Evidence of comb formation in terahertz quantum cascade lasers

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Recently, there has been much interest surrounding the generation of optical frequency combs using quantum cascade lasers (QCLs). The most straightforward way to accomplish this is through active mode-locking, in which the gain of the cavity is forced to oscillate at its round-trip frequency by RF injection, thereby producing broadband pulses. Such behavior has been observed in both mid-infrared [1] and in terahertz QCLs [2]. However, actively mode-locked lasers cannot easily exploit the full bandwidth of the gain medium being used, because to do so would require that the injected RF pulses have durations on the same order of magnitude as the desired laser pulse duration (e.g., picoseconds). An alternative approach that was recently demonstrated in the mid-infrared is the generation of a frequency comb by four-wave mixing in a low-dispersion gain medium [3]. Though this approach is a passive one, due the short gain recovery time in mid-infrared QCLs it yielded frequency-modulated light rather than pulsed light. Here, we demonstrate broadband terahertz QCLs that generate narrow beatnotes on fast detectors, providing evidence that the QCLs are acting as a frequency comb. In addition, these lasers also act as sources of narrowband microwave radiation while DC biased, potentially indicating that they are passively mode-locked.

In order for passive mode-locking to occur, several conditions must be met. First, the dispersion of the cavity must be eliminated, allowing for pulses to maintain their profile as they propagate through the laser. Instead of relying on the low dispersion of a particular gain medium, we designed cavities whose dispersion could be arbitrarily compensated by geometry. Ultimately, however, linear dispersion correction is not enough to create a mode-locked laser, because the cavity must have a way of favoring large intensities over small ones in order for pulses to spontaneously develop. Typically, this is done with a saturable absorber of some kind, such as a Kerr lens. Instead, we chose to use a double-peaked gain medium capable of experiencing negative differential gain in a bias regime of positive differential resistance. Large intensities locally deplete the bias field of the QCL while increasing the optical gain. Because the bias field of the QCL is in the same waveguide mode as the optical field, the depleted bias can co-propagate with the optical field and promote pulse formation.

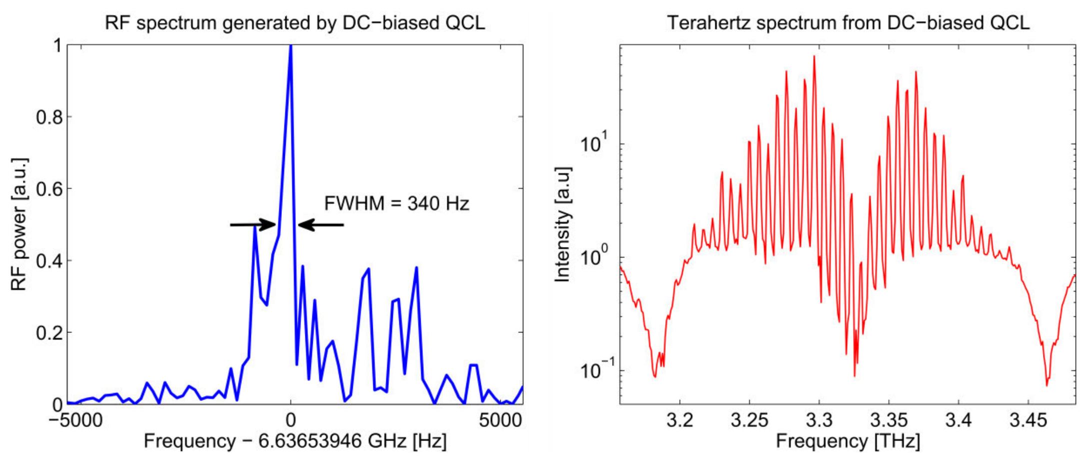

Fig. 1: RF spectra generated by a dispersion-compensated 5-mm THz-QCL at 55 K, as well as a corresponding terahertz spectrum. (The dips in the terahertz spectrum are from the FTIR beamsplitter.)

As a side effect of this process, we observe strong narrowband RF radiation leaking out of the bias line of correctly dispersion-compensated DC-biased devices, with sub-kHz linewidths and power levels on the order of hundreds of microwatts. (Note that these devices are operated squarely in a positive differential resistance regime.) Figure 1 shows an RF spectrum obtained from a 5-mm QCL using a bias tee, as well as a terahertz spectrum obtained under similar conditions. Approximately 35 modes of the cavity are lasing, separated by the frequency of the RF signal coming out of the laser, 6.6 GHz. The RF signal is extremely narrowband when measured on time scales of a few milliseconds, but when measured on longer timescales it fluctuates due to vibrational noise from the pulse tube cryocooler. It is also possible to detect harmonics of the 6.6 GHz signal, but these are weaker due to the use of non-coaxial cabling in the cryostat.

Because the gain recovery time of a 5-mm laser in question is significantly shorter than the round-trip time (150 ps), at biases when there is too much gain available the laser should become unstable or even capable of producing multiple pulses per round trip. Indeed, this is what is observed: at some biases the RF emission becomes dramatically broader (tens of MHz), and at other biases, the RF emission at 6.6 GHz vanishes, leaving terahertz spectra with a mode spacing of about 13 GHz (see Figure 2). This effect cannot be explained by simple multi-mode lasing, and is consistent with the laser producing two pulses per round trip instead of one. It would also be difficult to reconcile this type of behavior with the frequency-modulated signal observed in Ref. 3.

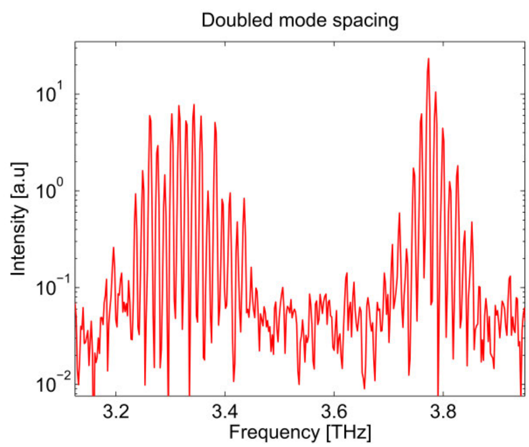

Fig. 2: At biases when both peaks of the gain medium are capable of lasing strongly, the mode spacing can double to 13 GHz, twice the normal repetition rate.

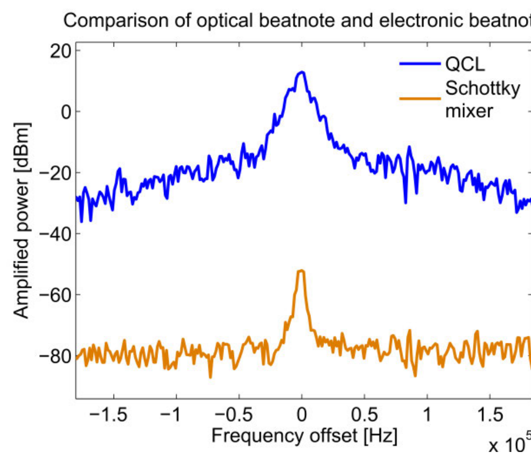

Fig. 3: Comparison of RF spectra measured directly from a lens-coupled QCL and from a terahertz Schottky mixer. The center frequencies have been removed to account for drift that occurred between the measurements.

To actually verify that the QCL is operating as a frequency comb, a room-temperature Schottky mixer was used to detect the optical beatnote between the laser modes. Because the device characterized in Figs. 1 and 2 had a power output too low to be detected by the mixer, a lens-coupled device with a power output of 4 mW had to be characterized instead. Figure 3 shows the RF spectra obtained both directly from the QCL and from the Schottky mixer. Though it was possible to obtain optical beatnotes whose linewidths were as narrow as the beatnotes directly from the QCL, both were substantially less stable than the device which was not lens-coupled. As a result, the linewidth was broader, almost 10 kHz. This is because the center frequency of the comb operation is extremely sensitive to optical feedback, and the addition of the lens increased this feedback and caused the laser to be even more sensitive to vibration from the QCL's cryocooler. Nevertheless, the optical beatnote observed is orders of magnitude less broad than what would be expected from a free-running laser (tens of MHz), and so it verifies that the device is operating as a comb. Future studies will be performed to probe the time-domain behavior of these lasers and to determine whether they are truly mode-locked or not.

[1] Wang et al. "Mode-locked pulses from mid-infrared Quantum Cascade Lasers", *Opt. Express* **17**, 12929–12943 (2009).
[2] Barbieri et al. "Coherent sampling of active mode-locked terahertz quantum cascade lasers and frequency synthesis", Nature Photonics **5**, 306–313 (2011).
[3] Hugi et al. "Mid-infrared frequency comb based on a quantum cascade laser", Nature **492**, 229–233 (2012).