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Fully Phase Stabilized Quantum Cascade Laser Frequency Comb

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The road towards the realization of quantum cascade laser (QCL) frequency combs [1,2] has undoubtedly attracted ubiquitous attention from the scientific community. These devices promise to deliver an all-in-one (i.e. a single, miniature, active device) frequency comb synthesizer in a range as wide as the QCL spectral coverage itself (from about 4 microns to the THz range), with the unique possibility to tailor their spectral emission by band structure engineering. For these reasons, vigorous efforts have been spent to characterize the emission of four-wave-mixing (FWM) multi-frequency QCLs, aiming to seize their comb-like mode-locked operation [3-6].

Nevertheless, in order to classify these devices as frequency combs, it is essential to show that their optical output is described by parameters that one can measure and, more important, control. Here, in analogy with the decisive turning point that transformed mode-locked pulsed lasers into the revolutionizing tool called *frequency comb*, we present the full phase-stabilization and independent control of the two comb degrees of freedom of a mode-locked multi-frequency QCL [7]. In this way we unleash its full metrological-grade potential, and definitely prove the realization of the first QCL frequency comb. Fig. 1 shows the optical beating generated by mixing a fully stabilized THz QCL comb with a reference frequency comb, generated by optical rectification. The obtained multi-heterodyne spectrum shows ultra-narrow beatnotes (limited by the 0.5 Hz resolution bandwidth of the spectrum analyzer).

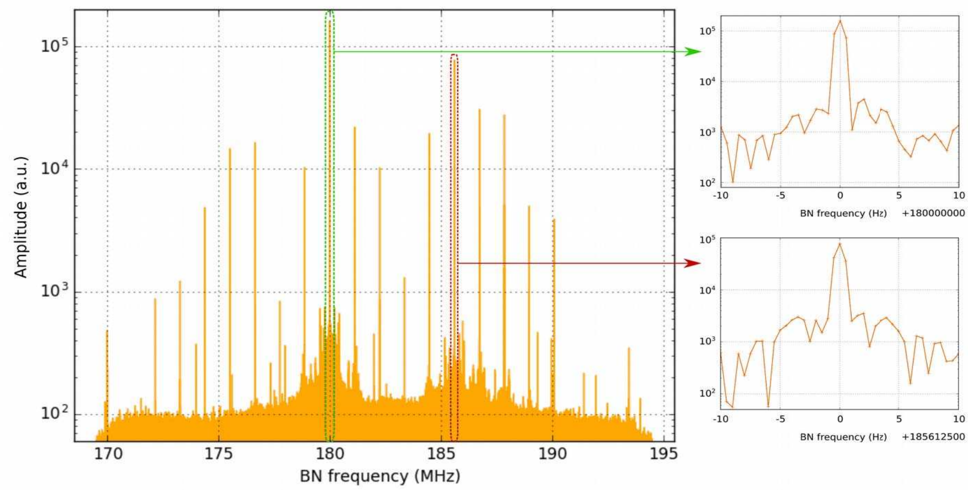

Fig. 1 Spectrum of the multi-heterodyne signal obtained by mixing an optically-rectified THz frequency comb and the fully stabilized QCL comb. The beat-notes are limited by the instrumental resolution bandwidth (0.5 Hz).

The full-phase-stabilization of the QCL comb emission against the atomic clock frequency standard is achieved by independently and simultaneously controlling the two comb degrees of freedom (frequency offset and modes spacing), and allows for the simultaneous measurement of the THz absolute frequencies with a 6 Hz accuracy. Moreover, by measuring the modes phases, we retrieve the electric field and the temporal emission profile of the phase-locked QCL, showing a reproducibility over different days. Finally, we perform a correlation analysis on the modes phases, unveiling a residual collective phase noise that confirms the FWM mode-locking mechanism.

References

[1] A. Hugi, et al. "Mid-infrared frequency comb based on a quantum cascade laser", Nature **492**, 229–233 (2012).
[2] D. Burghoff, et al. "Terahertz laser frequency combs", Nat. Photonics 8, 462–467 (2014).
[3] D. Burghoff, et al. "Evaluating the coherence and time-domain profile of quantum cascade laser combs", Opt. Ex. **23**, 1190 (2015).
[4] M. Singleton, et al. "Evidence of linear chirp in mid-infrared quantum cascade lasers", Optica **5**, 948 (2018).
[5] F. Cappelli, et al. "Frequency stability characterization of a quantum cascade laser frequency comb", Laser Photonics Rev. **10**, (2016).
[6] F. Cappelli, et al. "Retrieval of phase relation and emission profile of quantum cascade laser frequency combs", Nat. Phot. Accepted (2019).
[7] L. Consolino, et al. "Fully phase-stabilized quantum cascade laser frequency comb", arXiv:1902.01604 [physics.optics], sumbitted to Nat. Comm. (2019).