Rapid, High Resolution Frequency Comb Measurements.

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Abstract: Frequency combs serve as an extremely high accuracy reference across broad portions of the optical spectrum. Dual frequency combs harness this accuracy and allow for fast and highly flexible measurements of passive and active sources. Work of the U.S. government, not subject to copyright. OCIS codes: **120.0120** (Instrumentation, measurement, and metrology), 320.7090 (Ultrafast lasers)

Introduction

One can think of a stabilized frequency comb as a train of femtosecond pulses that are effectively the sum of a hundred thousand or more single frequency lasers (often referred to as comb teeth) [1, 2]. The teeth are phase coherent and the frequency of every tooth can be known with relative ease to a part in 10^{12} (10^{16} is possible [3]). Thus the comb provides a highly accurate frequency and phase reference over a broad optical bandwidth.

Heterodyning a mutually coherent pair of frequency combs with slightly different pulse repetition rates (tooth spacing) allows one to separately access each optical comb tooth using relatively slow electronics [4-7]. With this technique, sometimes referred to as multiheterodyning, one can recover highly accurate spectral information over the comb bandwidth. Possible applications range from spectroscopy, to component characterization, to LIDAR [8].

In a separate but related approach one can also employ dual frequency combs for rapid measurements of CW laser frequency. In this application the CW laser beats against each comb separately and the difference in beat frequencies reveals the tooth number against which the CW laser is beating. This Vernier approach allows for time bandwidth limited measurements of the laser frequency with near perfect accuracy.

This is particularly interesting since CW lasers set the standard for sensitive measurement. Having the combs continuously track the laser frequency allows one to combine the frequency accuracy and precision of combs with the high sensitivity of CW measurements.

Dual Comb Direct Sensing

The strengths of the multiheterodyne scheme in the direct sensing approach are at least three-fold. First, the mapping of optical combs into the rf allows for the straightforward retrieval of each comb line by use of a single photodiode and a fast digitizer. Second, the mapping also allows for near perfect knowledge of absolute frequency (1 Hz level). Finally, the heterodyne signal is really a mapping of the full electric field, thus optical amplitude and optical phase is retrieved for each comb tooth. As a corollary the time-domain signature from the interference of the optical pulses is recovered as well. Data is presented here for a dual comb lidar and spectroscopy setup.

For the experiments presented we use two erbium fiber femtosecond frequency combs. Each comb has a bandwidth of 125 nm centered around 1550 nm. The repetition rates (comb tooth spacing) of the two combs are $f_{r1} \approx f_{r2} \approx 100$ MHz and differ by $\Delta f_r = 3$ kHz. For spectroscopy experiments in particular we require high coherence between the lasers to allow for long averaging time. We achieve this coherence by stabilizing each comb to the same pair of CW reference lasers at the wavelengths 1535 nm and 1560 nm. This is sufficient to stabilize the two degrees of freedom in each frequency comb and allows us to achieve a linewidth of less than one hertz between the two combs. More information on this setup can be found in Refs [9, 10].



Fig. 1. (a) Simple depiction of the multiheterodyne approach. One comb passes through the sample (in this case a gas cell or open lidar path) and the teeth are attenuated and phase shifted according to the response of the system. The attenuation and phase shift are measured by heterodyning with a second comb. (b) Pairs of teeth from each comb generate a slightly different heterodyne frequency effectively mapping the optical frequencies down into the rf where the information can be easily digitized.

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Figure 2 shows data from two applications: (a) broadband spectroscopy (presented in the frequency-domain) (b) rapid, high-resolution ranging (seen in the time-domain). In both applications data can be acquired at high rates with an accuracy and resolution that pushes or exceeds the limits of conventional approaches.



Fig. 2. (a) By passing one comb through the gas cell we measure the amplitude and phase response of the gas. Data for the first vibrational overtone of HCN is shown here. Long averaging times allow for high signal to noise (>4000 in magnitude and phase). Simultaneous measurement of an empty reference path allows for near perfect background subtraction. (b) In a related experiment the "sample" is replaced with a lidar path consisting of two 4% back reflectors. The second comb measures the time delay between the two returning pulses. Data shows a series of measurements as the second reflector is moved. Measurement update rate is $1/\Delta f$ and the resolution is 3 μ m in a single measurement.

Rapid Measurement of CW Lasers

In an alternate experiment one can use the dual comb system to monitor a CW laser (Figure 3(a)). Here each comb is separately heterodyned with a CW laser. These recorded signals are then multiplied in the time domain (convolved in the frequency domain) to yield a high-resolution measurement of the CW laser absolute frequency over a bandwidth limited only by the comb spectral coverage [11-13]. To a large degree one can view this as a Vernier measurement as illustrated in Figures 3(b) and (c). By employing stabilized frequency combs this measurement can be extremely rapid, requiring only a few microseconds [13]. The rapidity of the measurement allows for precision frequency metrology of both continuously swept and frequency-hopped CW lasers systems. The ability to produce, and measure, arbitrary CW optical waveforms has many applications. In spectroscopy, one could tune the frequency profile of the CW laser for high sensitivity by jumping between spectroscopic features of interest while still maintaining calibration. Similarly, for coherent lidar systems one could employ complicated frequency profiles to trade off between Doppler and range ambiguities. The experimental setup is shown in Figure 3 and is largely similar to the direct sensing approach except that each comb separately heterodynes with the CW laser.



Figure 3. (a) Experimental setup. The CW laser beats against two frequency combs with different repetition rates. (b) and (c) The heterodyne beats between the combs and the CW lasers will differ by an amount equal to the tooth number times Δf_r . Measuring the difference in frequencies reveals the tooth number and allows for absolute frequency measurement of the CW laser with time-bandwidth limited resolution.

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As a demonstration, we measure an external cavity diode laser (ECL) swept in a nonlinear pattern over 28 nm (see Fig 4a). For much of the ramp the laser is swept with a mechanical motor that broadens the linewidth beyond 100 MHz over 300 μ s. In this case only a coarser autocorrelation spectrum, achieved by multiplying the detector signals from the two combs, is meaningful [13]. When the motor is stopped the scan continues at a slower rate and the ECL linewidth drops to a few MHz. A single comb and CW heterodyne signal yields the laser frequency spectrum at high resolution, as shown in Fig. 4b and 4c. Because the frequency measurement is absolute (to within 25 nm ambiguity, which is well within the a priori knowledge of the laser frequency), there is no need to continuously track the CW laser; every individual 300 μ s measurement is completely independently as opposed to earlier etalon or comb techniques [14].



Figure 4: Time dependant spectra of the swept ECL. (a) The ECL mean optical frequency profile during the sweep. The autocorrelation measurement [13] yields 100 MHz frequency resolution with 300 μ s time resolution. (b) Expanded view showing the frequency spectrum versus time of the ECL laser measured against a single comb, giving time-bandwidth limited resolution. White regions show the Nyquist limited measurement region defined by the comb repetition rate. To allow for continuous measurement an acousto-optic modulator is employed to create an additional shifted comb offset by $\sim f_{r,2}/4$. One simply selects the heterodyne signal from either the shifted or unshifted comb for continuous monitoring. (c) The electric field spectrum of the CW laser at a given time from (b).

In conclusion dual comb systems can be applied to direct sensing or used for rapid monitoring off CW lasers. In either capacity the system has a high update rate, high accuracy and fine resolution over broad bandwidth. This capability 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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