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Semiconductor THz frequency combs exploiting solution processed graphene

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Abstract — **We nano-engineer a miniaturized optical frequency comb synthesizer (FCS) comprising a heterogeneous THz quantum cascade laser integrated with a tightly coupled on-chip solution-processed graphene saturable-absorber reflector. This enable a high power (8 mW) FCS with over 90 optical modes to be demonstrated over more than 55% of the laser dynamic range, with over three-decade reduction of phase-noise over an additional 15% of this range. Furthermore, stable injection locking is demonstrated, paving the way to impact a number of key technologies and applications, including high-precision tunable broadband spectroscopy, quantum metrology and broadband THz nanoscopy.**

I. INTRODUCTION

Optical frequency combs (FCs) are coherent light sources that consist of large numbers of evenly spaced lasing modes, covering a broad gain bandwidth. These radiation sources are extremely attracting for many applications in nano-science as broadband near field nano-scale microscopy, high precision complex spectroscopy, quantum manipulations of atoms and molecules and for more exotic nanoscale applications as spectroscopic mapping of plasmons, plasmon-polaritons and phonon-polariton modes in bi-dimensional materials and related heterostructures.

Chip-scale terahertz (THz) frequency combs have been demonstrated using miniaturized architectures based on quantum cascade lasers (QCLs). In these compact semiconductor heterostructures, four-wave mixing, driven by the intrinsic third order susceptibility in the intersubband gain medium, allows self-locking of the phases of the optical modes, without any additional mechanism/component, allowing stable comb operation, albeit over a restricted dynamic range that is typically a few mA above the onset of multimode emission. To date, chirped-mirrors and coupled-cavity architectures have been exploited to compensate dispersion over a wider (≥ 28%) operational range. However, broadband THz QCL FCS with a large and regularly spaced number of optical modes, each of a comparable intensity, have not been demonstrated, so far.

II. RESULTS

In this work, we present a record dynamic range THz QCL FCS based on a monolithic coupled-cavity architecture comprising a heterogeneous THz-frequency QCL, with a wide (3.2) dynamic range, and an on-chip printed multilayer saturable absorber graphene (GSA) reflector, and demonstrate stable injection locking. The gapless nature of the reflector, and the related frequency-independent absorption, ultrafast recovery time, low saturation fluence, and ease of fabrication and integration, makes graphene an appealing non-linear optical component in the infrared, and ideal for developing THz QCL FCSs. Furthermore, graphene can be ideally employed to introduce intensity dependent losses into the external laser cavity.

We employ heterogeneous active region scheme having a current density dynamic range of 3.2, significantly larger than the state of the art, over a 1.3 THz bandwidth [1]. The graphene reflector is prepared by liquid phase exfoliation (LPE) of graphite in a water/surfactant solution [2] and tightly (at a 15 μm distance) coupled on-chip to the back facet of a 3.6-mm long, 50-μm wide heterogeneous THz QCL (Fig.1a).

Representative CW FTIR spectra under-vacuum (Fig. 1b), measured for different currents in the G sample, show that well above threshold (>880 mA) the GSA reflector does not induce major changes in the spectral behavior of the laser, which shows an emission bandwidth > 1THz with over 90 optical modes (Fig. 1b).

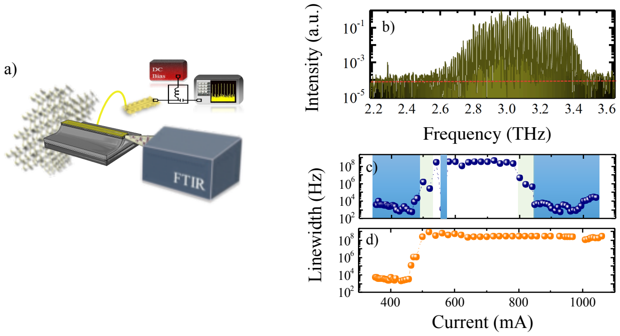

Figure 1. **a)** Device schematics; **b)** Under vacuum FTIR spectrum measured with a Bruker (Vertex 80) FTIR spectrometer in rapid scan mode, with a 0.075 cm-1 resolution. The QCL was operated in continuous wave at a fixed heat sink temperature of 15K and at a driving current of 880 mA. **c-d)** Intermode beatnote linewidth as a function of driving current measured on (c) the graphene saturable absorber-coupled QCL and (d) the bare laser. The beatnote signal is extracted from the bias line with a bias-tee and it is recorded

The comparative analysis of the beatnote linewidth (Figs. 1c-d) clearly discloses the efficacy of the employed approach. Specifically, a set of individual beatnotes, as narrow as 780Hz (Fig. 1c), persists in the current range between 350 mA and 480 mA. The beatnote is a factor of 5 narrower than measured in the reference sample (Fig.1d), at specific biases/currents, thus suggesting that the GSA integration improves the phase locking of the optical modes. The most remarkable effect of the GSA reflector appears at driving currents > 845 mA, (Fig. 1c) where single beatnote linewidth preserves its narrow nature (620 Hz – 10 kHz). We then applied a direct RF modulation at the comb cavity round-trip frequency. We retrieved the beat note spectra, measured in the single beatnote regimes, as the injected RF power is increased, demonstrating that the optical beatnote power is completely locked.

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