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Citation: Ren, Y., D. J. Hayton, J. N. Hovenier, M. Cui, J. R. Gao, T. M. Klapwijk, S. C. Shi, T.-Y. Kao, Q. Hu, and J. L. Reno. "Stabilized HEB-QCL Heterodyne Spectrometer at Super-Terahertz." Edited by Wayne S. Holland. Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VI (September 24, 2012). (Proc. SPIE 8452).

As Published: <http://dx.doi.org/10.1117/12.925651>

Publisher: SPIE

Persistent URL: <http://hdl.handle.net/1721.1/86384>

Version: Final published version: final published article, as it appeared in a journal, conference proceedings, or other formally published context

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Stabilized HEB-QCL heterodyne spectrometer at super-terahertz

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ABSTRACT

We report a new experiment on a high-resolution heterodyne spectrometer using a 3.5 THz quantum cascade laser (QCL) as local oscillator (LO) and a superconducting hot electron bolometer (HEB) as mixer by stabilizing both frequency and amplitude of the QCL. The frequency locking of the QCL is demonstrated by using a methanol molecular absorption line, a proportional-integral-derivative (PID) controller, and a direct power detector. We show that the LO locked linewidth can be as narrow as 35 KHz. The LO power to the HEB is also stabilized by means of swing-arm actuator placed in the beam path in combination of a second PID controller.

Keywords: terahertz heterodyne spectrometer, quantum cascade laser, frequency locking, stabilization

In the terahertz (THz) frequency range a high-resolution heterodyne spectrometer is of crucial importance for astronomical observations and atmospheric remote sensing applications, based on its combination of high spectral resolution and sensitivity. As the mixer, a superconducting NbN hot-electron bolometer (HEB) mixer has demonstrated excellent sensitivities up to 5.3 THz [1]. As the local oscillator (LO), terahertz quantum cascade lasers (QCLs) have shown advantages at frequencies above 2 THz, based on their single mode emission, wide frequency operating range, and high output power [2]. And several progresses have been made, such as a heterodyne spectroscopy measurement in the lab with a QCL operating in the free running mode [3]. Furthermore, for astronomical observation, like studying stars deeply embedded inside dense molecular clouds, the spectral signal is often weakly embedded in the noise. It not only requires high frequency resolution to resolve fine structures but also long integration time to establishing time efficient observation. It has been shown theoretically [4,5] and experimentally [6,7] that THz QCLs can have narrow intrinsic linewidths of below tens of kHz. However, caused by the fluctuations in the electrical bias and in the operating temperature, the practical linewidth of a free-running THz QCL measured over a long period (>1 s) is usually much

broader, typically greater than 1 MHz [6,8]. Moreover, practically, a THz QCL is usually operated with a pulse tube cryocooler. Temperature and mechanical fluctuations caused by the cryocooler not only induces broader emission linewidth, but also introduces more amplitude noise. As a result, it will deteriorate the performance of the entire spectrometer.

Here we report a new experiment on high-resolution heterodyne spectrometer using a 3.5 THz QCL as LO and a HEB as mixer by stabilizing both frequency and amplitude of the QCL. The frequency locking of the QCL was demonstrated by using a molecular absorption line, a proportional-integral-derivative (PID) controller, and a direct power detector [9,10]. The key results on the frequency locking part in the current paper have been published in Ref.[10]. The amplitude of the QCL emission is simultaneously stabilized by means of swing-arm actuator placed in the beam path using a second PID controller [11].

The QCL used in this experiment is a third-order DFB QCL. As demonstrated previously [3], by using the third-order periodic structure with strong refractive index contrast gratings, not only can single mode emission be achieved, but also a less divergent, single spot far-field beam. Our laser, based on a 10 μm thick active region, consists of 27 periods of gratings with a total length of 1070 μm . It provides a maximum output power of 0.8 mW and is mounted on the second stage of a pulse tube cryocooler (~ 12 K under load).

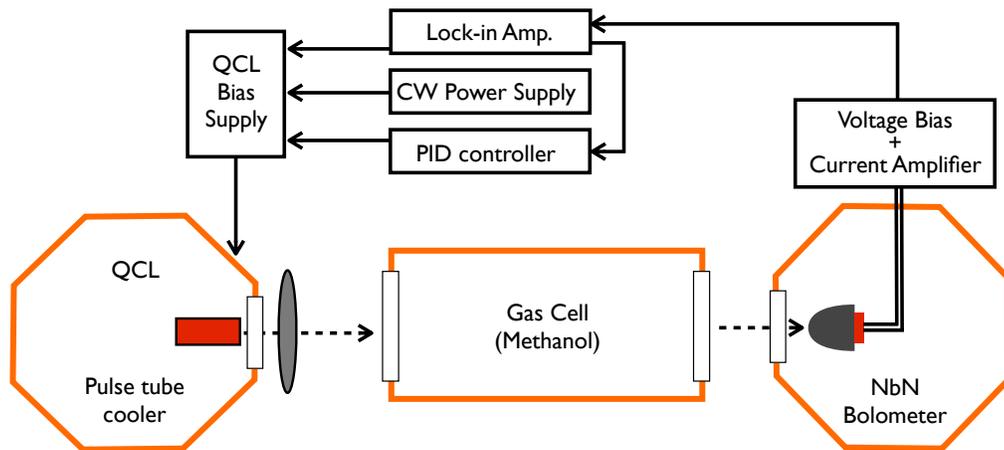


Fig. 1. (Color online) Schematic of the frequency locking measurement setup

The frequency locking measurement setup is schematically described in Fig. 1. The QCL beam is first focused with a high-density polyethylene (HDPE) lens ($f=26.5$ mm), and then guided through a gas cell. The gas cell, containing methanol gas at room temperature, is a 30-cm long cylinder with two 2-mm thick HDPE windows. Methanol gas is chosen since it contains abundant absorption lines around the QCL frequency. The transmitted signal through the gas cell

is monitored by a superconducting NbN bolometer operated at liquid helium temperature as a direct detector whereby we benefit from a NEP of $10^{-12}\sim 10^{-13}$ W/Hz^{1/2} [12] and a fast response (~ 40 psec).

To perform frequency locking, we apply a summing bias circuit that allows combining three input signals to independently control the bias voltage of a laser [9,10]. The first input is a standard DC bias voltage, which sets the operating point of the laser. The second input is an AC sinusoidal modulation signal at around 1 kHz with relatively small amplitude ($< 0.01\%$ of the DC bias). By feeding the detector output current to a lock-in amplifier with the AC modulation signal as reference frequency, the derivative signal of the absorption profile is obtained. The third one is the control signal from a feedback loop. A PID controller is used to actively lock this derivative signal to be maintained at zero value, and a compensatory signal is fed back to the bias circuit of the QCL. In this way, the QCL frequency can be stabilized to a particular molecular absorption line.

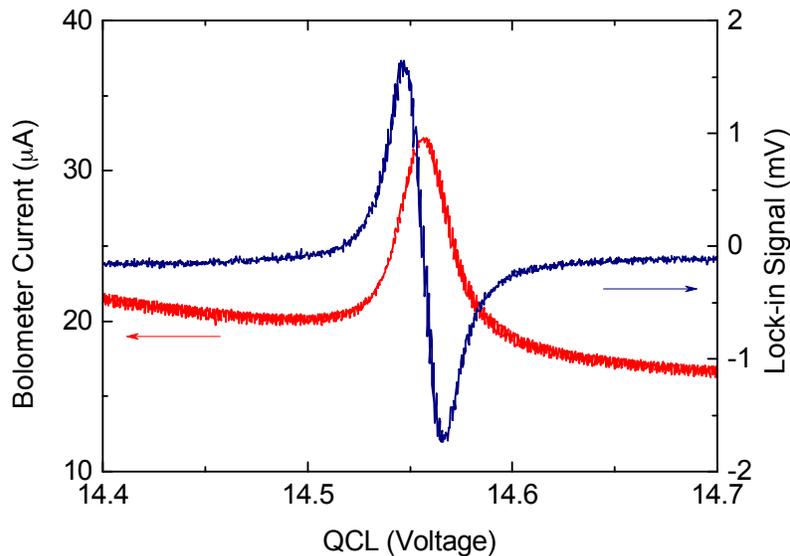


Fig.2. (Color online) Absorption profile of methanol lines at 1.8 mbar as measured. By using a NbN bolometer detector and a lock-in amplifier, the error signal was measured, labeled as lock-in signal.

We measured the methanol absorption spectrum (versus frequency) by sweeping the QCL bias voltage since the voltage regulates its emission frequency. Fig. 2 shows an obtained strong absorption line at around 3.45 THz. Also shown in the figure is the first derivative of the absorption profile, which is obtained by using a lock-in technique. The lock-in derivative signal is in turn utilized for the PID control loop, whereby a feedback signal is generated and fed to the bias circuit of the QCL in order to yield a stabilized lock-in signal. Around the frequency of the absorption peak, the linear region of the lock-in signal indicates the frequency locking range. To illustrate the locking process, Fig. 3 plots the lock-in signal. When the laser is unlocked, the observed fluctuations reflect the frequency fluctuations of the QCL. The

observed low frequency fluctuation in the lock-in signal is the result of the typical temperature oscillation of the pulse tube cooler. After the frequency locking feedback loop is enabled, the lock-in signal becomes well stabilized and maintained at the 0 mV setpoint. Thus, the laser frequency is stabilized.

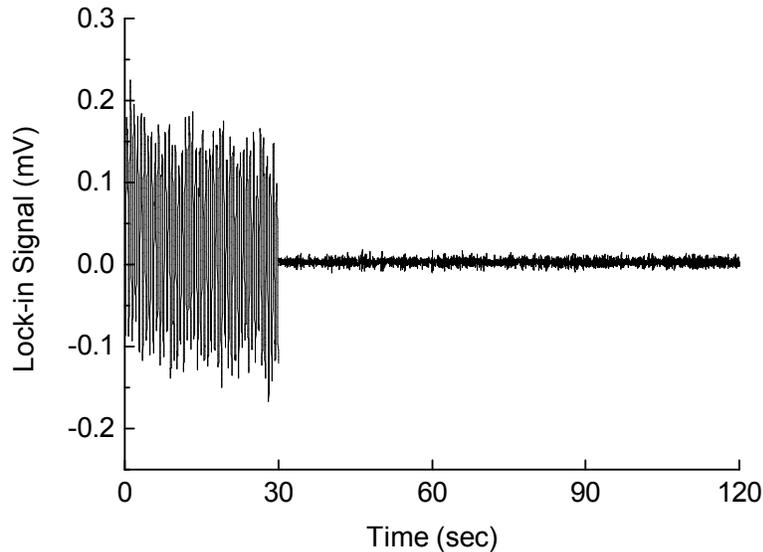


Fig.3. Lock-in signal in the free running state and frequency locked state after 30 sec.

The laser linewidth can be estimated by transforming the variation in voltage of the lock-in signal, which represents the error signal, into the frequency domain. The lock-in signal is first converted to the equivalent variation in the QCL bias voltage using the measured linear profile in the figure of Fig. 2. Subsequently, two different methods are applied to calibrate the numerical correspondence between frequency and voltage. Method one is based on spectroscopic measurements [3], where the frequency tuning coefficients of the QCL due to the bias voltage are obtained. Then the frequency can be obtained by multiplying the voltage (the lock-in signal) with the tuning coefficient. The second method is to make use of the methanol gas pressure broadening coefficient at 3.5 THz [3], which is established from a set of methanol absorption lines at different gas pressures. In this way a lock-in signal can also be transformed into frequency. We find that the two different approaches give similar results to within 10% [10]. Fig.4 plots a histogram of the relative frequency fluctuations of a 30 sec observation time in order to present the standard deviation of the center frequency. We find that the free running laser linewidth for laser A is roughly 1.5 MHz, while the locked linewidth is less than 35 kHz (both estimated using the full-width at half maximum of the profile).

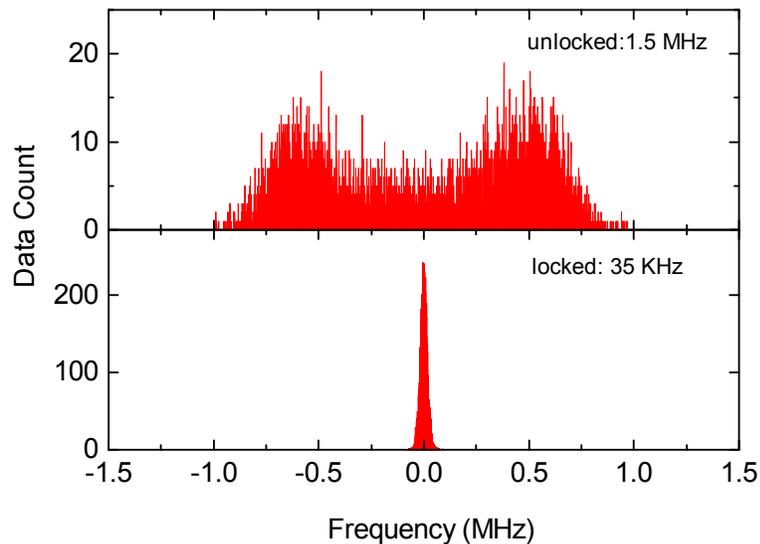


Fig.4. (Color online) Histogram of the relative frequency deviation to the center frequency of the QCL in the free running and frequency locked states, calculated based on the lock-in signal fluctuations of a 30 s observation time.

Furthermore, we also realized amplitude stabilization of the QCL. A swing-arm voice coil actuator [11] as a fast optical attenuator, is placed in the optical path. This device has a fast response (up to 200 Hz) and full dynamic range operation that allows adjustment of any percentage of the LO beam by varying its arm angle as a function of applied current. A beam-splitter is employed to divide the QCL beam into two parts, one being for frequency locking and another being used as local oscillator for a NbN HEB mixer. The QCL power drives the HEB mixer to the optimal operation region. And the DC bias current of the HEB mixer, namely the direct detection response, is used to set the reference power together with a second PID controller, which gives a feedback signal to drive the voice coil actuator in order to maintain stable LO power to the HEB. Thus, the effective amplitude of the local oscillator power is stabilized. By implementing these two stabilization schemes simultaneously, a both frequency and amplitude stabilized heterodyne spectrometer with a THz QCL as local oscillator is achieved.

In conclusion, we succeeded in demonstrating a fully stabilized high-resolution heterodyne spectrometer using a 3.5 THz third-order DFB QCL operated in a pulse tube cryocooler as a local oscillator. The LO linewidth is reduced to 35 KHz by locking it to a methanol absorption line, which is sufficiently small for LO applications. With the implement of a swing-arm actuator for rapid feedback LO intensity control the amplitude of LO is also stabilized.

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