FY23 Topic Areas Research and Technology Development (TRTD)

THz quantum-cascade laser sources for space science

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Strategic Focus Area: Direct/Coherent Detectors and Arrays

Objectives: The objective of this work was to develop terahertz (THz) quantum-cascade lasers (QCLs) primarily for use as local oscillators (LO) in THz heterodyne receivers, and potentially for in-situ laser absorption spectrometers. More specifically, we were developing a new, high-performance QCL design called a QC-Vertical-External-Cavity Surface-Emitting-Laser (QC-VECSEL). The goal was to develop devices that are small enough to fit on a space-based instrument, and frequency stable enough to provide the necessary spectroscopic resolution for the science objectives. We established the following performance objectives for a QC-VECSEL that can be used for a heterodyne receiver in a SmallSat configuration which could enable future space-based THz interferometers:·

- Produce between 0.3 – 1 mW of THz power.
- Operate on a miniature Stirling cryocooler requiring <20 W input power (~0.5 W of cooling power at 80 K).
- Are phase-locked and frequency tunable (>10%).
- Operate around important gas lines at 2.7 THz ([HD]) and 4.7 THz ([OI]).

Background: The purpose of this work is to expand upon JPL's heterodyne detector capabilities in the 2-6 THz frequency range needed for mapping atoms and molecules in the interstellar medium and Solar system bodies (planet atmospheres, comet comae, geysers, volcano plumes, etc.). Currently, capabilities at JPL are limited by a lack of local oscillator (LO) sources at THz fre1quencies. Frequency multiplier chains (FMC) have served well at lower frequencies, but the power drops to unusable levels above 2 THz. QCLs are a leading candidate to fill the technology gap at higher THz frequencies, providing milliwatt power levels from a semiconductor source. However, QCLs are largely unavailable commercially, and existing designs have relatively poor beam qualities and limited frequency tunability. We pursue a novel, external cavity QCL design that produces excellent beam quality, and can be frequency-tuned over a broad bandwidth (~10% fractional). In-house development of these new QC-VECSELs will build on JPL leadership in THz spectroscopic instruments.

Approach and Results: In FY23, our focus was on advancing the 4.7 THz QC-VESCEL technology. Our milestones and results were as follows:

1. Six different 4.7 THz QCL wafers were grown, fabricated, and characterized **(Fig. 1)**. Wafer material was characterized in terms of power consumption (bias voltage and current density), output power, and lasing frequency. The best-performing wafer was then selected and fabricated into amplifying metasurfaces for the construction of 4.7 THz QCVECSELs with target power dissipation of ~1 W at a heat sink temperature of 80 K. Devices were first tested in liquid nitrogen cooled dewars and power levels of ~0.4 mW were achieved. Devices were frequency tunable from ~4.8 THz to 5.1 THz (6% fractional tunability) **(Fig. 2)**.

2. Using a room-temperature sub-harmonic diode frequency mixer down-conversion of 4.7 THz QC-VECSEL signal to microwave frequencies for high spectral resolution characterization and phase-locking has been demonstrated. QCL signal was mixed with the 7th harmonic of a 670 GHz diode-multiplier chain. An intermediate frequency (IF) is successfully measured in the 1-2 GHz range with an estimated conversion loss of ~50 dB.

3. Stirling cooler consuming ~20 W and achieving ~1 W cooling power at 80 K was purchased. Cryosystem was designed and constructed around the cooler including a vacuum chamber and vibration isolation bellows and thermal straps **(Fig. 3).**

Significance/Benefits to JPL and NASA: The key significance of the results is achieving a 4.7 THz device that can be cooled with a compact cryocooler and downconverted using a compact room-temperature diode mixer setup. 4.7 THz (neutral atomic oxygen) is the most critical line of astrophysical interest that is only accessible with a QCL local oscillator. Previous 4.7 THz demonstrations have been on airborne platforms such as SOFIA, and balloon-borne instruments on the upcoming ASTHROS and GUSTO missions. However, previous generation QCLs on these instruments required large cryocoolers dissipating >100 W, and were either not frequency stabilized or required cryogenically cooled mixers. In order to advance THz QCL systems to space-based platforms, the SWaP of such instruments must be reduced. This task's developments advance QCL based heterodyne receivers towards a much more compact, low power configuration that can potentially operate on a space-based platform.

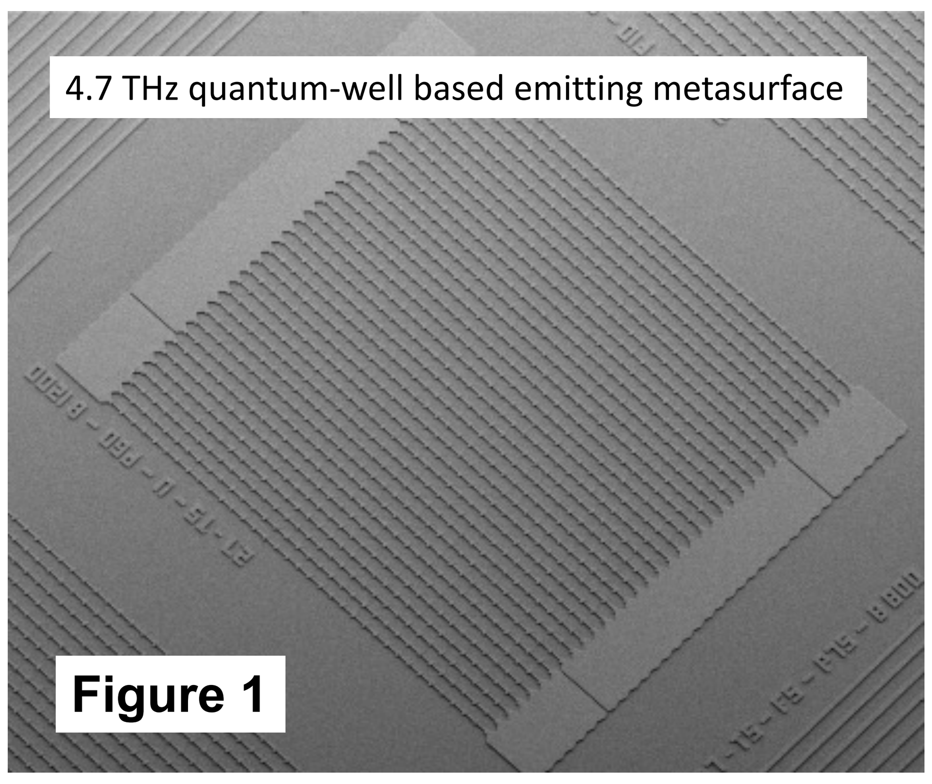

Figure 1

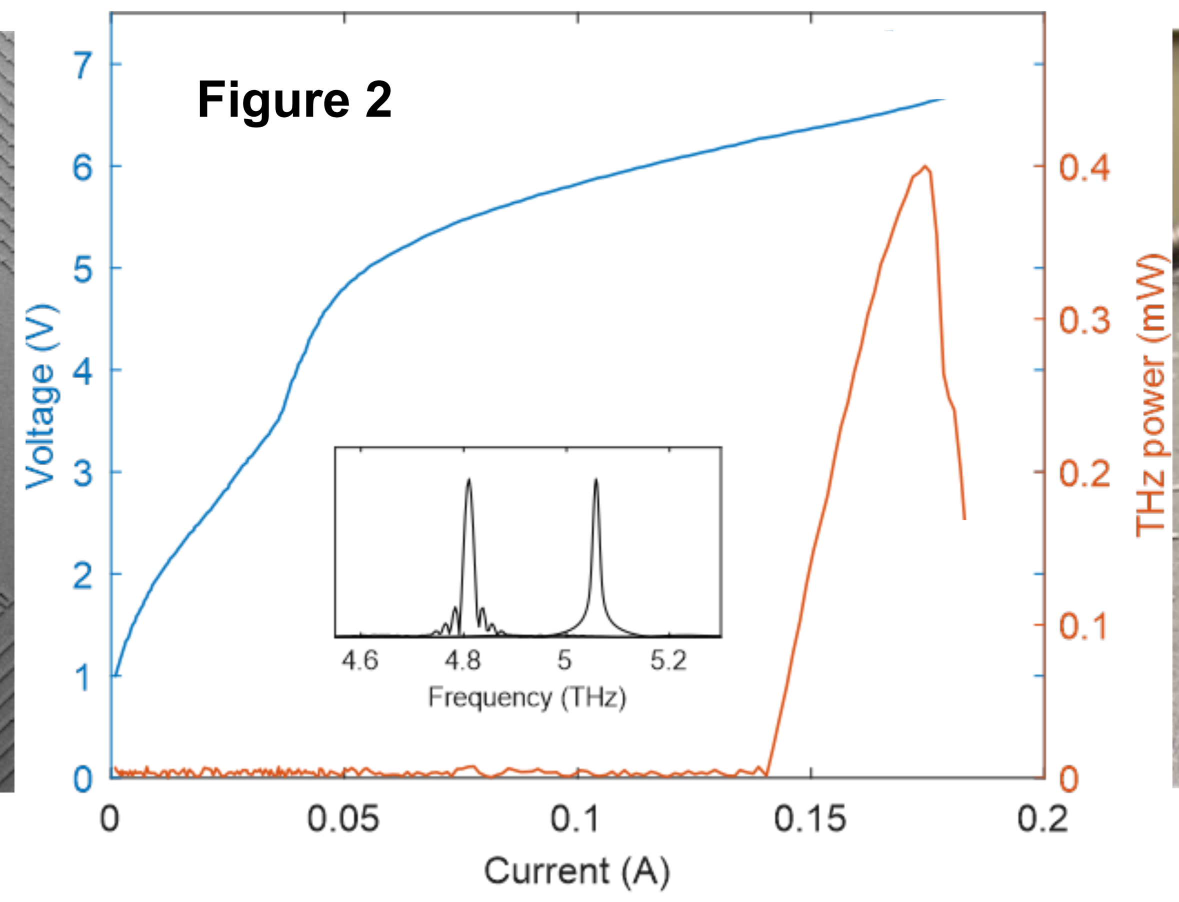

Figure 2

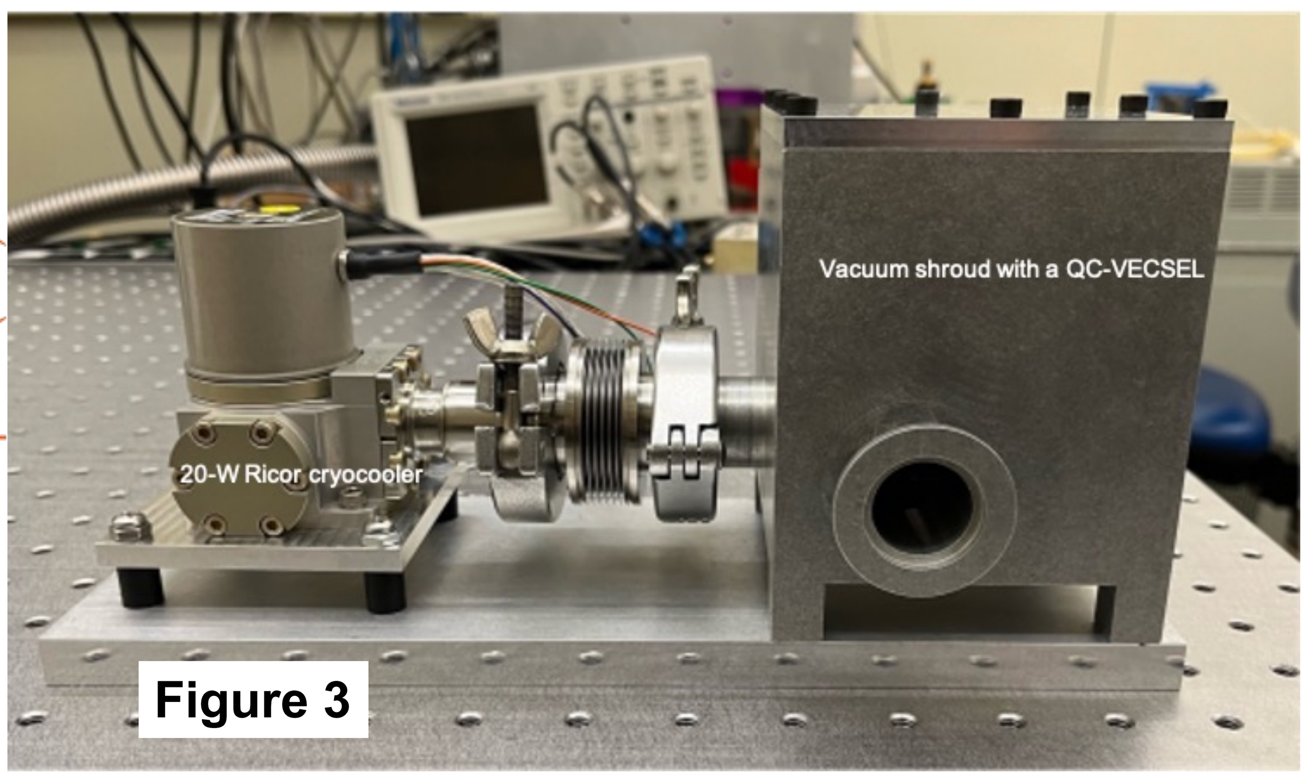

Figure 3

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Publications:

- C. A. Curwen, *ISSTT 2022,* Baeza, Spain, Oct. 16-20, 2022.
- C. A. Curwen et al., *IEEE Trans. THz Sci. & Technol.* **13**, 448-453 (2023).
- C. A. Curwen et al., *Opt. Lett.* **48**, 3809-3812 (2023).
- C. A. Curwen et al., *MIOMD - XVI,* OU, Norman, OK, USA, Aug. 6-10, 2023.

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