

Dual comb-based characterization of rapidly tuned lasers

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Time-resolved, high-accuracy and high-resolution spectroscopy of rapidly tuned cw lasers is critical to realizing their full potential for sensing, but is not possible with conventional spectrometers. We demonstrate a coherent dual-comb-based spectrometer capable of measuring the instantaneous frequency of cw optical waveforms up to chirp rates of 1500 THz/s over a span of 5 THz with time-bandwidth limited precision. Provided there is a brief (< 1 ms) period of low laser chirp (< 160 GHz/s) during the waveform measurement, the absolute frequency accuracy can be calibrated to an accuracy within 2.5 kHz, depending on the underlying frequency reference. This approach should enable optimized waveforms for sensing applications including multi-species gas detection, coherent laser radar, and optical metrology.

Continuous-wave (cw) lasers are the principal workhorse in high-sensitivity optical-based sensing because of their high photon flux, long interaction paths and ever-increasing frequency agility. Current cw lasers are capable of tuning rapidly or even hopping to different optical frequencies over terahertz of optical bandwidths [1-5]. However, the waveforms from free-running lasers are not predictable or even reproducible at a very high level of precision and accuracy resulting in a frequency uncertainty for the waveform far larger than the laser linewidth itself. Frequency-comb based actively controlled laser systems have well-controlled optical waveforms, but limited tuning speed and/or bandwidth [6-10]. Free-running tunable lasers are usually swept in a quasi-linear ramp and referenced (that is, linearized) against an etalon or, for higher linearity, phase-locked to an interferometer [11]. The accuracy of this method is significantly increased to megahertz levels by referencing the tunable laser to the evenly spaced modes of a self-referenced frequency comb [12]. However, one is still restricted to a quasi-linear continuous sweep with limited speed, since mode hops or frequency jumps will destroy the calibration. Furthermore, any absolute frequency determination requires a separate measurement. More importantly, a linear sweep is not the optimum waveform for many applications. For example in spectroscopy or optical metrology, the laser would ideally jump to spectroscopic features of interest and then scan slowly across the lineshape [2, 3, 13]. Similarly, in lidar (light detection and ranging), more complicated waveforms would allow lidar systems to more closely emulate radar systems and might enable optimized range-Doppler ambiguity functions or synthetic aperture lidar [11, 14, 15].

We demonstrate here a dual-comb spectrometer capable of rapid absolute measurements of a cw laser [16], thereby enabling the calibration of discontinuous/arbitrary cw waveforms from free-running, rapidly tuned lasers. Frequency combs are based on stabilized femtosecond lasers and create ideal spectral rulers against which to measure the instantaneous frequency of a cw laser. They have allowed for metrology of static lasers with unrivaled frequency accuracy [17-19]. However, one must remove the measurement ambiguity equal to the comb repetition rate. This can be done by a Vernier approach using combs with different repetition rates [20]; absolute laser frequencies were measured within seconds in this way [21]. Here, we extend this technique to optically coherent combs, allowing for time-bandwidth limited measurements at a submillisecond time resolution. We demonstrate measurements of sinusoidal waveforms with instantaneous frequency chirps up to 1500 THz/s. Our approach is similar to coherent dual-comb spectroscopy [22-27], except that here we apply the basic concept to an active source instead of a passive sample.

Our setup is based on two erbium-doped fiber frequency combs (comb 1 and comb 2) (fig. 1) which are phase-locked to two cavity-stabilized cw lasers at 1535 nm and 1560 nm [27]. A small part of the light from a tunable cw laser is individually combined with both combs and detected with a photodiode. The resulting electric signal $V(t)$ corresponds to the heterodyne difference waveform between the tunable cw laser and the nearest comb tooth; this can be compared to standard heterodyne detection of the cw laser with ten thousands of reference cw lasers spaced exactly by the comb repetition rate f_r (100 MHz in our case), mapping a ~ 5 THz optical bandwidth on a ± 50 MHz microwave signal. To determine the mode number n of the specific comb tooth involved in the heterodyne detection, the cw laser is simultaneously heterodyned with comb 2 (fig. 2), which has a repetition rate $f_r^2 = f_r^1 + \Delta f$ (Δf is chosen such that $f_r^1 / \Delta f = N$ is an integer number to ensure a repetitive pattern for both time pulses and frequency teeth). The difference between the instantaneous frequencies of both heterodyne signals equals $n \times \Delta f$, where $n = 0$ corresponds to

the comb tooth locked to one of the cavity-stabilized cw lasers modulo an ambiguity $N \times f_r^2$, which is typically much larger than the uncertainty on the a-priori knowledge of the tunable laser frequency. To extract n computationally, we digitize $V_1(t)$ and $V_2(t)$ at a sample rate f_r^1 , and calculate the spectrum of $V_1(t) \times V_2(t)$ measured over N points; the frequency at its peak intensity corresponds to $n \times \Delta f$.

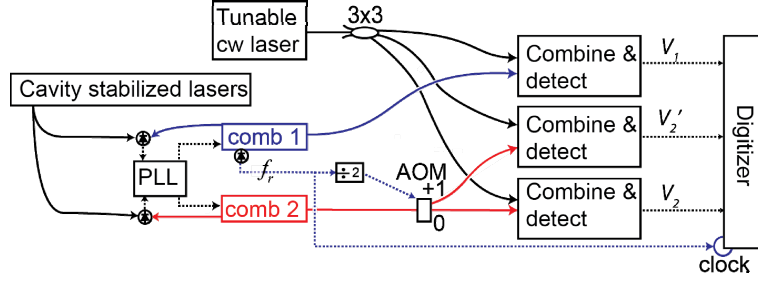


Figure 1: Schematic of the dual-comb spectrometer. A small portion of a tunable cw laser’s light is split with a 3x fiber coupler and then combined with the combs’ light either with an optical IQ demodulator or a 50:50 fiber-coupled combiner. Then, the heterodyne signal is detected with balanced photodetectors and digitized at a sample rate of f_r^1 . The combs are both locked to two cavity-stabilized lasers with four phase-locked loops (PLL).

This dual-comb frequency calibration has a measurement rate of Δf_r and requires the cw laser to stay within a frequency bin of width $f_r^1/2$ within N samples. For $\Delta f \approx 3.1$ kHz and $N \approx 32000$, the laser chirp can thus not surpass ~ 160 GHz/s. cw laser waveforms with faster chirps can still be characterized through the heterodyne signal with a single comb; the absolute frequency (ie. the current comb tooth number n) can be determined by counting the number of tooth crossings since the last dual-comb calibration (assuming that there are times where the laser chirp is below 160 GHz/s and there are no frequency discontinuities). For our setup, the theoretical maximum chirp that can be tracked with a comb is $(f_r/2)^2$ or 2500 THz/s [28].

In order to avoid the Nyquist frequency around $f_r^1/2$ (50 MHz) and thus continuously cover the instantaneous heterodyne frequency of the tuned cw laser, either one of the combs or the cw laser is split with an acousto-optic modulator (AOM) driven by an RF signal with frequency $f_r^1/2$, resulting in a replica of the instantaneous frequency, f_V' , shifted by 50 MHz.

It should be noted that above discussion assumes in-phase/quadrature (IQ) detection of the heterodyne signal, which allows to map the instantaneous frequency within a range of $[-f_r^1/2, f_r^1/2]$ [28]. For conventional detection, this frequency range is reduced to $[0, f_r^1/2]$ and additional processing is required to determine the absolute heterodyne frequency [16].

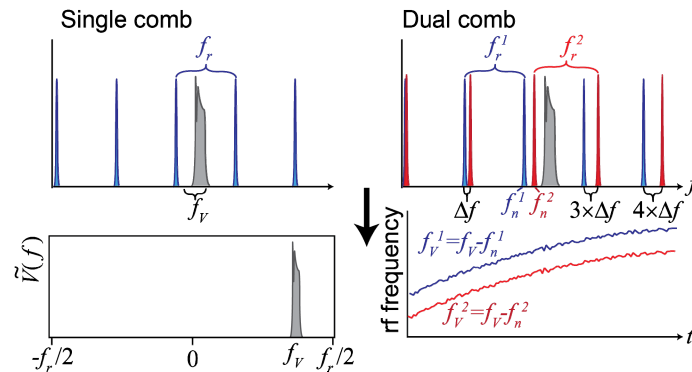


Figure 2: Schematic for heterodyne spectroscopy of a quasi-static cw laser (grey) with the dual comb system. Detection of the added comb and cw laser light results in a heterodyne spectrum $\tilde{V}(f)$, which is the difference between the laser frequency f_L and the nearest comb tooth f_n (left panels). By detecting the heterodyne signal with a second comb with offset repetition rate $f_r^2 = f_r^1 + \Delta f_r$ (right panels), the comb tooth number n can be extracted from the difference of the instantaneous heterodyne frequencies f_V through $f_V^1 - f_V^2 = n \times \Delta f_r$.

Fig. 3 shows the instantaneous frequency of a micro-electromechanical-system (MEMS) external cavity diode laser (ECDL) measured with our dual comb spectrometer [28]. It starts with a short quiet period (~ 1 ms) to calibrate the absolute frequency, followed by a chirped-sine modulation spanning 3 THz of optical bandwidth. The maximum chirp rate is 1500 THz/s, more than half the theoretical maximum of 2500 THz/s. In a similar experiment, a single frequency comb was used to characterize an actively linearized chirp laser, demonstrating a constant linear chirp with less than 15 parts per billion deviation across a 5 THz sweep [29].

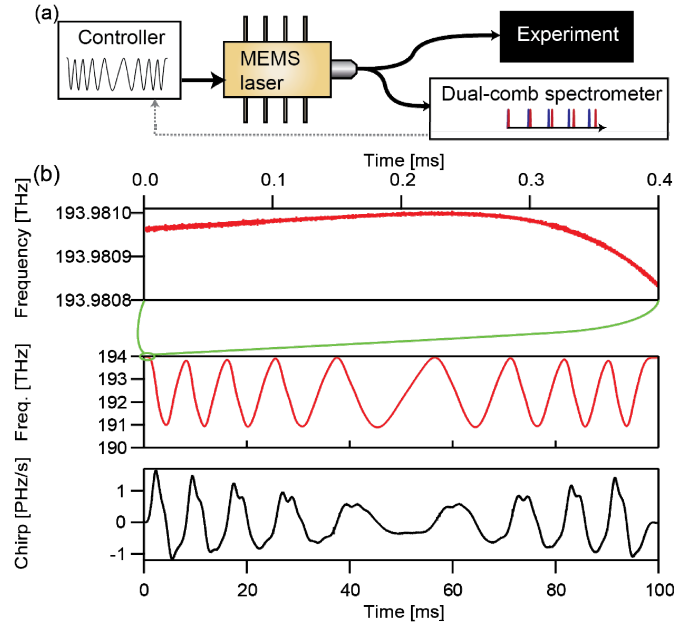


Figure 3: MEMS laser measurement. a) A laser controller drives the MEMS laser with the approximate desired waveform. A small part of the laser light is then split off to the dual-comb spectrometer. b) Actual measurement of the MEMS waveform driven with a chirped sine varying between 50 Hz and 120 Hz. The characterization starts shortly before the modulation to calibrate the measurement with the initial low-chirp section (upper panel). The waveform spans 3 THz and the time resolution is 20 ns (center panel). The lower panel shows the derivative of the waveform (the chirp) smoothed to a 2 μ s resolution.

In another experiment, selected absorption lines of CO_2 , CO , and C_2H_2 were measured with an ECDL calibrated with our dual comb spectrometer (fig. 4) [16]. This is a typical example where one wants to slowly tune the laser across a spectral region of interest (the absorption line) and then jump to the next region of interest. The ECDL was driven with a staircase voltage with small step height corresponding to roughly 100 MHz across absorption lines and large steps up to 2 THz between absorption lines, avoiding the long delays associated with conventional wavelength meter readings [13]. At each step, the laser transmission is averaged over the sample time $1/\Delta f = 320 \mu\text{s}$ and the absolute ECDL frequency is simultaneously determined. The frequency axis accuracy is ~ 1 kHz and the absorption line center frequencies have an accuracy of ~ 1 MHz limited by the measurement noise. The total measurement time for the data presented in fig. 4 was ~ 5 s.

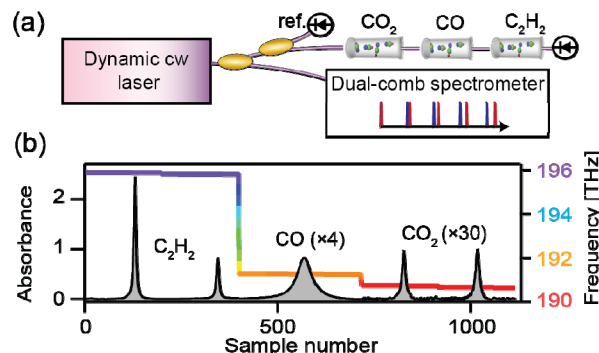


Figure 4: Gas spectroscopy. a) The tunable cw laser is split in three parts: to a reference transmission measurement, a gas transmission measurement, and the dual-comb spectrometer for wavelength calibration. For the gas transmission, three separate gas cells, containing 50 Torr C_2H_2 , 1000 Torr CO , and 115 Torr CO_2 respectively, were concatenated. b) The tunable laser frequency (rainbow line) and absorbance (black line) of the three gas cells. The five absorption lines are separated by 42 nm (5 THz). The laser was scanned slowly across the lines (the frequency span of ~ 2 GHz across a single line is imperceptible on the rainbow scale) and at maximum speed between absorption lines.

In conclusion, we have demonstrated a coherent dual-comb spectrometer for time-resolved measurements of the cw optical waveform output by a rapidly tuned cw laser. The spectrometer covers an optical bandwidth of 5 THz and has a time resolutions of $\sim 320 \mu\text{s}$ for absolute frequency measurements and 20 ns for relative frequency measurements. This technique allows for metrology of rapidly tuned cw lasers. With further improvement in the size, compactness, and robustness of fiber frequency combs, one can envision a highly accurate optical waveform source for use in broadband optical sensing.

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