National Aeronautics and Space Administration

FY24 Strategic University Research Partnership (SURP)

Injection-locking of THz quantum-cascade laser local oscillators

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Objectives: The objective of this work is to frequency-stabilize a terahertz quantum cascade laser (QCL) by injection locking: a comparatively weak fundamental or fractional subharmonic terahertz tone generated by an electronic Schottky-diode frequency multiplier chain is coupled to the quantum cascade laser. This will transfer the frequency knowledge and line-width of a low-power, microwatt-power level electronic source onto that of a high-power output of a quantum cascade laser, which is three orders of magnitude more powerful. This method is superior to other methods of frequency stabilization such as frequency-locking or phase-locking, because it eliminates the need for a secondary THz detector and may result in improved amplitude stability. The lock state may be read directly from the laser device itself, as it is a highly non-linear device. This method will enable quantum cascade lasers to find practical applications as local oscillators, frequency reference tones, and components in terahertz communications.

Background: Quantum cascade lasers operating in the far-infrared (150-60 µm or 2-5 THz) range were invented about 20 years ago and have since gained widespread use in laboratories as powerful and versatile monochromatic and comb sources. Prior to their invention, the only sources available in this wavelength range were bulky CO_2 laser-pumped molecular gas lasers at certain spot frequencies, and, at the lowest frequency range, tunable microwatt-level sources from Schottky diode-based frequency-multiplier chains. With typical output power of several milliwatts, QCLs have numerous applications including active remote sensing systems, spectroscopy, communications, and as frequency references. They are especially attractive as local oscillator sources for heterodyne receivers used for high-resolution spectroscopy and for potential THz interferometry in astrophysics. However, unambiguous frequency stability and metrology have proved to be challenging to implement with QCLs. We explore a simple and novel method of injection locking to meet this goal.

Approach and Results: We first performed a demonstration at 2.5 THz using a QCL that is optically coupled to a tunable electronic terahertz source, and a small portion of the laser's output is coupled to a harmonic mixer for monitoring (Figure 1). Successful locking of a quantum cascade laser occured, with a full-width locking range of about 400 MHz and a pull range of >800 MHz (full-width). Measured line widths from the QCL replicates that of the master source very closely, indicating coherence between the master and slave sources and that the laser does not add phase noise. We have also demonstrated the utility of using the quantum cascade laser itself for lock detection. The microwave output of the quantum cascade laser shows a peak at the difference frequency between the injection tone and free-running laser. When locking occurs, the spectrum (and noise) is abruptly minimized as no difference frequency signal is generated under this condition.

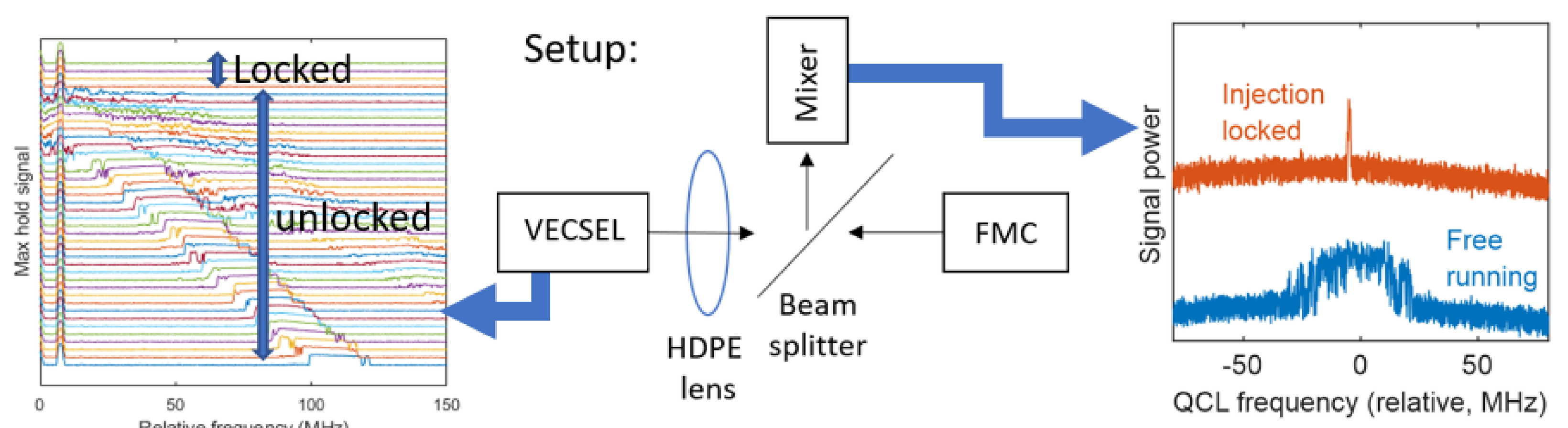

Figure 1. Center: A block diagram of the experimental set up. The QCL (in this case a VECSEL) bias port is monitored using a bias-tee and a microwave amplifier (left), and the lock condition is monitored using a harmonic mixer (right). Lock condition is unambiguously detected using both methods.

We have focused our recent efforts to prepare to demonstrate subharmonic injection locking, which is particularly attractive because electronic sources are generally more powerful at lower frequencies, and at frequencies above 3 THz, they are still under development. Two aspects were addressed: 1) create a metasurface (the amplifying medium) capable of free-space coupling to a tone at the half or third harmonic; 2) Produce an output coupler that permits the subharmonic frequency radiation to pass but is sufficiently reflective at the fundamental to form the laser cavity. Figure 2 shows the concept of the high-contrast grating, which is a suspended grid of silicon with modeling for the 2.5 THz coupler. Figure 3 shows the demonstrated behavior of a 4.7 THz output coupler.

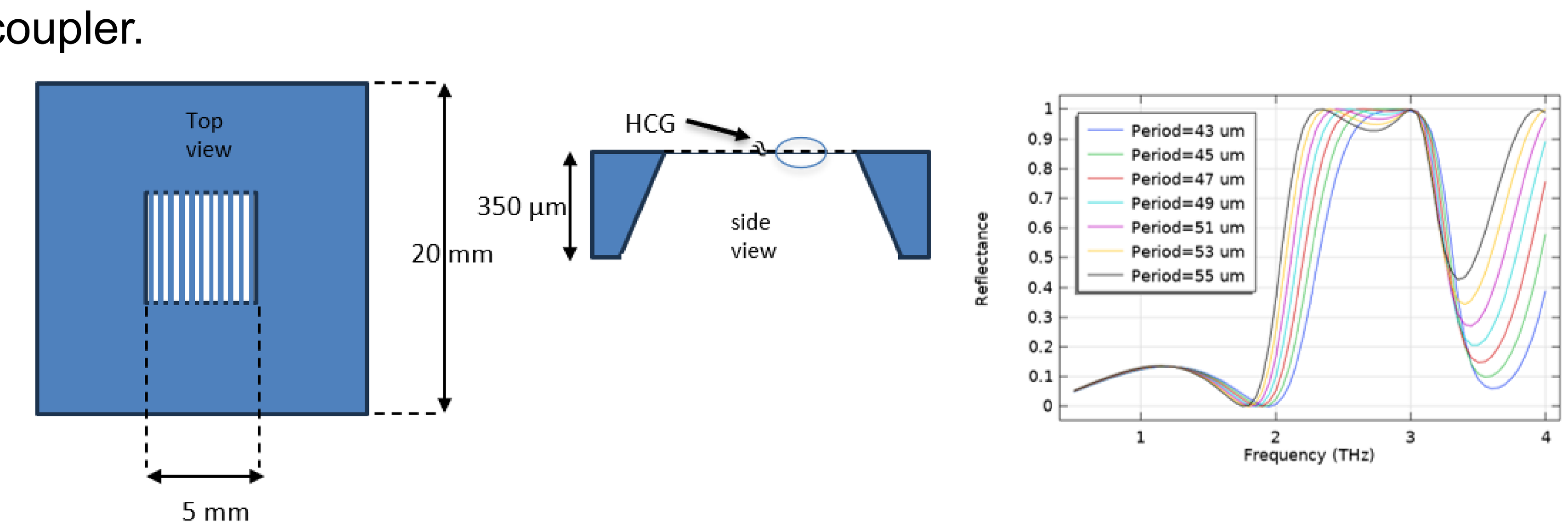

Figure 2. The high-contrast grating is a simple structure made from high-purity silicon. The predicted performance of a 2.5-2.7 THz output coupler shows high reflectivity required at the fundamental, and low reflectivity at the both the half and third harmonic.

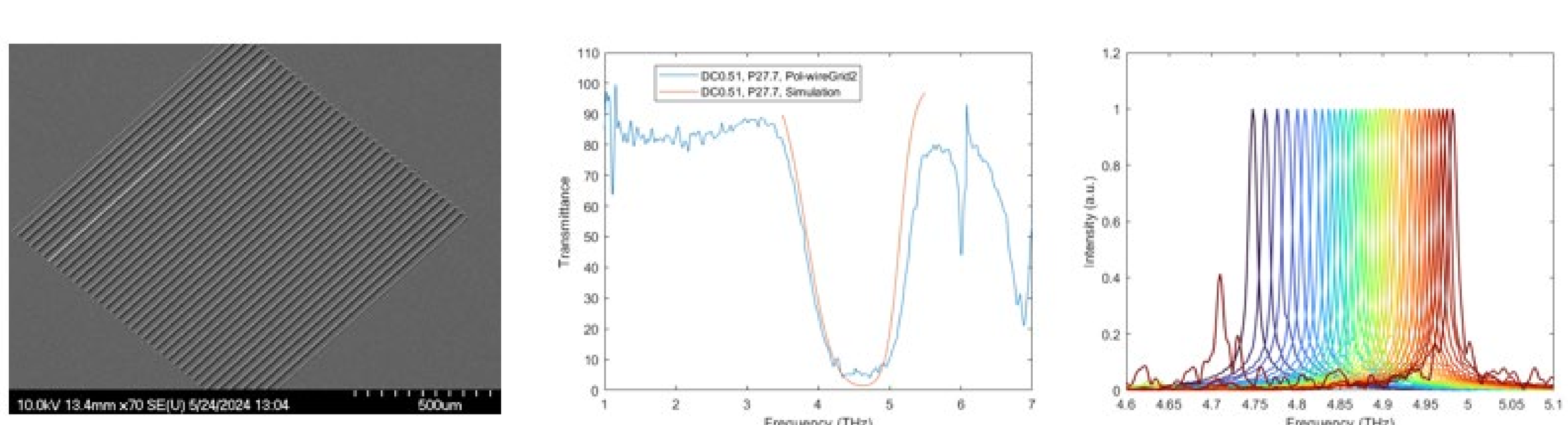

Figure 3. Demonstration of a high-contrast grating at 4.7 THz. The left shows the actual devices, center the measured transmittance, and right the actual performance using the same device as the output coupler for a QCL.

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Publications:

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