**Terahertz and Infrared Quantum Cascade Lasers, and Real-time Imaging**

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**Introduction**

THz frequencies ($f = 1-10$ THz, $\hbar \omega = 4-40$ meV, $\lambda = 30-300$ µm) remain one of the most underdeveloped frequency ranges, even though the potential applications in remote sensing and imaging, spectroscopy, and communications are great. This is mainly due to lack of coherent sources with high output power levels. The difficulty to generate THz radiation is because of the so-called "THz gap" in conventional semiconductor devices, which falls between two other frequency ranges in which solid-state sources have been well developed. One is the microwave and millimeter-wave frequency range, and the other is the near-infrared and optical frequency range. Semiconductor electronic devices that utilize oscillating conduction current $G_J$ (such as transistors, Gunn oscillators, Schottky-diode frequency multipliers, and photomixers) are limited by the transit time and parasitic $RC$ time constants. Consequently, the power level of these electronic devices decreases rapidly as the frequency $f$ increases above 1 THz. In contrast to the electronic devices, photonic or quantum electronic devices (such as laser diodes) generate radiation by oscillating bounded dipoles (which give rise to an oscillating displacement current $\frac{\partial \mathbf{P}}{\partial t}$). As a result, they are not limited by the transient time and/or the $RC$ time constant. However, for conventional bi-polar laser diodes, they are limited to frequencies above that corresponds to the semiconductor energy gap, which is higher than 10 THz even for narrow-gap lead-salt materials. Thus, the frequency range below 10 THz is inaccessible for the conventional semiconductor bi-polar diode lasers.

Semiconductor quantum-effect devices (which can be loosely termed "artificial atoms"), including both vertically grown quantum-well structures and laterally confined mesoscopic devices, are human-made quantum mechanical systems in which the energy levels can be chosen by changing the sizes of the devices. Typically, the frequency corresponding to the intersubband transitions is in the millimeter-wave range ($\Delta E \sim 1-4$ meV) for the lateral quantum-effective devices, and THz to infrared for the vertical quantum wells. It is therefore appealing to develop ultrahigh-frequency devices, such as THz lasers utilizing the intersubband transitions in these devices.

In our group, we are systematically investigating physical and engineering issues that are relevant to devices operating from millimeter-wave and THz to infrared frequencies. Specifically, we are working on THz quantum cascade lasers based on intersubband transitions in quantum wells, their applications as local oscillators in heterodyne receivers, and real-time THz imaging using focal-plane array cameras. Recently, we have started a new project in collaboration with MIT Lincoln laboratory to develop high-efficiency mid-infrared quantum-cascade lasers at ~4-5 µm wavelength. This development could lead to important applications in infrared counter measures in protecting airplanes, and in sensitive infrared sensing.
Chapter 29. Terahertz and Infrared Quantum Cascade Lasers, and Real-time Imaging

Development of terahertz quantum cascade lasers

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Semiconductor quantum wells are human-made quantum mechanical systems in which the energy levels can be designed and engineered to be of any value. Consequently, unipolar lasers based on intersubband transitions (electrons that make lasing transitions between subband levels within the conduction band) were proposed for long-wavelength sources as early as the 1970s. However, because of the great challenge in epitaxial material growth and the unfavorable fast nonradiative relaxation rate, unipolar intersubband-transition lasers (also called quantum-cascade lasers) at mid-infrared wavelengths were developed only recently at Bell Laboratories. This achievement paved the way for development of coherent laser sources at customized frequencies ranging from THz to near-infrared. However, compared to the infrared QCLs, THz QCLs at much longer wavelengths face unique challenging issues. First, the energy levels corresponding to THz frequencies (1 THz = 4 meV) are quite narrow, so it is very challenging to design quantum well structures for selective injection to the upper level and selective depopulate electrons from the lower level. The requirements for fabrication of such quantum-well structures with adequate accuracies are also demanding. Because of the narrow separation between subband levels, heating and electron-electron scattering will have a much greater effect. Second, mode confinement, which is essential for any laser oscillation, is difficult at longer wavelengths. Conventional dielectric-waveguide confinement is not applicable because the evanescent field penetration, which is proportional to the wavelength and is on the order of several tens of microns, is much greater than the active gain medium of several microns. Recently (November 2002), we made a breakthrough in developing quantum-cascade lasers at 3.4 THz (corresponding to 87 μm wavelength). Since then, we have made rapid progress in developing many lasers with record performance, including but not limited to the highest pulsed operating temperature of ~170 K, highest CW operating temperature of 117 K, and the longest wavelength of 188 μm (corresponding to 1.6 THz). Key results are summarized in the following sections.

THz quantum cascade lasers based on resonant phonon scattering for depopulation

The direct use of LO-phonon scattering for depopulation of the lower state offers several distinctive advantages. First, when a collector state is separated from the lower state by at least the phonon energy $\hbar \omega_{LO}$, depopulation can be extremely fast, and it does not depend much on temperature or the electron distribution. Second, the large energy separation provides intrinsic protection against thermal backfilling of the lower radiative state. Both properties are important in allowing higher temperature operation of lasers at longer wavelengths.

The present design combines advantages of our two previously investigated THz emitters. As shown in Fig. 1, the radiative transition between levels 5 and 4 is spatially vertical, yielding a large oscillator strength. The depopulation is highly selective, as only the lower level 4 is at resonance with a level 3 in the adjacent well, where fast LO-phonon scattering takes place. The four-well structure inside the
dashed box is one module of the structure, and 175 such modules are connected in series to form the quantum cascade laser.

Figure 1. Conduction band profile calculated using a self-consistent Schrödinger and Poisson solver (80% conduction band offset) biased at 64 mV/module. Beginning with the injector barrier, the layer thickness in Å are 54/78/24/64/38/148/24/94. The 148-Å well is doped with Si at $1.9 \times 10^{16}$/cm$^3$, yielding a sheet density of $2.8 \times 10^{10}$/cm$^2$.

Mode confinement in this laser device was achieved using a surface plasmon layer grown under the active region. The schematic of the device structure and the calculated mode profile and waveguide loss are shown in Fig. 2. The calculated waveguide loss of 7.1 cm$^{-1}$ and mode confinement factor $\Gamma \approx$
29% are quite favorable compared to the calculated gain of our laser device. After the rear facet was high-reflection (HR) coated, lasing was obtained in this device and a typical emission spectrum above threshold is shown in Fig. 3(a). The emission frequency corresponds to a photon energy of 14.2 meV, close to the calculated value of 13.9 meV. Pulsed lasing operation is observed up to 87 K with a power level of 13 mW at 5 K, and ~4 mW even at liquid-nitrogen temperature of 78 K, as shown in Fig. 3(b).

Figure 3. (a) Emission spectrum above threshold. The inset shows a set of emission spectra that are Stark-shifted to higher frequencies with higher bias. (b) Pulsed power-current relations taken from a similar laser device at different heat-sink temperatures.

THz quantum cascade lasers using metal waveguides for mode confinement

After our initial success in the development of 3.4-THz quantum cascade laser, one of the improvements made was the mode confinement. As shown in Fig. 2, the mode confinement using surface plasmon layer yields a relatively low mode confinement factor of $\Gamma \approx 0.29$. This mode confinement is sufficient for lasing at 3.4 THz. However, as we are developing even longer wavelength quantum cascade lasers, the mode confinement will become much worse or even unconfined at frequencies lower than 2 THz for the carrier concentration in our laser structures. An alternative method for mode confinement is to use metal waveguides. As shown in Fig. 4, the mode is now tightly confined between the top and bottom metal contacts, yielding a confinement factor close to 100%. Fig. 4 also shows the process of wafer bonding and selective etching to fabricate such a metal waveguide structure.

Using a combination of the metal-metal waveguides and improved gain medium, we have developed THz QCLs with many record performance in the last year. Some of the highlights of these achievements are summarized in Fig. 5, including the highest operating temperature of ~170 K in the pulsed mode (at this temperature $k_B T / \hbar \omega = 1.2$, which is unprecedented for any solid-state photonic devices), 117 K in CW mode, and the longest wavelength (188 µm, corresponding to 1.6 THz) QCL to date.
Figure 4. Left: Schematic of the wafer bonding process for double-side metal-metal waveguide. Right: A SEM picture of a fabricated device.

Figure 5. Top left: Pulsed power-current relations measured up to ~164 K heatsink temperature. Top: CW power-current and voltage-current relations measured up to ~117 K heatsink temperature. Left: Lasing emission spectrum at ~1.6 THz.
In addition to the record performance in operating temperatures and wavelength, we have recently developed high-power THz quantum-cascade lasers that produce ~250 mW of power, as shown in Fig. 6. Using these high-power lasers, we are now able to perform THz imaging in real time at a video rate of ~20 frames/second, that is, making movies in T-rays.

![Graph showing current density and peak optical power vs. frequency and current for THz quantum-cascade lasers.]  

**Figure 6.** A 4.4-THz quantum-cascade laser with peak power level of ~250 mW.

### Analysis of transport properties of THz quantum cascade lasers

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Even though mid-infrared and THz quantum cascade lasers operate on the same principle, that is, intersubband transition in semiconductor heterostructures, they show a qualitative difference in the dynamics of electron transport. For mid-infrared QCLs, the subband separations exceed the LO-phonon energy $\hbar \omega_{LO}$ and electron transport is dominated by LO-phonon scattering. For THz QCLs, many subband separations are smaller than $\hbar \omega_{LO}$, only the high-energy tail of a hot electron distribution is subject to the LO-phonon scattering, which results in a significantly higher temperature sensitivity for the electron transport and a far greater importance of electron-electron (e-e) scattering.
The long delay in the development of THz QCLs is testimony to the difficulty of achieving population inversion involving these complicated transport mechanisms. It is thus important to quantitatively model these transport processes to extend the operation of THz QCLs to broader frequency ranges and higher temperatures.

Our transport analysis is based on Monte Carlo (MC) simulations, which have been used to analyze and design mid-infrared and THz QCLs. Compared to conventional rate-equation analysis, the MC method is especially useful for THz QCLs, as it does not rely on a specific model for carrier distributions and can easily handle temperature- and density-dependent scattering times. Fig. 7 illustrates the flow chart of our Monte Carlo simulation scheme. It follows a conventional scheme for an ensemble of particles, in our case $10^4$ particles, with a focus on e-e and e-phonon interactions involving the electrons in one module of the device under study. An electron that scatters out of a module is reinjected with identical in-plane $k$-vector into a subband equivalent to its destination subband, in accordance with the spatial periodicity of QCLs.

The results of the Monte Carlo simulations, focused on the 3.4-THz laser structure shown in Fig. 1, are summarized in Fig. 8. All simulations assumed a lattice temperature of 25 K, corresponding to a 10 K heat sink temperature. In Fig. 8(a), the calculated I-V relation qualitatively resembles that of measured one, with the calculated peak current density is noticeable lower without including electron-impurity scattering. With the inclusion of electron-impurity scattering, the agreement is much better. The two horizontal lines are calculated total cavity losses with one facet Au coated and without any facet coating. Our device lased only with one facet coating, thus the two lines define the range of material gain in our laser device. The qualitative agreement between the MC and experimental results indicate the usefulness of MC simulation as a design tool.

![Figure 7. Flow chart of our ensemble Monte Carlo simulation scheme.](image)
Despite the reasonably good agreement shown in Fig. 8, however, a challenging problem remains in our transport analysis in how to deal with wavefunction localization caused by dephasing scattering. In all the MC studies on transport properties in QCL structures, the entire multiple quantum-well structure is treated as a single quantum mechanical system, for which Schrödinger's equation is solved to yield spatially extended subband states. In general, coherent interaction and time evolution is ignored, and transport is modeled as intersubband scattering among these spatially extended states, in a way similar to the Boltzmann transport equation. In this Boltzmann-like picture, potential barriers do not cause any bottlenecks in the transport process. For example, a thicker injection barrier only yields a smaller anticrossing gap, and thus will not affect the peak current density at resonance but will only makes the resonance sharper. In this picture, both the injection to the upper radiative level and removal of electrons from the lower radiative level tend to be quite efficient at resonance. As a result, our transport analysis based on this Boltzmann-like model predicted appreciable levels of gain in most of the structures that we have experimentally investigated for THz lasing. In real devices, however, dephasing scattering (due to interface roughness, alloy, and impurity scatterings) interrupts the coherent interactions between states and effectively localizes wavefunctions, making transport between weakly coupled states (characterized by a small anticrossing gap between these states) mostly an incoherent tunneling process. This incoherent sequential tunneling process is much less efficient than the injection and removal rates predicted by the Boltzmann-like model. A possible solution to deal with the problem of wavefunction localization is to start from a tight-binding model in a density-matrix formalism. In this model, the dephasing scattering damps the Rabi oscillation between two states across an energy barrier and therefore it comes in naturally in the reduction of the coupling/transport among spatially localized basis states. Another possible approach is based on a nonequilibrium Green's function theory, although not as intuitive as the MC approach, it takes all the dephasing processes into account and calculates...
important parameters such as the gain and current density. Both tasks are presently under our current investigations. Fig. 9 illustrates the flow chart of nonequilibrium Green’s function analysis of our THz QCL devices. This simulation analysis is highly computation intensive and the required memory scales with $n^4$, where $n$ is the number of subband levels involved in the transportation process ($n = 5$ for the structure shown in Fig. 1). Nevertheless, it has yielded results far better than those from semiclassical Boltzmann approach when compared with experimental results.

Figure 9. Flow chart of transport analysis using nonequilibrium Green’s function approach.

Terahertz heterodyne receiver using QCLs and hot-electron bolometers

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The terahertz (THz) region of the electromagnetic spectrum (300 GHz – 10 THz) is the least explored spectral region in astronomy, despite the fact that it contains half the luminosity and 98% of the photons of the universe. This is mainly caused by the absence of sensitive detectors and the fact that the earth’s atmosphere is opaque for large fractions of this spectral region. Ground, air and space based observatories are now starting to lift the veil but they are limited by the current state-of-the-art radiation detectors. In particular, there are no spectrometers capable of performing very high-resolution spectroscopy above 2 THz suitable for space-based observatories. Here we report the first demonstration of an all solid-state heterodyne receiver that can be used as such a spectrometer at frequencies above 2 THz. The system we present uses a hot electron bolometer as mixer and a quantum cascade laser as the local oscillator, operating at 2.8 THz, with an unprecedented combination of sensitivity and stability. The complete system provides a unique solution for THz spectroscopy for astronomy as well as Earth science.

Figure 10 shows a schematic view of the experimental setup with the QCL and the HEB mounted in two separate dewars. A wideband spiral antenna coupled NbN HEB mixer is used with a superconducting bridge of 4 µm wide, 0.4 µm long, and about 4 nm thick. The normal state resistance $R_N$ of the device, measured above the critical temperature of about 9 K, is 65 $\Omega$. Without radiation applied a critical current $I_c$ of 320 $\mu$A is observed at 4.2 K. The radiation is coupled to the antenna using a standard quasi-optical technique: the Si chip with the HEB is glued to the back of an elliptical, anti-reflection coated Si lens. The lens is placed in a metal mixer block thermally anchored to the 4.2 K cold plate. The divergent beam from the QCL passes through a high-density polyethylene (HDPE) dewar-window and is collimated with a parabolic mirror. The radiation is further guided to the HEB dewar through a flat mirror and a 6 $\mu$m thick Mylar beam splitter, which acts as a directional coupler. A blackbody source (of Eccosorb) is used as the signal source, which defines a hot load at 295 K and a cold load at 77 K. The signal is combined with the QCL beam through the beam splitter. Both signals pass through the thin HDPE window and a metal mesh heat filter at 77 K of the HEB dewar. The IF signal, resulting from the mixing of the LO and the hot/cold load signal, is amplified using a low noise amplifier operated at 4.2 K, and is further fed to a room temperature amplifier and filtered at 1.4 GHz in a band of 80 MHz.
The key result of this work is demonstrated in Figure 13. A set of current versus voltage (I-V) curves of the HEB is shown for various levels (270, 300, 330 nW) of the effective power of radiation absorbed at the HEB, together with the receiver noise temperature, $T_{N,\text{rec}}$, as a function of voltage. (The inset shows a top view of the HEB with its spiral antenna). The power is varied by changing the DC current of the QCL, and the level is estimated by evaluating the absorbed power by the HEB through the isothermal technique. The noise temperature $T_{N,\text{rec}}$ is determined from the ratio of the IF output noise power for a hot and a cold load. Each set of $T_{N,\text{rec}}$-V data shows a minimum region, indicating the optimum bias point. Best results are obtained for 300 nW LO power and 0.7 mV DC bias with $T_{N,\text{rec}}$ being as low as 1400 K, which is among the lowest obtained at this high frequency. This work, along with the phase-locking measurement described in the next section, has firmly established QCL’s suitability in local-oscillator applications in a frequency range where no solid-state sources are available prior to our work.
Current-voltage characteristics (solid line, left axis) of a NbN hot-electron bolometer (HEB) without and with radiation from a QCL at 2.814 THz. The measured receiver noise temperature $T_{N,rec}$ is shown as symbols (right axis) versus the bias voltage at different LO power levels. The inset shows a top view of the HEB with its spiral antenna.

Beam pattern measurements and analysis based on an antenna model of wire lasers

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Because of the subwavelength dimension of the cross section of our metal-metal waveguides at THz frequencies, a large fraction of the mode propagate outside of the lasing gain medium. As a result, the measured far-field beam pattern is quite different from what would be expected based on the field at the aperture. The results from two lasers with different lengths are shown in Fig. 12. They both show ring-like interference patterns along the laser axis with the longer laser showing a denser...
interference fringes. This result was somewhat surprising as we initially expected an end-fire type of beam pattern from an aperture with subwavelength dimensions.

As it turns out, because of the large fraction of mode propagating outside of the laser ridge, conventional diffraction theory based on Huygens' principle is no longer valid if one only considers the field at the aperture as the source. All the field inside and outside of the laser ridge must be taken into account in calculating the far-field pattern of the laser beam. Essentially, now the laser ridge acts as a continuously distributed phased antenna array. As a result, the length of the laser ridge, as well as the cross section dimensions, plays a major role in the laser beam pattern, as shown in Fig. 12. This unexpected result has some important consequences. For example, the angle of the main lobe scales with $1/L^{1/2}$, where $L$ is the length of the laser structure. As a result, the laser beam can be "focused" much tighter than predicted from conventional diffraction theory, if a long laser device is used.

![Figure 12. Set-up for laser beam pattern measurements. Right: Measured laser beam patterns and calculated results based on an antenna model.](image)
Real-time terahertz imaging using a microbolometer focal-plane array camera

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Imaging using radiation in the terahertz frequency range, 0.3 THz to 10 THz, has demonstrated the ability to see the details within visibly opaque objects such as: integrated circuits packages, leaves, teeth, thin tissue samples, and illicit drugs in envelopes. The vast majority of THz imaging has been done by linearly scanning an object through a tightly focused THz beam – a practice which limits the acquisition time to the mechanical scan rate of the system. With upper limits of 100’s of pixels/second for mechanical scanning, a complete image takes minutes to acquire.

Real-time imaging (30 frames per second or more) has previously been demonstrated by using an electro-optic crystal for frequency upconversion so that THz images can be viewed with a CCD focal-plane camera. However, this setup requires precise timing of the optical and THz pulses, necessitating a scanning delay mechanism, adding to its complexity. Furthermore, because of the short THz pulses (<1 ps), this scheme is inherently broadband (>1 THz). In applications such as the drug detection scheme, where detection of narrow-band fingerprint is required, a coherent narrow-band illumination source is crucial. Because of their compact sizes, many THz quantum-cascade lasers with different frequencies, corresponding to different chemical absorption bands, can be packaged tightly, forming a frequency agile coherent radiation source. In combination with a focal-plane imager, such a system can perform frequency-sensitive THz imaging at a rate far greater than the previous methods, allowing real-time THz monitoring and screening.

In this work, real-time, continuous wave (CW) terahertz imaging is demonstrated for the first time using THz QCLs and a focal-plane array camera. The experimental arrangement is shown in Fig. 13. The terahertz QCL is cooled by a cryogen-free pulsed-tube thermomechanical cooler, produces ~50 mW of power at ~30 K. As shown in the figure, imaging experiments in both transmission and reflection mode can be performed. Since the microbolometer camera was initially designed for the 10-µm wavelength range for night-vision applications, we developed a differential scheme to subtract the strong ambient background at ~300 K and reduce 1/f noise.
Figure 13. Experimental setup of the THz imaging system. The photo shows a vanadium oxide microbolometer (Courtesy of BAE Systems, Lexington, MA). Cutaway depicts alternate reflection mode setup.

Fig. 14. Pencil letters written on the inside of a paper security envelope at visible frequencies (a), in THz transmission mode (b, 1 frame, 1/20 second) and THz reflection mode (c, 20 frames, 1 second). Visible frequency thumb print (d), and THz reflection mode image the thumb of the leading author (e, 20 frames).
An example of the real-time imaging experiment is shown in Fig. 14, in which several hand-written characters inside a regular mail envelope are clearly visible in THz imaging, in both transmission and reflection mode. It should be pointed out that this particular imaging application cannot be done at other frequencies: x-rays lack contrast; millimeter-waves do not provide sufficient spatial resolution; and infrared radiation is heavily scattered and/or absorbed by fibrous materials. While these still images are recognizable, when they are viewed in real-time the integration of the eye and pattern recognition of the brain aid tremendously as seen in real-time video. With additional QCL’s the system will allow analytic, real-time multi-frequency imaging.

Recently, we demonstrated the use of a terahertz (THz) quantum cascade laser (QCL) for real-time imaging in transmission mode at a standoff distance of 25 meters. The lasing frequency was selected for optimum transmission within an atmospheric window at ~4.9 THz. Coarse frequency selection was made by design of the QCL gain medium. Finer selection (to within 0.1 THz) was made by judicious choice of laser cavity length to adjust the facet loss and therefore the lasing threshold bias, in order to overlap the peak frequency of the Stark-shifted gain spectrum with the atmospheric window. Because of distinctive THz spectral “fingerprints” found in many chemical compounds, THz sensing and imaging could have important military and security applications. For these applications, imaging at a standoff distance (~10-25 meters) is essential. However, water vapor strongly absorbs radiation at THz frequencies, which results in heavy atmospheric attenuation, >10 dB/m, outside of isolated low-loss transmission windows, which are only a few hundred GHz wide. These narrow transmission bands favor the use of narrowband sources. Far-infrared gas lasers are bulky and power hungry, and they have only limited selection of lasing frequencies. Schottky-diode frequency multipliers can only produce sub-milliwatt power levels at f > 1 THz, and are not suitable for illuminating focal-plane arrays for real-time imaging. By comparison, THz QCLs have demonstrated peak power levels of ~250 mW in pulsed and ~130 mW in CW operations. Their intersubband-transition nature implies that any desired frequency can be achieved by bandgap and waveguide engineering over a continuous frequency range from 1.59 to 5 THz, over which these lasers have been demonstrated. In this work, we demonstrate the use of a frequency optimized THz QCL for real-time imaging in transmission mode over a standoff distance of 25.8 meters.

The experimental set-up for long-range imaging is shown in Fig. 15. The emitted light was collected and collimated by an f/1 off-axis parabolic mirror with a 5-cm diameter. In configuration (1), an f/3, high-resistivity Si lens was used to focus the light transmitted through an object placed at 2 meters in front of the spherical mirror, onto a 320×240 microbolometer focal plane array (optical NEP ~ 320 pW/√Hz at 4.3 THz). Note that in the object plane, which is ~23-meters from the laser source, the beam pattern is highly symmetric as measured by the focal-plane array camera with 1-second integration time. In configuration (2), the reflected beam from the spherical mirror was further focused by an f/2 off-axis parabolic mirror and was used to back illuminate a smaller object. Transmitted light was collected and focused by an f/1 high-resistivity Si lens onto the focal plane array.

The resulting images are shown in Fig. 16. A dried seed pod is used as the see-through object to simulate foliage penetration (FOPEN). In part (a) a white light image of the dried seed pod is shown, with the corresponding THz transmission images shown in parts (b) and (c) for configurations (1) and (2) respectively. After transmission over the 25.75-m path, the resulting focal-plane average SNR was ~2.5 and 10, for a single-frame and a 20-frame average (0.05 and 1 second of integration, respectively) respectively. The 20-frame average images shown in (b) and (c) were normalized to the beam pattern and were spatially low-pass filtered to smooth out isolated pixels with low SNR. This post detection signal processing is performed in real time, and only adds a ~5-ms delay in displaying the images. The image in part (b) has low spatial resolution due to the 2-meter distance from the spherical mirror. Part (c) shows a much higher spatial resolution, due to the closer positioning of the object to the camera. As a result, the fine ridges of the seed pod (~millimeter spacing) can be resolved, as predicted by the ray tracing resolution of ~0.75 mm.
Fig. 15. Experimental setup for imaging over a distance of 25.75 meters. A QCL device is mounted in a pulse-tube cryocooler, with emitted beam collimated by an off-axis paraboloid mirror, for transmission over a 24.5-m path before collection by a 15-cm diameter spherical mirror. In configuration (1), an object is placed 2 meters before a spherical mirror; in configuration (2), an object is placed after a second off-axis paraboloid mirror. Also shown is the beam pattern for configuration (1), measured at ~23 meters from the laser source and taken with a 320×240 element focal-plane array camera with 1-second integration.

Fig. 16. Sample images of a dried seed pod: (a) image at visible frequency; (b) terahertz image taken with configuration (1); (c) terahertz image taken with configuration (2). Both (b) and (c) are taken with 1-second integration (average of 20 frames).
Surface-emitting THz quantum-cascade lasers using 2nd-order DFB gratings

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The metal-metal waveguides, shown in Fig. 4, have several important advantages at THz frequencies in terms of high mode confinement factor and low cavity losses. However, because of the small dimensions of the facet (~10 µm) compared to the wavelength (~100 µm), the beam pattern for edge-emitting ridge lasers are quite divergent. As a result, the facet reflection is quite high (>80% at frequencies below 3 THz), which results in a low output power level. Both features are drawbacks of the metal-metal waveguide lasers for high-power applications with good beam patterns. The surface-plasmon on semi-insulating substrate waveguides produce higher output power levels and better beam patterns because of their looser mode confinement. However, their waveguide losses are much higher, likely due to dopant absorption (both inter-impurity transitions and donor ionization frequencies are in THz) in the nominally semi-insulating substrate where a large fraction of the mode (1-Γ) resides. As a result, the thresholds are higher and the maximum operating temperatures are far lower than those of metal-metal waveguide lasers. In our recently developed high-power THz QCLs based on surface-plasmon on semi-insulating substrates, even though the pulsed power levels are as high as ~250 mW and CW as high as ~135 mW at ~10 K, the maximum CW operating temperature is below 40 K.

It will be highly desirable to develop waveguide structures that preserve the advantage of tight mode confinement in the metal-metal waveguides, but produce higher output power levels and better beam patterns. The best solution is to use second-order distributed feedback (DFB) gratings to construct surface-emitting lasers. The schematic of which is shown in Fig. 17. Since the selection rule of intersubband transition dictates that the generated electric field is normal to the quantum-well planes (the y-direction in Fig. 17), the waves will propagate along the z-direction for unpatterned surface, resulting in an edge-emitting laser structure. With patterned metallic grating structures, the electric field lines will "bend" and have components in the z-direction, allowing surface emission in the y-direction, as illustrated in Fig. 17. The lower left panel of Fig. 17 shows that the lasing frequency can be chosen by the grating period Λ. For the second-order DFB lasing condition $\Lambda = \lambda_s$ (the wavelength in the semiconductor), the field at all apertures are in phase, resulting in a surface emission at the normal angle. It is clear that the diffraction limit for the surface-emitting structures is no longer determined by the facet dimensions, rather, it is determined by the surface dimensions which can be made much greater than the wavelengths. As a result, much narrower and symmetric beam patterns can be generated, as illustrated in the right panel in Fig. 17. Furthermore, now the coupling coefficient (output power/power inside the cavity) can be easily controlled by the filling factor of the apertures, we can couple more power out at a modest cost of slightly higher lasing thresholds. Last but not least, this structure is a DFB in nature, allowing a robust single-mode operation.
After an extensive effort, we have developed a fabrication process so that we can coat all the sidewalls with dielectrics and metals which prevent higher-order lateral modes from lasing. SEM pictures of several devices are shown in Fig. 18, with both the extra facet lengths and central phase shift highlighted. The former helps to maintain a robust single-mode operation and the latter for a single-lobe far-field beam pattern.
The measurement results are summarized in Fig. 19. As can be seen, the grating-coupled surface-emitting THz QC lasers yield robust single-mode operations over a frequency range >0.3 THz. The maximum operating temperature of grating-coupled laser devices are only marginally lower than their Fabry-Perot counterparts. The beam patterns are more convergent and with a single central lobe. The power level, at ~6 mW, is more than a factor of two higher than that measured from Fabry-Perot lasers with comparable areas. This work has clearly demonstrated viability of surface-emitting scheme in terms of greater power levels, better beam patterns, and single-mode operations.
Efficient mid-wave infrared lasers (EMIL)

Sponsors
Defense Advanced Research Project Agency
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Project Staff
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The original invention of quantum-cascade lasers in 1994 opened up a broad electromagnetic spectrum where solid-state laser sources was underdeveloped. A slightly over a decade later, QCLs are now developed over two decades of frequency range from THz to infrared. There are many potentially important applications in this broad frequency range. One of them is infrared counter measures (IRCM) to protect airplanes from heat-seeking missiles in the atmospheric window of 3-5 µm wavelength. Under the sponsorship of DARPA, along with Dr. Turner's group at MIT Lincoln laboratory, we have started this project recently. The goal is to develop mid-infrared quantum-cascade lasers with high wall-plug power efficiency of 50% at room temperature in the CW mode. Those lasers will produce more than 1-W output power and with diffraction-limited beam patterns. Such high-efficiency and high-power solid-state diode lasers could find immediate applications in IRCM. In combination with external gratings and packaging systems that are well developed in the telecom industry, those lasers could enable compact and broadly tunable laser systems. Such a system will be quite useful in biochemical sensing for both military/security and medical/environmental applications.

Our team has unique advantages in pursuing this challenging, but highly rewarding project. The MIT group has more than a decade of experience in the development of quantum-cascade lasers. Many numerical simulation codes, such as the Monte Carlo code, can be easily modified for the infrared quantum-cascade lasers. Such a numerical code will allow us to explore many new and different designs before going through the full process of growth and fabrication. The Lincoln lab group has many years of experience in working on high-power infrared lasers (Sb-based), and it has close interaction with the Airforce end users of IRCM.

In order to achieve the objective of high wall-plug efficiency. We will pursue several aspects.

- Developing robust quantum-cascade gain medium with high voltage efficiencies.
- Reducing waveguide loss to improve external power extraction efficiency.
- Fabricating narrow (~2 µm) laser ridges using ICP, incorporating InP regrowth and Au electroplating to improve heat removal for robust CW operations.
- Beam combining using external gratings to achieve high-power and broadband output.
In Fig. 20, we illustrate the band diagram and wavefunctions of a 4.7-µm QC laser based on the so-called bound-to-continuum design. Fig. 20 also illustrates the mode profile of a 2-µm-wide laser ridge with InP regrown cladding layer and top Au layer.

**Figure 20.** Left: Band diagram and wavefunctions of a bound-to-continuum quantum-cascade laser at 4.7 µm wavelength. Right: Mode profile of a narrow (2 µm) laser ridge with regrown InP cladding layer and top Au layer.

**Patent applications, Publications, and Conference Presentations**


Chapter 29. Terahertz and Infrared Quantum Cascade Lasers, and Real-time Imaging


Chapter 29. Terahertz and Infrared Quantum Cascade Lasers, and Real-time Imaging


27. Q. Hu, "Terahertz quantum cascade lasers and real-time T-rays imaging," Electrical and Computer Engineering seminar, University of Wisconsin, Madison, April 23 (2007). (Invited)


30. Sushil Kumar, Qi Qin, Benjamin S. Williams, Qing Hu, Zbig R. Wasilewski, Xiaohua Wu, Hui C. Liu, "Quantum-Cascade Lasers with One-Well Injector Operating at 1.59 THz (λ = 188.5 μm)," CLEO/QELS 2007, Baltimore, Maryland, May 9 (2007).


Chapter 29. Terahertz and Infrared Quantum Cascade Lasers, and Real-time Imaging

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Theses
Ph.D. thesis