Phase locking and spectral linewidth of a two-mode terahertz quantum cascade laser

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We have studied the phase locking and spectral linewidth of an ~2.7 THz quantum cascade laser by mixing its two lateral lasing modes. The beat signal at about 8 GHz is compared with a microwave reference by applying conventional phase lock loop circuitry with feedback to the laser bias current. Phase locking has been demonstrated, resulting in a narrow beat linewidth of less than 10 Hz. Under frequency stabilization we find that the terahertz line profile is essentially Lorentzian with a minimum linewidth of ~6.3 kHz. Power dependent measurements suggest that this linewidth does not approach the Schawlow-Townes limit. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2227624]

Significant progress has made terahertz quantum cascade lasers[1] (QCLs) promising coherent solid-state sources for various applications in spectroscopy, sensing, and imaging. As demonstrated at several frequencies, a terahertz QCL can be used as a local oscillator (LO) for a heterodyne receiver[2,3] which is a crucial instrument for astronomical and atmospheric high-resolution spectroscopy. For those applications a narrow emission linewidth (LW) from a QCL under frequency stabilization is essential. In the case of a heterodyne space interferometer,[4] phase locking to an external reference is also required.

Ideally, phase locking of the terahertz QCL would take place with respect to a harmonic of a microwave reference signal; however, it has not yet been demonstrated. Recent work has demonstrated frequency locking of a QCL to a far-infrared (FIR) gas laser line at 3.105 THz.[5] This same work demonstrated a lasing LW of 65 kHz, which could be maintained indefinitely as a result of the frequency stabilization. The LWs of QCLs that were reported earlier than Ref. 5 were unstabilized and could be measured only for a short sweep time of ~3 ms. They were measured using room-temperature Schottky diodes to mix signals from a terahertz QCL and a FIR gas laser,[6] two terahertz QCLs,[7] or two longitudinal emission modes of a single QCL.[3] A LW as small as 20 kHz was observed.[7] When averaged for a longer time period, however, the single LWs in those experiments could exceed 1 MHz due to fluctuations of temperature and bias current, which affect the refractive index of the laser gain medium. Here we report the demonstration of phase locking of the beat signal of a two lateral-mode terahertz QCL to a microwave reference. Additionally, under frequency stabilization conditions we are able to study the emission spectrum of the terahertz QCL as a function of the laser power, in order to investigate the nature of the limit to its LW.

We use a terahertz QCL based on the resonant phonon design[8] with an active region containing 176 $GaAs/Al_{0.15}Ga_{0.85}As$ quantum-well modules and having a total thickness of 10 μm. The cavity of the QCL is a double-sided metal waveguide, which is 40 μm wide and 1 mm long. In order to facilitate the experiment described in this letter, we specifically selected a laser with two closely spaced lasing modes. When operated in cw mode at a heat-sink temperature (T_{hs}) of below 15 K, the emission spectrum measured by a Fourier-transform spectrometer (FTS) shows two lines at 2.742 and 2.749 THz, respectively. They correspond to two different order lateral modes of the cavity that are lasing with unequal intensities, but with a total maximum lasing output power of roughly 1 mW/facet. Their intensities and frequencies depend on the bias current of the QCL and the T_{hs}. Frequency tuning via the current bias is expected to be almost completely due to thermal effects as a result of Ohmic heating since intersubband lasers are expected to have almost negligible LW enhancement factors.[9] Because both modes have large confinement factors with the active region (close to unity), they should largely experience the same thermal environment. However, each lateral mode has a slightly different modal overlap since higher-order modes will extend further into free space and will have lower effective refractive indices n_{eff}. As a result, n_{eff} of each mode will have a different dependence on the refractive index of the active region. Hence each mode will have a different temperature or current dependence, which means that the beat signal of the QCL will behave as a current controlled oscil-

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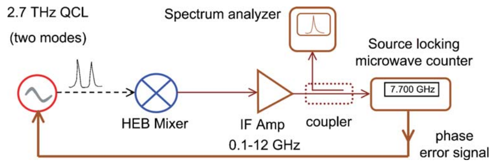

FIG. 1. (Color online) Schematic diagram of the experimental setup to phase lock the beat signal of a two-mode terahertz QCL. Not shown is that the spectrum analyzer is also phase locked to the same microwave reference signal as for the source-locking microwave counter.

lator. This is the basis of our frequency and phase locking using current feedback control.

To obtain the beat signal of the QCL, we use a spiral antenna coupled NbN hot electron bolometer (HEB) mixer, which is similar to those described in Ref. 10. It works at liquid helium (L-He) temperature and requires less than 300 nW LO power. Although the 3 dB intermediate frequency (IF) noise bandwidth of the mixer is only about 6 GHz, its sensitivity at the beat frequency (~8 GHz) of the present experiment is still much better than that of Schottky mixers.

Figure 1 shows a schematic diagram of our measurement setup. The QCL is mounted in a L-He flow cryostat, while the HEB mixer is mounted in a separate vacuum-cryostat. The output beam of the QCL is focused onto the quasioptically coupled HEB mixer. The IF (beat) output is first amplified by a 0.1–12 GHz cryogenic monolithic microwave integrated circuit (MMIC) IF amplifier, and then by a room temperature amplifier. Finally it is fed into an EIP 575 source-locking microwave counter. The phase error correction voltage of this counter is fed back into the dc bias-current circuit of the QCL through a variable feedback resistor (not shown). To monitor the IF spectrum, a fraction of the beat signal is coupled into a spectrum analyzer. Both spectrum analyzer and EIP 575 are phase locked to the same microwave frequency reference signal. The maximum loop bandwidth allowed by the EIP 575 counter is 10 kHz. This bandwidth can be reduced by adjusting the variable feedback resistor to decrease the phase locking loop (PLL) gain. The dc bias-current circuit of the QCL consists of a car battery (to reduce fluctuations) and a variable resistor to change the bias current. Typical operating conditions are a dc bias voltage of 12.9 V, a current of 0.28 A, and a T_{hs} of 7 K. The latter can be varied through a heater.

We create a phase lock condition by using the PLL with a high loop gain that gives the maximum regulation bandwidth of 10 kHz. The PLL, which is to reproduce the reference signal, rejects all amplitude modulation noise and all other noise that is separated sufficiently in frequency from the signal. It acts like a filter to track the reference signal frequency by suppressing phase noise within the bandwidth of the loop. Figure 2 shows a typical set of power spectra of the beat signal recorded by the spectrum analyzer using different resolution bandwidths (RBWs) and spans. Both the T_{hs} and the dc bias current are fixed. As indicated in the figure, the LW appears to decrease as the RBW of the spectrum analyzer is reduced. Apparently the LW is smaller than 10 Hz, which is the minimum RBW of the spectrum analyzer. The data demonstrate that for an offset from the center frequency less than the PLL regulation bandwidth most of the signal power is located in a central peak of narrow bandwidth. *This is a clear indication of phase locking*. The re-

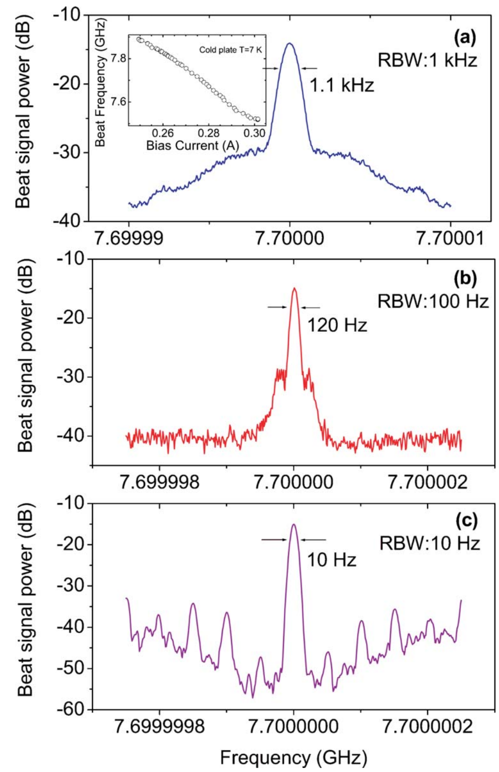

FIG. 2. (Color online) The power spectra of the beat signal of two lateral-mode terahertz QCL that is phase locked to a microwave reference recorded by the spectrum analyzer with different resolution bandwidths (RBWs) and spans, but a fixed video bandwidth (VBW) of 30 Hz. Other lines appeared in (c) are due to the pickup of 50 Hz power-line signals. The 3 dB linewidth of each spectrum is also indicated. The inset in (a) shows the beat frequency as a function of the bias current of the QCL at a heat-sink temperature of 7 K.

corded spectra resemble those found typically in a phase locked Josephson flux flow oscillator.[11] The spectra are reproducible and stable for an arbitrarily long time.

Experimentally, we can show that the beat signal behaves as a current controlled oscillator, which is the key to enable phase locking. As shown in the inset of Fig. 2, the beat frequency decreases monotonically with increasing bias current for a given T_{hs}, e.g., from 7.9 to 7.5 GHz with the rate of roughly 10 MHz/mA. This means that phase locking conditions can be realized for the entire bias range above the lasing threshold, and moreover that phase locking of the beat signal implies stabilization of the terahertz signals of both lasing modes.

The second part of our study involves the measurement of the laser line profile and LW under frequency stabilization only. Starting from phase locking conditions we now reduce the loop gain such that the central frequency of the beat remains stable but the line shape is no longer influenced by the phase locking.[11] This is essentially a frequency-locking scheme of the two lasing modes. Under this frequency stabilization, we are able to measure the power spectrum of the beat signal of the QCL in a controlled way (reproducible and stable for an arbitrarily long time), for example, as a function of the T_{hs}. Figure 3 shows a measured beat signal with the minimum LW observed in this experiment,[12] fitted with a Lorentzian curve. The fit shows the spectrum to be predominantly Lorentzian, as expected if the noise is due to spontaneous emission.[13] In some other cases, we find that a Voigt function gives a better fit than the Lorentzian, suggesting the coexistence of other noise sources, e.g., $1/f$ noise[14] and in-

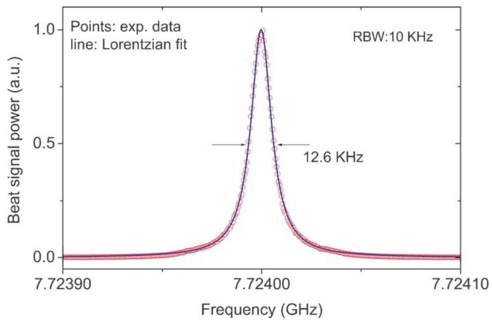

FIG. 3. (Color online) Measured power spectrum of the beat signal under frequency stabilization (data points) (Ref. 12). A similar spectrum was obtained with a reduced RBW. The curve is a fit with a Lorentzian profile.

terference from pickup noise. The minimum [Full width at half maximum (FWHM)] LW is found to be 12.6 kHz. Since this beat signal results from a convolution of two similar lines, the LW of *an individual emission line* should be 6.3 kHz if we assume that their profiles are both Lorentzian. This is the narrowest LW ever reported in terahertz QCLs and is much smaller than what is required for astronomical ($\leqslant 0.1$ MHz) and atmospheric ($\leqslant 1$ MHz) observations. It must be noted that this derivation of the LW for an individual mode is only correct in the absence of correlations between the frequency fluctuations of the two modes. This assumption is justified as the LWs observed without frequency stabilization are ~ 0.1 MHz for a sweep time of 1 s.

The LW of any lasers is limited by quantum noise through spontaneous emission and is expected to follow the Schawlow-Townes limit,[13]

$$\Delta\nu_{\mathrm{ST}} = \left(\frac{N_2}{N_2 - N_1}\right)\frac{\pi h\nu(\Delta\nu_c)^2}{P}. \quad (1)$$

Here $N_{1,2}$ are the populations in the upper and lower laser states, $\Delta\nu_c$ is the cold cavity LW that equals $\alpha v_g/2\pi$ with the group velocity v_g and the total loss α of the waveguide and mirror losses ($\alpha=\alpha_w+\alpha_m$), and P is the internal power in the mode relating to P_{out} by $P_{\mathrm{out}}=(\alpha_m/\alpha)P$. We assume Eq. (1) to be valid for each of the two emission lines. Using the following parameters: $N_2/(N_2-N_1)\sim 1.3$, $\alpha_w \sim 20\ \mathrm{cm}^{-1}$ at 2.7 THz, $\alpha_m=2.2\ \mathrm{cm}^{-1}$, and $P_{\mathrm{out}}\sim 1$ mW, we derive a Schawlow-Townes LW $\Delta\nu_{\mathrm{ST}}\approx 0.7$ KHz, which is approximately nine times smaller than the measured LW. In view of large uncertainties in the input parameters, this result alone is not conclusive.

Equation (1) suggests that the LW should be inversely proportional to the laser power. To test this, we have studied the LW of the beat signal as a function of T_{hs}, which influences the laser power at a fixed bias current. The results are shown in Fig. 4. We notice that despite the fact that the intensity (considered to be equivalent to the power) of both emission lines decreases monotonically (see the inset of Fig. 4), the LW remains essentially independent of T_{hs} up to 12 K (the internal lattice temperature is likely higher), beyond which a sharp increase is seen. Clearly the LW does not follow Eq. (1) in the operating range of high power (low device temperature), and consequently it does not approach the quantum-noise limit in that operating range.

In summary, we have succeeded in phase locking of two lateral modes of an $\sim$2.7 THz QCL, demonstrating the feasibility of phase locking of the terahertz laser to an external reference. Under frequency-stabilization conditions we have been able to study the intrinsic linewidth of the QCL in a controllable manner and found the narrowest linewidth of 6.3 kHz.

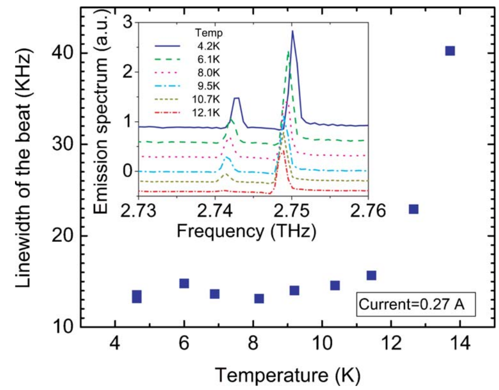

FIG. 4. (Color online) Linewidth of the beat signal as a function of the heat-sink temperature of the QCL. The inset shows emission spectra of the two-mode QCL taken at several temperatures. For clarity an offset in the intensity for each spectrum is introduced.

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[1] R. Köhler, A. Tredicucci, F. Beltram, H. E. Beere, E. H. Linfield, A. G. Davies, D. A. Ritchie, R. C. Iotti, and F. Rossi, Nature (London) **417**, 156 (2002).
[2] J. R. Gao, J. N. Hovenier, Z. Q. Yang, J. J. A. Baselmans, A. Baryshev, M. Hajenius, T. M. Klapwijk, A. J. L Adam, T. O. Klaassen, B. S. Williams, S. Kumar, Q. Hu, and J. L Reno, Appl. Phys. Lett. **86**, 244104 (2005).
[3] H.-W. Hübers, S. G. Pavlov, A. D. Semenov, R. Köhler, L. Mahler, A. Tredicucci, H. E. Beere, D. A. Ritchie, and E. H. Linfield, Opt. Express **13**, 5890 (2005).
[4] W. Wild, Th. de Graauw, A. Baryshev, J. Baselmans, J. R. Gao, F. Helmich, B. D. Jackson, V. P. Koshelets, P. Roelfsema, N. D. Whyborn, and P. Yagoubov, Proceedings of the 16th International Symposium on Space Terahertz Technology, Göteborg, Sweden, 2–4 May 2005, pp. 68–73.
[5] A. L. Betz, R. T. Boreiko, B. S. Williams, S. Kumar, and Q. Hu, Opt. Lett. **30**, 1837 (2005).
[6] A. Barkan, F. K. Tittel, D. M. Mittleman, R. Dengler, P. H. Siegel, G. Scalari, L. Ajili, J. Faist, H. E. Beere, E. H. Linfield, A. G. Davies, and D. A. Ritchie, Opt. Lett. **29**, 575 (2004).
[7] S. Barbieri, J. Alton, H. E. Beere, E. H. Linfield, D. A. Ritchie, S. Withington, G. Scalari, L. Ajili, and J. Faist, Opt. Lett. **29**, 1632 (2004).
[8] Q. Hu, B. S. Williams, S. Kumar, H. Callebaut, S. Kohen, and J. L. Reno, Semicond. Sci. Technol. **20**, S228 (2005).
[9] J. Kim, M. Lerttamrab, S. L. Chuang, C. Gmachl, D. L. Sivco, F. Capasso, and A. Y. Cho, IEEE J. Quantum Electron. **40**, 1663 (2004).
[10] J. J. A. Baselmans, M. Hajenius, J. R. Gao, T. M. Klapwijk, P. A. J. de Korte, B. Voronov, and G. Gol'tsman, Appl. Phys. Lett. **84**, 1958 (2004).
[11] V. P. Koshelets, S. V. Shitov, L. V. Filippenko, V. L. Vaks, J. Myginda, A. M. Baryshev, W. Luinge, and N. Whyborn, Rev. Sci. Instrum. **71**, 289 (2000).
[12] We notice that the beat frequency of this QCL has shown a downshift of about 0.6 GHz after the measurements in Fig. 2.
[13] A. Yariv, *Quantum Electronics*, 3rd ed. (Wiley, New York, 1989), p. 199.
[14] G. M. Stéphan, T. T. Tam, S. Blin, P. Besnard, and M. Têtu, Phys. Rev. A **71**, 043809 (2005).