Phase Locking of a 2.5 THz Quantum Cascade Laser to a Microwave Reference using THz Schottky Mixer

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***Abstract*—The frequency of a 2.5 THz QCL are stabilized to sub-hertz accuracy by phase-locking to a stable 100 MHz microwave reference, using a 2.3–3.2 THz room temperature Schottky diode based harmonic mixer. The down-converted phase locked beat note is stable over a long term test.**

***Index Terms*—Harmonic Mixer, THz Circuit, Quantum Cascade Laser (QCL), Phase Locking.**

INTRODUCTION

Terahertz-frequency quantum-cascade lasers (THz QCLs) are compact electrically-driven sources of narrowband, coherent radiation in the 1 – 5 THz band. Although peak output powers in excess of 1 W have been demonstrated, most potential applications of THz QCLs as a local oscillator (LO) in THz astronomy and atmospheric spectroscopy require both frequency stability better than 1 ppm and narrow linewidth, with low phase noise sidebands [1]. However, temperature and current bias fluctuations in the gain media of the QCL can cause the refractive index to change with time, which affects the lasing frequency. A phase locking system improves the stability by using a negative-feedback system that combines a current-controlled QCL with a phase comparator so that the QCL maintains a constant phase angle relative to a reference signal. Since it is challenging to find a stable THz-frequency source to use as a reference, a THz mixer is needed to down-convert the signal to a lower frequency where frequency and phase comparisons are possible. A number of groups have accomplished QCL phase locking using a hot electron bolometer (HEB) or semiconductor superlattice (SSL) nonlinear device as mixers [2]. However, these mixers require an additional cryo-cooler, which increases the size and the complexity of the phase locking system. Furthermore, room temperature SSL devices exhibit conversion loss of 80 dB or more, and makes phase locking difficult [3]. Therefore, a room-temperature, solid-state mixer with lower conversion loss is desirable to produce more compact phase-locked THz sources. In this work, we have demonstrated phase locking of a free-running QCL at 2.518 THz to a stable quartz-based 100 MHz reference using a Schottky diode based WM-86 (WR0.34) harmonic mixer.

QUANTUM CASCADE LASER

The THz QCL used in this work is based on a 12.5 um-thick bound-to-continuum active region, on a ~200 um-thick GaAs substrate. The active region was processed using conventional photolithography and wet-etching techniques into a gold semi-insulating single-plasmon ridge waveguide configuration with contacts consisting of a thin layer of evaporated AuGeNi. The QCL was mounted in a two-stage closed-cycle cryogenic system and cooled to 5 K.

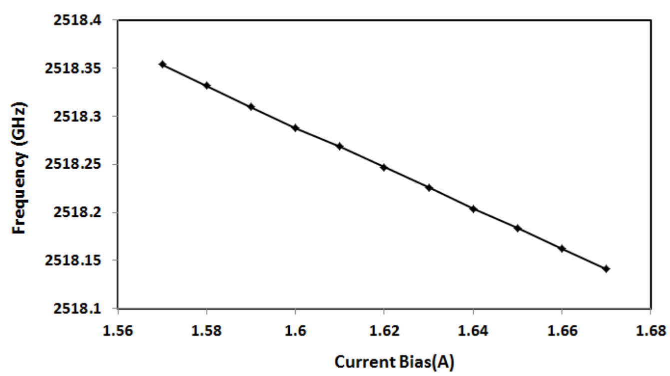

Figure 1. A 2.5 THz QC current bias versus output frequency with current tuning factor of $\Delta f/\Delta I$ = -2.1 GHz/A at 5 K.

The resonant frequency of the QCL Fabry–Pérot cavity is given by $f = mc/2nL$, where m is the mode number, L is the length, n is the effective refraction index of the gain media. The refractive index of the gain media of the QCL is a function of both the temperature and the electric field across the device (i.e. Stark tuning); therefore, the output frequency can be controlled by changing the bias current [1], [3].

An initial characterization of the QCL (Fig. 1) showed that a linear shift in frequency was obtained for currents in the 1.56–1.68 A range, with a tuning coefficient of -2.1 GHz/A.

PHASE LOCKING A 2.518 THZ QCL

A WM-86 (WR0.34) 2.3–3.2 THz mixer is used as part of an ambient temperature receiver to enable phase locking of a 2.5 THz QCL. The mixer consists of quartz-based LO and intermediate-frequency (IF) circuits and a GaAs based THz circuit with an integrated diode. The RF input is a diagonal horn coupled to WM-86 rectangular waveguide. The waveguide is coupled to the diode using a waveguide probe with an integrated DC bias line [4]. Measurements of the mixer were performed using a 2 THz solid state source and 2.5 THz QCL, and yielded a conversion loss of 35 dB for the 4^{th} harmonic mixing. The THz harmonic mixer is used to down convert the QCL radiation into a lower frequency to compare its phase with a stable 100 MHz reference. A 13.114 GHz phase locked microwave synthesizer is used as an LO source to drive a Virginia Diodes, Inc. (VDI) Amplifier Multiplier Chain (AMC) with a multiplication factor of N=48. The system produces a 629.46 GHz signal with an output power of 1.5 mW.

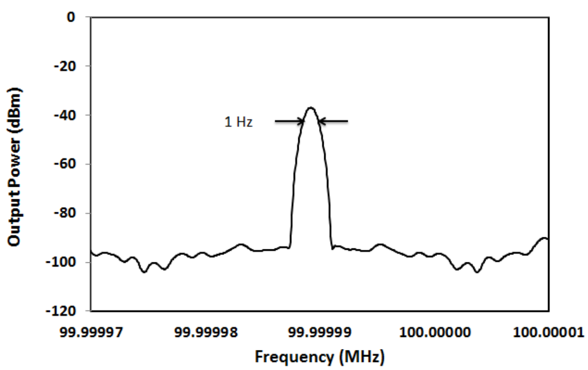

Figure 2. Power spectra of the beat signal of the phase locked 2.51825 THz QCL recorded by spectrum analyzer with 1 Hz RBW and video bandwidth of 300 Hz. A 3 dB linewidth of the beat signal is also indicated.

When the LO source pumps the harmonic mixer, it generates the 4^{th} harmonic at 2.5183 THz and mixes with the 2.5184 THz QCL radiation resulting in a 100 MHz beat signal (Fig. 2) . The beat signal from the mixer feeds into a low-pass filter with a cutoff frequency of 190 MHz, which is used to remove unwanted intermodulation products and to set the noise bandwidth.

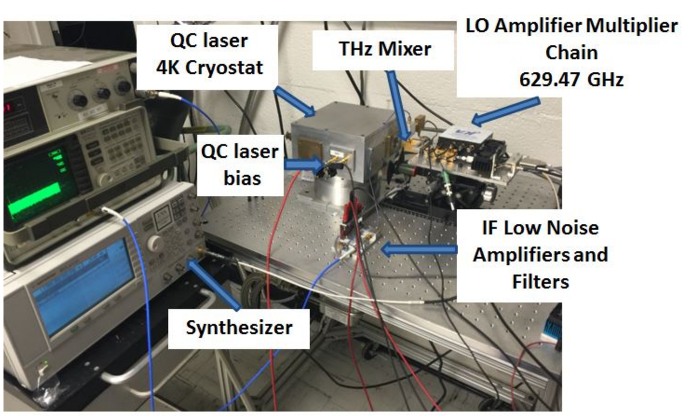

Figure 3. System setup to down convert a 2.5 THz QCL's radiation.

The digital phase detector compares the phase of the IF signal from the mixer with the 100 MHz reference. This generates a DC voltage that is proportional to the phase difference between the two signals. The DC voltage is applied to the loop filter with 1 MHz loop bandwidth. The loop bandwidth characteristics determine the range in which the phase-locked loop tracks the signal and sets the locking range. The DC voltage produced due to the phase difference feeds back into the QCL to complete the phase locked loop (Fig. 4). Phase locking of a free running QCL compensated approximately a 50 MHz instability due to bias and temperature fluctuation and cryocooler vibrations to sub-Hertz accuracy.

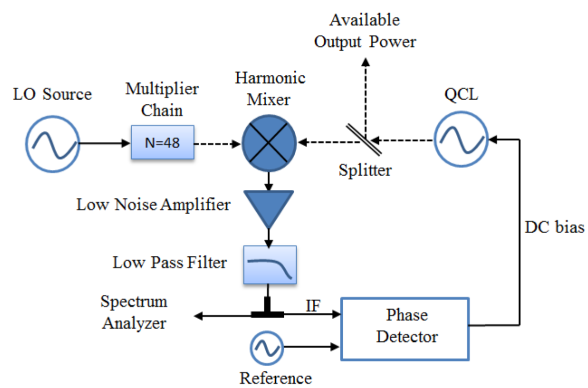

Figure 4. Schematic of the setup for phase locking a QCL.

To further use the phase locked THz radiation for different applications, such as to pump HEB based receivers, the system needs to include focusing mirrors and a beam splitter to use part of the QCL radiation for phase locking and the rest as an LO source. Since the THz harmonic mixer requires less than 10 uW power to produce a down-converted beat signal with sufficient power to phase lock, a significant amount of the available THz power can be split for other uses.

Conclusion and Future Work

A 2.5 THz QCL is phase locked to an external 100 MHz microwave reference using a room temperature THz harmonic mixer. Furthermore, using similar harmonic mixers, different frequency QCLs such as 2.7 THz, 2.9 THz and 4.7 THz will be phase locked.

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