Linewidth and tuning characteristics of terahertz quantum cascade lasers

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Received October 8, 2003

We have measured the spectral linewidths of three continuous-wave quantum cascade lasers operating at terahertz frequencies by heterodyning the free-running quantum cascade laser with two far-infrared gas lasers. Beat notes are detected with a GaAs diode mixer and a microwave spectrum analyzer, permitting very precise frequency measurements and giving instantaneous linewidths of less than ~30 kHz. Characteristics are also reported for frequency tuning as the injection current is varied.

OCIS codes: 140.3070, 140.3600, 300.3700.

The recent development of quantum cascade lasers (QCLs) operating at far-infrared wavelengths has generated a great deal of interest.[1,2] These QCLs offer an entirely new option for narrowband sources at terahertz (THz) frequencies and have many of the advantages of more traditional mid-infrared QCLs,[3] including milliwatts of average power, narrow bandwidth, and some limited tunability in an extremely compact and potentially inexpensive package. Because of the flexibility in the molecular beam epitaxial growth of the heterostructures, it is also possible to fabricate devices for lasing action over a broad frequency range, to wavelengths beyond 100 μm.[4] As a result, THz QCLs offer great promise for use in a diverse range of applications such as absorption spectroscopy,[5,6] heterodyne spectroscopy in which a narrowband local oscillator (LO) is required,[7] and THz imaging.[8] However, to begin to exploit many of these applications, a good understanding of the performance characteristics of the devices is required.

Here we report what is to our knowledge the first high-resolution study of the linewidth and tuning characteristics of THz QCLs. Several authors have reported linewidth measurements of mid-infrared QCLs,[5,6,9–15] with wavelengths ranging from 5 to 24 μm. The reported values range from several tens of megahertz down to just a few hertz, depending on the measurement technique used and on the steps taken to stabilize the QCL. In this work we are interested in the intrinsic linewidth of THz QCLs, and so we have not used any extracavity stabilization methods.

The THz QCLs used in our study are described in detail elsewhere.[2,16] Two QCLs, nominally operating at 4.66 THz, produce ~400 μW of output power in continuous-wave operation at a temperature of 10 K. One device is 100 μm wide, and the other is 200 μm wide; both are 1.85 mm long and have a high-reflection coating on their back facet. The threshold current is approximately 500 mA, and the current at peak laser power is approximately 800 mA. A third QCL operating at 3.69 THz, with similar characteristics,[17] was also investigated. In our data only one laser mode is observed, consistent with previously published low-resolution Fourier-transform infrared spectra.[16] Higher-order modes have been reported for many QCLs,[2] but preliminary studies of the threshold current for our QCLs indicate that only the fundamental mode has sufficient gain for lasing.

A schematic representation of the experiment is shown in Fig. 1. We note that measurements in this part of the electromagnetic spectrum are often hindered by difficulties in generating, manipulating, and detecting the radiation. One common approach[7] is to use heterodyne techniques to convert the high-frequency radiation under study to a more convenient intermediate frequency by mixing with a LO of known frequency. In the THz range few LO sources are readily available, so our measurements require a slightly more complex approach. Two far-infrared gas lasers (Coherent DEOS SIFIR) are used for LOs, one lasing on the 3.1059368-THz line of CH_3OH (Ref. 18) and the other on the 1.5626559-THz line of CH_2F_2.[19] Using wire-grid polarizers as partially transmitting mirrors, the two gas lasers are coupled into a GaAs monolithic membrane–diode mixer[20] that was designed for high-frequency and LO inputs from 1.5 to 4 THz and intermediate-frequency outputs from 1 to 20 GHz. The QCL is mounted on a liquid-helium-cooled cold finger in a vacuum cryostat. The

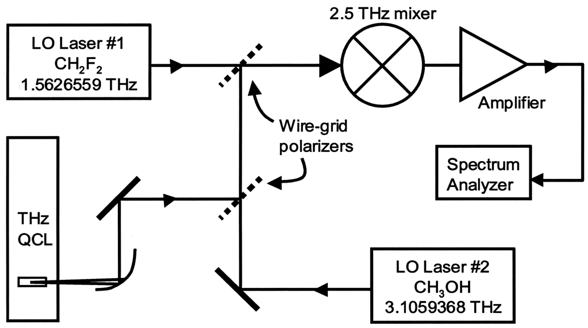

Fig. 1. Diagram of the experimental setup, showing the two independent LOs, whose sum frequency is close to that of the QCL.

highly divergent beam from the QCL passes through a thin polyethylene window on the cryostat and is collimated using a parabolic mirror. This radiation is also coupled into the mixer and beats with the sum frequency ($\nu_{\mathrm{sum}} = 4.6685927$ THz) from the two LO lasers. The difference frequency $|\nu_{\mathrm{QCL}} - \nu_{\mathrm{sum}}|$ is less than 20 GHz, which is within the bandwidth of standard microwave electronics.

For a given value of injection current and device temperature, we record a fast scan of the beat note at the highest possible resolution bandwidth, generally 30 kHz. A typical beat note is shown in Fig. 2. To determine the linewidth at a given current and temperature, we repeat the measurement eight times and average the results. The QCLs have linewidths of $\Delta\nu_L = 32$ kHz $\pm$ 16 kHz for the 200-μm-wide device and $\Delta\nu_L = 28$ kHz $\pm$ 12 kHz for the 100-μm-wide device; this does not vary significantly over the current range in our data (which, however, does not extend close to the threshold currents of the QCLs). Data were also acquired during 30-s intervals by use of the maximum-hold feature of the spectrum analyzer to determine the effective free-running linewidth in the absence of thermal or electrical stabilization. This result is shown in Fig. 3. As one would expect, a much broader line is observed because the narrow instantaneous laser line randomly fluctuates within a broader range. Expressing this ~21-MHz instability entirely in terms of temperature fluctuations as $(1/\lambda)(\delta\lambda/\delta T) \cong 2 \times 10^{-5}\ \mathrm{K}^{-1}$ (Ref. 16) we find an equivalent temperature fluctuation of ~0.2 K. It has been shown that with improved current and temperature stabilization these low-frequency fluctuations can be suppressed.[12]

In Fig. 4 the laser frequency, ν_L, is plotted as a function of current to illustrate the tuning capabilities of the QCL. As in the case of other semiconductor lasers, the tuning originates from changes in the refractive index of the gain region that are due to ohmic heating. The tuning rates of the two lasers are similar: -5 (-4) GHz/A for the 100- (200-) μm-wide device. These values are a factor of 10–20 less than the comparable figures for mid-infrared QCLs,[5] which is not unexpected given the factor-of-10–20 difference in wavelength. In addition, numerous other factors can play a role in this tuning rate.

We note that the measured linewidths are all comparable to the 30-kHz resolution bandwidth of the spectrum analyzer. Improving the resolution bandwidth requires longer scan times, which is problematic because of the low-frequency noise illustrated in Fig. 3.[13] Therefore, it is likely that these results represent only an upper limit to the intrinsic THz QCL linewidth. However, we can make a rough estimate of the Schawlow–Townes linewidth limit for these lasers. This intrinsic limit is given by[21]

$$\Delta\nu_L = \frac{N_2}{N_2 - N_1}\,\frac{2\pi h\nu_L(\Delta\nu_c)^2}{P},$$

where ν_L is the frequency of the laser (~4.66 THz), P is the laser power (~0.5 mW), $\Delta\nu_c$ is the inverse of

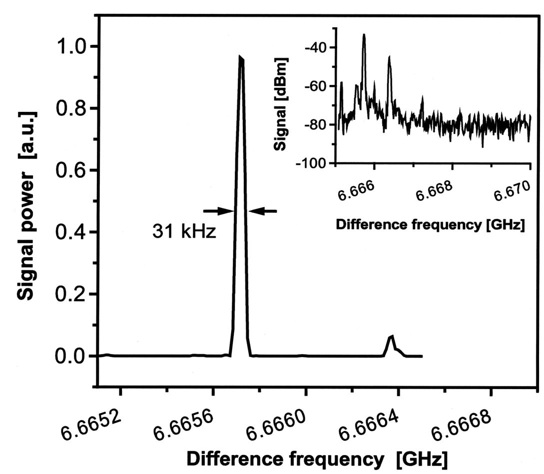

Fig. 2. Typical fast scan of the difference frequency (QCL frequency less 4.6685927 THz). The sweep time for this scan is 3 ms. Inset, the same beat note shown on a log scale. The smaller peaks on either side of the main peak are attributed to instrumentation noise, as in Ref. 13.

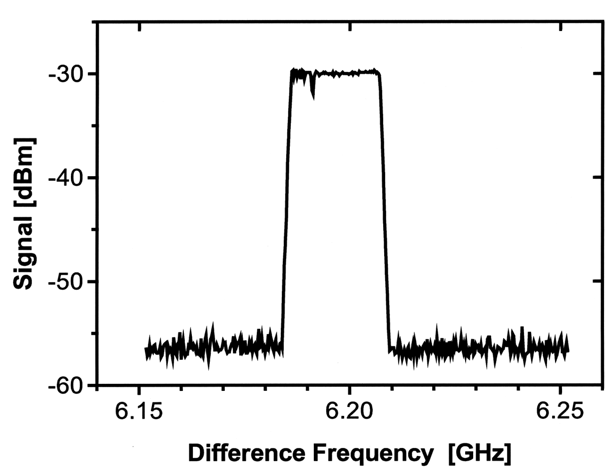

Fig. 3. Measurement of the QCL beat note with the maximum-hold feature of the spectrum analyzer, with a 30-s acquisition time. The 3-dB width of this line is ~21 MHz. This illustrates the broadening due to electrical, thermal, and acoustic noise for this unstabilized QCL.

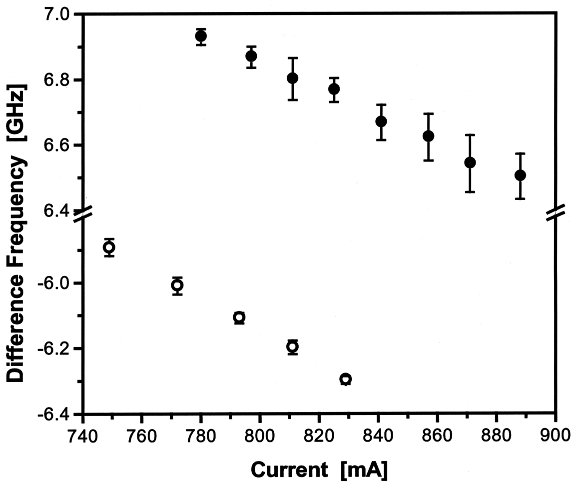

Fig. 4. Tuning of the laser frequency as a function of current for two THz QCLs, both nominally operating at 4.66 THz. The vertical axis shows the difference frequency $\nu_{\mathrm{QCL}} - \nu_{\mathrm{sum}}$. Open (filled) circles are for the 100- (200-) -μm-wide laser. The error bars are not due to uncertainty in the measurement but instead indicate the noise broadening illustrated in Fig. 3.

the cavity lifetime, and N_1 and N_2 are the ground- and the excited-state population factor, respectively. We estimate that $\Delta\nu_c = \alpha c/2\pi n_{\mathrm{eff}}$ with $n_{\mathrm{eff}} \approx 3.7$, and $\alpha \approx 5.5\ \mathrm{cm}^{-1}$ for the mirror and waveguide losses.[2] Neglecting the population factor by setting $N_1 \approx 0$, we obtain $\Delta\nu_L \approx 2.5$ kHz, which is somewhat below our measured linewidths. However, it is known that N_1 cannot generally be neglected,[2] and accurate estimates of these population factors are difficult to obtain. Further measurements might provide new insight into the population dynamics of these lasers.

Measurements on a third QCL at 3.69 THz were carried out in the same setup, using only one LO. In this case the mixer generates the second harmonic of the 1.8388394-THz line of CH_3OH (3.6776788 THz),[18] and this beats with the QCL radiation. The measured linewidths for this laser are approximately 35 kHz, similar to those of the two 4.66-THz lasers.

In conclusion, we have used a highly efficient diode mixer to measure the upper limits of the linewidth of three THz quantum cascade lasers and found values somewhat larger than the Schawlow–Townes linewidth limit. Current tuning rates are determined by high-resolution measurement of the laser frequency. These results confirm the importance of THz QCLs as tunable narrowband sources for use in high-resolution spectroscopy.

This work was supported in part by the R. A. Welch Foundation, the European Commission (through a Framework V project WANTED), the Swiss National Science Foundation, the Engineering and Physical Sciences Research Council (UK), the Royal Society (A. G. Davies), and Toshiba Research, Ltd. (E. H. Linfield). The work at the Jet Propulsion Laboratory was supported by the NASA Office of Aerospace Technology through a contract with the California Institute of Technology. D. M. Mittleman's e-mail address is daniel@rice.edu.

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