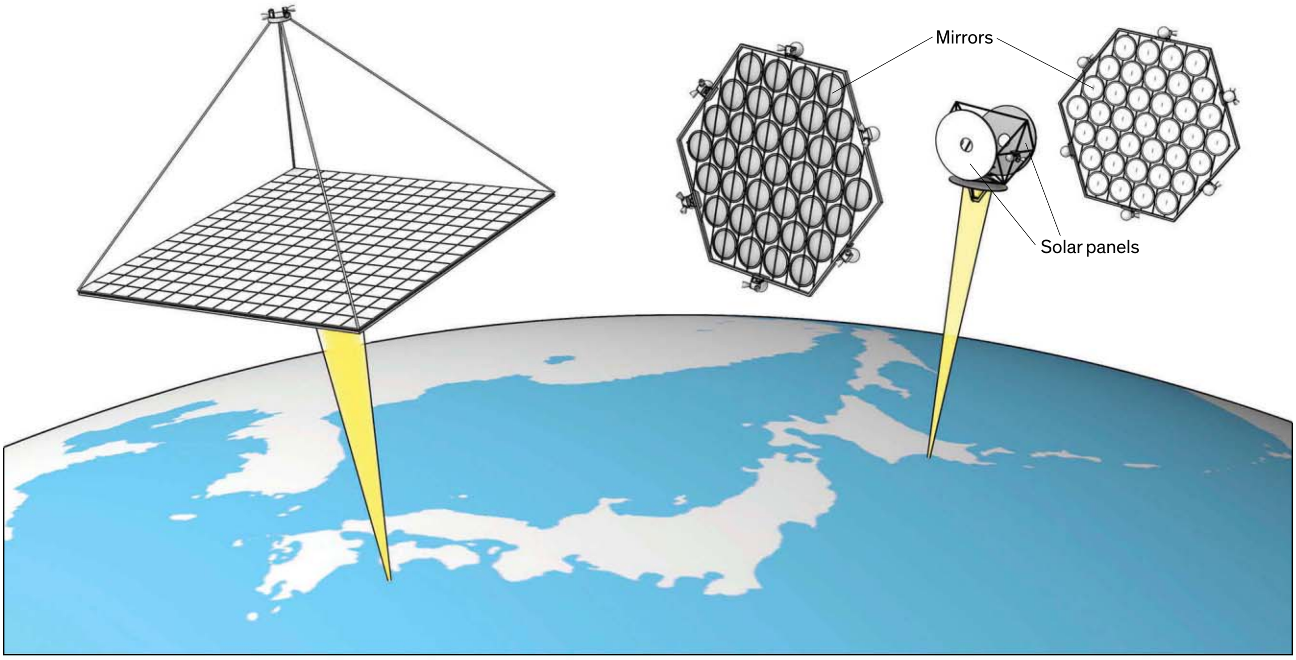
To send power over distances measured in millimeters or centimeters–for example, to charge an electric toothbrush from its base or an electric vehicle from a roadway–electromagnetic induction works fine. But transmitting power over longer distances can be accomplished efficiently only by converting electricity into either a laser or a microwave beam.

The laser method's main advantages and disadvantages both relate to its short wavelength, which would be around 1 micrometer for this application. Such wavelengths can be transmitted and received by relatively small components: The transmitting optics in space would measure about 1 meter for a 1-GW installation, and the receiving station on the ground would be several hundred meters long. However, the short-wavelength laser would often be blocked by the atmosphere; water molecules in clouds would absorb or scatter the laser beam, as they do sunlight. No one wants a space-based solar power system that works only when the sky is clear.

But microwaves–for example, ones with wavelengths between 5 and 10 centimeters–would have no such problems in transmission. Microwaves also have an efficiency advantage for a space-based solar power system, where power must be converted twice: first from DC power to microwaves aboard the satellite, then from microwaves to DC power on the ground. In lab conditions, researchers have achieved about 80 percent efficiency in that power conversion on both ends. Electronics companies are now striving to achieve such rates in commercially available components, such as in power amplifiers based on gallium nitride semiconductors, which could be used in the microwave transmitters.

In their pursuit of an optimal design for the satellite, JAXA researchers are working on two different concepts. In the more basic one, a huge square panel (measuring 2 km per side) would be covered with photovoltaic elements on its top surface and transmission antennas on its bottom. This panel would be suspended by 10-km-long tether wires from a small bus, which would house the satellite's controls and communication systems.

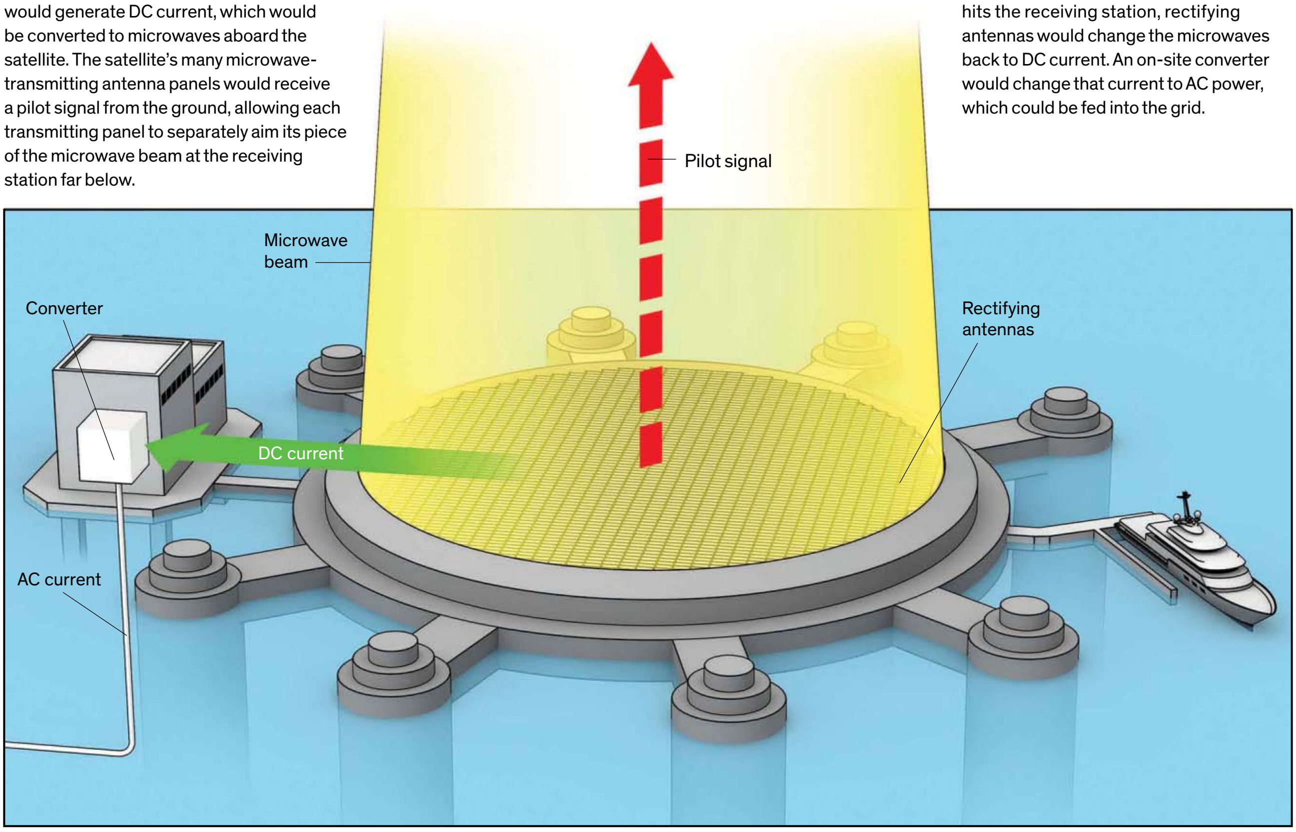
HOW TO BEAM CLEAN ENERGY DOWN FROM ORBITAL SOLAR FARMS



THE JAPAN AEROSPACE EXPLORATION AGENCY is working on several models for solar-collecting satellites, which would fly in geosynchronous orbit 36 000 kilometers above their receiving stations. With the basic model [left], the photovoltaic-topped panel's efficiency would decrease as the world turned away from the sun. The advanced model [right] would feature two mirrors to reflect sunlight onto two photovoltaic panels. This model would be more difficult to build, but it could generate electricity continuously.

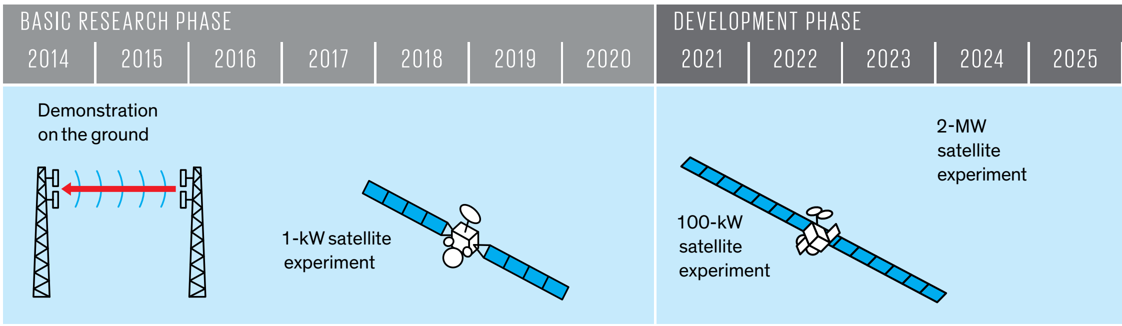
IN EITHER MODEL, the photovoltaic panels would generate DC current, which would be converted to microwaves aboard the satellite. The satellite's many microwave-transmitting antenna panels would receive a pilot signal from the ground, allowing each transmitting panel to separately aim its piece of the microwave beam at the receiving station far below.

ONCE THE MICROWAVE BEAM hits the receiving station, rectifying antennas would change the microwaves back to DC current. An on-site converter would change that current to AC power, which could be fed into the grid.



HOW TO LAUNCH AN ORBITAL INDUSTRY

Establishing commercial solar power stations in space would be a decades-long enterprise



Using a technique called gravity gradient stabilization, the bus would act as a counterweight to the huge panel. The panel, which would be closer to Earth, would experience more gravitational pull down toward the planet and less centrifugal force away from it, while the bus would be tugged upward by the opposite effects. This balance of forces would keep the satellite in a stable orbit, so it wouldn't need any active attitude-control system, saving millions of dollars in fuel costs.

The problem with this basic SPS configuration is its inconstant rate of power generation. Because the photovoltaic panel is fixed, the amount of sunlight that hits it varies greatly as the geosynchronous satellite and Earth spin.

So JAXA has come up with a more advanced SPS concept that solves the solar collection problem by employing two huge reflective mirrors. These would be positioned so that between the two of them, they would direct light onto two photovoltaic panels 24 hours a day. The two mirrors would be free flying, not tethered to the solar panels or the separate transmission unit, which means that we would have to master a sophisticated kind of formation flying to implement this system. Space agencies have some experience with formation flying, most notably in the docking maneuvers performed at the International Space Station, but coordinating a formation flight involving kilometer-scale structures is a big step from today's docking procedures.

We would also have to make several other breakthroughs before this advanced type of SPS could be built. We'd need very light materials for the mirror structures to allow for the formation flight, as well as extremely high-voltage power transmission cables that could channel the power from the solar panels to the transmission unit with minimal resistive losses. Such technologies would take years to develop, so if one or more nations do embark on a long-term project to exploit space-based solar power, they may employ a two-phase program that begins with the basic model while researchers work on the technologies that will allow for next-generation systems.

To generate the microwaves, researchers have proposed vacuum tubes such as magnetrons, klystrons, or traveling wave tubes, because their power conversion efficiency is reasonably high—typically 70 percent or higher—and they're relatively inexpensive. Semiconductor amplifiers are getting better all the time, however; their efficiencies are going up, and their costs are coming down. Cost is important here because a 1-GW commercial SPS would have to include at least 100 million 10-watt semiconductor amplifiers.

To choose a microwave frequency for transmission, we have to weigh several factors. Low-frequency microwaves penetrate the atmosphere well, but they require very large antennas, which would make construction and maintenance more complicated. Frequencies in the range of 1 to 10 gigahertz offer the best compromise between antenna size and atmospheric attenuation. Within this range, 2.45 and 5.8 GHz are the potential candidates because they are in the bands set aside for industrial, scientific, and medical uses. Of these, 5.8 GHz seems particularly desirable because the transmitting antennas can be smaller.

MAKING A POWERFUL BEAM of microwaves is important, of course, but the next step is a lot trickier: aiming the beam precisely so that it travels the 36 000 km to hit the rectifying antennas spot on.

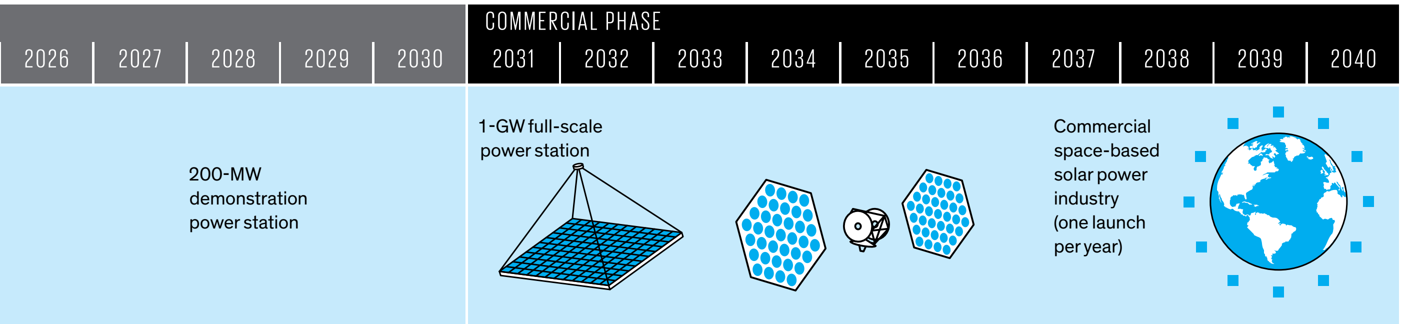
Consider that the microwave transmission system would be composed of a number of antenna panels, each measuring perhaps 5 meters long, that would be covered in tiny antennas: In total, more than 1 billion antennas would likely be installed on a single SPS. Coordinating the microwaves generated by this vast swarm of antennas won't be easy. To produce a single, precisely focused beam, the phases of the microwaves sent from all the antenna panels must be synchronized. That would be hard to manage, as these panels would move relative to each other.

This challenge of precisely directing a beam from a moving source is unique and hasn't been solved by existing communication technologies. The beam must have very little divergence to prevent it from spreading out over too large an area. To send power at the 5.8-GHz frequency to a rectifying antenna, or rectenna, with a diameter of 3 km, the divergence must be limited to 100 microradians and the beam must have a pointing accuracy of 10 μrad.

JAXA's solution involves a pilot signal that would be sent from the rectenna on the ground. As each individual antenna panel on the satellite received the pilot signal, it would calculate the necessary phases for its microwaves and adjust accordingly. The sum of all these adjustments is a tight beam that would zing down through the atmosphere to hit the rectenna. Such phase-adjusting technologies, known as retrodirective systems, have been used in small-scale antenna arrays in space, but additional work would be needed before they could coordinate several kilometers of orbital transmitters.

Once the beam reaches the receiving site, the rest of the process would be relatively easy. Arrays of rectennas would convert the microwave power to DC power with an efficiency greater than 80 percent. Then the DC power would be converted to AC and fed into the electrical grid.

When laypeople hear these orbital solar farms described, they often ask if it would



be safe to send a powerful beam of microwaves down to Earth. Wouldn't it cook whatever's in its path, like food in a microwave oven? Some people have a grisly mental image of roasted seagulls dropping from the sky. In fact, the beam wouldn't even be intense enough to heat your coffee. In the center of the beam in a commercial SPS system, the power density would be 1 kilowatt per square meter, which is about equal to the intensity

10X In space there is 10 times as much available solar energy as on Earth: There are no efficiency reductions due to the day-night cycle, seasonal variation, or weather conditions.

of sunlight. As the regulatory limit for sustained human exposure to microwaves is typically set at 10 watts per square meter, however, the rectenna site would have to be a restricted area, and maintenance workers who enter that zone would have to take simple precautions, such as donning protective clothing. But the land outside the rectenna site would be perfectly safe. At a distance of 2 km from its center, the beam's power density will have already dropped below the regulatory threshold.

IN 2008, ON A MOUNTAINTOP on Hawaii's main island, a rectenna received a beam of microwaves sent from the slopes of a volcano on the island of Maui, about 150 km away. That demonstration project, led by former NASA physicist John Mankins and recorded for a show on the Discovery Channel, was modest in its ambitions: Only 20 W of power were generated by the solar panels on Maui and beamed across the ocean. This setup was far from ideal because the microwaves' phases were disturbed during this horizontal transmission through the dense atmosphere. Most of the power was lost in transmission, and less than a microwatt was received on the Big Island. But the experiment did demonstrate the general principle to an admiring public. And it's worth remembering that in a space-based system, the microwaves would pass through dense atmosphere only for the last few kilometers of their journey.

In Japan, we are now planning a series of demonstrations for the next few years. By the end of this year, researchers expect to perform a ground experiment in which a beam of hundreds of watts will be transmitted over about 50 meters. This project, funded by JAXA and Japan Space Systems, will be the world's first demonstration of high-power and long-range microwave transmission with the critical addition of retrodirective beam control. The microwave transmitter consists of four individual panels that can move in relation to one another in order to simulate antenna motion in orbit. Each panel, measuring 0.6 meter by 0.6 meter, contains hundreds of tiny transmitting antennas and receiving antennas to detect the pilot signal, as well as phase controllers and power management systems. Each panel will transmit 400 W, so that the total beam will carry 1.6 kW; in this early-stage experiment, we expect the rectenna to have a power output of 350 W.

Next, JAXA researchers hope to conduct the first microwave power transmission experiment in space, sending several kilowatts from low Earth orbit to the ground. This step, proposed for 2018, should test out the hardware: We hope to demonstrate microwave beam control, evaluate the system's overall efficiency, and verify that the microwave beam doesn't interfere with existing communications infrastructure. We also have some space science to conduct. We want to be sure that the intense microwave beam isn't distorted or absorbed by the plasma of the ionosphere, the upper-atmosphere layer that contains electrically charged particles. We're pretty sure that the beam won't interact with this plasma, but our hypothesis can be confirmed only in the space environment.

If all goes well with these initial ground and space demonstrations, things will really start to get interesting. JAXA's technology road map calls for work to begin on a 100-kW SPS demonstration around 2020. Engineers would verify all the basic technologies required for a commercial space-based solar power system during this stage.

Constructing and orbiting a 2-megawatt and then a 200-MW plant, the next likely steps, would require an international consortium, like the ones that fund the world's giant particle physics experiments. Under such a scenario, a global organization could begin the construction of a 1-GW commercial SPS in the 2030s.

It would be difficult and expensive, but the payoff would be immense, and not just in economic terms. Throughout human history, the introduction of each new energy source–beginning with firewood, and moving on through coal, oil, gas, and nuclear power–has caused a revolution in our way of living. If humanity truly embraces space-based solar power, a ring of satellites in orbit could provide nearly unlimited energy, ending the biggest conflicts over Earth's energy resources. As we place more of the machinery of daily life in space, we'll begin to create a prosperous and peaceful civilization beyond Earth's surface. ■

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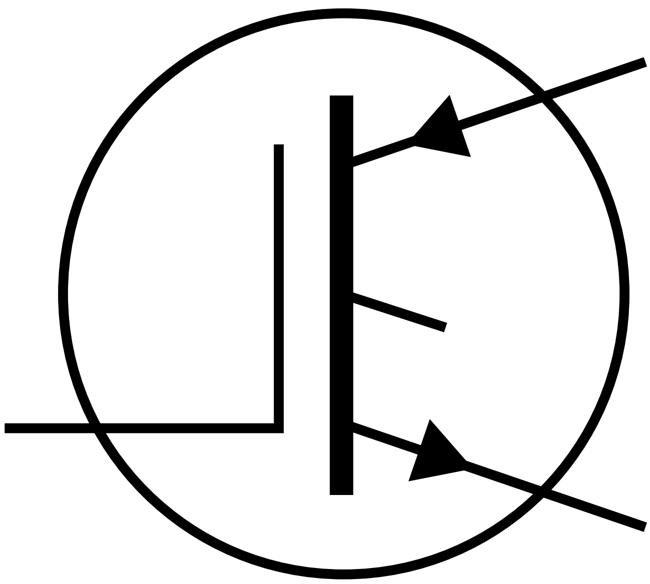
BY DAVID SCHNEIDER

THE POWER BROKER



2014 IEEE Medal of Honor recipient B. Jayant Baliga energized the field of power semiconductors

IT'S THE LATE 1970S, the U.S. economy is reeling from years of sky-high oil prices, and President Jimmy Carter desperately wants to reverse the downward spiral in the nation's prosperity and morale. Seeking wisdom from the crowd, he brings ordinary citizens to Camp David, who, as he later recounts in his famous "malaise" speech, tell him: "Be bold, Mr. President. We may make mistakes, but we are ready to experiment."

One person ready to experiment–in the literal sense–was B. Jayant Baliga, the recipient of this year's IEEE Medal of Honor. At the time, he was developing semiconductor power devices for General Electric, which used countless electric motors in its many products–countless motors that drew countless watts.

Most were induction motors, whose speeds were governed by the power-line frequency. So when a machine required less oomph, there was no good way to slow it down. The usual work-around was to insert a physical barrier into the stream of air or water that was being pumped around. No wonder electric appliances of that generation were atrociously inefficient.

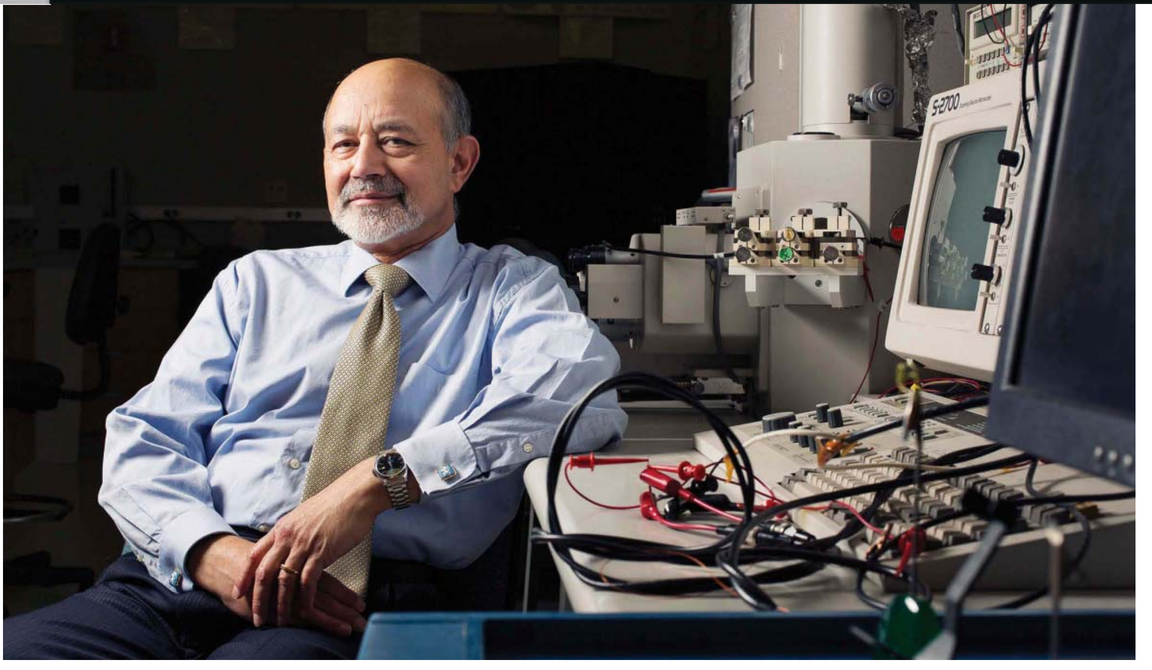
Some GE engineers wanted to pursue a simple energy-saving idea: Just drive the motor at the desired speed. But that required adding electronics to send power to a motor's windings at variable frequencies, which wasn't easy to do back then. The voltages were too high for metal-oxide-semiconductor field-effect transistors (MOSFETs) to work efficiently, and ordinary bipolar power transistors required bulky and expensive control and protection circuits.

Facing those difficulties, a GE manager in charge of drives for air conditioners appealed to the company's researchers. "You guys need to give me some innovation that will make my business succeed," Baliga recalls him saying.

And that's exactly what Baliga did. Around 1980, he created the insulated-gate bipolar transistor, or IGBT, which today is found in household appliances, factory robots, fluorescent lights, automobiles, trains, televisions, photovoltaic installations–anywhere modestly high voltages need to be switched on and off quickly.

As influential as it has been, the IGBT is far from Baliga's only contribution to power semiconductors. Now a professor of electrical and computer engineering at North Carolina State University, in Raleigh, he has spent his career not only pursuing experimental

PHOTOGRAPHS BY D.L. Anderson



MANY HATS: Although busy writing books and managing university programs, Baliga still oversees students in his lab.

advances but also developing fundamental semiconductor theory, writing textbooks, and laboring in the business trenches bringing devices to market. Along the way, he's garnered plenty of honors, including the 2010 National Medal of Technology and Innovation.

His pivotal role in the evolution of modern power semiconductors is all the more surprising given that, at the start of his career, Baliga wasn't at all interested in working on such devices. But as a young man, he wandered into that territory and found some surprisingly fertile ground.

Baliga enjoyed a privileged upbringing in India, living in the then rural outskirts of Bangalore. His father, who would later become chairman and managing director of Bharat Electronics Limited, ran a large factory there, and the company provided his family with a mansion close by. "We had five servants inside the house and six gardeners, a chauffeur-driven car–but the whole yard was infested with cobras," Baliga recalls with a laugh. Taking advantage of his father's technical library, he developed an interest in electrical engineering, which he later studied at the Indian Institute of Technology Madras.

There he eventually discovered a subject he liked even better. "I came across these books–*The Feynman Lectures on Physics*," Baliga remembers fondly. "But I did not have the option of switching from what I was doing, electrical engineering, to physics. So I figured I'd do the next best thing: semiconductors."

After graduating in 1969, Baliga chose to continue his studies abroad–it seemed the best way to escape the shadow of his father, one of India's preeminent electrical engineers. So he applied to and was accepted by Rensselaer Polytechnic Institute (RPI) in Troy, N. Y., to study semiconductor engineering under Sorab K. Ghandhi.

As a master's student, Baliga worked on gallium arsenide semiconductors. For his Ph.D., he decided to investigate a technique he could use for growing indium arsenide and gallium indium arsenide semiconductors, a process now called metal-organic chemical vapor deposition. Some initial library research revealed it would be a dangerous undertaking because the compounds involved would detonate when exposed to air.

"If something goes wrong, I know I'll be killed, but so will everyone else in this building," Baliga told his advisor. Ghandhi wasn't put off. He simply counseled his student to build a reaction vessel that was "really tight." It worked, and it taught Baliga an important lesson: Even the most risky and difficult technical challenge could be overcome if he put his mind to it.

After earning a Ph.D. in 1974, Baliga hoped to land a research position with IBM or Bell Laboratories. But with only a student visa, he couldn't even get an interview at such prestigious institutions. Then a fellow graduate student at RPI who was working at the General Electric Research Laboratory, in nearby Niskayuna, N.Y., told him about a position there investigating power devices, offering to arrange an interview if Baliga wanted.

Baliga was unenthusiastic. "Why would I want a job working on power devices?" he recalls asking. "Power devices have been worked on since the 1950s. Everything that's interesting has already been done." Lacking better options, though, he applied for and got the job. "It was my only opportunity," says Baliga, who above all didn't want to return to India.

Some of his early research for GE involved thyristors–semiconductor devices now mostly used for handling extremely high voltages. Switching thyristors on is easy, but they don't turn off until the voltage reverses polarity, which severely limits their application. While studying thyristors, though, Baliga got hints that they could be made to work like regular transistors, which can be switched on and off on command. And after learning of GE's need for energy-saving variable-frequency motor drives, Baliga came up with the design for a thyristor-like device that combined the best attributes of MOSFETs and bipolar transistors, which at that point were considered separate semiconductor universes.

"It was like Kipling's 'East is East and West is West, and never the twain shall meet,' " quips Baliga. His proposal to merge the two technologies in a single device

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was audacious, and yet he showed that the new transistor could be made relatively easily, using one of GE's MOSFET-production lines.

His colleagues shared Baliga's idea with GE's new chairman and CEO, Jack F. Welch Jr., whose draconian management style had earned him the nickname Neutron Jack. "If he visited a plant and he was not happy, the building was left and all the people were gone—like a neutron bomb," explains Baliga.

Thomas Jahns, a researcher who worked with Baliga at GE and is now a professor of engineering at the University of Wisconsin-Madison, confirms what it was like under Welch. "It was an intense time. [The researchers] were called on the carpet to come up with solutions: Either you deliver or you get out."

In early 1981, Welch traveled to GE's research center to be briefed about the new transistor concept—a high-pressure presentation for Baliga if ever there was one. "A lot of careers were on the line—mine in particular," he says. But all went well, and within a year, Baliga and his colleagues were fabricating wafers with the new design. Initially, he dubbed the device the "insulated-gate rectifier," in an attempt to distinguish it from ordinary transistors. But he later changed the name to insulated-gate bipolar transistor to avoid confusing application engineers.

The new IGBT successfully avoided catastrophic "latch up"—the thyristor-like continuation of current flow after a transistor is turned off. But it still switched off too slowly to be used for variable-frequency motor drives, and known methods for upping the speed of a transistor would ruin a MOS device such as this one. "We can use it for 60 hertz. Maybe we can run a steam iron," was the disappointed conclusion of his GE associates, recalls Baliga.

With thoughts of Welch's neutron irradiation no doubt swirling in his mind, Baliga devised a clever way to speed up the IGBT: *electron* irradiation. Such treatment had been used on bipolar power rectifiers, but it damaged MOS devices. Baliga figured out how to apply just enough heat to repair the damage to the MOS structure while keeping the speed boost.

"I could control the speed all the way from low frequencies to as high as I wanted," says Baliga. Within a few months the new process was being used to make chips. "Now everybody went bananas with this—now they had fast devices. They could start running with it. It just took off."

Among the places that IGBTs went airborne was Japan, where Fuji Electric, Hitachi, Mitsubishi Electric, and others took interest in Baliga's work and eventually began manufacturing these devices, in stiff competition with GE. And GE's investments at this time in making very-large-scale integrated circuits went badly. In 1988, Welch decided to sell off GE's entire semiconductor business. That move in turn rendered Baliga's research expertise useless to the company.

Baliga's bosses said they'd find a place for him in upper management, he recalls. "But in my heart, I still felt like I was a scientist," he says. The offers he was getting from other companies weren't attractive, however, and academic activity in power devices was nonexistent in the United States, Baliga says. But that didn't mean he couldn't create his own research program. The question was, where?

Baliga had often visited North Carolina's Research Triangle Park, where GE had a power-electronics group, and he knew that MCNC, the Microelectronics Center of North Carolina, housed a state-of-the-art CMOS-fabrication line. With access to that facility, he figured he could do good research at nearby North Carolina State University, which was eager to recruit him. "He could have gone almost anywhere," says Nino Masnari, who then headed the department, which was building up its semiconductor research program on a newly opened satellite campus.

So in August of 1988, Baliga moved to NC State, where he has taught and done research for a quarter of a century now. It's also where President Obama visited just a few months ago to announce the creation of the Next Generation Power Electronics Innovation Institute–and a corresponding US $140 million grant to the university, which Baliga's team at the university's Future Renewable Electric Energy Delivery and Management Systems Center helped to win.

One goal of the new federally sponsored institute is to speed the development of MOSFETs and other power devices made with what are called wide-bandgap semiconductors, which outperform those made of silicon. One day wide-bandgap MOSFETs should be cheap and reliable enough to replace IGBTs. "If all goes well, my baby, which is now a big gorilla, will go away," jokes Baliga.

But that's fine with him. Despite his status as the father of the silicon IGBT, a narrow-bandgap device, Baliga has long championed its wide-bandgap rivals. Indeed, even while he was developing the IGBT at GE, he was also creating the first wide-bandgap power semiconductor, a gallium arsenide rectifier. About that same time, he devised a way to calculate from basic theory what semiconductor types function best for power devices–an expression now known as Baliga's figure of merit–which highlighted the promise of silicon carbide and other wide-bandgap semiconductors. The trick is learning how to make these exotic devices cheaply enough to compete with silicon, a quest that Baliga and his students, along with many other researchers, are actively pursuing.

Baliga has also been deeply involved in the start-up scene. Companies he launched in the 2000s have created power semiconductors for cellular base stations and for managing the huge currents fed to modern microprocessors, to give just two examples. While all were commercially successful, none of these ventures has made him rich. "But that's okay," he says. "I get very excited just that people are using my chips."

Indeed, without being at all aware of his role, millions of people around the world are benefitting from the power semiconductors Baliga pioneered. And with the demand for ever-more-efficient devices only going up, they will no doubt continue to do so for many years to come. ■

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IEEE

CANDIDATES IN 2014 ELECTION

THE IEEE BOARD OF DIRECTORS has received the names of the following candidates to be placed on this year's ballot. The candidates have been drawn from recommendations made by regional and divisional nominating committees. In addition, the names include candidates for positions in the IEEE Standards Association, IEEE Technical Activities, and IEEE-USA.

For more information on IEEE elections and candidates, please visit http://www.ieee.org/elections or e-mail election@ieee.org.

Electronic ballot access and paper ballot packages will be mailed on or before 15 August to all IEEE members who are eligible to vote as of 30 June. To ensure all ballot packages are delivered to the proper mailing address, please visit http://www.ieee.org/go/my_account and update your member profile if necessary.

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Second candidate to be announced

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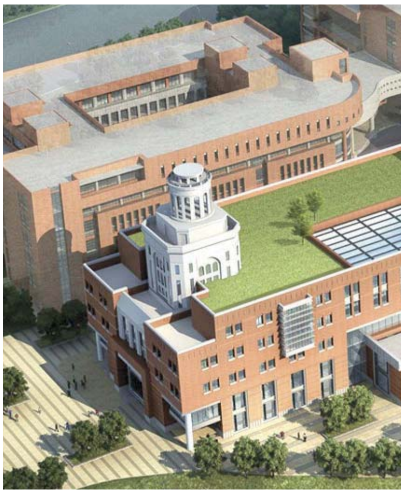

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Applications should include a full CV, three to five professional references, a statement of research and teaching interests, and copies of up to five research papers.

Please submit the letters of reference and all above materials to the address below.

Application review will continue until the position is filled.

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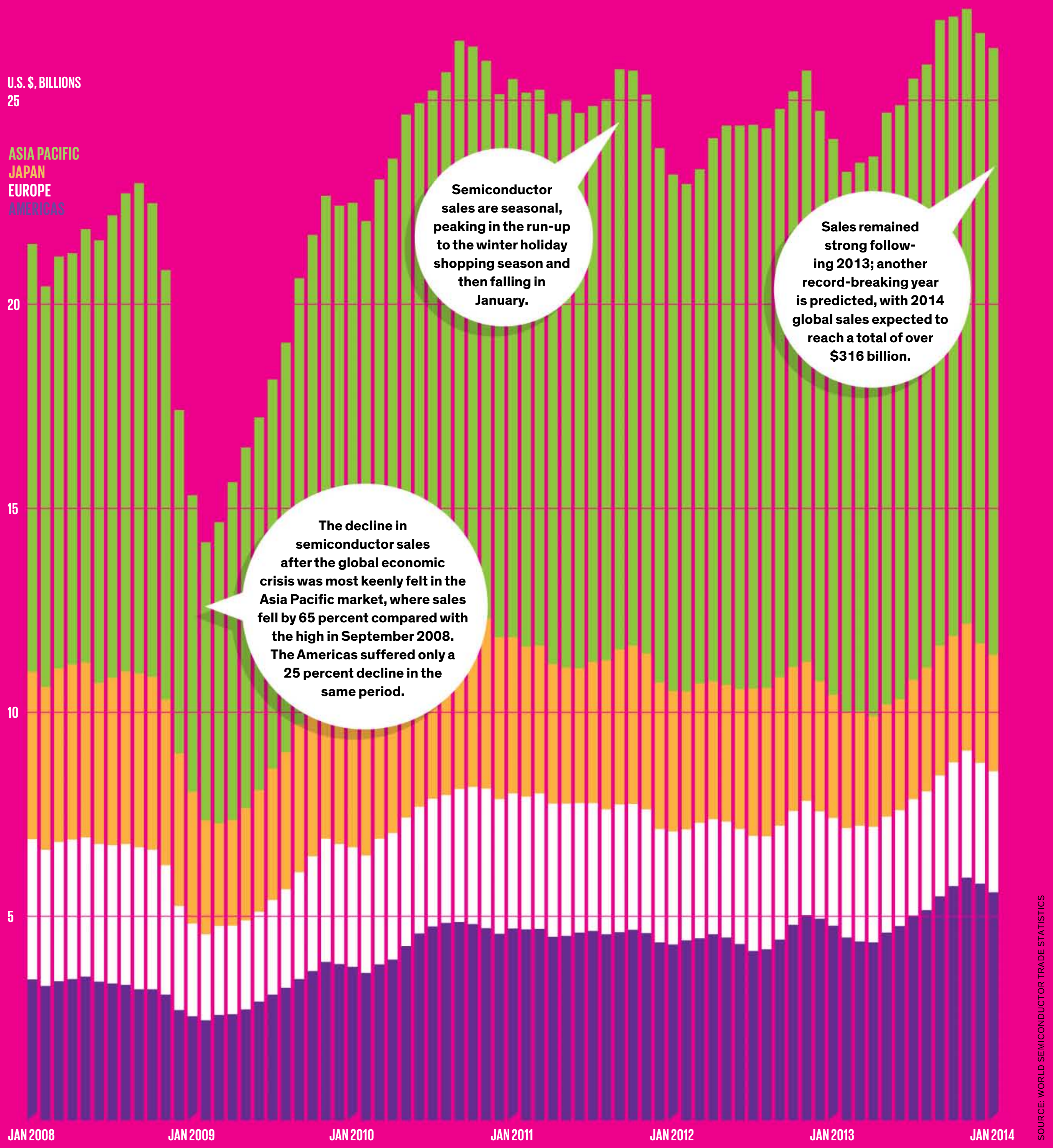
DATAFLOW_

THE SEMICONDUCTOR BOOM
GLOBAL SALES REACH RECORD HEIGHTS

In the most recent figures released by the World Semiconductor Trade Statistics organization, January 2014 was the best ever January on record, clocking in with sales figures hitting over US $26 billion worldwide. This follows the banner year of 2013, in which annual sales reached an all-time high of more than $305 billion. This marks a 35 percent increase over the depths of the post-recession slump in 2009, when global sales declined to $226.3 billion. “We expect the industry to maintain this momentum for the foreseeable future,” says Brian Toohey, president and CEO of the U.S. Semiconductor Industry Association. —STEPHEN CASS



INFOGRAPHIC BY Brandon Palacio

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