Simultaneous frequency locking and monitoring using a bi-directional THz quantum cascade laser

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Abstract— **We have performed frequency locking of a dual, forward reverse emitting 3rd order distributed feedback quantum cascade laser (QCL) at 3.5 THz. By using both directions of THz emission in combination with two gas cells and two power detectors, we can for the first time perform frequency stabilization, while monitor the frequency locking quality independently. We also characterize how the use of a less sensitive pyroelectric detector can influence the quality of frequency locking, illustrating experimentally that the sensitivity of the detectors is crucial. Using both directions of THz radiation has a particular advantage for the application of a QCL as a local oscillator, where radiation from one side can be used for frequency/phase stabilization, leaving the other side to be fully utilized as a local oscillator to pump a mixer.**

INTRODUCTION

Terahertz (THz) quantum cascade lasers (QCLs) have been demonstrated as local oscillators for high resolution spectroscopy both in the lab [1] and more recently, in a real astronomic instrument [2]. In general, since the QCL is not inherently frequency stable, a system of frequency or phase locking [3], [4] is required. So far, the radiation emitted from only one direction of the QCL has been used for both pumping a mixer and stabilizing the frequency of the source [5]. In this way, to achieve frequency locking, part of the beam power is unavailable which can be half of the total power available from the laser, making it very difficult to pump a mixer.

It is known that both a standard Fabry-Perot QCL and a distributed feedback (DFB) QCL can emit radiation from both forward and backward directions [6]. To take full advantage of the total radiating power available from a QCL, it is very beneficial to make use of the radiation from both directions. For example, one direction acts as a local oscillator source whilst the other is used for frequency or phase locking. Although it seems obvious that one should take advantage of both beams, in practice no one has ever reported the use of a QCL in this configuration as local oscillator at the high end of THz frequencies (e.g. 4.7 THz), where the available power is still relatively low.

This conference paper is based on our recent publication in J Infrared Milli Terahz Waves [7]. We develop a measurement setup that allows the detection of the radiation simultaneously from both directions. We start with the basic characterization of the radiation beam patterns and emitted power of a 3.5 THz, 3rd-order distributed feedback (DFB) QCL [8]. We demonstrate a practical application of the dual emitting QCL by applying 2 gas cell based frequency discriminators, one for each emission. Specifically, one side is used to realize frequency locking whilst the other side is used to monitor frequency stability. We find that the sensitivity of the detectors is crucial for both frequency locking and frequency monitoring. Finally, we describe briefly an experiment to make use of one side of radiation to carry out the frequency locking and other side of the radiation to pump a superconducting NbN hot electron bolometer (HEB) mixer [9].

QCL AND MEASUREMENT SETUP

We use a 3rd-order DFB THz QCL based on a four-well resonant phonon depopulation design [10] developed at MIT (Fig.1. a). It emits a single mode at 3.490 THz, as measured by a Fourier Transform Spectrometer (FTS) with a resolution of 0.6 GHz. The device comprises 27 lateral corrugated grating periods over a ~1 mm long active region, which is 10 µm thick and 50 µm wide. We make a symmetric sample holder (Fig. 1. b) such to make the same conditions for the out coming beams from both directions. The only difference is that the bonding wire appears only on one end of the laser.

The setup for the key measurement of this paper is illustrated in Fig. 2. The QCL is mounted in a pulse tube cryocooler that reaches ~4 K without load and typically ~12 K with the ~3 W electrical power dissipated by the QCL. The QCL is positioned in such a way where one end of the laser with the bonding pad and wire points to the backward direction. To allow both forward and backward radiation to exit the cryostat, two windows are installed. The front window (corresponding to the forward direction) is a 3 mm thick high

density polyethylene (HDPE) with a transmission of 71% measured at the laser frequency, while the rear window is a 1 mm thick ultra-high-molecular-weight polyethylene (UHMW-PE) with a transmission of 89% obtained at the same frequency. The QCL is placed in the centre of the cryocooler with roughly an equal distance of ~ 80 mm to the windows.
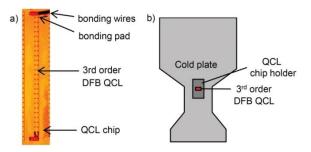

Fig. 1. (a) Photo of the 3rd-order DFB QCL used for the experiment. One end with the bonding wire/pad is positioned towards the backward direction in the setup shown in Fig. 2. (b) Sketch of the QCL sample holder. The QCL (red) is mounted on a Cu chip holder (dark grey). The chip holder is attached to a cold plate (light grey) connected to a cryocooler.
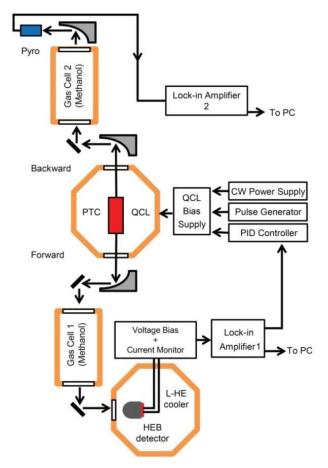

Fig. 2. Schematic of the measurement setup. The QCL is operated in a pulse tube cryocooler (PTC). The combination of a gas cell and a HEB detector is applied to generate an error signal to a PID controller for frequency locking (forward), and a 2nd gas cell with a pyroelectric detector to monitor the quality of frequency locking (backward).

Both forward and backward radiation are collimated and reflected through each of two gas cells with lengths of 41 cm and 27 cm, respectively. Due to the abundance of absorption lines in the THz, methanol is used as the reference gas in both gas cells.

The forward radiation beam is then reflected into a Si lens/antenna coupled superconducting NbN HEB [1], [9], which is operated as a bolometric power detector. It produces an error signal that is fed, via a lock-in amplifier, to a Proportional Integral Derivative (PID) controller. The PID controller makes a correction signal that is added into the QCL bias voltage to hold the error signal at zero, and therefore to stabilize the frequency. The feedback bandwidth, limited by the lock-in amplifier time constant, is ~10 Hz although the PID bandwidth is much higher (~1 kHz). As indicated by the measured frequency noise power spectral density [11], a bandwidth of ~10 Hz is in practice sufficient to stabilize the average laser frequency and to remove low-frequency jitters.

The backward radiation beam after passing through the gas cell 2 is focused onto a room temperature pyroelectric detector that is used for monitoring the quality of the frequency locking. We read out the signals from both detectors via two separate lock-in amplifiers connected to a PC. Since we have the same gas and roughly the same pressures in the gas cells, we expect to see a similar changing behaviour from the signals detected by both detectors. The two detectors however have very different sensitivities. The HEB has a noise equivalent power (NEP) of 10-12 ~10-13 [12], whereas the pyroelectric detector has an NEP of ≥10-9 [13]. Also, the former works at 4 K, while the latter operates at room temperature.

EXPERIMENTAL RESULTS AND DISCUSSION

We start with the measurements of the far-field QCL beam patterns in both directions by using a small aperture pyroelectric detector scanned within a plane normal to the direction along the laser structure indicated in Fig. 2b (z-axis). Fig. 3 shows the measured beam patterns of the radiation from both directions.
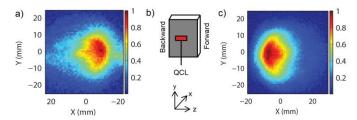

Fig 3. (a) Measured beam pattern (normalized) from the backward radiation. The observation plane (x,y) is about 90 mm to the QCL. (b) Orientation of the QCL. The arrows indicate the positive x, y and z directions. (c) Measured beam pattern (normalized) from the forward radiation. The observation plane (x,y) is also about 90 mm to the QCL.

We find that the backward direction emits less power and has only 56% power from the forward direction, obtained after correcting the effect due to two different transmissions of the windows. The difference by nearly a factor of two in power is attributed to the bonding pad/wire on the laser in the backward direction. The power result is consistent with the beam pattern measurement, where the S/N ratio is worse in the backward direction.

Prior to frequency locking, we measure methanol absorption lines by sweeping the QCL bias voltage from 13.5 V to 14.5 V, which tunes the frequency electrically, as confirmed by a separate FTS measurement. Both gas cells are

filled with methanol at a pressure of ~1.7 mbar. Results are plotted in Fig. 4, where the signals from both detectors are recorded with two lock-in amplifiers simultaneously.
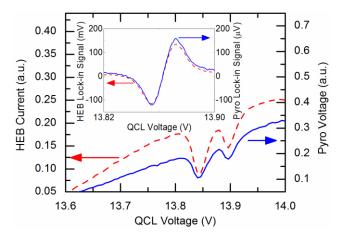

Fig. 4. Absorption lines of methanol at 1.7 mbar. The lines are measured with an HEB (red dashed) and a pyro (blue), respectively. The inset shows the derivative of an absorption line around 13.8 V measured with the HEB (red dashed) and the pyro (blue) by a lock-in amplifier when QCL is modulated with a small AC signal.

As expected, the absorption lines appeared at exactly the same bias voltages. The derivative of the absorption line at ~13.84 V was also measured by applying a small 70 Hz, 10 mVp-p AC modulation [14] (inset of Fig. 4). They change linearly with the QCL bias voltage over a range close to the absorption line center.

In this way, we can make use of an absorption line for frequency stabilization of the QCL because its frequency is known to be fundamentally stable [11], [14]. Any fluctuations in the frequency of the QCL below the bandwidth of ~10 Hz will cause proportional changes in the derivative output. In practice, we set the QCL bias voltage so as to have its frequency close to the center of a specific absorption line and then feed the derivative signal as the error input to the PID controller. The controller produces a feedback to the QCL bias voltage to keep its frequency aligned to the center of the absorption line where the derivative is equal to zero.

Now we focus on the key experiment of this paper using the setup in Fig. 2 by applying this method to gas cell 1 by feeding the HEB's derivative signal to the PID controller to stabilize the frequency, while utilizing output from the gas cell 2 to monitor the quality of frequency locking. A time series of the error signals measured simultaneously from both lock-in amplifiers is plotted in Fig. 4.

In the time interval from 0 to 9 seconds (mode 1), the QCL was free running and the error signals recorded in both detectors are relatively large, which is primarily due to the ~1 Hz frequency of the pulse tube cooler. Afterwards (mode 2, 10-24 sec), the PID is turned on reducing the error signal from the HEB by a factor of 20. In the same time interval, the fluctuations of the pyroelectric signal is not as strongly suppressed as the one for the HEB. To understand this, we actually block the radiation to the pyroelectric detector and record its error signal, while the frequency locking is maintained by the HEB (referred as the mode 3 in Fig. 5). We find that the intrinsic noise level of the pyroelectric detector

dominates in both cases; no matter whether there is a radiation signal to the pyroelectric detector or not. Thus, we realize that the error signal from the pyroelectric detector does not directly correspond to the frequency locking quality, but rather to the noise floor of the detector.
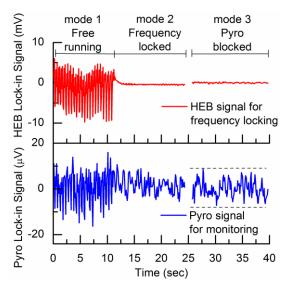

Fig. 5. The lock-in amplifier signal from the HEB (top, red) and the pyroelectric detector (bottom, blue), reflecting the frequency stability of the QCL. Frequency locking is engaged to the forward radiation after 12 sec using the HEB signal (control), while the pyroelectric detector monitors the frequency of the backward radiation. After 30 sec the radiation to the pyroelectric detector is blocked. The dashed line represents the pyroelectric detector noise limit.

Since the derivative signal is linear versus the QCL voltage around the locking frequency, we can estimate the frequency fluctuation, knowing the QCL voltage tuning coefficient of about 0.6 GHz/V determined from a separate FTS experiment. We find a free running QCL linewidth of around 800 KHz. After turning the frequency locking on, this linewidth is reduced to about 40 kHz. This analysis is based on the observation from the HEB. In contrast, if we make use of the error signal from the pyroelectric detector, we would record a linewidth of 300 kHz, which contradicts obviously with the first result.

To verify the importance of the noise level of the detector in such a frequency locking experiment, we modify the experiment slightly and take the error signal from the pyroelectric detector for the frequency locking and the HEB's signal for the monitoring. The results, plotted in the same manner as in Fig. 5, are shown in Fig. 6.

Looking at the mode 2, the error signal from the pyroelectric detector has been reduced considerably relative to the free running case from 800 KHz to 100 KHz. However, compared with the results by using the HEB for the frequency locking in Fig. 5, the residue on the locked signal is large. We attribute these fluctuations to the intrinsic noise of the pyroelectric detector. In this case, the PID controller cannot distinguish the changes between the QCL frequency and the noise from the detector. Consequently the feedback signal to the bias of the QCL cannot be appropriately applied. The lack of suppression in the frequency fluctuations can be monitored by the HEB. Since the (intrinsic) noise floor of the HEB is at

least three or four orders of magnitude lower than that of the pyroelectric detector [12], the error signal in this case reflects more accurately the quality of the frequency locking. Because of the higher sensitivity of the HEB, these fluctuations are exclusively due to the frequency fluctuations of the QCL and they show only a mild reduction in the linewidth of the QCL from 800 KHz to 300KHz.
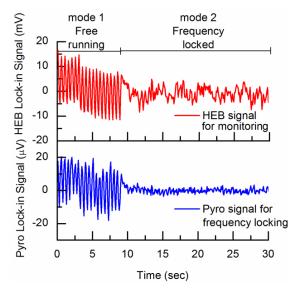

Fig. 6. The lock-in amplifier signal from the HEB (top, red) and the pyroelectric detector (bottom, blue) reflecting the frequency stability of the QCL. Frequency locking is engaged to the backward radiation after 9 sec using the pyroelectric detector signal (control), while the HEB monitors the frequency of the forward radiation.

It is worthwhile to stress that our experiment represents the first one to make use of the bi-directional radiation from a single THz QCL for a frequency locking experiment, where the laser can be locked, while the quality of the locking can be evaluated in the same time. It is also the first to experimentally demonstrate the importance of the detector sensitivity in a frequency lock loop.

A key demonstration of the advantage in using a dual emitting QCL is to show that a superconducting NbN HEB mixer can be appropriately pumped using one side of the laser whilst the other side is used for frequency locking. We perform such an experiment by using a standard NbN HEB mixer, which has a NbN area of 2 μm×0.2 μm, corresponding to a power requirement of 200 nW at the detector itself [1]. We apply a setup simplified with respect to the one in Fig. 2 by removing the gas cell 1 in the forward direction. We then lock the frequency of the QCL using the backward beam. At the same time, we apply the forward beam to pump the superconducting mixer. We find that it can pump the HEB to its nearly optimum operating points. With further optimization of the optics to match the beam to the HEB we expect that the forward beam can provide sufficient power to pump the HEB to its optimum operating points, while the frequency locking is realized with the backward beam.

In this way we can in essence make use of 100% available power from a frequency locked QCL. This approach is certainly beneficial for the case where a QCL is applied as a local oscillator for a superconducting mixer. This approach will be even more attractive for the cases where a QCL is applied as a local oscillator for a semiconductor Schottky mixer and an array of mixers, both of which require high power.

CONCLUSIONS

By making use of the radiation from the forward and backward directions of a 3rd-order DFB QCL at 3.5 THz, we demonstrate for the first time that we can introduce the frequency locking, while can monitor the quality of the locking simultaneously. Furthermore, by applying two power detectors with a different noise level, we show that the frequency locking quality, namely the linewidth derived from the error signal, depends strongly on the noise level of the detector used. In the case of applying a high noise power detector for the locking, the PID controller not only corrects the frequency fluctuations of the laser, but also compensates the noise from the detector by adjusting the QCL frequency, which can lead to a much wider locked linewidth than what is indicated by the (locking) detector.

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