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THz quantum cascade laser frequency combs

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***Abstract*— We demonstrate THz optical frequency comb (FC) operation based on ultra-broadband, record dynamic range Quantum Cascade Lasers (QCLs) which exploit a heterogeneous active region design to achieve low and flat chromatic dispersion at the center of the gain curve. By implementing a Gires-Tournois Interferometer (GTI), as tightly coupled at one end of the QCL cavity, we provide lithographically-independent control of the free-running coherence properties of such THz-QCL FC and attain wide dispersion compensation regions, where stable and narrow (~3 kHz linewidth) single beatnotes extend over an operation range that is significantly larger than that of dispersion-dominated bare laser cavity counterparts.**

I. INTRODUCTION

THz Quantum Cascade Lasers (QCLs)-based frequency combs (FC) represent a promising technology to generate uniformly spaced spectral lines in the terahertz frequency domain, without requiring any additional mode-locking mechanism [1-3]. Broadband frequency coverage is achieved by quantum-designing heterogeneous active regions, featuring flat-top gain profiles over the optical bandwidth which provide low chromatic dispersion [2.3]. Consequently, phase-locking of the lasing modes is permitted owing to intracavity nonlinear four wave mixing (FWM) which arises from the inherently high third-order susceptibility. Although group delay dispersion (GDD) can be low, stable comb operation is typically restricted to finite fractions of the QCL dynamic range, as given by a strong electric field-dependence of the GDD associated with intersubband transitions, that is particularly important for heterogeneous designs. This in turn limits the spectral range of the QCL comb. In order to allow FC operation over the entire laser dynamic range and the spectral bandwidth, an accurate control of the dispersion among different longitudinal modes subsets needs to be managed.

II. RESULTS

We report on the development of ultrabroadband QCLs emitting at Terahertz frequencies [3], which exploit a heterogeneous active region scheme and have a current density dynamic range of 3.2, significantly larger than the state of the art, over a 1.3 THz bandwidth (2.25−3.55 THz) in continuous-wave (CW) at a current density of 450 A/cm^2 at 15 K (Fig. 1a). We demonstrate their operation as optical frequency comb synthesizers in CW, with optical output powers of 4 mW (0.73 mW in the comb regime). The intermode beatnote map in Fig. 1b reveals a clear dispersion-compensated frequency comb regime extending over a continuous 106 mA current range, significantly larger than the state of the art reported under similar geometries, with a corresponding emission bandwidth of ≈ 1.05 THz and a stable and narrow beatnote (4.15 kHz linewidth) detected with a signal-to-noise ratio of 34 dB.

Analysis of the electrical and thermal beatnote tuning reveals a current-tuning coefficient ranging between 5 MHz/mA and 2.1 MHz/mA and a temperature-tuning coefficient of –4 MHz/K [3]. The ability to tune the THz QCL combs over their full spectral range by temperature and current paves the way for their use in high-resolution molecular spectroscopy that can provide broad frequency coverage combined with high precision spectral accuracy.

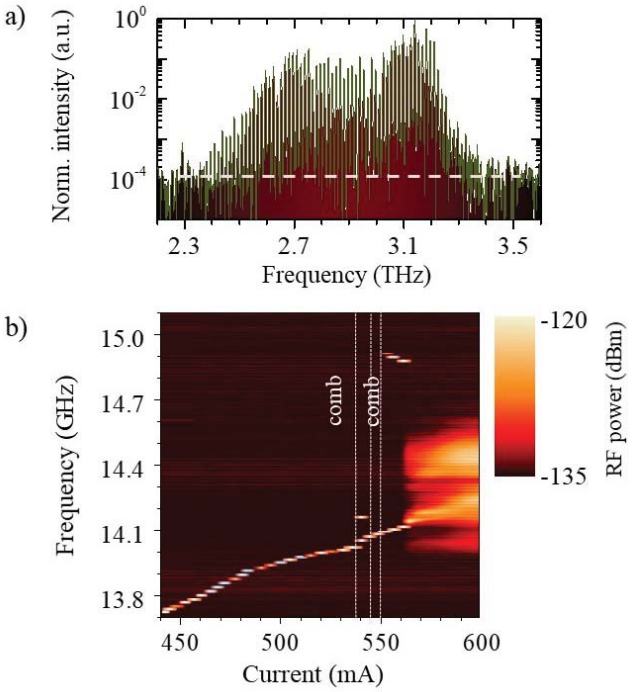

Fig. 1. a) CW emission spectrum of the THz QCL comb obtained from a 2.9-mm-long, 85-µm-wide laser bar by FTIR operating in rapid scan mode, under vacuum with a 0.075 cm^{-1} resolution. The dashed line marks the emission bandwidth driving the QCL in continuous wave at 450mA/cm^2 at 15 K. b) Intermode beatnote map as a function of drive current. The beatnote signal is extracted from the bias line using a bias-tee, and is recorded with an RF spectrum analyzer (Rohde & Schwarz FSW; resolution bandwidth (RBW): 500 Hz, video bandwidth (VBW): 500 Hz, sweep time (SWT): 20 ms, RMS acquisition mode)

We also demonstrate a tunable scheme for lithographically independent compensation of the GDD over the majority of the laser operational range and spectral bandwidth, while achieving evenly spaced optical modes with similar intensities [4]. As most dispersion compensation techniques in the THz range are not tunable [1,5-6], this limits the spectral coverage of the comb and the emitted output power, restricting potential applications in, for example, metrology and ultrashort THz pulse generation.

Here, we engineer a mechanically driven Gires-Tournois Interferometer (GTI) by positioning a moving gold retro-reflector, in close proximity to the back facet of a THz QCL, as shown in the inset of Fig.2, to effectively exploit its sensitivity to back reflected radiation. In particular, fine adjustments of the air-gap of the GTI external cavity disclose 'on-resonance' dispersion compensation regions where intermode beatnote measurements reveal stable and narrow (~3 kHz linewidth) single beatnotes (Fig.2, red dots) extending over an operation range that is significantly larger than that of dispersion-dominated bare laser cavity counterparts (green dots in Fig.2).

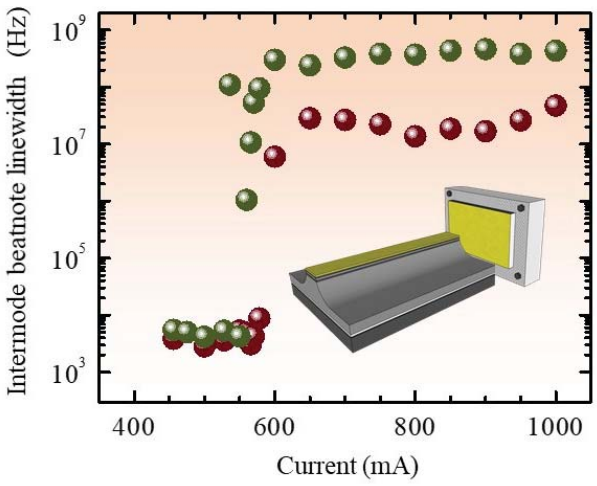

Fig. 2. Intermode beatnote linewidth plotted as a function of the driving current for the 'on-resonance' GTI integrated THz QCL (red dots), with the bare THz QCL laser cavity (green dots) acting as a reference. All measurements are performed in CW at 15 K. The 'on resonance' GTI-coupled THz QCL preserves the narrow single beat-note regime over a continuous 150 mA current range (430-580 mA) for the QCL comb, which is almost 35% wider than that recorded in the dispersion-dominated THz QCL laser cavity. The inset shows a schematic of the external Gires-Tournois Interferometer (GTI) which provides a tunable, lithographically independent control of the free-running coherence properties of the THz QCL comb when part of the light emitted from the back facet is reflected back into the waveguide mode. The metal etalon is mounted on a piezoelectric actuator controlled by a stepper motor.

Finally, we show that our THz QCL-combs are suitable for metrological grade applications, as a sub-Hz level stabilization of each individual emitted mode can be achieved, against the atomic clock frequency standard [7]. Moreover, independent and simultaneous full control of the two comb degrees of freedom is also proven. The retrieved phase relation characteri--zing the device, that enables the reconstruction of the intensity profile and of the instantaneous frequency, is impressively reproducible over different operating conditions, permitting a route to further enhance the performance of THz QCL-combs for metrological and quantum-technology oriented applications. The degree of coherence induced by the FWM mode-locking mechanism is confirmed by correlation analysis [7].

III. Summary

In conclusion, we have developed ultra-broadband THz QCLs with a heterogeneous active region core operating as a frequency comb without requiring any additional mode-locking. We demonstrate current and temperature induced comb tuning, which may provide useful insight on the suitability of the THz QCL combs as metrological tools for high resolution spectroscopy at THz frequencies and as local oscillators for heterodyne detection.

Moreover, we report on effective control of the free-running coherence properties of THz QCL FCs with the chip-scale integration of a tunable GTI micro-cavity, which enables adjustable compensation of chromatic dispersion. Continuous tuning of the feedback re-injected into the QCL waveguide then permits gain competition amongst the lasing modes to be modulated, and provides a unique capability for post-fabrication control of GDD. Further improvements in GDD compensation of QCL-combs can be realized by the agile accommodation of even angled or curved mirrors with optimal reflection properties in the THz spectral range.

Fully-controlled, frequency-scalable, ultra-compact THz QCLs-based frequency comb emitters are ideal to innovative applications including fundamental time metrology and optical coherent tomography, and also promise to pervade an increasing number of key quantum technologies.

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