Frequency Locking of a 4.7 THz Quantum Cascade Laser using a Delay Line

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***Abstract*—Quantum Cascade Lasers (QCLs) are powerful monochromatic radiation sources at higher THz frequencies and are highly favorable for heterodyne receivers such as the upGREAT of the SOFIA telescope. Apart from their advantages, they can suffer from different line-broadening mechanisms, such as optical feedback, that broaden the effective linewidth and reduce the receiver's spectral resolution. In this work, we present frequency stabilization of a 4.7 THz QCL based on a delay line frequency discriminator. The latter comprises a power divider, a delay line, and a double-balanced mixer that forms a frequency discrimination constant of 91.5 mV/MHz. The QCL emission is down-converted with the help of a Superlattice harmonic generator and mixer, itself pumped with a diode multiplier chain at 182.6 GHz. The QCL line in the intermediate frequency band is then amplified and filtered to feed the frequency discriminator, where its output is used to stabilize the QCL frequency. More than 10 MHz of frequency deviations can be reduced to a static and stable line with an FWHM of 780 kHz.**

***Index Terms*—Quantum Cascade Laser, Local Oscillator, Frequency stabilization, Delay line frequency discriminator, Superlattice harmonic generator and mixer**

I. Introduction

QCLs are the most convenient sources of THz emission at higher THz Frequencies, such as 4.7 THz [1]. Heterodyne receivers operating at these frequencies, therefore, use them as Local Oscillators (LO). UpGREAT of the SOFIA telescope and STO and GUSTO balloon-born missions are examples of such receivers. QCLs usually suffer from different mechanisms that broaden the effective linewidth of the laser. These include current noise, temperature fluctuations, and optical feedback. Since in a heterodyne receiver, the LO line shape convolves with the observed line, frequency stabilization of the LO eventually increases the spectral resolving power of the receiver. In addition, providing an absolute frequency reference for the QCLs will increase the frequency accuracy of those receivers.

II. Delay Line Frequency Discriminator

In order to stabilize the frequency, it is crucial to be able to discriminate it with a frequency detector. This frequency discriminator works as the following. Since this experiment is heterodyne, a small, down-converted signal from the QCL is available in the IF. A power divider divides this signal into two equal amplitude outputs. One is delayed through the delay line cable, and both are mixed with a double-balanced mixer. Both mixer inputs have the same frequency, but the phase difference between them is frequency dependent due to the delay. As a result, a DC is created at the output of the mixer, which is variable with the frequency of the input. Figure 1 shows this DC output during a frequency sweep as a calibration measurement. One can also see this as a Michelson interferometer with unequal arm length. When the frequency of incoming light changes, the brightness of the fringe changes subsequently.

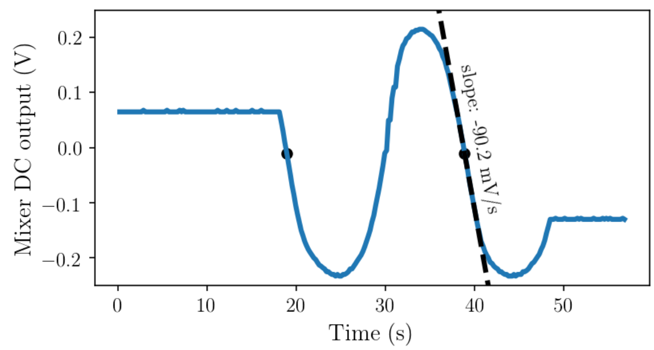

Fig. 1. The output of the delay line frequency discriminator during a frequency sweep with a rate of 1 MHz/s, centered at 400 MHz. The shown slope in this measurement is taken as a calibration of frequency to voltage conversion of this frequency discriminator.

III. Method

Figure 2 shows the schematic of this experiment. The QCL is housed inside a pulse-tube cryostat where the coldhead is thermally coupled and mechanically isolated from the QCL. QCL's emission is coupled to a superlattice harmonic generator and mixer (SLD) [2] using three mirrors. The SLD is pumped with the mm-wave power generated in a VDI diode multiplier chain with the 26th harmonic close to the QCL frequency. The SLD also mixes the two signals, and the difference signal is extracted at the IF port of the SLD. The latter is amplified and band-pass filtered to the optimum level to drive the frequency discriminator. The latter detects the frequency deviations and creates a proportional voltage, which is processed in the control electronics to form the correction signal. This correction signal is then added to the QCL current, and since the QCL frequency is current tunable, the correct settings on the control electronics stabilize the QCL's frequency.

IV. Experimental Setup

Figure 3 shows a photo of the experimental setup. The QCL is running at a current of 160 mA and 32 K bath temperature. The SLD is pumped with the diode multiplier

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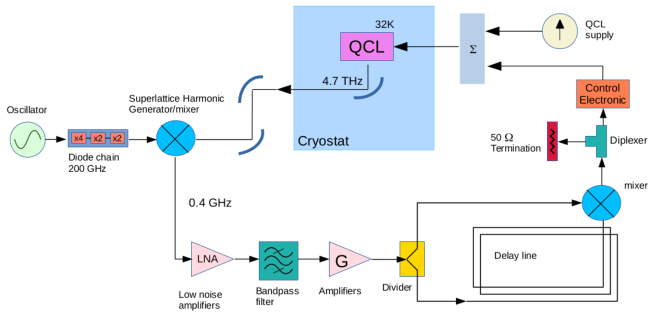

Fig. 2. Schematic of the experiment.

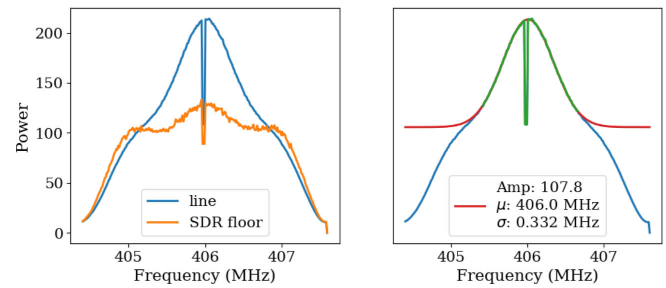

Fig. 4. Left: Example of the integrated SDR noise floor without and with the QCL line in the IF monitor output. Right: A Gaussian function is fitted to the line segment of the same data, with the joint parts used for the fit colored in green.

chain generating 182.6 GHz. The SLD's IF output contains the down-converted QCL signal of 9 dB over the noise floor (Resolution Bandwidth = 3 MHz) at an IF frequency of 400 MHz. While amplifying, it is essential to filter the wide-band noise generated by the SLD. The delay line is a 10-meter coax cable that introduces 50 ns of delay, resulting in a 91.5 mV/MHz frequency discrimination constant. The high-frequency products in the mixer are dumped into a 50-ohm termination load. The low-frequency components are processed in an OPAMP circuit as an amplifier and filter, where its output is the correction signal.

V. Results

Before stabilization, the spectrum of the QCL emission suffered from more than 10 MHz of frequency fluctuations. Figure 4 presents the IF output spectrum with the stabilized QCL. An FWHM of 780 kHz corresponds to the width of the Gaussian function fitted to the QCL line. The narrow dips on the plots correspond to three SDR channels that were not functional, and they were excluded in the Gaussian fit. During the measurement, it was understood that the primary source of the frequency instabilities in this experiment had been the optical feedback to the laser: Inserting attenuators in the beam reduced the strength of frequency modulation. Stabilization could be kept for many hours, and the method showed the needed robustness for use in an actual receiver. Interestingly, stabilization was still possible at small SNRs, such as only 2 dB over the noise floor. This means a significant fraction of the QCL power can be used to pump an array of mixers.

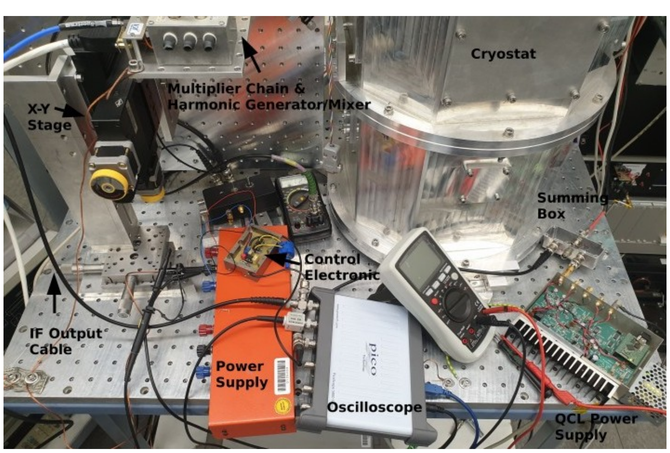

Fig. 3. A large fraction of the experimental setup: Optics bench, cryostat, and a part of the electronics.

VI. Conclusion

In conclusion, we have shown a robust frequency locking of a 4.7 THz QCL using a room-temperature superlattice device. The achieved locked linewidth of 780 kHz is enough for heterodyne astronomical spectrometers to reach a velocity resolution of 50 m/s, which is more than needed. In addition to this work, with a similar setup in the future, we hope to down-convert the SLD emission with an HEB mixer and demonstrate robust phase locking.

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References

[1] L. Bosco, C. Bonzon, K. Ohtani, M. Justen, M. Beck, and J. Faist, "A patch-array antenna single-mode low electrical dissipation continuous wave terahertz quantum cascade laser," *Applied Physics Letters*, vol. 109, no. 20, 11 2016, 201103. [Online]. Available: https://doi.org/10.1063/1.4967836

[2] D. Paveliev, Y. I. Koshurinov, A. S. Ivanov, A. N. Panin, V. L. Vax, V. I. Gavrilenko, A. V. Antonov, V. M. Ustinov, and A. E. Zhukov, "Experimental study of frequency multipliers based on a GaAs/AlAs semiconductor superlattices in the terahertz frequency range," *Semiconductors*, no. 46, pp. 121–125, 2012.