Terahertz quantum cascade laser frequency combs

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Abstract: We discuss the development of broadband terahertz laser frequency combs, compact semiconductor devices that combine the high power of lasers with the broad spectra of pulsed sources.

1. Introduction

Optical frequency combs [1] have had a revolutionary impact on high-precision metrology and spectroscopy. At longer-wavelength terahertz frequencies, combs generated by pulsed lasers [2] have proven to be useful sources of radiation for detecting molecular fingerprints, since many molecules have strong rotational and vibrational resonances in the terahertz regime. Recent years have also seen the development of terahertz quantum cascade lasers, which are compact semiconductor sources of high-power narrowband terahertz radiation [3]. However, typical pulsed terahertz sources require bulky optics and produce only microwatts of average power due to their low efficiencies, while most terahertz lasers are narrowband and are thus unsuitable for broadband spectroscopy.

2. Key results

Here we demonstrate passive terahertz frequency combs based on quantum cascade lasers, which combine the high power of fundamental oscillators with the broadband capabilities of pulsed sources. By accurately measuring and properly compensating for the dispersion of the laser waveguide, we can generate spectra covering the broad gain-bandwidth of terahertz quantum cascade lasers. Figure 1 shows the beatnote generated by such a device at its repetition rate, offset from its center frequency of 6.82 GHz. As the device is in a cryocooler, environmental fluctuations cause the beatnote to drift over millisecond timescales, but removing these fluctuations shows its intrinsically long-term phase coherence.

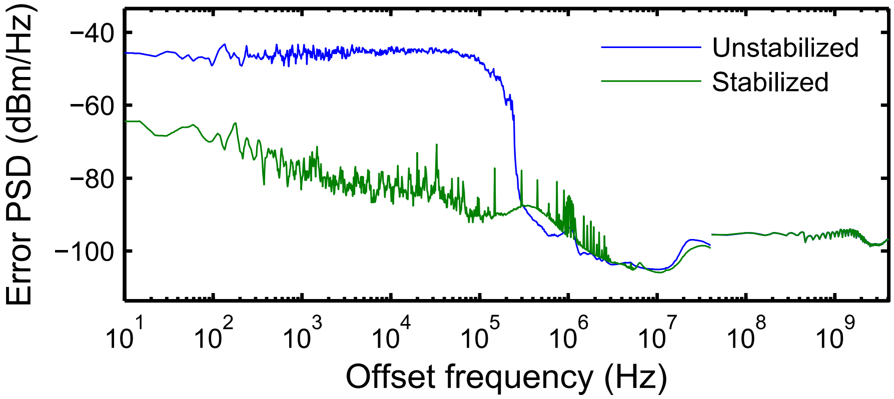

Figure. 1. Beatnote from QCL offset relative to 6.82 GHz, shown with the environmental fluctuations stabilized and unstabilized. 99.92% of the free-running phase noise is removed. (The spectra are discontinuous at 40 MHz because the signal below 40 MHz was measured using downconversion and a fast ADC, while the signal above 40 MHz was measured with an RF spectrum analyzer.)

To determine how much of the laser's spectrum is actually spaced by the observed repetition rate, we developed Shifted Wave Interference FTS, or SWIFT spectroscopy, an interferometric scheme that quantitatively characterizes how much of the laser's energy is spaced by this frequency. By detecting the quadrature of the RF beatnote as a function of a Michelson interferometer's stage delay, we can determine the following quantity:

$$\langle E^*(\omega)E(\omega \pm \Delta\omega)\rangle = \frac{1}{2}(S_I(\omega) \mp iS_Q(\omega)) \equiv X_\pm(\omega) \tag{1}$$

where Δω is the laser's repetition rate, E(ω) is the electric field of the source, angle brackets represent an integration over laboratory timescales (seconds) and convolution with the instrument apodization function, $S_I(\omega)$ and $S_Q(\omega)$ are the Fourier transforms of the measured quadrature interferograms, and $X_\pm(\omega)$ are referred to as "correlations." By comparing the correlation measurement with the same quantity digitally calculated from the normal laser spectrum, we can determine whether the laser's spectrum truly consists of evenly-spaced modes. Figure 2 shows the result of this process. Because the correlation spectrum agrees with the same quantity calculated from the laser spectrum, this shows that the laser lines are all contributing to the frequency comb.

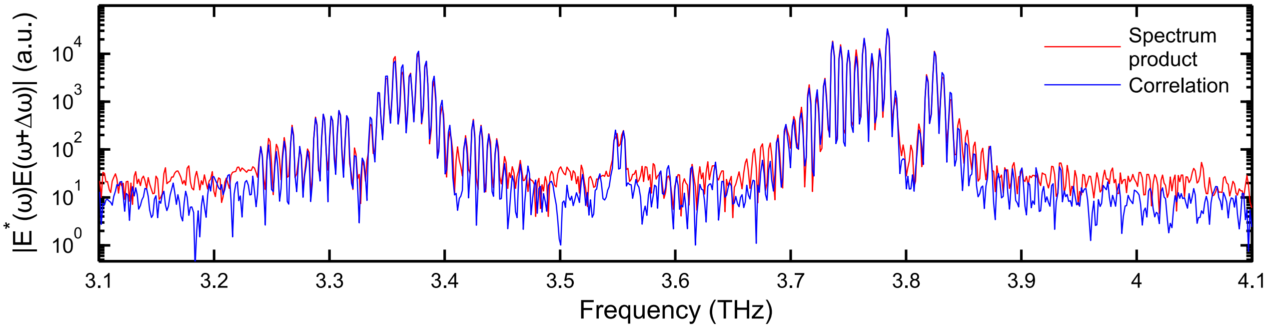

Figure 2: Red line: spectrum product, the product of each laser line and its adjacent line computed from its spectrum. Blue line: correlation product, which represents the same quantity but measured using a fast detector and an analog quadrature technique. Their agreement indicates that the spectrum consists completely of evenly-spaced lines.

By examining the heterodyne beating between two lines of the comb and a free-running narrow-linewidth third-order DFB laser (see Figure 3), we find that the absolute linewidth of these lasers is similar to the linewidth of normal DFB lasers. These lasers can generate more than 70 lines covering a frequency range of ~500 GHz (14% of the center frequency) with ~5 mW of power, and fully exploit the lasers' gain bandwidth. Because this radiation is sufficiently powerful to be detected by Schottky-diode mixers, our result could lead to compact solid-state terahertz spectrometers and portable molecular sensors. These lasers can also serve as the broadband sources needed for useful terahertz computed tomography.

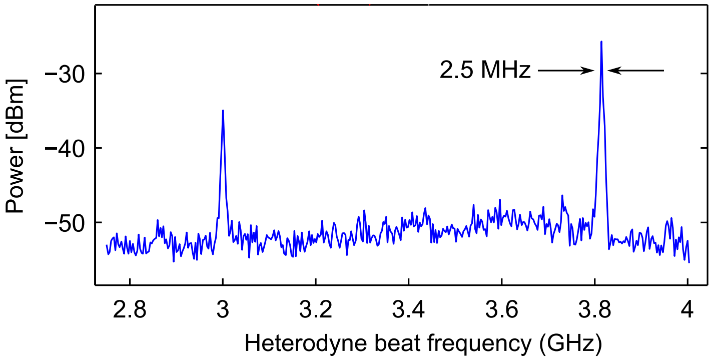

Figure 3: Heterodyne beating measured between two lines of the comb and a third-order DFB.

4. References

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