Frequency and phase-lock control of a 3 THz quantum cascade laser

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We have locked the frequency of a 3 THz quantum cascade laser (QCL) to that of a far-infrared gas laser with a tunable microwave offset frequency. The locked QCL line shape is essentially Gaussian, with linewidths of 65 and 141 kHz at the −3 and −10 dB levels, respectively. The lock condition can be maintained indefinitely, without requiring temperature or bias current regulation of the QCL other than that provided by the lock error signal. The result demonstrates that a terahertz QCL can be frequency controlled with 1-part-in-10^8 accuracy, which is a factor of 100 better than that needed for a local oscillator in a heterodyne receiver for atmospheric and astronomic spectroscopy. © 2005 Optical Society of America

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Recently, quantum cascade lasers (QCLs) have been shown to be effective as local oscillators (LOs) at terahertz frequencies.[1] For most applications in astronomic and atmospheric spectroscopy, the LO should have a frequency accuracy better than 1 part in 10^6, so that Doppler motions can be measured with 1 km s^{-1} accuracy. Equally important is that the LO linewidth be correspondingly narrow, with low phase-noise sidebands. Fortunately, terahertz QCLs, like all intersubband lasers, are expected to have small or negligible linewidth enhancement factors and consequently to have inherent linewidths that approach the Schawlow–Townes limit. Nevertheless, environmental effects such as temperature and bias current also affect the QCL frequency, so phase-lock techniques will still be needed to control the QCL frequency and linewidth to submegahertz accuracy.

The first heterodyne measurements of the linewidth of a terahertz QCL were made by Barkan *et al.*,[2] who mixed signals from a 4.7 THz QCL and a far-infrared (FIR) gas laser to measure an instantaneous linewidth of 31 kHz for a 3 ms sweep time. Shortly thereafter, Barbieri *et al.*[3] reported a 20 kHz linewidth for a 3.6 ms averaging time for a 3.3 THz QCL. These QCLs were free running, with long-term averaged linewidths exceeding 10 MHz because of temperature drifts and fluctuations that affect the index of refraction of the gain medium. To control a QCL to 1-part-in-10^6 accuracy by using just temperature stabilization would require the temperature of the active region to be controllable within millikelvins. It is far easier to measure the frequency of the QCL relative to a stable reference source and to use the difference as an error signal for stabilization. Here we investigate the applicability of conventional phase-lock techniques for QCL stabilization by locking the QCL signal to that of a stable FIR gas laser with a microwave offset frequency that can be changed under computer control.

The QCL, with our designation FL178C-M6mm, has an active region that is 10 μm thick, 40 μm wide, and 0.73 mm long. This QCL has its lower level depopulated by resonant optical phonon scattering,[4] and mode confinement is achieved by a metal–semiconductor–metal waveguide.[5] The laser operates cw near 3.0 THz up to $T_{\mathrm{max}} = 75$ K and emits ~1 mW of power when it is cooled to $T_{\mathrm{coldplate}} = 10$ K. For this experiment we cooled the laser only to $T_{\mathrm{coldplate}} = 59$ K by pumping on a solid nitrogen cryogen. Bias current was supplied by an automobile battery connected to the QCL through a 9 Ω series resistor. Typical bias conditions were 10.43 V and 208 mA for 2.17 W dc power dissipation. No attempt was made to stabilize either the operating temperature or the bias current.

Figure 1 shows a schematic of the experimental apparatus. The outputs of the QCL and the FIR laser are combined by a wire grid polarizer and focused onto a room-temperature GaAs–Schottky-diode mixer in a corner reflector mount.[6] The FIR line is the 3105.9368 GHz transition of methanol.[7] Also incident on the mixer, through its coaxial intermediate-frequency (IF) port, is a 24.6 GHz signal that is produced by frequency doubling the output of a phase-locked YIG oscillator. The mixer generates a large number of sum- and difference-frequency terms from these inputs. The response of the diode is fast enough that sum-frequency terms exceeding 6 GHz are produced,[8,9] but for this experiment we are interested only in one fourth-order difference term that is the product of four ac electric fields:

$$P_{\mathrm{IF}} \propto E_{\mathrm{IF}}{}^2 \propto (E_{\mathrm{QCL}} E_{\mathrm{FIR}} E_{\mathrm{rf}} E_{\mathrm{rf}})^{1/2}. \quad (1)$$

The rf field appears twice in this relation because we are using the second-harmonic term at 49.2 GHz that is internally generated in the Schottky mixer. Simplistically, the second-order beat note $|f_{\mathrm{QCL}}-f_{\mathrm{FIR}}|$ at 48 GHz mixes with this second-order 49.2 GHz signal to produce a detectable IF output at 1.2 GHz. The IF signal is amplified, sampled by a spectrum analyzer, and directed to the EIP 575 source-locking counter. The EIP unit is programmed to phase lock the IF signal to 1200 MHz by sending an error signal to control the QCL bias current. The error voltage is linearly proportional to phase error between the signal inputs up to $+-\pi$ rad. For larger phase differences, the error voltage saturates at a ±dc value and thus provides only frequency control. The maximum loop bandwidth allowed by the EIP 575 counter is 10 kHz, which fortunately is adequate for a weak phase lock of the QCL, with occasional phase excursions exceeding $+-\pi$. The frequency of the locked QCL is 3057.9368 GHz, which is 48 GHz lower than the FIR laser line. This mixing scheme was chosen because of the availability of hardware. Ideally, we would have used only the $|f_{\mathrm{QCL}}-f_{\mathrm{FIR}}|$ term at 48 GHz. In an earlier experiment with a different QCL and the same FIR laser line, we were able to amplify this difference term at 3.5 GHz, with a signal-to-noise ratio of ~20 dB higher than that seen here.[10]

We measured the temperature tuning of this QCL to be -202.2 ± 1.4 MHz/K and the current tuning to be -45.2 ± 0.4 MHz/mA. In both cases the QCL tunes to a lower absolute frequency as either the cold plate temperature or the current is increased. The total tuning range in a single mode was observed to be 3 GHz, limited by the 15 K temperature range (52 to 67 K) available with our pumped solid-nitrogen Dewar.

The resonant frequency of the QCL's Fabry–Perot cavity is given by $\nu=mc/2n_{\mathrm{eff}}L$, where m is the longitudinal mode number, L is the length, and n_{eff} is the effective index of refraction. The spacing of longitudinal modes indicates that $n_{\mathrm{eff}}\approx3.8$. The index of refraction for bulk GaAs can be calculated for a specific frequency and temperature by use of the formula provided by Moore and Holm.[11] At $f=3.058$ THz and $T_{\mathrm{active}}=95$ K (justified below), $n_{\mathrm{bulk}}=3.596$. We can express the index as $n_{\mathrm{eff}}=n_{\mathrm{bulk}}+\Delta n$, where Δn is a device-dependent correction that accounts for free-carrier effects and for changes in the modal spectrum that are due to subwavelength confinement in metal–metal waveguides. However, we are interested primarily in temperature tuning and hence $\mathrm{d}n_{\mathrm{eff}}/\mathrm{d}T=\mathrm{d}n_{\mathrm{bulk}}/\mathrm{d}T+\mathrm{d}\Delta n/\mathrm{d}T$, where the latter factor should be relatively insignificant. We can then differentiate the resonance equation listed above and normalize to get the fractional change of frequency as a function of temperature:

$$1/\nu\,\mathrm{d}\nu/\mathrm{d}T=-\,(1/n\,\mathrm{d}n_{\mathrm{bulk}}/\mathrm{d}T+1/L\,\mathrm{d}L/\mathrm{d}T),\qquad(2)$$

where $\mathrm{d}n_{\mathrm{bulk}}/\mathrm{d}T$ is the temperature coefficient of the bulk index of refraction[11] and $\mathrm{d}L/\mathrm{d}T$ is the coefficient of thermal expansion.[12] For GaAs at $T_{\mathrm{active}}=95$ K,

$$1/n_{\mathrm{bulk}}\,\mathrm{d}n_{\mathrm{bulk}}/\mathrm{d}T=6.17\times10^{-5}/\mathrm{K},\qquad(3)$$

$$1/L\,\mathrm{d}L/\mathrm{d}T=0.16\times10^{-5}/\mathrm{K}.\qquad(4)$$

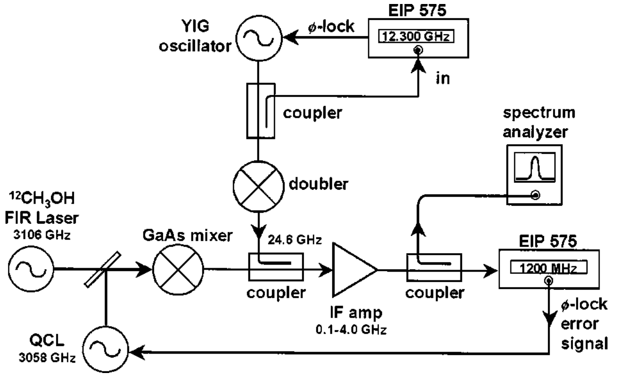

Fig. 1. Diagram of the experimental apparatus. The 24.6 GHz signal is injected into the coaxial IF port of the Schottky mixer by use of a directional coupler backward. Not shown are the dc bias circuits for the QCL and the GaAs mixer.

These coefficients are themselves temperature dependent but positive for $T>25$ K, so $1/\nu\ \mathrm{d}\nu/\mathrm{d}T$ is negative (i.e., ν decreases as T increases). From above we estimate that $1/\nu\,\mathrm{d}\nu/\mathrm{d}T=-6.33\times10^{-5}/\mathrm{K}$, which differs by only 4% from the measured value of $-6.61\times10^{-5}/\mathrm{K}$. Furthermore, if we interpret current tuning to be entirely a temperature-related effect, then at the bias point we have $\partial T_{\mathrm{active}}/\partial I=0.224$ K/mA. We can then calculate the thermal resistance as

$$R_{\mathrm{thermal}}=(\mathrm{d}P/\mathrm{d}T)^{-1}=[(I\partial V/\partial I+V)\partial I/\partial T]^{-1}$$
$$=16.4\ \mathrm{K/W},\qquad(5)$$

where we have substituted the following measured quantities: $I=208$ mA, $V=10.43$ V, $\partial V/\partial I=15.6\ \Omega$, and $\partial I/\partial T=4.47$ mA/K. This R_{thermal} is close to the R_{thermal} value estimated from the difference in threshold temperature between pulsed and cw operation.[13] From R_{thermal} and the total bias power of 2.17 W, we deduce that $\Delta T=(T_{\mathrm{active}}-T_{\mathrm{coldplate}})=35.6$ K. With $T_{\mathrm{coldplate}}=59.2$ K, we then get $T_{\mathrm{active}}=94.8$ K.

Figure 2(a) shows the phase-locked IF signal. The line shape is essentially Gaussian. Figure 2(b) provides an expanded view of line center, with a −3 dB width of 65 kHz and a −10 dB width of 141 kHz. For comparison, the −3 dB linewidths of the 12.3 GHz oscillator and the FIR laser are both <3 kHz. The spectrum of Fig. 2 can be maintained indefinitely if the FIR laser cavity is repeaked manually every 15 min.

In conclusion, we have demonstrated that a THz QCL can be controlled with conventional phase-lock techniques to have a long-term linewidth of 65 kHz and a frequency accuracy limited only by that of the reference oscillator. This stability is already more than adequate for LO applications in remote sensing. In the near future it should be possible to lock the QCL to a harmonic of a microwave source that is itself referenced to a GPS-disciplined crystal oscillator. Such an arrangement would allow the QCL fre-

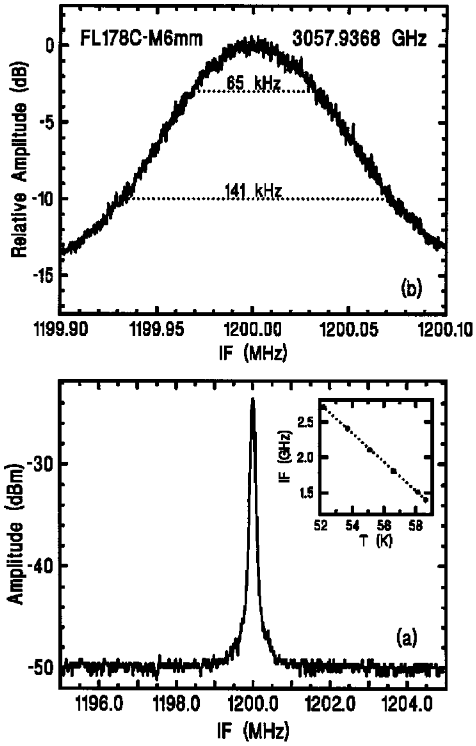

Fig. 2. IF signal at 1200 MHz under locked conditions: (a) The frequency resolution of the spectrum analyzer is 100 kHz. Inset, temperature tuning with the QCL unlocked at constant bias. Uncertainties are smaller than the data point sizes. (b) Magnified view at line center with a frequency resolution of 1 kHz and a scan time of 1 min.

quency to be controlled with 1-part-in-10^{11} absolute accuracy. We also should be able to extend the loop bandwidth to 1 MHz and thereby achieve additional narrowing of the QCL linewidth and perhaps approach the Schawlow–Townes linewidth of a few kilohertz.

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