Room Temperature Terahertz Frequency Comb Using Quantum Cascade Lasers

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ABSTRACT

Researchers at Northwestern University, Illinois have designed a terahertz (THz) frequency comb using a Quantum Cascade Laser (QCL) with a Distributed Feedback (DFB) grating inside the cavity. The DFB grating addition allows for dual wavelength emission from the QCL. A single-mode state and a harmonic comb state combine inside the cavity for a THz frequency comb. The device generates THz frequencies at room temperature without any external optical setup. This allows for a harmonic frequency comb at 3.0 THz with a range of 2.2 to 3.3 THz. With the single QCL dual wavelength emission, the THz comb is more stable than multiple sources. This devices enables a greater current dynamic range for harmonic comb operation, especially useful in spectroscopy applications. Two uses of QCL frequency combs demonstrated by researchers at Harvard University are also discussed.

QCL FREQUENCY COMBS

Quantum Cascade Lasers (QCLs) can be useful for creating optical frequency combs (OFCs) due to the engineered properties of intersubband transition, fast phonon scattering, high power efficiency, and dispersion management.[1] QCLs also exhibit four distinct laser states. Injection currents in the QCL determine the state from lowest current to highest: single mode, harmonic frequency comb, fundamental frequency comb, and high-phase noise state.[2] Single mode state will only emit one mode or frequency peak. Harmonic frequency combs emit multiple modes equally spaced by higher harmonics of the cavity free spectral range (FSR). Fundamental frequency combs emit multiple modes, but the adjacent cavity modes are populated. High-phase noise state is when the comb is destabilized and exhibits a high-phase-noise pedestal.[2]

Terahertz (THz) QCL combs show potential for spectroscopy and imaging, but the cryogenic aspect of operation is a barrier to commercial production. Cryogenic operation increase setup and application complexity and cost. Room temperature QCLs for THz frequency combs are difficult to design compared to the mid-infrared (mid-IR) QCL.

When operating in the mid-IR to the THz range, techniques used to generate OFCs are not easily executed or possible. Techniques such as difference-frequency generation, optical parametric oscillation, and photoconductive antenna have been employed to create OFCs up to the THz range. However, these techniques require intricate optical layouts.[1] Down-converting a mid-IR comb to THz range can prove difficult. Northwestern University has a novel approach to eliminate external optics while downconverting.

WHAT IS A FREQUENCY COMB?

A frequency comb is a laser with a spectrum of equidistant-spaced frequency peaks (**Figure 1**). This can be used as an optical ruler for frequency measurements. Performing measurements on a wide range of frequencies requires a large overall bandwidth of the frequency comb.[3]

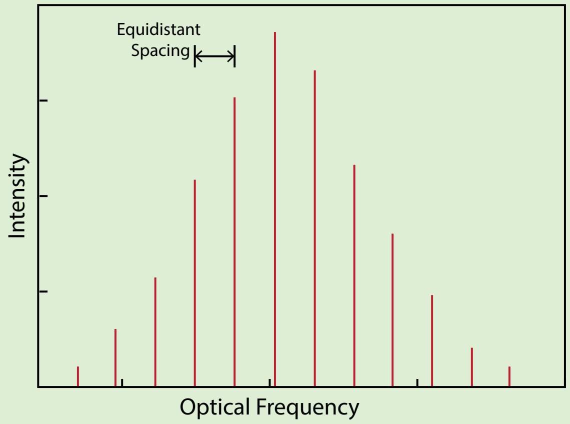

Figure 1. Frequency Comb Illustration

Optical frequency combs (OFCs) can be generated with a variety of techniques: mode-locked lasers (amplitude-modulated), microresonators,[2] optical parametric oscillation, difference-frequency generation, and four-wave mixing (FWM).[1] Applications include: metrology, chemical sensing, atomic clocks, wireless communication, data transmission and spectroscopy.

SOLUTION DESIGN

To down-convert to the THz range, another mid-IR comb or a single mode is needed at a different frequency. This must be generated in the same cavity simultaneously, or it must be generated with two QCL sources as in Reference 2. It is difficult for QCLs to emit two separate wavelengths at the same time owing to the gain competition of the QCL design. Solutions to this problem can bring dispersion in the cavity and can suppress comb operation.

Researchers from Northwestern University, Illinois have developed a THz frequency comb using a mid-IR QCL and difference-frequency generation. A distributed feedback (DFB) grating is inserted into the QCL cavity so a single mode can be created along with the harmonic comb at the same time. The DFB grating is largely frequency-detuned to ensure the emission of both the single mode and harmonic comb. This wavelength is detuned ~80-90 cm^{-1} with regards to the comb emission wavelength.[1] This generates the least effect on laser dispersion. This DFB grating design in the cavity of the QCL does not negatively affect the four-wave mixing for comb operation. **Figure 2** shows the QCL and DFB grating design.

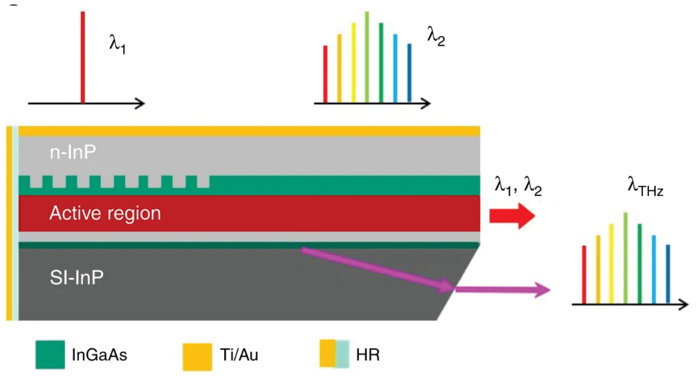

Figure 2. Schematic of largely detuned DFB QCL design for THz frequency comb operation. Both the single-mode (λ_1) and harmonic (λ_2) states are shown in the QCL cavity to produce the THz frequency comb (λ_{THz}). Also shown are the layers of the QCL material and the DFB addition[1]

Figure 3 shows the single-mode and multimode (harmonic comb) state generation from the single mid-IR QCL. The current is increased from two single-mode states operation to a stable harmonic comb and a single mode state operation above 1.5 A.

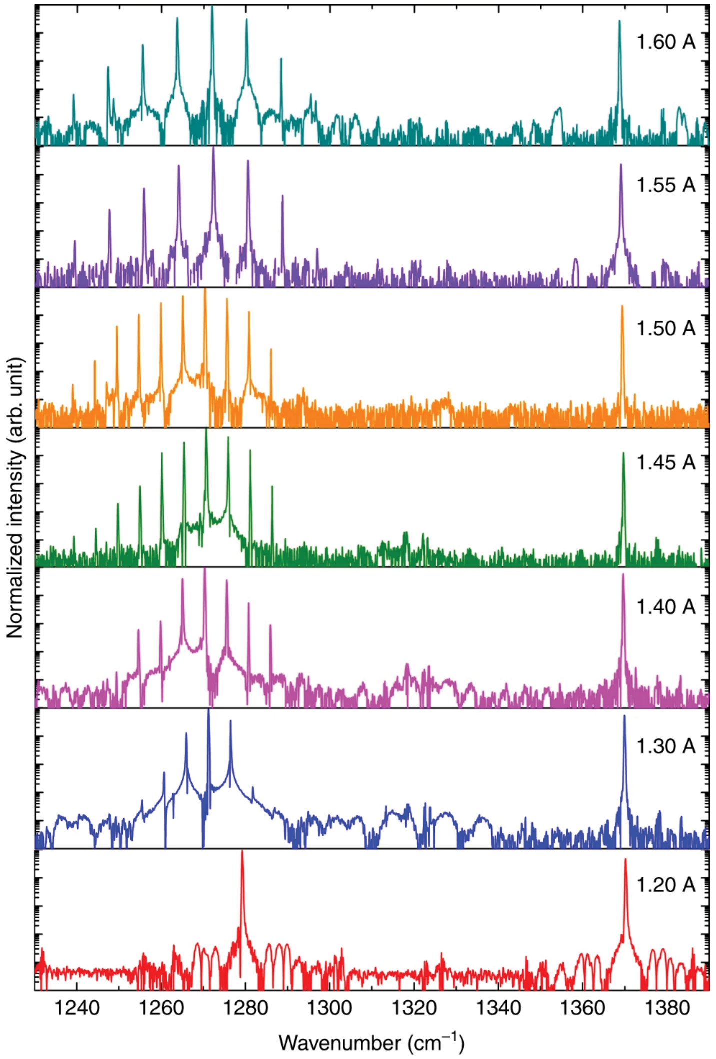

Figure 3. On-chip generation of single mode and multimode comb from a single mid-IR QCL. Lasing mid-IR spectra of a 4-mm long DFB QCL evolving with currents from 1.2 to 1.60 A at room temperature in continuous wave operation[1]

The DFB QCL device generates two distinct states: a single mode (λ_1 = 7.25 μm) and a multimode emission (λ_2 = 7.81 μm) with mode separation of 14 or 22 times the FSR depending on the current. Lu states,

> The impact of the DFB element is twofold. The single mode emission resulted from the DFB section forms a spatial population grating in the cavity and induces an incoherent gain for multimode operation near the gain peak at higher currents. On the other hand, the beating between the single DFB mode and the multimode introduces additional population pulsation nonlinearity which in turn contributes to the mode skipping of the multimode emission in the working current range.[1]

Conventional mid-IR detectors are not useful in this experiment to analyze the comb operation as the mode spacing of the harmonic comb is too great for the bandwidth of the detector. Researchers at Harvard University[2] use a multi-heterodyne beating experiment between two QCLs. One QCL is in the harmonic comb state, and the other QCL is in the fundamental comb state as the reference comb device. At Northwestern University, a reference Fabry-Pérot (FP) QCL is used as a reference comb in the fundamental comb state to verify the THz comb operation.

The FP QCL is operated at a current of 1.52 A to establish the fundamental state. The DFB QCL is operated at a current of 1.45 A in the multimode harmonic state. Both are measured using a Fourier Transform Infrared (FTIR) Spectrometer. These settings can be seen in **Figure 4**.

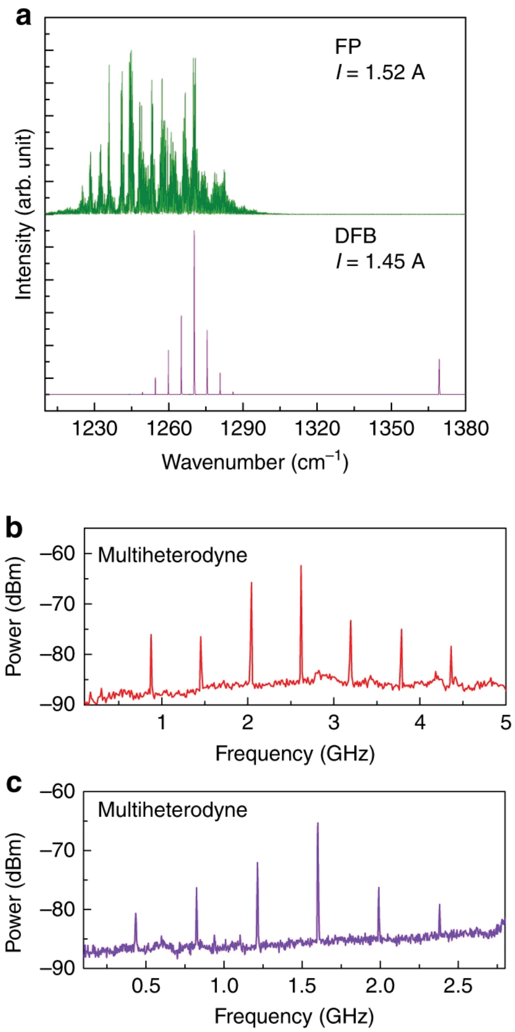

Figure 4. Multi-heterodyne characterizations based on the DFB and FP QCL combs. (a) Lasing spectrum of the FP and DFB combs recorded with the FTIR. Multi-heterodyne beating of the FP comb at 1.52 A and the DFB comb at 1.45 A (b), and the DFB comb at 1.55 A (c). Total acquisition time: 100 ms[1]

The heterodyne spacing is determined by the frequency difference between mode spacing of the DFB harmonic comb and the multiple of FP mode spacing.[1] This experiment confirms the harmonic comb generation of the DFB QCL.

The DFB QCL, with dual wavelength operation, enables the second-order difference-frequency generation that can transfer the mid-IR comb into the THz range.

RESULTS

With this innovative technique, the researchers have achieved a THz harmonic frequency comb at 3.0 THz at room temperature with a range of 2.2 to 3.3 THz. All testing was performed on a thermoelectric cooler (TEC) stage precisely controlled to room temperature (293 K). **Figure 5** shows the THz frequency results at different currents of the DFB QCL harmonic comb.

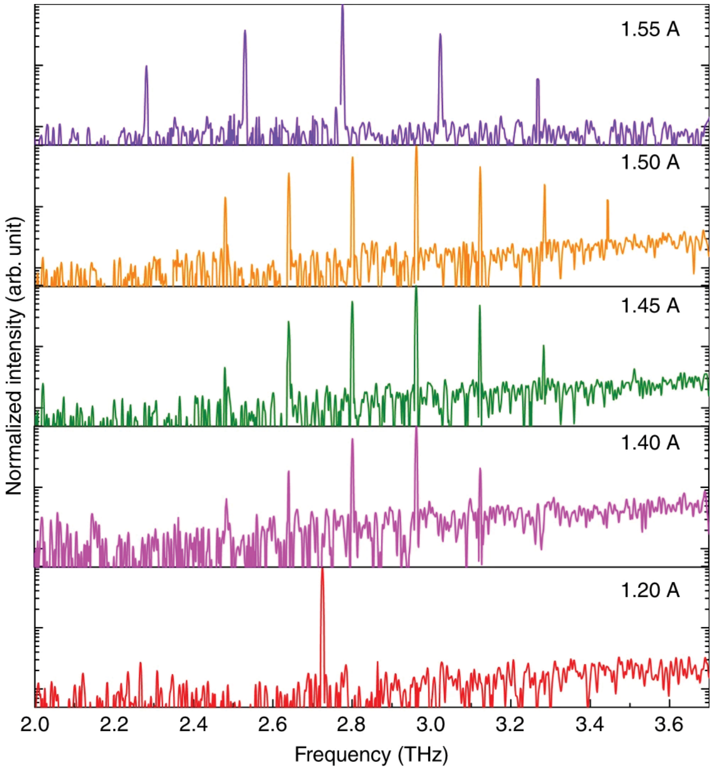

Figure 5. On-chip generation of THz frequency comb from a mid-IR QCL. Lasing THz spectra of the DFB QCL comb evolving at different currents from 1.20 to 1.55 A at room temperature continuous wave operation[1]

The frequency spacing between modes, in **Figure 5**, is 157 GHz for currents from 1.3 - 1.5 A and 245 GHz for currents above 1.5 A. This corresponds to 14 FSR and 22 FSR mode spacings. Because the two mid-IR pumping sources are simultaneously generated from the same QCL chip, the stability of the THz comb is greatly improved from the frequency tuning rates that are shared.[1] The THz comb tuning rates of the emitting frequency and carrier frequency are estimated to be -.56cm^{-1}/A and 6.9 MHz/mA. These values are over ten times smaller than the mid-IR comb values, increasing stability.[1]

The DFB QCL design has the increased current dynamic range for harmonic comb operation and increased reproducibility while operating at room temperature. It has also decreased complexity in the setup - no cryogenic cooling or external optical elements are needed. Further research and experimentation could enable monolithic control and tuning of emission of harmonic combs as well as realization of fundamental THz frequency comb through the DFB QCL design.

ALTERNATIVE APPLICATIONS

Self-Starting Harmonic Frequency Comb

Researchers at Harvard University, Massachusetts have developed frequency combs using QCLs for other applications based on a self-starting comb generation design.[2] Researchers from Harvard University have developed a terahertz harmonic frequency comb using a QCL device.

This experiment studies the harmonic comb state of the QCL and its possibilities. Two FP QCLs are used to produce and confirm the presence of a harmonic comb. Injected current is increased from the lasing threshold of single-mode operation to harmonic comb state. The second FP QCL has a higher injection current to operate at the fundamental comb state for reference to verify the equidistant spacing between modes in the harmonic comb QCL.

This multiheterodyne beating technique allows the measurement of terahertz-scale beatnote frequency of the harmonic state. This allows for the sample spectrum to be down-converted from the optical domain to the radiofrequency (RF) domain. The RF comb that is created can be measured and verified using electronic frequency counters.

The harmonic comb QCL operates with a repetition rate of 400 GHz, and the reference fundamental comb QCL operated with a repetition rate of 7.7GHz. The light emitted from the harmonic comb QCL is passed through the reference QCL. This enables extraction of the multiheterodyne signal for verification.

The optical carrier frequency of the laser was found to be f_c = 66.7 THz with improvements of the stability of the signal due to the self-detection design using a reference QCL. This concept utilizes intermodal comb spacing of hundreds of gigahertz up to the terahertz range. Applications for this compact comb device range from terahertz wireless communication systems, telecommunications, radioastronomy, quantum optics, to spectroscopy seen in the previous design. Due to the QCL's versatile composition, microwaves can be generated and modulated to wirelessly transmit information.[2]

Radio Frequency Transmitter

Other research from Harvard University realizes a compact radio frequency transmitter based on a QCL frequency comb.[4] With demand for wireless communication and devices increasing, the need for higher frequency operation also increases. Extremely narrow linewidth can be generated at room temperature, and modulation and emission of subterahertz waves are attainable. This can compensate the growing need for high-frequency communication technology with high-speed data transfer.

In this experiment, a FP QCL operating in the fundamental frequency comb state is used with a narrow linewidth beat note at f_B = 5.5 GHz. An Antenna is attached to the top of the QCL and connected to two top laser contacts, and a gap is created in the top electrode. This allows researchers to use the radio frequency alternating currents from within the QCL to generate into the antenna enabling wireless microwave emission as well as the mid-IR radiation output from the QCL. This creates the Laser Radio Transmitter (LRT).

An audio analog signal can modulate the laser current which modulates the laser beat note frequency. This encodes the baseband information onto the 5.5 GHz carrier wave which is received by a horn antenna away from the laser. This signal is filtered and down-converted to fit the bandwidth of a software-defined radio. The audio track can be retrieved after demodulation. This device shows the success of a radio frequency transmitter using a QCL device.

Further advancements show wireless frequency sensitivity capabilities with the LRT. This would allow the laser beat note to be wirelessly injection locked to an external microwave reference. This single device can be used in applications similar to the ones previously listed.[4]

WAVELENGTH'S ROLE

The QCLs operation state is highly dependent on the injection current. Because the harmonic comb state is accomplished with slightly more current than single-mode state, it is crucial that the QCLs are properly and accurately driven and have stable temperature control.

Wavelength Electronics' QCL2000 LAB QCL drivers (**Figure 6** left) provide up to 2.0 A of current to the QCLs with noise current as low as 0.4 µA (RMS). The average noise density of 4 nA/√Hz is necessary for the design of the room temperature frequency comb. These high-precision and ultra-low noise current sources provide the necessary stability for harmonic frequency combs.

Wavelength Electronics' PTC10K-CH temperature controller (**Figure 6** right) provides up to ±10 A of current to the TEC to stabilize the temperature of the QCLs. The PTC has temperature stability of less than 0.0012ºC which surpasses the required temperature stability of less than 10 mK in the experiment. The compact and accurate design of the PTC enables total temperature control of the lasers.

At Harvard University, both studies use Wavelength Electronics' TC5 LAB (**Figure 6** top) to control the temperature of the QCLs. The TC5 LAB has temperature stability as precise as 0.0002ºC which also surpasses the precision of better than 10 mK required. QCL2000 LABs are also used to drive the QCLs at the varying current levels with the same noise levels listed for the Northwestern University study.

Figure 6. Wavelength Electronics' TC5 LAB (top), QCL2000 (left), and PTC10K-CH (right)

PRODUCT USED
QCL2000 LAB, PTC10K-CH, TC5 LAB

KEYWORDS
Quantum Cascade Laser, Frequency Comb, Room Temperature, Terahertz, Harmonic, Distributed-feedback Grating, Mid-IR, Multiheterodyne Spectroscopy

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USEFUL LINK

- QCL2000 LAB Product Page
- PTC10K-CH Product Page
- TC5 LAB Product Page

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Figures 2 and 4 were cropped or the format was changed. No changes were made to the other images. They are presented here in their original form.

The captions for Figures 2 and 4 have been modified from their original form.

REVISION HISTORY

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REVISION	DATE	NOTES
A	June 2020	Initial Release