A portable laser system fills the terahertz gap

With the right dimensions, a laser composed of a series of quantum wells emits hard-to-produce terahertz-frequency light without the usual need for cryogenic cooling.

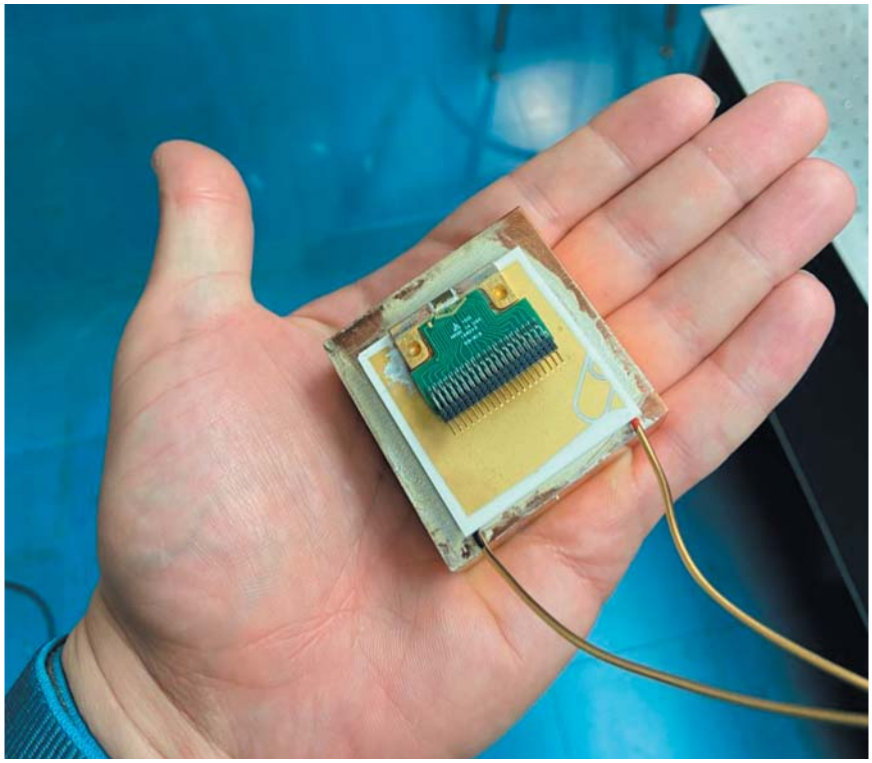

FIGURE 1. THE TERAHERTZ QUANTUM CASCADE LASER and thermoelectric cooler shown here are all the equipment necessary for the portable laser developed by Qing Hu and his colleagues. The compact design opens up potential applications, such as security scans for drugs and skin cancer screening. (Photo courtesy of Qing Hu and colleagues, MIT.)

Many illicit drugs, including methamphetamines and heroin, have distinctive spectral peaks at terahertz frequencies. Terahertz is a happy medium between microwave and IR: Characteristic molecular absorption features are present in the IR and terahertz ranges but largely absent in millimeter and microwave ranges, and many packaging materials that are opaque to IR frequencies are transparent to terahertz light. Such transparent materials include paper, cardboard, wood, textiles, and plastic.

A portable terahertz spectrometer would allow security personnel to nondestructively scan for illegal substances in luggage and other packages. And unlike x-ray screening, it can distinguish materials of similar densities and textures and even offer chemical identification. Researchers have already demonstrated terahertz spectroscopy's ability to distinguish the shape, position, and concentrations of baggies of methamphetamine, MDMA, and aspirin inside a sealed envelope.[1]

Drug scanning and other practical applications, such as skin cancer screening, have been held back, however, because researchers have trouble producing light from about 1 to 10 THz, the so-called terahertz gap. Quantum cascade lasers (QCLs) are a promising photonic method to bridge that gap. But terahertz QCLs typically operate at a maximum temperature of 210 K, which requires bulky, nonportable cryogenic cooling equipment.

MIT's Qing Hu and his colleagues have now developed a terahertz QCL that operates at 250 K. Their compact laser needs only a palm-sized thermoelectric cooler,[2] like that shown in figure 1. The system could broaden the application of terahertz spectroscopy to medical imaging, security screening, and quality inspection.

Bridging the gap

The terahertz gap lies between the frequencies accessible to photonic and electronic technologies. Microwave ovens, cell-phone towers, and walkie-talkies rely on alternating currents to produce electromagnetic waves. But currents can only go back and forth so fast, and that limitation puts an upper bound on how quickly the produced waves can oscillate. Electronic devices readily pump out radio waves and microwaves, but the power drops off above 1 THz as $1/f^4$ or faster in terms of the frequency f.

A semiconductor laser produces light through an electron transition from the conduction band to the valence band. In principle, it's possible to yield frequencies as low as 10 THz. But materials with the requisite small bandgaps are temperature sensitive and difficult to process. Nonlinear optical techniques can circumvent that limit—for example, through down-conversion—but a lot of power is lost.

Quantum cascade lasers create lower energy transitions through periodic layers of different semiconductors, sometimes called a superlattice (see the article by Federico Capasso, Claire Gmachl, Deborah Sivco, and Alfred Cho, PHYSICS TODAY, May 2002, page 34). The layers form quantum wells, and the electrons' spatial confinement splits the conduction band into discrete subbands with energy gaps in the IR or terahertz range. Because the widths of the wells—controlled by the thicknesses of the layers—determine the emission wavelength, researchers are not limited to the naturally occurring properties of semiconducting materials.

Over the years many terahertz QCL shortcomings, such as poor collimation, have been mitigated (see, for example, PHYSICS TODAY, February 2016, page 16). But improving the instruments' maximum operating temperature has been a long-standing challenge.

Cascading effects

Hu first heard about the concepts underlying QCLs at the American Physical Society's March Meeting in 1990, just before he joined the MIT faculty. At the meeting, Manfred Helm, now at Helmholtz-Zentrum Dresden-Rossendorf in Germany, presented his and his colleagues' observation of inter-subband spontaneous emission in the terahertz range from a semiconductor superlattice. A superlattice laser, he argued, should be possible. Even though Hu's background wasn't in laser development, he decided the topic was too interesting and potentially useful to pass up. Terahertz QCLs became a focal point of his research.

Lasing from superlattices was proved possible in 1994, when Bell Labs researchers produced the first QCL, which emitted in the IR. But the move from IR to terahertz laser took another eight years.[3] The difficulty lay in maintaining population inversion, a state in which a higher energy level is teeming with electrons while a lower energy level is relatively empty. Population inversion produces the optical gain necessary for a laser.

In its simplest form, a QCL works as shown in figure 2a. An electron in the nth set of quantum wells starts in the upper lasing level u_n. When the electron drops down to the lower lasing level l_n, a photon is emitted. The electron then scatters to the ground state, known as the injector level i_n, which is still in the conduction band. An applied electric potential offsets the modules energetically, so the electron tunnels from the injector level into the next module's upper lasing level, u_{n+1}. That cascade effect is responsible for the high power in QCLs.

When u_n and l_n are close in energy—as in terahertz QCLs, which have about 16 meV gaps to produce 4 THz photons—maintaining the requisite population inversion is difficult. To do so, researchers design devices that slow the rate of transfer from u_n to l_n to keep electrons in the upper level, increase the rate of transfer from l_n to i_n and i_n to u_{n+1} to quickly move electrons out of the lower level, or some combination. Those tactics hinge on the energetic and spatial relationship between the states' probability density functions.

Each repeating module of a QCL contains multiple quantum wells. The simplest case of two wells is shown in black in figure 2b, but many QCLs have far more wells in a module. To speed up the so-called injection rate—the transfer from i_{n-1} (red) to u_n (blue)—Hu and his group designed QCLs whose states have high spatial overlap.

To slow the transfer from u_n to l_n (yellow), the researchers determined quantum well dimensions that produced low spatial overlap for the lasing states; u_n is localized more in the left well of the nth module whereas l_n is localized more in the right well. That way, even though electrons could scatter between the states instead of making an optical transition, the effect will be small.

To counterbalance the slow rate of the optical transition from u_n to l_n across a barrier and get a decent signal, the device needs more electrons. High electron concentrations produce a charging effect, which changes the states' relative energies. The result is that i_{n-1} might be misaligned with u_n and that the energy spacing between l_n and i_n isn't guaranteed. An applied voltage can restore the injection alignment of i_{n-1} and u_n, but the uncertainty in the l_n to i_n transition limits the options for efficiently shuffling electrons out of l_n.

Direct-phonon scheme

In most terahertz QCL devices, electrons rapidly scatter out of l_n through an interwell transition resonant with a phonon. (The electrons typically move first to an intermediary energy level above i_n not shown in figure 2.) But that route depends on a specific and fixed energy difference between the two states. Hu and his colleagues instead moved to a direct-phonon scheme, in which electrons scatter directly to the injector state within the same well, with no specific energy spacing needed.

Those and other population inversion strategies have been developed gradually over the past 18 years since terahertz QCLs were introduced. In that time, the

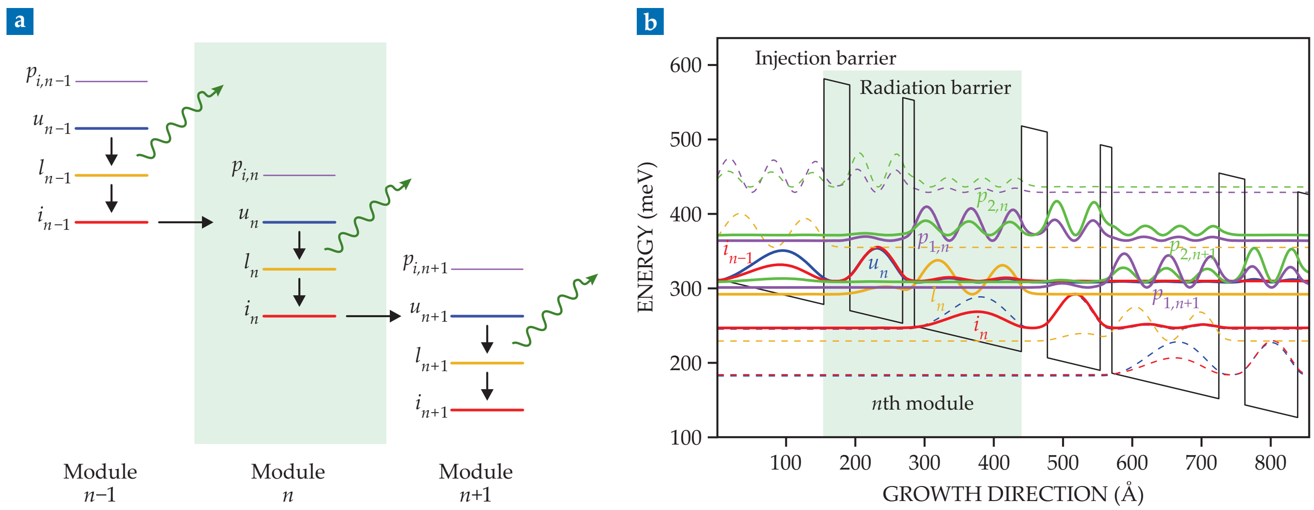

FIGURE 2. A CASCADE OF ENERGY LEVELS produces laser light. **(a)** Electrons in a quantum cascade laser follow the black arrows from module to module. Within each module n, an electron in the upper lasing level u_n moves to the lower lasing level l_n and emits a photon. It then quickly scatters into the ground state i_n and proceeds to the next module. With the right design, electrons never enter the higher-energy $p_{i,n}$ states, $p_{1,n}$ and $p_{2,n}$, which don't have available optical transitions. **(b)** Each module comprises a pair of quantum wells (black lines) defined by an injection barrier and a radiation barrier. The wells' dimensions determine how the energy states' probability density functions (colored lines) distribute. Transitions between levels with high spatial overlap are more likely to occur than between those with low overlap. (Adapted from ref. 2.)

maximum operating temperature T_{max}—the temperature at which thermal effects overwhelm lasing—initially increased rapidly from 50 K in 2002 to 164 K in 2005. Then progress stalled at 200 K from 2012 until 2019, when Jérôme Faist's group at ETH Zürich finally inched T_{max} up to 210 K.[4]

All terahertz QCL lasers except Faist's from 2019 required cryogenic cooling. To move to a portable thermoelectric cooler, which reaches 210 K to 235 K, T_{max} ideally needs to be higher than 235 K to ensure there's sufficient power for imaging. Many researchers argued that 200 K was a fundamental limit of T_{max} related to the point where thermal energy is comparable to the subband gaps. But Hu was never convinced that such a limit is relevant in a nonequilibrium system, such as a laser.

In 2015 Hu and former postdoc Asaf Albo, now at Bar-Ilan University in Israel, suggested that at high temperatures electrons jump over the potential barriers between quantum wells rather than dropping from upper to lower lasing levels and emitting photons. Higher barriers between wells should therefore improve T_{max}.

Physically, barrier heights depend on the materials in the layers of the QCL. The quantum wells are typically composed of gallium arsenide, and the barriers are aluminum gallium arsenide. Alloying GaAs with Al widens the bandgap, so the alloy's conduction band is at a higher energy. That energy difference provides the barrier height for the well.

Until now, the best-performing terahertz QCLs all used $Al_{0.15}Ga_{0.85}As$ barriers, and early studies on higher-aluminum-content devices found decreased T_{max}, despite the higher barriers. As a result, researchers have largely ignored the high-barrier strategy because they assumed the lower T_{max} was an unavoidable consequence of increased scattering from interface roughness, which scales with barrier height.

In their own experiment with high barriers from 2016, Hu and Albo noted an additional limiting factor on T_{max}: the introduction of higher-energy states, which electrons tunnel into without emitting light.[5] To avoid electrons jumping into nonlasing states in the devices in their new study, Hu's student Ali Khalatpour used numerical band-structure calculations, made easier by the device's simple two-well design, to optimize the dimensions with high barriers.

Reaching new heights

Previous models often assumed that the upper laser level was the highest subband. But higher barriers introduce other bound states, such as $p_{1,n}$ and $p_{2,n}$ in figure 2b. The Hu group's QCL design had to trade off minimizing leakage into such nonlasing states and maximizing the injection rate and optical gain. For example, increasing the radiation barrier thickness reduces leakage into the nonlasing states, but it also makes the radiative transition harder and thus reduces the gain.

In collaboration with Zbig Wasilewski's group at the University of Waterloo in Canada, the researchers produced four of their designs for QCLs made of $Al_{0.3}Ga_{0.7}As$ and GaAs. Creating terahertz QCLs takes high-quality growth with molecular beam epitaxy. Because the wavelengths are long in the terahertz range, the devices are thick, around 10 µm, and take around 15 hours to grow. Maintaining stable growth conditions over that long period is tricky. QCLs also depend on crisp interfaces, otherwise significant scattering will occur. The small subband energy gaps relative to IR devices make those effects even more important.

Paired with a room-temperature detector and camera, the team's best 4 THz laser, with a compact and portable thermoelectric cooler, produced power sufficient for real-time imaging. And future design tweaks and optimization should make room temperature operation possible.

Portable terahertz sources offer promising applications, including skin cancer screening.[6] To look for cancer now, doctors slice off and dye the affected skin and scan it under a microscope. "My mother was a pathologist," says Hu. "I used to peek through her microscope, and it really took trained eyes to identify cancer cells. I couldn't tell the difference between normal and cancer cells."

Water absorbs terahertz frequencies too strongly to do a full body scan, but surface penetration even up to a few millimeters is possible. Terahertz imaging wouldn't require the excision of skin, and it's sensitive to the increased blood supply and water content indicative of cancer in skin tissue.

Heather M. Hill

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A galactic fast radio burst finally reveals its origin

Observations at multiple wavelengths provide compelling evidence that the first example of a fast radio burst detected in our galaxy came from a magnetized neutron star.

In 2007 a bright, brief burst of radio waves emanating from far outside the Milky Way captured the attention of astronomers. Short-duration pulses are not uncommon in radio astronomy. Pulsars in our galaxy produce intermittent, milliseconds-long flares of radio waves. The new phenomenon was orders of magnitude more luminous than those familiar signals and was spectrally different. The fast radio burst (FRB) was a perplexing new phenomenon.

Since that first discovery, radio telescopes have detected dozens of FRBs, some of them recurring sporadically from the same location. (See PHYSICS TODAY, March 2017, page 22.) Astronomers have pinpointed the galaxies that host just a few of them. To account for the signals, some theories invoke high-energy bursts of radiation emitted by compact stellar remnants—in particular, highly magnetized neutron stars called magnetars. But until now, observational evidence has not directly associated an FRB with a magnetar or other specific astronomical entity.

This year an international effort has identified the first known FRB from within the Milky Way and determined that the signal coincides with x-ray and gamma-ray emissions from the same location. The site corresponds to a magnetar in the constellation Vulpecula. The findings provide new observational constraints on FRB progenitor theories and a direction for future study.

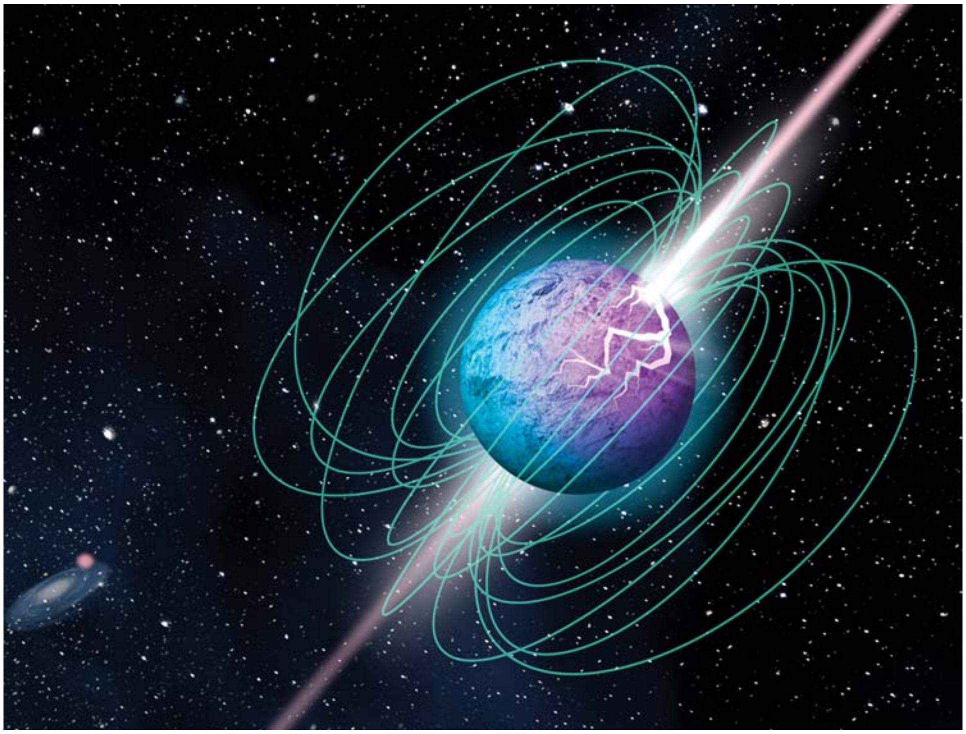

FIGURE 1. THIS ARTIST'S IMPRESSION OF A MAGNETAR represents the one now believed to be the source of the fast radio burst that was observed in April 2020. Shown here are the complex magnetic field structures (green lines) and radio, gamma-ray, and x-ray emissions that are produced from the magnetar's poles following a crust-cracking starquake episode. (Image courtesy of the McGill University Graphic Design Team.)

Team effort

Magnetars are spinning neutron stars, each left over from the explosion of a star tens of times the mass of the Sun, and they have magnetic fields 100 trillion times stronger than Earth's. Strain induced by the intense magnetic field increases until it's abruptly relieved in a starquake, which gives rise to characteristic bursts of x rays and gamma rays, depicted in figure 1.

Of the 30 magnetars currently known in our galaxy and the Magellanic Clouds, five have exhibited faint, transient radio pulses coincident with what is presumed to be the magnetar's spin period. A leading model for repeating FRBs suggests that they come from extragalactic magnetars. However, for that model to hold, some magnetars must be capable of generating radio emissions that exceed