Terahertz Quantum-Cascade Laser Operating Up to 137K

by J. L. Reno

Motivation—Terahertz (1-10 THz, or 4-40 meV, or 30-300 μm) frequencies are among the most underdeveloped electromagnetic spectra, even though their potential applications are promising for spectroscopy in chemistry and biology, detection of trace gas for military and security applications, astrophysics, plasma diagnostics and end-point detection in dry etching processes, remote atmospheric sensing and monitoring, imaging, noninvasive inspection of semiconductor wafers, high-bandwidth free-space communications, and ultrahigh-speed signal processing. This underdevelopment is primarily due to the lack of coherent solid-state THz sources that can provide high radiation intensities (greater than one mW) and continuous-wave (CW) operation.

Semiconductor quantum wells are human-made quantum-mechanical systems in which the energy levels can be designed and engineered to be 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 (Kazarinov & Suris 1971). However, because of the great challenge in epitaxial material growth and the unfavorable fast nonradiative relaxation rate, it took more than two decades to realize this proposal experimentally. Electrically pumped unipolar intersubband-transition lasers (also called quantum-cascade lasers (QCL)) at ~ 4-μm wavelength were first developed at Bell Laboratories in 1994 (Faist *et al.* 1994). Since then, the frequency characteristics have been extended from mid-infrared frequencies to the terahertz range.

Accomplishment—In collaboration with the group at MIT lead by Qing Hu, we have pursued a unique approach to achieve lasing in QCLs at THz frequencies. We have investigated the possibility of using fast LO-phonon scattering to depopulate the lower radiative level (Xu et al. 1997, Williams *et al*. 1999), and using double-sided metal waveguides for THz mode confinement (Xu 1998). These efforts are bearing fruit. The calculated band structure of one such device is shown in Fig. 1a. This structure lased at about 3.8THz. One-dimensional mode profiles were calculated for both the earlier semi-insulating (SI)-surface-plasmon waveguide and the new metal-metal waveguide. The results shown in Fig. 1b-c clearly demonstrate the improved confinement that has been achieved using the metal-metal waveguide. This structure was grown by molecular beam epitaxy on a semi-insulating GaAs substrate with 178 cascaded modules. When the device was fabricated into a ridge structure with the metal-metal waveguide it lased in a pulsed mode up to 137K. Pulsed spectra taken over a range of temperatures are shown in Fig. 2.

Significance—To use QCLs as a compact, coherent THz source in applications, the operating temperature must be raised and cw operation improved. We have significantly extended the temperature range for lasing in resonant phonon terahertz QCLs by improving device design and reducing waveguide losses. Improved design of the injector region, along with improvements in metallic wafer bonding and heat sinking will allow for robust cw operation.

Sponsors for various phases of this work include: Nuclear Weapons/Science & Technology
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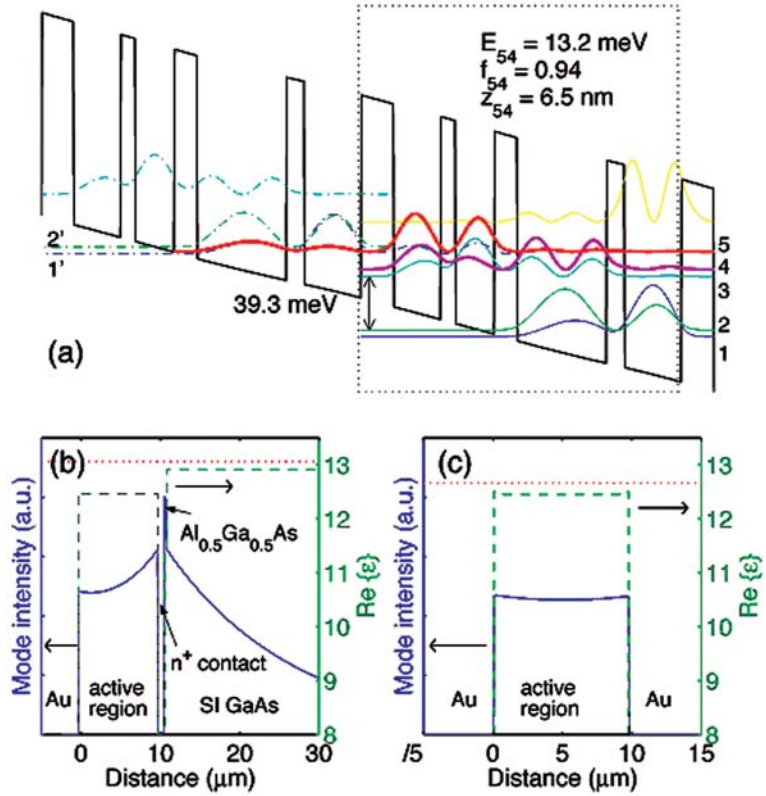

Figure 1. (a) Calculated conduction band profile for the QCL. The lasing transition is from the n = 5 state to the n = 4 state. Also shown are the mode profiles (solid lines) and the real part of the dielectric constant e(w) (dashed lines) for (b) SI-surface-plasmon and (c) metal-metal waveguides.

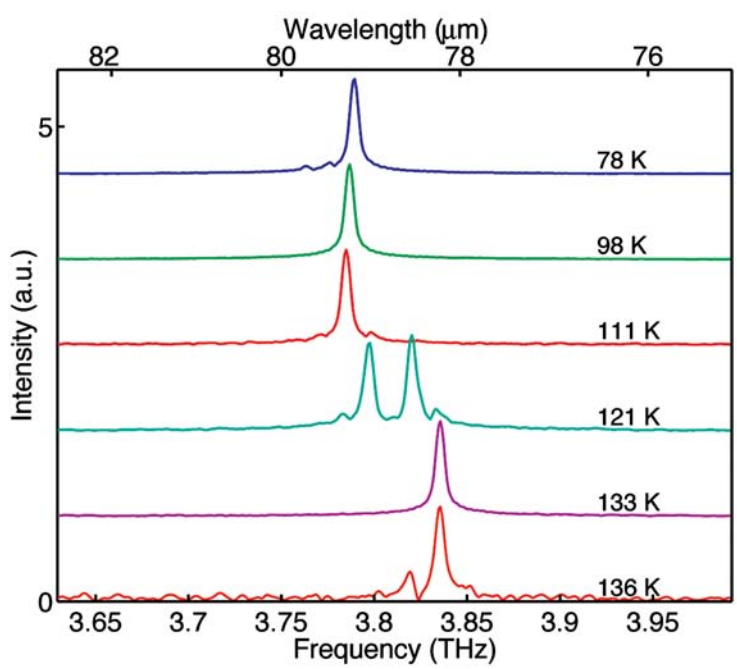

Figure 2. Laser emission spectra taken during pulsed operation at various heat sink temperatures. The linewidth is limited by the spectrometer resolution.