# Coherent breathing of laser modes in terahertz quantum cascade lasers

**David Burghoff**[1,*], Yang Yang[1], John L. Reno[2], Qing Hu[1]
[1] *Department of Electrical Engineering and Computer Science, Research Laboratory of Electronics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
[2] *Center for Integrated Nanotechnology, Sandia National Laboratories, Albuquerque, New Mexico 87123, USA*
**Contact Email: burghoff@mit.edu*

Frequency combs based on quantum cascade lasers have attracted much attention as potential sources for broadband compact broadband spectroscopy, and have been demonstrated in both the mid-infrared [1] and terahertz [2]. One of the signature features of such combs is the existence of a narrow beatnote measured on a fast detector, reflecting the fact that all of the laser modes are separated by the same spacing. Such combs typically form in the presence of low-dispersion cavities; nonlinearity is able to then overcome residual non-uniformity and phase-lock the modes.

However, even at electrical biases at which combs are not able to form a number of rich dynamics can be observed, including the so-called multiple and broad beatnote regimes. In order to fully understand the mechanisms limiting comb formation, it is necessary to experimentally characterize the dynamics of such modes of operation. For practical applications, it is also important to investigate the extent to which these regimes possess any of the attractive features typically ascribed to the comb state.

We first examine the broad beatnote regimes of dispersion-compensated terahertz quantum cascade lasers (THz QCLs) similar to those in Ref. 2. The device is biased in continuous wave mode using a bias tee, and a radio frequency (RF) spectrum is collected from the device, shown in Fig. 1a. The RF spectrum shows a broad beatnote, exhibiting multiple peaks and a linewidth of several MHz.

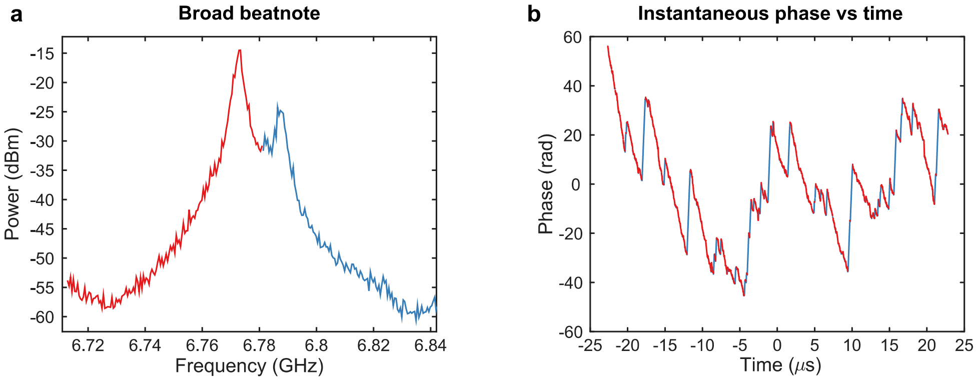

**Fig. 1**: **a.** Broad beatnote associated with a low-dispersion THz QCL in a non-comb state. Two sub-peaks are evident. **b.** Instantaneous phase of the beatnote measured as a function of time. Regions of negative slope are associated with the lower peak; regions of positive slope are associated with the upper peak.

By utilizing an I/Q demodulator and an oscilloscope to downconvert the beatnote, we can measure its instantaneous phase and frequency, shown in Fig. 1b. We find that the phase remains linear within short timescales (indicating a constant frequency), but chaotically switches over longer timescales. This switching is aperiodic in time and gives rise to the double peak in the frequency domain.

Even though such a laser cannot be considered coherent in the conventional sense, we investigate whether it can be considered coherent relative to an unconventional clock: the beatnote itself. To do this, we perform a self-referenced SWIFTS measurement [3], i.e. we use the beatnote from the QCL itself as the local oscillator for a demodulator detecting the optical power of the QCL through an interferometer. (This measurement is essentially a multiplexed measurement of the coherence of each laser line with the line next to it.) The results are shown in Fig. 2a.

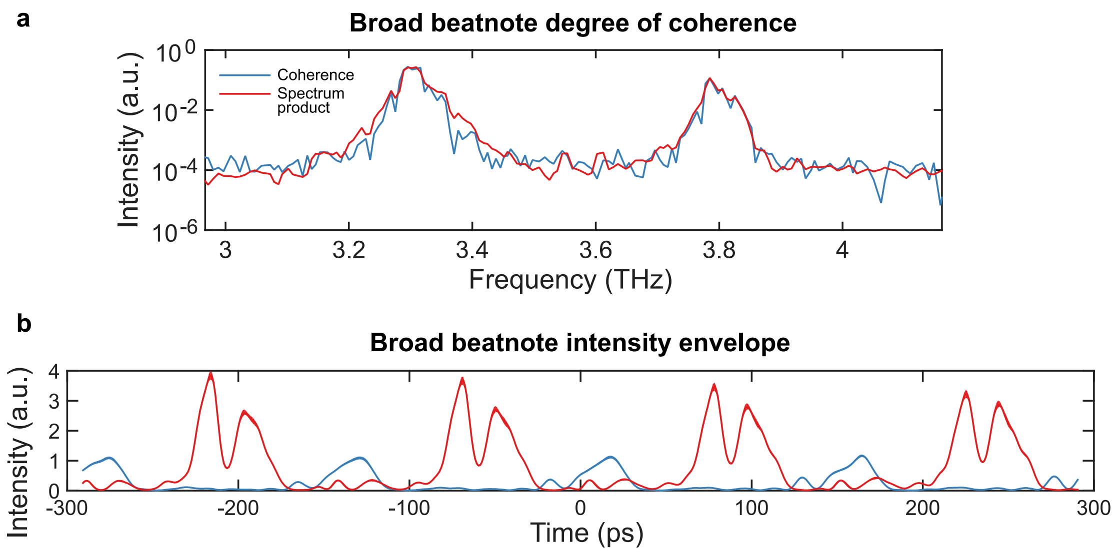

**Fig. 2**: **a.** Degree of coherence measured by self-referenced SWIFTS in a broad-beatnote regime. **b.** Reconstructed time-domain intensity envelope.

The close agreement between the coherence measured by SWIFTS and the spectrum product measured by FTS over a large bandwidth shows that even though the frequency of the beatnote varies over short timescales, the lines of the laser continue to be uniformly spaced. In other words, the spectrum coherently “breathes.”

We can also use the SWIFT spectrum to reconstruct the intensity envelope of such a beatnote; the results are shown in Fig. 2b. For the sake of clarity, the two portions of the laser spectrum are separated into two intensity envelopes, representing the lower (red) and upper (blue) portions of the spectrum. Although previous work has identified both frequency-modulated and soliton regimes in passive QCL combs [3], the data shown here represents a multi-pulse regime, with two pulse trains interleaved by half a repetition period. We will discuss how such a configuration impacts the timing jitter of such a laser and impacts its ability to form frequency combs.

## References

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