Phase-locking and Linewidths of a Two-color THz Quantum Cascade Laser

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***Abstract*— We report the phase stabilization and spectral linewidth of a 2.7 THz quantum cascade laser by heterodyning its two nearby lateral mode lasing lines using a superconducting NbN bolometer mixer. The beat signal at about 8 GHz is compared with a microwave reference by applying a conventional phase lock loop circuitry with a feedback to the laser bias current. Phase locking has been for the first time demonstrated, resulting in an extremely narrow beat linewidth of less than 10 Hz (limited by the resolution bandwidth of the spectrum analyzer). Moreover, our result demonstrates the feasibility of phase-lock of the THz signal itself. Under frequency-stabilization conditions we are able to study the emission spectrum of a THz QCL in a systematic way, which previously was impossible. We find that the line profile is virtually Lorentzian with a long-term minimum linewidth of the THz modes of about 6.3 kHz. Temperature dependent measurements suggest that this linewidth does not approach the Schawlow-Townes limit.**

I. INTRODUCTION

Significant progress has made quantum cascade lasers1 (QCLs) promising coherent solid-state THz sources for various applications in spectroscopy, sensing, and imaging. As demonstrated at several frequencies, a THz 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 of 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 THz 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 [6]. This same work demonstrated a lasing linewidth of 65 kHz, which could be maintained indefinitely as a result of the frequency stabilization. The linewidths of QCLs that were reported earlier than ref. [6] could be measured only for a short sweep time of ~3 ms. They were measured using a room-temperature Schottky-diode to mix signals from a THz QCL and a FIR gas laser [7], two THz QCLs [8] or two longitudinal emission modes of a single QCL [3]. Linewidths as small as 20 kHz were observed [8]. When averaged for a longer time period however, the linewidths in those experiments could exceed 10 MHz due to fluctuations of temperature and bias current, which affect the refractive index of the laser gain medium.

Here we report the first demonstration of phase locking of the beat signal of a two lateral-mode THz QCL to a microwave reference. Under frequency stabilization conditions, we are able to study the emission spectrum of the THz QCL as a function of the laser power, in order to investigate the nature of the limit to its linewidth.

II. QCL DESIGN

We use a THz QCL based on the resonant phonon design [9] also shown in figure 1. The active region contains 176 GaAs/$Al_{0.15}Ga_{0.85}As$ quantum-well modules, with 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 article, we selected a laser with two closely spaced lasing modes. When operated in a CW mode at a heat-sink temperature of below 15 K, the emission spectrum measured by a Fourier-transform spectrometer (FTS) shows two lines at 2.742 THz 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 heat-sink temperature. Frequency tuning via the current bias is expected to be almost completely due to thermal effects as a result of ohmic heating. 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 η_{eff}. As a result, η_{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 is the basis why the beat of the QCL should behave as a current controlled oscillator.

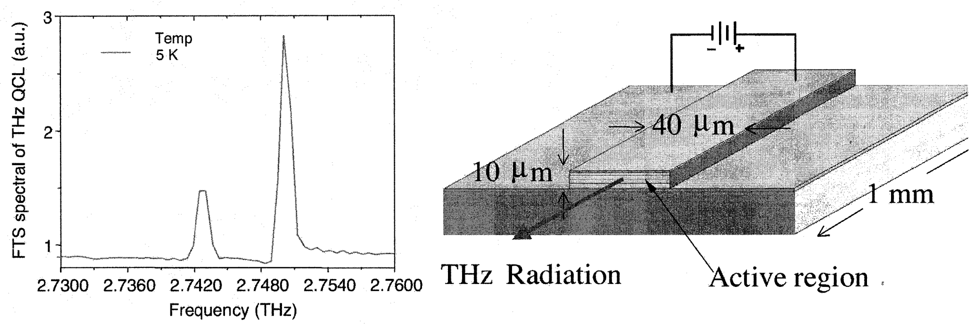

Fig. 1. FTS spectrum of two moded QCL (to the left) and layout of QCL chip (to the right).

III. EXPERIMENTAL SET-UP

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. [5]. 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 2 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 quasi-optically coupled HEB mixer. The IF (beat) output is first amplified by a cryogenic MMIC IF amplifier of 0.1-12 GHz, 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. 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

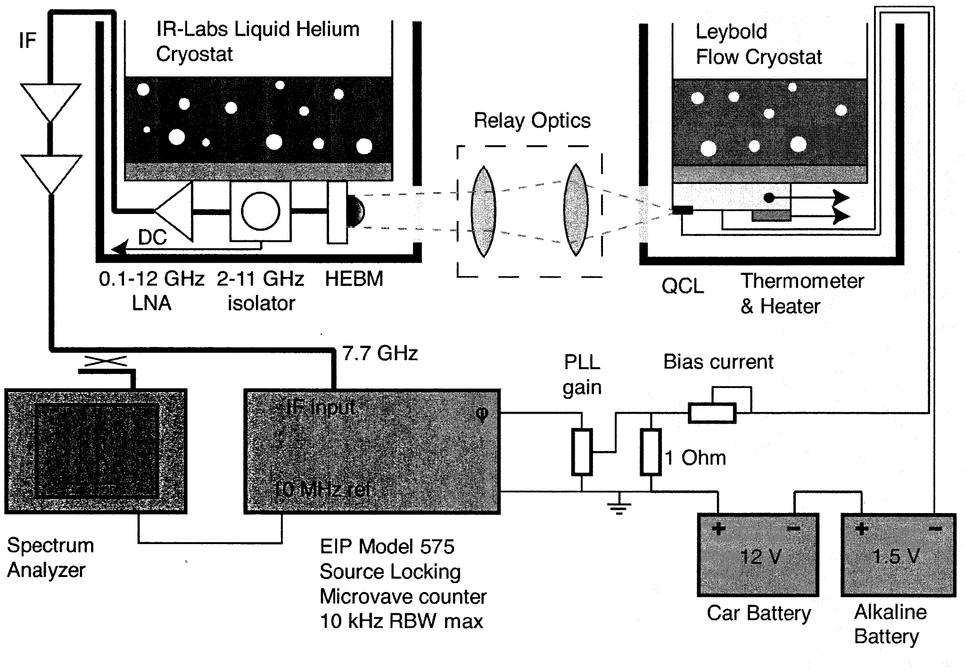

Fig. 2. Schematic diagram of the experimental setup to phase lock the beat signal of a two-mode THz QCL. Additional attenuators in the warm IF amplifier chain are not shown.

decreasing the phase locking loop (PLL) gain by adjusting the variable feedback resistor.

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: DC bias voltage of 12.9 V, a current of 0.28 A and a heat-sink temperature 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. Ideally, the spectrum of the beat signal will be the clean-up version of the reference spectrum.

IV. MEASUREMENT RESULTS AND DISCUSSION

Figure 3 shows a typical set of power spectra of the beat signal recorded by the spectrum analyzer using different resolution bandwidths (RBW) and spans. Both the temperature and the DC bias current are fixed. As indicated in the figure, the linewidth appears to decrease as the RBW of the spectrum analyzer is reduced. Apparently the linewidth is smaller than the instrumental RBW of 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 recorded spectra resemble very much those found typically in a phase-locked Josephson flux flow oscillator [10]. The spectra are reproducible and stable for an arbitrarily long time. Experimentally, we can show that the QCL behaves as a current controlled oscillator, which is the key to enable phase locking. As shown in the inset of figure 3, the beat frequency decreases monotonically with increasing bias current for a given heat-sink temperature, 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 stabilization of the beat frequency implies stabilization of the THz frequencies of both lasing modes. The second part of our study involves the measurement of the laser line profile and linewidth 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 [10]. 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), e.g. as a function of the heat-sink temperature. Figure 4 shows a measured beat signal with the minimum linewidth observed in this experiment [11], fitted with a Lorentzian curve. The fit shows the spectrum to be predominantly Lorentzian, as expected if the noise is due to spontaneous emission [12]. 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 [13] and interference from pick-up noise. The minimum (FWHM) linewidth is found to be 12.6 kHz. Since this beat signal results from a convolution of two similar lines and assuming that their profiles are both Lorentzian, the lower limit of the linewidth of an individual emission line should be 6.3 kHz. This is the narrowest linewidth ever reported in THz QCLs and is much smaller than what required for astronomical ($\leq$0.1 MHz) and atmospheric ($\leq$1 MHz) observations.

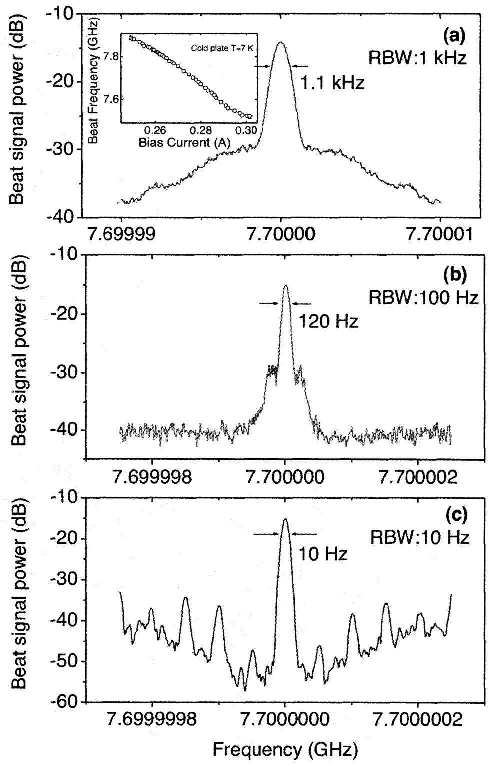

Fig. 3. The power spectra of the beat signal of two lateral-mode THz QCL that is phase locked to a microwave reference recorded by the spectrum analyser with different resolution bandwidths (RBW) and spans, but a fixed video bandwidth (VBW) of 30 Hz. Other lines appeared in (c) are due to the pick-up 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.

The linewidth of any lasers is limited by quantum noise through spontaneous emission. Since intersubband lasers are not expected to have significant linewidth enhancement factors [14], the linewidth in our case is expected to follow the Schawlow-Townes limit [12]

$$\Delta\nu_{ST} = \frac{N_2}{N_1 + N_2} \frac{\pi h\nu(\Delta\nu_c)^2}{P} \tag{1}$$

Here $N_{1,2}$ are the populations in the upper and lower

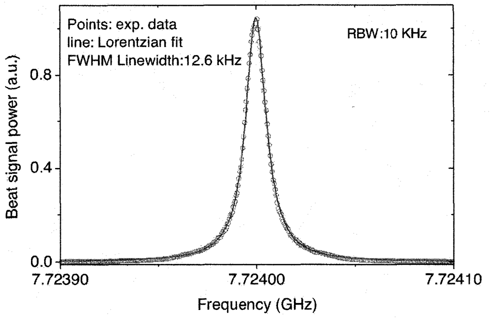

Fig. 4. Measured power spectrum of the beat signal under frequency stabilization (data points) [11]. A similar spectrum was obtained with a reduced resolution bandwidth (RBW). The curve is a fit with a Lorentzian profile.

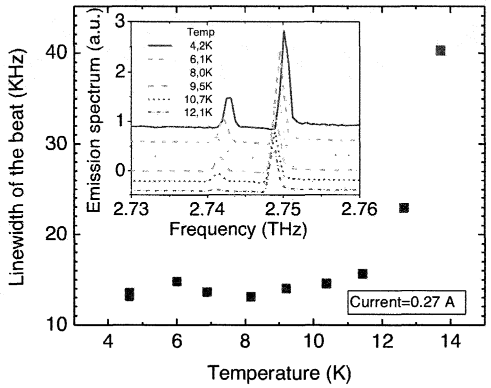

Fig. 5. Linewidth of the beat signal as a function of the heat-sink temperature of the QCL. The inset shows emission spectra of the two-mode QCL taken at several temperatures. For clarity an offset in the intensity for each spectrum is introduced.

laser states; $\Delta\nu_c$ is the cold cavity linewidth that equals $\alpha v_g/2\pi$ with the group velocity v_g and the total loss α of the waveguide and mirror losses $\alpha = \alpha_w + \alpha_m$; P is the internal power in the mode relating to P_{out} by $P_{out} = \alpha_m P/\alpha$. We assume Eq. 1 to be valid for each of the two emission lines. Using the following parameters: $N_2/(N_2 - N_1)$ ~1.3, α_w ~20 cm^{-1} at 2.7 THz, α_m =2.2 cm^{-1}, and P_{out} ~1 mW, we derive a Schawlow-Townes linewidth $\Delta\nu_{ST} = 0.7$ kHz, which is ~9 times smaller than the measured linewidth. In view of large uncertainties in the input parameters, this result alone is not conclusive.

Eq. 1 suggests that the linewidth should be inversely proportional to the laser power. To test this, we have studied the linewidth of the beat signal as a function of heat-sink temperature, which influences the laser power for a fixed bias current. The results are shown in figure 5. We notice that, despite that the intensity (considered to be equivalent to the power) of both emission lines decreases monotonically (see the inset of figure 5), the linewidth remains essentially independent of heat-sink temperature up to 12 K (the internal lattice temperature is likely higher), beyond which a sharp increase is seen. Clearly the linewidth 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.

V. CONCLUSION

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

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