Terahertz Quantum Cascade Laser Frequency Combs

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***Abstract*— Optical frequency combs are light sources that consist of many evenly-spaced lines. I will discuss recent developments in frequency combs based on terahertz quantum cascade lasers, which emit broadband comb light in a compact package. I will also discuss spectroscopic applications and short-term stability requirements.**

Keywords—frequency combs, terahertz, quantum cascade lasers, four-wave mixing, optoelectronics

I. Introduction

Optical frequency combs—light sources whose lines are evenly spaced—have proven to be remarkable tools for spectroscopy and for metrology. As the optical version of gearboxes, they are able to link microwave frequencies with optical frequencies. Traditionally, these combs were generated using mode-locked solid-state lasers, which can provide very stable combs with hundreds of thousands of comb lines, but at the cost of being relatively large (~10 cm).

In the last few years, there has been tremendous interest in chip-scale frequency combs, such as microresonator combs and semiconductor mode-locked sources, particularly for spectroscopic applications. At long wavelengths, it has been shown that quantum cascade lasers (QCLs) are capable of forming a comb state that does not possess the properties of conventional mode-locking, wherein the dispersed cavity modes of a Fabry-Perot cavity synchronize by four-wave mixing [1]–[3]. By incorporating proper dispersion engineering, we have shown that it is possible to create QCL frequency combs at terahertz (THz) wavelengths, which enable offer broad bandwidths in a compact package [4]. These combs are particularly attractive as sources for compact spectroscopy: by using a dual-comb technique, it is possible to perform high-sensitivity spectroscopy without moving parts [5]. In addition, due to the semi-continuous nature of the temporal output of these lasers [6], it is possible to *continuously* track the instantaneous phase and timing signals of a dual-comb waveform, enabling computational self-correction of the dual-comb signal even without a reference [7]. As long as the signal-to-noise ratio of the acquired dual-comb signal is sufficiently high, one does not require stability for many spectroscopic measurements.

II. Comb Formation in Terahertz Quantum Cascade Structures

Comb formation in QCLs is mediated by $\chi^{(3)}$ nonlinearities, but for this process to occur the Fabry-Perot modes of the cavity must be approximately evenly-spaced to begin with. In other words, the intracavity group velocity dispersion (GVD) must be sufficiently low. In terahertz (THz) QCLs, this is a challenge since all III-V materials have strong GVD due to the presence of the Restrahlen band of the host material (i.e., electron-phonon coupling) [8]. However, dispersion in THz QCLs can be mitigated by a number of strategies, in particular double-chirped mirrors [4], [9], [10]. These are demonstrated in Fig. 1a.

When the dispersion is appropriately minimized, the laser is able to act as a comb: the lasing is broadband, the intermode beatnote becomes narrow, and all of the lines are separated by the *same* intermode beatnote. In order to measure the coherence of these sources, we developed Shifted Wave Interference Fourier Transform Spectroscopy (SWIFTS), a technique wherein the laser is passed through an FTS and the beatnote is coherently demodulated [6]. This allows us to compare the cross-correlation of adjacent modes with the spectral product—the cross-correlation of a perfect comb. This is demonstrated in Fig. 1b, showing that the comb is uniformly spaced over nearly its whole bandwidth.

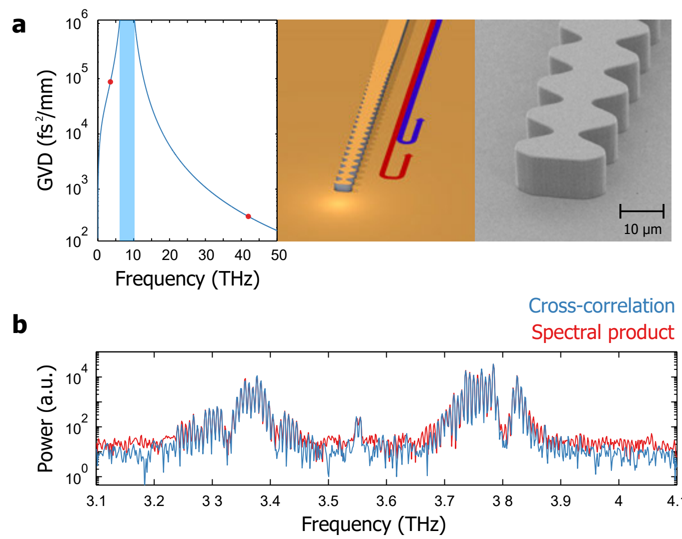

Fig. 1. (a) Dispersion engineering of a THz QCL comb. Group velocity dispersion (GVD) of GaAs at terahertz and mid-infrared frequencies (left), schematic of a double-chirped mirror that compensates dispersion (center), SEM of a double-chirped mirror (right). (b) Coherence measurement of a comb. By comparing the cross-correlation to the spectral product, first-order coherence is measured. [4], [6]

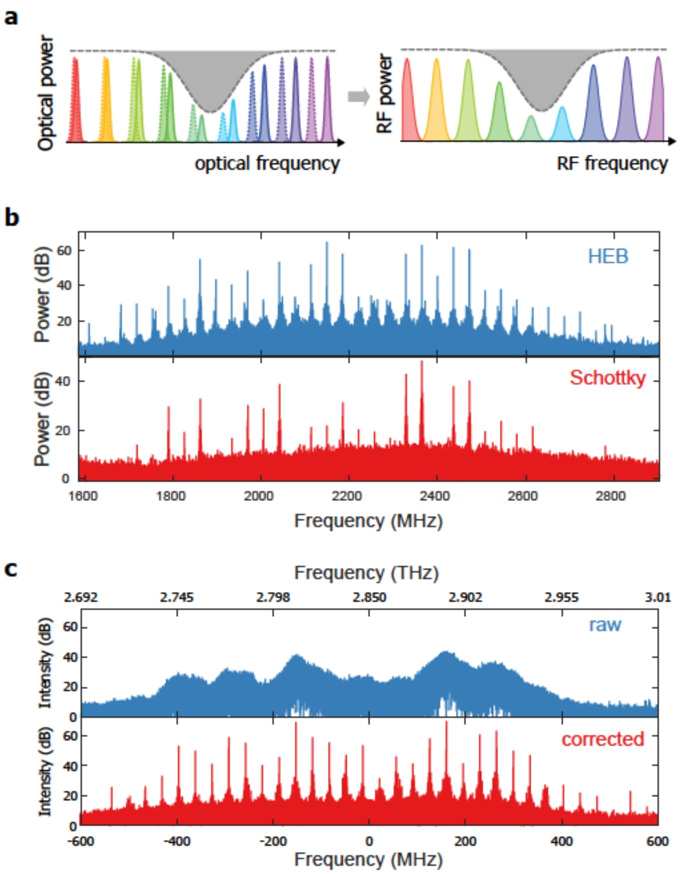

Fig. 2. (a) Schematic version of dual comb spectroscopy. Two combs with a slightly different repetition rate are detected with a square-law detector, giving rise to an RF comb that encodes the optical spectrum. (b) THz QCL dual comb spectroscopy, measured on a hot electron bolometer (HEB) and Schottky mixer [5]. (c) Computation self-correction of an unstable dual comb signal. Using this approach, even highly unstable environments can be used for dual comb spectroscopy [7].

III. DUAL COMB SPECTROSCOPY AND COMPUTATIONAL SELF-CORRECTION

Using these combs, it is possible to perform dual-comb spectroscopy (DCS), the basic idea of which is illustrated in Fig. 2a. Essentially, two combs with slightly different repetition rates are shined onto a common square-law detector, and the different multiheterodyne beatings give rise to an *electrical* (RF) comb whose lines encode the optical spectrum. The primary advantage of THz QCL-based DCS compared with conventional techniques (e.g., THz time-domain spectroscopy) is that the technique is able to achieve high sensitivity without moving parts. In principle, the only active optical elements required to make such a system are two lasers and a detector, meaning that a chip-scale spectrometer is possible.

Figure 2b illustrates some example dual comb signals, recorded simultaneously on two high-speed THz detectors. The first detector—a hot electron bolometer (HEB)—is a helium-cooled superconducting bolometer with excellent sensitivity and response speed (~8 GHz). The second detector—a silicon Schottky mixer—is a room-temperature detector with less sensitivity. Both dual comb signals are acquired over an integration time of 100 us, and the average signal-to-noise ratios in this time are 34 dB and 24 dB, respectively.

Finally, we discuss the role of stability in dual comb measurements. Conventionally, DCS is considered to have high coherence and stability requirements, on account of the fact that heterodyne detection preserves linewidth. Even if a comb tooth has a small linewidth relative to its absolute frequency, if that linewidth is too large the electrical RF comb will be smeared in the frequency domain. As a result, various adaptive sampling approaches have been developed that correct the dual comb signal using reference signals. However, THz QCLs have a unique disadvantage in that they are both cryogenically cooled—giving them high environmental noise—and are also detector-starved—fast THz detectors are difficult to come by. Instead, we developed an extended Kalman filter model that is capable of continuously tracking the offset and the repetition rate of a dual comb signal, which is capable of using the dual comb signal to correct *itself* [7]. This approach requires no extra sources and no extra lasers, making the resulting optical system far simpler. This approach is viable precisely because of the semi-continuous (not pulsed) nature of the comb sources, which ensures that the filter is continuously able to measure the phase of the impinging comb lines. More recently, similar approaches have been shown to allow for self-correction in other dual comb systems, including interband cascade lasers and chip-scale mode-locked lasers.

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