even more powerful. "It is pretty exciting technology," says Dayton, "and very relevant to our work."

To obtain the crisp image in figure 1, Tanter and colleagues had to thin down the rat's skull from 700 μm to 100 μm; images taken through an intact skull still had superresolution features, but they were significantly less detailed in deep regions. That's because bone is a strong scatterer of ultrasound. Thinning a human skull—normally 7 mm thick—is clearly out of the question. Still, Tanter notes that other tumor-prone organs, such as the liver and breast, are not surrounded by bone, so they could be more easily imaged. And he plans to try imaging through an intact human skull using a longer ultrasound wavelength.

Johanna Miller

References

1. C. Errico et al., *Nature* **527**, 499 (2015).
2. E. Betzig et al., *Science* **313**, 1642 (2006); M. J. Rust, M. Bates, X. Zhuang, *Nat. Meth.* **3**, 793 (2006); S. T. Hess, T. P. Girirajan, M. D. Mason, *Biophys. J.* **91**, 4258 (2006).
3. O. M. Viessmann et al., *Phys. Med. Biol.* **58**, 6447 (2013); K. Christensen-Jeffries et al., *IEEE Trans. Med. Imag.* **34**, 433 (2015).
4. R. C. Gessner, S. R. Aylward, P. A. Dayton, *Radiology* **264**, 733 (2012); S. E. Shelton et al., *Ultrasound Med. Biol.* **41**, 1896 (2015).

A quantum cascade laser gets a geometric makeover

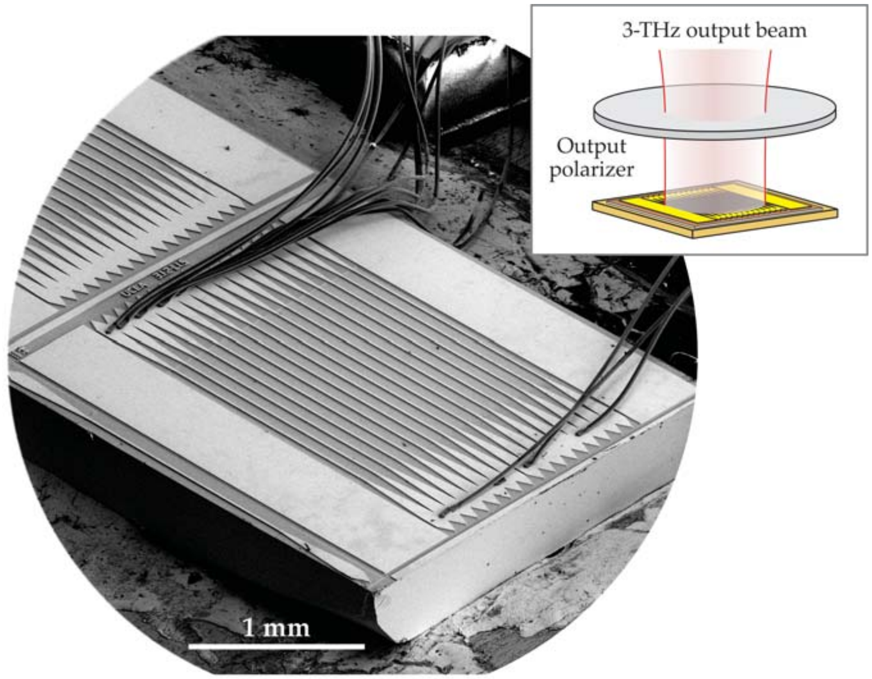
A change in the cross section and orientation of the laser's optical cavity collimates an otherwise highly divergent terahertz-frequency beam.

Achieving a high-quality beam—one whose profile is near Gaussian and as narrow as diffraction allows—can be a challenge in semiconductor laser design. That's especially true in the few-terahertz frequency regime, an elusive part of the electromagnetic spectrum just below the reach of most optical technologies and just above the reach of electronics.

No natural material has an open bandgap small enough to emit coherent photons below tens of terahertz. The quantum cascade laser (QCL), one of the few devices that can operate at a few terahertz, relies on stacked, two-dimensional layers of semiconductors, which create quantum wells that act as gain material. The spatial confinement of electrons in the wells splits the conduction band into discrete subbands, separated by energies as small as a few meV, depending on the semiconductor-layer thickness (1 THz corresponds to about 4 meV).

Transitions between the subbands are at the heart of the QCL (see the article by Federico Capasso, Claire Gmachl, Deborah Sivco, and Alfred Cho, PHYSICS TODAY, May 2002, page 34). As in other semiconductor lasers, the gain material in a QCL is embedded in a relatively long but thin waveguide, and photons are usually emitted in-plane from one end of the waveguide. But because the active-region thickness—typically about 10 µm—is so much smaller than the wavelength of a terahertz photon, the light that emerges is highly divergent, often with interference fringes.

To provide better collimation, a group led by UCLA's Luyao Xu and her thesis adviser, Benjamin Williams, altered the usual geometry of a QCL to create a larger aperture.[1] In their device, shown here, a single waveguide is replaced by an array of them that emits out of plane. Each waveguide is composed of a 10-µm-thick stack of gallium arsenide and gallium aluminum arsenide layers sandwiched between copper electrodes; the waveguide ends are tapered to quench in-plane lasing. Furthermore, the waveguide width is carefully chosen so that each effectively acts like an elongated, surface-emitting antenna.



A QUANTUM CASCADE LASER ordinarily lases in-plane, from within a long, thin waveguide filled with quantum wells. Fashioned from an array of such waveguides (thin strips), this metasurface emits out of plane, thanks to the waveguides' tapered ends, which quench in-plane lasing. The metasurface also serves as a mirror that can both amplify and reflect terahertz radiation. With a second mirror, or output polarizer, added 6 mm away, the two surfaces form an external cavity (inset) that can lase 3-THz photons. (Adapted from ref. 1.)

With their subwavelength (90-μm) spacing, the antennas collectively form a 1.5 mm × 1.5 mm metasurface that amplifies radiation and reflects it vertically.

To complete the device, the team placed a wire-grid polarizer 6 mm away and parallel to the metasurface, as sketched in the inset. At terahertz frequencies, the output polarizer behaves like a mirror with a tunable reflectivity. Together the two surfaces form a new, external cavity that lases at its resonance frequency—in this geometry, 2.9 THz. And thanks to the array's large area, the beam's divergence—about 4° by 5°, measured at full width half maximum—is lower, and its profile more symmetric, than the emission from any previous terahertz QCL.

Polarization flips

The team's approach—turning a waveguide laser geometry into a so-called vertical-external-cavity surface-emitting laser (VECSEL) geometry—isn't new. It's a common solution for improving beam quality among visible and near-IR semiconductor lasers. But the VECSEL approach was thought impossible for QCLs, whose intersubband transitions couple only to an electric field polarized perpendicular to the plane of the quantum wells. That polarization is in the same vertical direction that the beam is supposed to travel in a VECSEL.

In the new work, Xu, Williams, and

PHYSICS UPDATE

These items, with supplementary material, first appeared at www.physicstoday.org.

A SHARPER VIEW OF OUR GALAXY'S BLACK HOLE

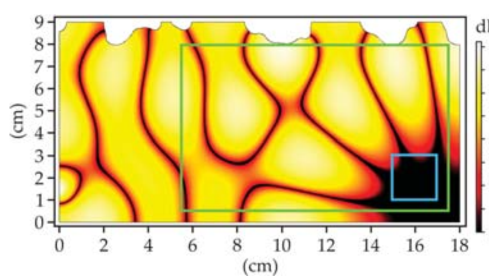
The spectacular jets that shoot from radio galaxies are fueled by plasma swirling around the galaxies' central black holes. Because the black hole at the heart of the Milky Way has comparatively little fuel to draw on, the emission it engenders is feeble. Whether it sustains jets is uncertain. Still, thanks to the black hole's relative proximity, astronomers hope to resolve the structures close to the event horizon that might be responsible for launching jets. With that and other goals in mind, Michael Johnson of the Harvard–Smithsonian Center for Astrophysics and his collaborators have observed the Milky Way's center using the Event Horizon Telescope, an interferometric array of four millimeter-wavelength telescopes at sites in Arizona, California, and Hawaii. In the millimeter band, the emission from the center of the galaxy is dominated by synchrotron radiation from relativistic electrons spiraling around magnetic field lines. By measuring and mapping the radiation's polarization, the researchers identified regions that extend up to six Schwarzschild radii from the event horizon where the magnetic field lines appear to be ordered. What's more, they also identified turbulent regions with intense temporal variability, which may explain how black holes can efficiently pull matter inward. Although the origin of the ordered regions is uncertain, their presence lends support to theories in which magnetic fields redirect and channel orbiting plasma into outward flowing jets. (M. D. Johnson et al., *Science* **350**, 1242, 2015.) —CD

COMPLEX PATTERNS IN FRUSTRATED SYNCHRONIZATION

Although best known for his roles in founding the field of computer science and in cracking the German Enigma cipher, Alan Turing also made a profound impact on developmental biology. In a 1952 paper, he proposed that a system of chemical substances that react together and diffuse through a tissue could account for morphogenesis—the differentiation of identical cells to form patterns and structures, such as our off-center hearts, zebra stripes, and the formation of fingers and toes. In 2014 Seth Fraden and colleagues at Brandeis University experimentally tested Turing's model in rings of coupled microdroplets undergoing the famous oscillating Belousov–Zhabotinsky chemical reaction. Brandeis's Bulbul Chakraborty and her colleagues have now traced the roots of the observed complex spatiotemporal patterns. The theorists worked with a well-studied oscillating reaction model that incorporates an activator and an inhibitor, and they applied it to "cells" arranged in a ring. They found that in the strongly coupled regime, fast inhibitor dynamics endow the cells with a robust preference to be 180° out of phase with their neighbors. But that phase configuration couldn't be satisfied for rings containing an odd number of cells. Such geometric frustration arose first in a system of three cells, which either had all cells in phase or had one cell out of phase. A ring of five cells was even more interesting; it exhibited an explosion of complex synchronization patterns with overlapping regions of stability. One mode even featured cells oscillating at different frequencies. (D. Goldstein, M. Giver, B. Chakraborty, *Chaos* **25**, 123109, 2015.) —RJF

VALIDATING TOPOLOGY OPTIMIZATION FOR ACOUSTICS

Topology optimization is a mathematical method for tuning a system's shape or mass distribution to achieve a specific function or behavior. Used for more than two decades in structural mechanics—for such purposes as maximizing stiffness or minimizing cost—it has found application in numerous other areas, including acoustics. But regardless of how optimized the calculated designs are in theory, they must still satisfy such real-world constraints as manufacturability. The methodology must also be validated through real-world confirmation. Rasmus Christiansen, Ole Sigmund, and Efren Fernandez-Grande of the Technical University of Denmark now provide that validation in an acoustics setting: the topological optimization of an acoustic cavity. The design goal was to minimize, in two dimensions, the acoustic pressure in a 2 cm × 2 cm region (blue in the figure) near the lower right corner of an 18 cm × 9 cm rectangular cavity by allowing the shape of the upper wall to vary. The walls are perfectly reflecting, except for a speaker near the lower left corner that outputs a single frequency. The figure shows the calculated optimized design of the upper wall and the resulting simulated sound pressure in decibels. The researchers fabricated the contoured surface using a 3D printer and then, while precisely controlling the cavity humidity



their colleagues realized that the metal edges of each antenna would bend the horizontal electric field of any normal-incidence photons by 90° and thereby satisfy the QCL selection rule. The photons become loosely trapped between the metal cladding layers and are amplified as they interact with the subbands in the quantum wells. The antenna structures likewise bend outgoing photons' field by 90°, which recovers their horizontal polarization.

The new device's geometry and large cross section offer further advantages. With 17 antennas packed together and receiving the same reflected light from an output polarizer, the laser is easy to lock into a single-cavity mode whose shape, polarization, and spectral properties can be controlled through the design of the metasurface and external cavity. What's more, the beam power is scalable. So far, Williams and his team have generated beams of a few milliwatts—a respectable output. To increase the output power, they could lithographically add more antennas.

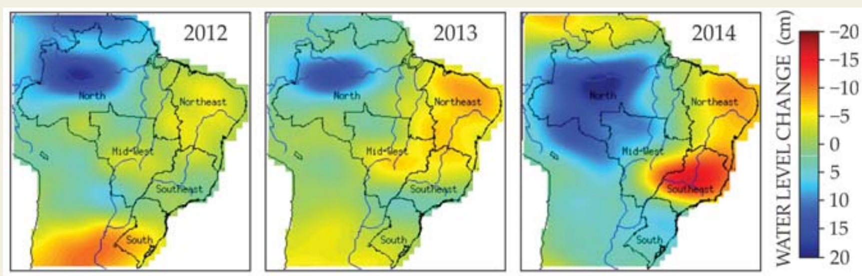
"We've shown the VECSEL configuration yields good power with a great beam," Williams says. "Our goal is to demonstrate that it yields great power in a great beam."

Mark Wilson

Reference

1. L. Xu et al., *Appl. Phys. Lett.* **107**, 221105 (2015).

WEIGHING BRAZIL'S DROUGHT FROM SPACE



The drought that has been afflicting southeastern Brazil for three years has become the country's worst since the 1920s. Water is rationed in São Paolo and other cities. Crop yields are plummeting. If the drought does not break, energy rationing could follow, as Brazil's hydropower stations struggle to operate. To gain a continent-scale overview of the disaster, Augusto Getirana of NASA's Goddard Space Flight Center turned to data from the Gravity Recovery and Climate Experiment (GRACE). The two GRACE spacecraft circle Earth in a low-altitude polar orbit, one trailing the other by 220 km. Whenever the lead craft flies over, say, a mountain, it feels a slightly increased gravitational tug, which temporarily pulls it farther away from the trailing craft. Measured interferometrically, such fluctuations in separation—positive and negative—are translated into a time-dependent map of Earth's gravity. On seasonal time scales, the fluctuations arise largely from changes in the disposition of the planet's liquid and frozen water. When Getirana looked at GRACE maps of Brazil, he could see the seasonal changes in the total amount of water above and below ground. As the figure shows, by 2014 a severe drought had stricken the southeast. Because droughts arise from planet-scale shifts in climate, Getirana's study suggests that gravitational data could help tie those shifts to local shifts in ground and surface water. (A. C. V. Getirana, *J. Hydrometeor.*, in press.) —CD

and temperature, used a microphone to measure the sound at a regularly spaced array of points in the green region. The experimental positions of the pressure maxima and nodal lines agreed well with optimization results, especially when factoring in microphone positioning errors and background noise. But the measurements highlighted the need for the calculations to account for damping, frequency and environmental variations, and manufacturing tolerance. (R. E. Christiansen, O. Sigmund, E. Fernandez-Grande, *J. Acoust. Soc. Am.* **138**, 3470, 2015.) —RJF

SWIMMING SPHERES

The gliding motion of jellyfish, eels, and other sea creatures is not just captivating to watch in an aquarium. Understanding the mechanics of swimming can, for example, help life scientists explicate biological functions and engineers design tiny robots for targeted drug delivery. Now, Daphne Klotsa of the University of North Carolina at Chapel Hill and colleagues from the University of Nottingham in the UK have carried out a detailed observational and simulation study of an extraordinarily simple type of artificial swimmer: two spheres attached by a spring and placed in a saltwater bath. The researchers caused the bath to vibrate vertically, both to provide energy that the swimmer could convert into translational motion and to allow for control of the streaming Reynolds number—loosely speaking, the ratio of inertial to viscous forces acting on the swimmer. For low Reynolds number, the experimental team observed oscillations of the spheres, but no center-of-mass motion. When they raised the Reynolds number, however, by increasing the vibration frequency or amplitude, the simple swimmer began to move through the saltwater as it oscillated. The simulation cross section illustrated here shows the essential mechanism at play when the spherical components (filled circles) are of unequal size and density. Arrows give the direction of the liquid flow averaged over the spheres' oscillation cycle. The crosses indicate vortex rings surrounding the spheres. At low Reynolds number (left), the flows around the two oscillating spheres are similar and the swimmer is stationary. High Reynolds number (right) breaks that symmetry of flow; indeed, a forceful jet of water emerges from below the smaller, denser sphere, propelling the swimmer upward. (D. Klotsa et al., *Phys. Rev. Lett.* **115**, 248102, 2015.) —SKB PT