

# Dual-Comb Based Measurement of Frequency Agile Lasers

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**Abstract:** Properly stabilized, frequency combs form high accuracy references across much of the optical spectrum. Here we employ dual frequency combs to harness this accuracy for fast and high resolution measurements of frequency agile CW lasers.

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We demonstrate a dual comb spectrometer to characterize rapidly frequency tuned or frequency jumped optical waveforms with an eye towards LIDAR, spectroscopy and trace-gas detection. These CW arbitrary waveforms are ideal for measurements requiring high sensitivity but they face two significant challenges: the need for a rapidly tunable frequency agile CW source and for rapid, high resolution characterization of the source frequency. Here we use a MEMS-based external cavity diode laser that can be frequency swept at rates exceeding 2000 THz/s over a 3 THz bandwidth. Over this 3 THz bandwidth the CW laser tuning parameters allow a crude knowledge of frequency. For precise characterization of the laser frequency profile we employ a dual-comb spectrometer [1] that allows tracking of sweeps as fast as 1500 THz/s.

This hybrid dual-comb and cw laser system potentially allows for a significant increase in sensitivity [2] over previously demonstrated direct dual-comb spectroscopy [1, 3-8] and LIDAR [9] results, while still maintaining the excellent resolution and accuracy of this earlier work. Recent work has shown that the dual-comb system can be used to track CW lasers [10-12], and if the combs are highly mutually coherent, frequency sweeps as fast as 1 THz/s can be accommodated [13]. In the dual comb approach, the CW laser beats against a tooth from each comb and the difference in beat frequencies reveals the tooth number against which the CW laser is beating and thereby the absolute laser frequency. This Vernier approach allows for time-bandwidth limited measurements of frequency with high accuracy. Combining this absolute frequency measurement approach with a relative measurement approach similar to [14] allows us to accommodate frequency sweeps as fast as 1500 THz/s (12000 nm/s) with a resolution of 1.5 MHz at 20 ns (averaging down linearly with time) and with ~100 kHz accuracy [15].

The experimental setup is shown in fig. 1. Two combs with similar repetition rates ( $f_r \sim 100$  MHz), differing by  $\Delta f_r = 3$  kHz-30 kHz, are separately heterodyned with the CW laser. The heterodyne beats of the CW laser against each comb will differ in frequency by an amount equal to  $\Delta f_r$  times the comb tooth number, relative to a reference tooth whose frequency is well known via the phase locking conditions. Knowing the tooth number (and the frequency of the reference tooth) we recover the absolute frequency of the CW laser. To a large degree we can view this as a Vernier measurement as illustrated in figs. 1(b)-(c). Employing stabilized frequency combs allows this absolute frequency measurement to be made rapidly, requiring a 30  $\mu$ s to 300  $\mu$ s ( $1/\Delta f_r$ ) measurement period [13].

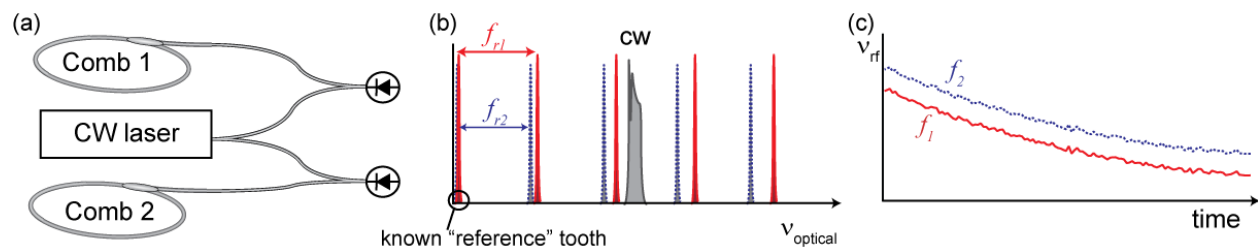


Figure 1. (a) Experimental setup. The CW laser beats against two frequency combs with different repetition rates. (b-c) The heterodyne beats between the combs and the CW lasers will differ by an amount equal to the tooth number times  $\Delta f_r$ . Measuring the difference in frequencies reveals the tooth number relative to a reference tooth that is known via the comb phase locking conditions.

At relatively low sweep rates ( $< f_r \Delta f_r$ ) the frequency measurement is absolute (to modulo a  $f_r^2/\Delta f_r$  ambiguity, which is well within the *a priori* knowledge of the laser frequency) [13]. In this case there is no need to continuously track the CW laser as each measurement is independent. If the CW laser is swept very fast ( $> f_r \Delta f_r$ ) it may not interact with a single comb tooth for the several microseconds ( $1/\Delta f_r$ ) necessary to determine the absolute frequency.

In this case we can switch to a relative measurement and track changes in the change laser frequency while performing absolute calibrations at slow points in the sweep.

The previous discussion assumes a well defined CW carrier. We can also recover a frequency spectrum of the CW laser as it beats with the combs, potentially accommodating more complicated behavior. Again there are two regions to consider. If the laser spectrum spans less than  $f_r$  for a period  $1/\Delta f_r$  we can recover an absolute frequency spectra of the CW laser as it beats with a single comb tooth, with time bandwidth limited resolution. For spectra that are broader than  $f_r$  in a  $1/\Delta f_r$  period we can construct a spectra from the difference of the two comb measurement to yield an absolute frequency spectrum of the laser over a broad bandwidth and with resolution ( $f_r$ ) and update rate ( $1/\Delta f_r$ ), greatly exceeding the capabilities of conventional optical spectrum analyzers [13]. The combination absolute/relative measurements and the broadband spectra are shown in fig. 2.

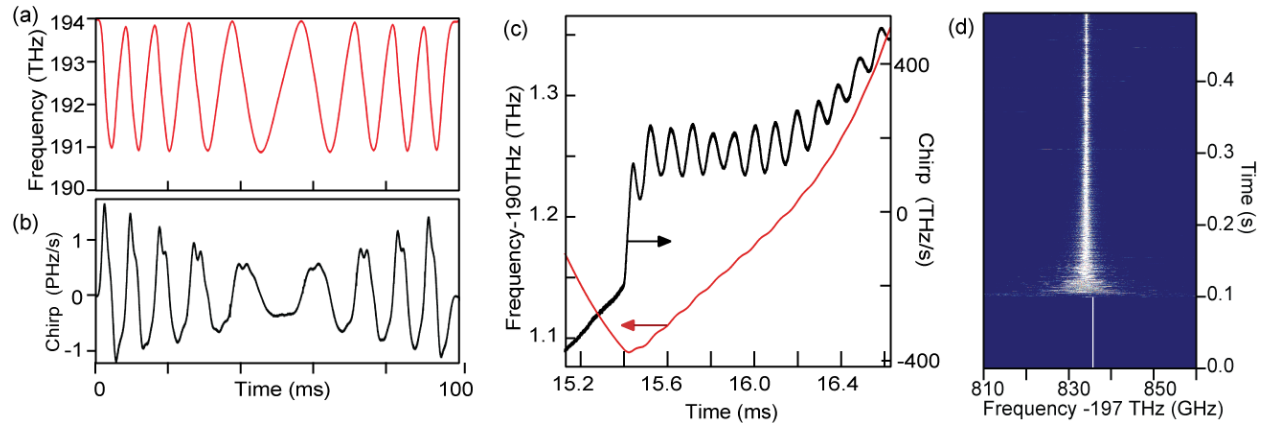


Figure 2: Time dependant spectra of the swept CW laser. (a) Example waveform with a 3 THz peak-to-peak amplitude and a modulation frequency that varies from 125 Hz to 50 Hz. The mean instantaneous CW laser frequency is plotted at 10 ns intervals. The measurement accuracy is 100 kHz and the uncertainty is ~1.5 MHz per point using a central difference calculation [15]. The brief unswept period at the beginning of the waveform allows for absolute frequency calibration. (b) The time derivative of (a) (chirp), which is boxcar smoothed to a 2  $\mu$ s resolution. Chirp exceeding 1.5 PHz/s is observed. (c) The high resolution and update rate of the system can reveal mechanical effects of the swept laser. The structure at 15.4 ms is the response of the CW laser as it encounters the edge of its tuning range. (d) Shown is the broadband frequency spectrum of a laser that was mechanically jolted at 0.1 s and continuously monitored at a time-resolution of 30  $\mu$ s. When the laser frequency changes more slowly (>1 THz/s), an absolute frequency spectrum with time-bandwidth limited resolution can also be created. It should be noted that fast frequency shifts will introduce some systematic shifts in the spectrum as discussed in [13].

In conclusion, we have demonstrated rapid comb based frequency monitoring of CW lasers accommodating frequency sweeps 1000 times faster than previous comb work. The system resolution is 1.5 MHz at 20 ns with a limitation on sweep rates of 1500 THz/s set by the need to sample the CW laser multiple times as it crosses each comb tooth. This maximum chirp scales with the square of the comb repetition rate, thus much higher sweep rates could be monitored with a modest increase in  $f_r$ . This ability to monitor CW waveforms is particularly interesting as it potentially combines the high sensitivity of CW based measurement with the accuracy of frequency combs.

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