

Evaluating the temporal profile of quantum cascade laser frequency combs

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Abstract: The temporal profile of frequency combs based on quantum cascade lasers has been unclear for some time. We show how the SWIFTS technique directly measures such properties, obtaining combs' intensities and frequencies versus time.

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1. Introduction

Recently, much attention has been focused on the generation of optical frequency combs from quantum cascade lasers (QCLs). Such combs have been demonstrated in both the mid-infrared [1] and terahertz (THz) [2], and offer much promise as sources for compact multi-heterodyne spectroscopy [3,4]. However, despite the fact that narrow beatnotes have been observed for some time [5], the temporal profile of such combs is frequently ambiguous, owing to the fact that conventional techniques like autocorrelation are difficult to perform at long wavelengths and low intensities. It is possible to use direct sampling techniques [6] to get around these restrictions, but such techniques are not self-referenced and may not be able to probe (for example) broad beatnote regimes.

Instead, a series of techniques have been developed by evaluating the beatnote produced by combs on sufficiently fast optical detectors, as measured through a Fourier transform spectrometer (FTS). As such techniques require only linear detectors and interferometers, they are more suitable for evaluating combs operating at long wavelengths. In shifted wave interference FTS (SWIFTS), the optical beatnote through an FTS is demodulated and used to measure the phase difference between adjacent comb lines, effectively providing information similar to that obtained by line-by-line pulse shaping. By cumulatively summing these differences, the phase of the electric field can be inferred.

2. Results

Because only the phase of adjacent lines are measured by SWIFTS, a large amount of statistical uncertainty remains in the electric field extracted from the measurement, uncertainty that is determined using Monte Carlo methods. Though this precludes the meaningful characterization of quantities which are highly sensitive to the phase difference between lines that are far from each other (including the electric field itself), quantities that are less sensitive to distant phase differences nevertheless have meaningful signal-to-noise ratios (SNR). Fortunately, the latter category contains the instantaneous frequency and instantaneous intensity.

Figure 1 shows the instantaneous intensity and frequency corresponding to a particular regime of comb formation in the THz QCL comb described in Ref. [2]. The gain spectrum of this device has two separated peaks, and so for ease of understanding the time-domain data is split into two components, indicated by different colors. Lines represent mean values, and the shaded regions indicate a single standard deviation (68% confidence interval). First, consider the intensity versus time. The lower (red) lobe of the gain spectrum produces a time-domain pulse that arrives at $t=20$ ps. Even though there is some uncertainty in the precise height of the pulse near its peak, it is clear that measurement noise does not prevent this conclusion. The upper (blue) lobe of the gain spectrum, meanwhile, lases at practically all times during the laser's period *except* for the time at which the red lobe is lasing. In other words, the red lobe only lases at times during which the upper lobe shuts off: its pulse-like behavior actually results from a type of temporal hole burning.

Shifting focus to the frequency versus time, note first that in each case the standard deviation of the frequency measurement grows large whenever the corresponding intensity is small, which is of course expected since the instantaneous signal-to-noise ratio at these times is low. Next, note that the red lobe's frequency is essentially time-independent in the region in which its SNR is high, meaning that the pulse is not chirped and is nearly transform-

limited. In contrast, the blue lobe is strongly frequency-modulated and has a sawtooth-like profile in the time-domain. It is interesting to note that the total intensity (red plus blue) is approximately constant in time, whereas the center frequency is strongly modulated. This analysis confirms that the type of behavior described in Ref. [7], in which four-wave mixing leads to self-frequency modulation, can also occur in THz QCLs.

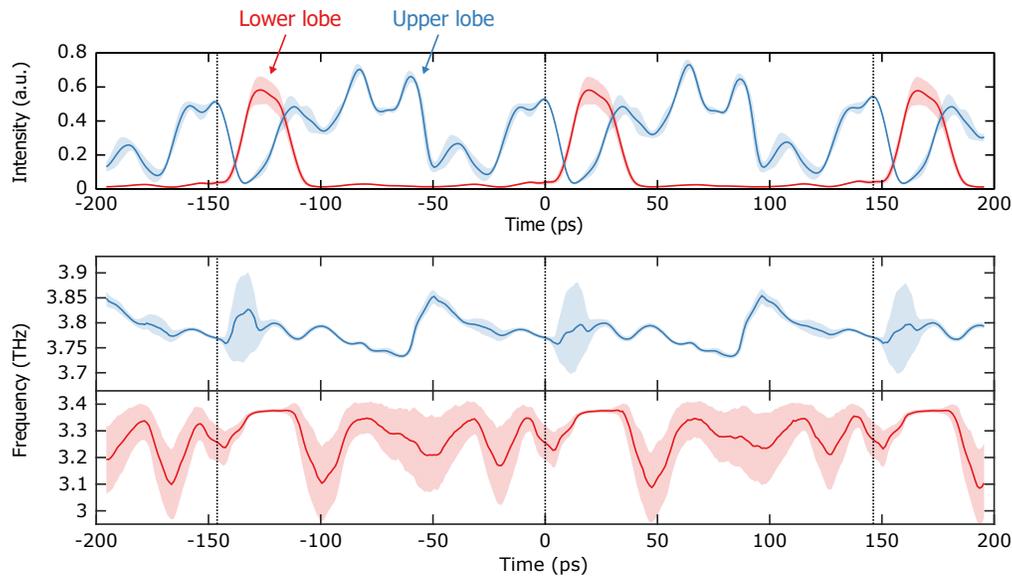


Fig. 1. Time-dependent intensity and frequency inferred from SWIFTS, filtered with a 10 ps window. Solid lines indicate the mean of the measurement, the shaded region indicates the standard deviation, and the dashed lines indicate a single repetition period (i.e., the round trip time).

This information is extremely useful for characterizing the different regimes of comb operation, perhaps even more so than frequency domain measurements alone. Because this technique is agnostic with respect to the combs' time-domain profile, it can handle combs of many varieties. Indeed, we will use this technique to show that low-dispersion THz QCLs can operate in many different regimes, including the aforementioned regime of frequency modulation, a regime of weak amplitude modulation, and even a regime of unstable passive mode-locking.

3. References

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