not the second, so when conversion of reactants to products is the rate-limiting step, the reaction is zeroth order. In *E. coli*, an "affinity-enhancing protein" helps the protein-degradation enzymes find the proteins they degrade at the end of the translation process. Both Noireaux and Shin's system and the researchers' model include that protein, but some other experiments did not and would only regard protein degradation as a first-order reaction.

The next step for the researchers is to extend the experiment to study more complicated systems, including gene circuits. Using a biochip developed by Bar-Ziv and his group for immobilizing DNA on a surface,[5] they'd also like to develop a quantitative approach to study the spatial patterns that can form in gene-expression systems.

Johanna Miller

References

1. E. Karzbrun et al., *Phys. Rev. Lett.* (in press).
2. V. Noireaux, R. Bar-Ziv, A. Libchaber, *Proc. Natl. Acad. Sci. USA* **100**, 12672 (2003).
3. J. Shin, V. Noireaux, *J. Biol. Eng.* **4**, 8 (2010); **4**, 9 (2010).
4. W. W. Wong, T. Y. Tsai, J. C. Liao, *Mol. Syst. Biol.* **3**, 130 (2007).
5. A. Buxboim et al., *Small* **3**, 500 (2007).

Room-temperature source delivers record-power terahertz beam

The nonlinear optics device could help to resolve one of astronomy's lingering blind spots.

The universe teems with terahertz radiation. A byproduct of thermal motions of atoms and molecules, it is shed in abundance by cool interstellar dust, protostars, and other celestial objects. A blackbody at 30 K, for example, radiates most strongly at frequencies near 1 THz. Along with the adjacent far-IR—which ranges roughly from 5 to 20 THz—terahertz radiation is estimated to account for 98% of all the photons that have been emitted since the Big Bang.[1]

Here on Earth, however, you'd never know. That's partly because terahertz, or submillimeter, radiation is resonant with the vibrations and rotations of atmospheric molecules; most of it is absorbed and never reaches the ground. It's also quite tricky to produce in the lab, with the swath between about 0.8 and 4 THz—known as the terahertz gap—being particularly elusive. A no man's land in the heart of the electromagnetic spectrum, the terahertz gap encompasses frequencies just below the reach of optics technologies and just above the reach of electronics.

The few devices that have encroached into the gap have eked out beams of just a few microwatts or so. That's enough power to serve some spectroscopy purposes—say, detecting trace amounts of hydrogen cyanide in a plume of smoke[2]—but not enough to drive the arrays of heterodyne receivers that might scan the skies for protostars. Some pulsed sources attain larger powers, but with relatively poor frequency resolution.

Now Jerome Moloney of the University of Arizona in Tucson and a team of US and German researchers have designed a continuous, room-temperature source that delivers narrowband, milliwatt beams at terahertz-gap

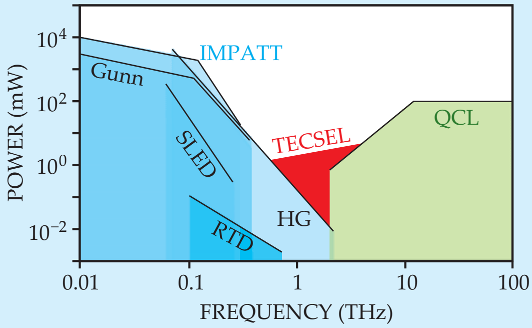


Figure 1. Terahertz gap. Optical electromagnetic wave sources such as quantum cascade lasers (QCLs, green) fade in power at frequencies below about 10 THz, as do electronic sources such as the diode devices shown here (all shaded blue) above 0.1 THz. A team of US and German researchers have now bridged a crucial part of the intervening gap with a so-called terahertz external-cavity surface-emitting laser, or TECSEL (red). (Chart provided by Jerome Moloney.)

frequencies.[3] Their device incorporates a nonlinear optics element into an external-cavity laser.

A tough itch to scratch

Scientists typically turn to one of two strategies to generate narrowband electromagnetic radiation. In optics, the idea is to orchestrate electron transitions—from an excited state to the ground state in gas lasers, from the conduction band to the valence band in semiconductor lasers—to produce coherent photon emissions. But such large electron leaps beget relatively energetic photons, so most lasers emit at near-IR (roughly, a few hundred terahertz) or higher frequencies.

Lower-frequency waves call for smaller energy transitions. To that end, quantum cascade lasers forgo conduction- to valence-band transitions, establishing instead small, intraband transitions between permissible electron states in quantum wells (see the article by Federico Capasso, Claire Gmachl, Deborah Sivco, and Alfred Cho, PHYSICS TODAY, May 2002, page 34). That strategy works well down to 10 THz or so, below which power fades, as shown in figure 1. Adding further inconvenience, quantum cascade lasers—if their tiny electron transitions are to stand out from the din of thermal fluctuations—must typically operate at cryogenic temperatures.

Alternatively, electronic devices generate electromagnetic waves by way of an alternating current. Various semiconductor diode schemes exploit that strategy to produce the radio waves and microwaves now prevalent in data transmission and communications. But such waves oscillate only as fast as current can be made to go back and forth, and that ability wanes as frequencies increase to terahertz levels.

Minding the gap

Suspecting, then, that the best path to the terahertz range might be indirect, many researchers have begun to explore a nonlinear optics effect known as difference-frequency generation, whereby two light beams are mixed to emit a beam whose frequency is the difference of the two. That would allow two IR beams whose wavelengths differ by 5 nm or so to be converted in part to terahertz radiation.

In a 2004 experiment headed by Martin Hofmann (Ruhr University Bochum, Germany), Moloney and coworkers found they could indeed mix two IR beams to generate a narrowband emission at the uppermost frequencies of the terahertz gap.[4] Other groups demonstrated similar schemes. None, however, managed to produce more than a microwatt or so of terahertz radiation.

Conservation laws were largely to blame. As Bell Labs scientists Jack Manley and Harrison Rowe described some 60 years ago, the nonlinear process essentially yields one low-energy photon for every two high-energy photons, which entails a loss in power that's commensurate with the drop in frequency. The extraction, then, of terahertz from IR radiation is inherently inefficient.

Outside in?

Although the researchers couldn't escape the Manley–Rowe relations, they could adjust for them. Around the time of the initial photomixing experiments, Moloney and Stephan Koch (Philipps University Marburg, Germany) had been developing expertise with vertical external-cavity surface-emitting lasers, or VECSELs. Unlike the more common edge-emitting semiconductor lasers, VECSELs emit orthogonally from the surface of a gain chip—a wafer of quantum wells buttressed by a mirror-like structure known as a distributed Bragg reflector. In a key distinguishing feature, the opposing cavity mirror—which helps to establish the dominant frequency modes—can be positioned up to tens of centimeters away.

Under normal high-power operation, a VECSEL can lase IR light anywhere within a bandwidth of about 30 nm. To obtain terahertz radiation, one would need to extract two appropriately spaced frequencies from that bandwidth, polarize the resulting two-color beam, and then pass it through a photomixing material.

Crucially, Koch realized that the VECSEL's external-cavity design permits all of those operations to be carried out inside the cavity. In 2008 the Arizona and Marburg researchers teamed with Martin Koch—then at the Braunschweig University of Technology in Germany—and colleagues to equip their VECSEL with the necessary elements: a thin quartz etalon, to establish two-frequency lasing; a Brewster window to polarize the beam; and a nonlinear crystal, lithium niobate, to do the photomixing. Rounding out the design,

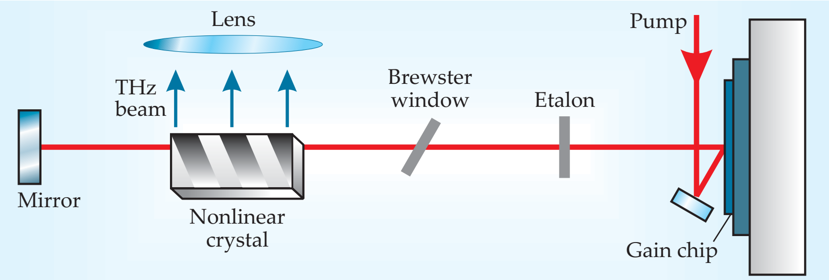


Figure 2. The experimental setup. A pump laser illuminates a semiconductor gain chip, initiating the circulation of IR light between the chip and a distant mirror. An etalon establishes two lasing frequencies, a Brewster window polarizes the beam, and a nonlinear crystal converts the dual-color beam to terahertz waves. Because the nonlinear crystal absorbs terahertz waves, the IR beam is aligned to skim just across its surface. The terahertz output is shaped into a Gaussian beam by a pair of lenses, only one of which is depicted here. (Adapted from ref. 3.)

sketched in figure 2, was a pair of lenses to shape the line-source emission into a Gaussian beam.

Exposed to the circulating intracavity beam, a photomixing crystal should, in principle, emit higher-intensity terahertz radiation than it would were it illuminated by an external laser beam. The team's initial experiments, however, were rendered inconclusive due to calibration difficulties.

A second attempt last year—this time in collaboration with Desert Beam Technologies, a small University of Arizona spinoff company—was more decisive. The team's device, coined a terahertz external-cavity surface-emitting laser (TECSEL), yielded 2 mW of 1.9-THz radiation and, in a separate trial, 0.5 mW of 1-THz radiation—both records.

Catching waves

The TECSEL addresses one of astronomy's long-standing problems. The emission lines of several substances of astrophysical interest, including singly ionized carbon (1.9 THz), carbon monoxide (1.27 THz), and singly ionized nitrogen (1.46 THz), fall squarely into the terahertz gap. So-called heterodyne receivers can detect over that range but must be driven by a local oscillator—a continuous, narrowband source tuned to the frequency of interest.

In a proof of concept at the University of Arizona's Steward Observatory, the TECSEL successfully drove a heterodyne receiver at 1.9 THz—a result that bodes well for terahertz astronomy applications. Explains Moloney, "A milliwatt of power at 1.9 THz could drive 100 pixels in a receiver array. That may not sound like much, but the current state of the art is a single pixel."

Still, Moloney acknowledges, more work remains to make the TECSEL a practical option for space- and balloon-borne observation. Aside from improving its conversion efficiency, the team hopes to shrink the device from its initial footprint of about 10 × 20 cm down to length scales of a few millimeters.

The utility of the continuous-wave terahertz source may not be limited to stargazing. Caltech's Peter Siegel envisions applications in areas as far-flung as communications, security screening, and atmospheric chemistry. In fact, he suggests, the most important applications might be at the level of basic science. "This may be a case where technology drives new science, instead of the other way around. It opens up a new area of development that I think will be quite fruitful."

Ashley G. Smart

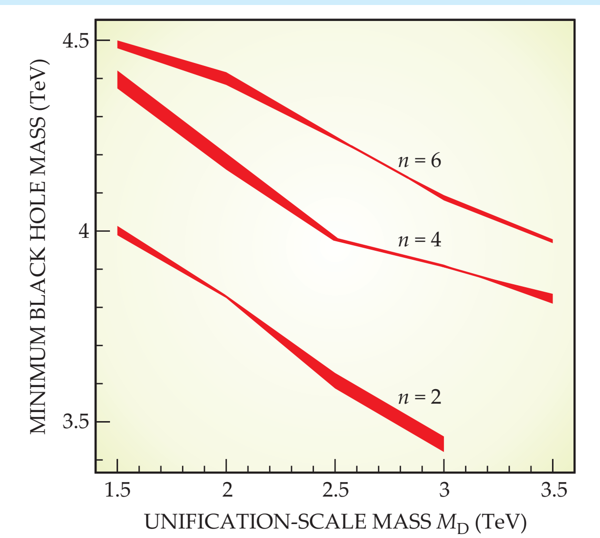
References

1. P. H. Siegel, *IEEE Trans. Microwave Theory Tech.* **50**, 910 (2002).
2. D. Bigourd et al., *Opt. Lett.* **31**, 2356 (2006).
3. M. Scheller et al., *Opt. Express* **18**, 27112 (2010).
4. S. Hoffmann et al., *Appl. Phys. Lett.* **84**, 3585 (2004).

physics update

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

No microscopic black holes yet. From among 10^{13} proton–proton collisions at 7 GeV in its first year of operation, the Large Hadron Collider (LHC) at CERN has as yet yielded no evidence of black hole production. The detectable creation of microscopic black holes at the LHC follows from speculative but attractive theories that seek to explain the puzzling weakness of gravity by positing curled-up extra spatial dimensions accessible only to gravitons. In such theories, the intrinsic strength of gravity would be comparable to those of the electromagnetic and weak interactions at energies near 1 TeV, where electroweak unification occurs. But now the collaboration that runs the LHC's Compact Muon Solenoid (CMS) detector, having found no evidence of black holes, has published the first experimental lower limits on their masses. A black hole produced in a 7-TeV collision would decay by Hawking radiation within 10^{-27} s into perhaps half a dozen extraordinarily energetic particles—mostly quarks and gluons manifesting themselves as jets of hadrons. Such a spectacular decay would be conspicuous not only by the number of emerging ultrahigh-energy jets, but also by their unusually isotropic distribution. Even in the absence of true black hole events, however, 10^{13} collisions will create many imposters. So determining limits on black hole production requires painstaking estimation of the resulting backgrounds. The figure shows the minimum black hole mass deduced from the CMS null result as a function of two parameters of the extra-dimension theories: the number n of extra spatial dimensions, and the characteristic mass scale M_D of the putative unification of the gravitational and electroweak interactions. (CMS collaboration, http://arxiv.org/abs/1012.3375.) —BMS



Superplastic mantle minerals. Superplasticity is the ability of some crystalline materials to stretch up to several times their own length when heated. Although the minerals in Earth's mantle don't endure such large strains, circumstantial evidence suggests that superplasticity helps them respond to the subduction of continental plates and other tectonic processes. Now, a team led by Takehiko Hiraga of Tokyo University and Hidehiro Yoshida of Japan's National Institute for Materials Science has found direct evidence that mantle minerals are indeed superplastic. Like other superplastic materials—real or presumed—those in the mantle are polycrystalline aggregates. For their study, Hiraga, Yoshida, and their team sintered nanoscale powders to make two analogues of mantle minerals, both of which consisted mostly of forsterite (Mg_2SiO_4). In the absence of strain, a superplastic material is made up of nanoscale grains of the majority component interspersed with smaller grains of the minority component. When heated under strain, the majority and minority grains both grow by merging with their neighbors.