Fast and Accurate Comb-based Spectral Analysis of a Frequency Agile CW Laser

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Abstract: The time-resolved frequency spectrum of a frequency agile CW laser is measured with a 300 μs update rate and 3 kHz resolution/accuracy over a 28 nm wavelength range with a coherent dual comb setup.

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Frequency combs can be used to measure optical frequencies with unprecedented accuracy [1, 2]. However, absolute frequency measurements with combs are slow and somewhat cumbersome due to the need to resolve ambiguities caused by the relatively fine comb tooth spacing and it is challenging to apply them to absolute frequency measurements of rapidly tuned CW sources. A frequency agile CW laser can be measured by starting from a known frequency and monitoring crossings of the CW source and comb teeth, provided that the laser is mode hop free and continuously swept [3]. Peng *et al.* [4] have shown that the use of two frequency combs at different repetition rates can greatly relax the time constraint, and determination of absolute frequency is possible in seconds. However, even faster frequency measurements are desirable for frequency agile CW lasers [5-7]. Here, we demonstrate that a comb-based spectrometer using dual, optically coherent frequency combs can provide very rapid, absolute-accuracy spectral analysis of an agile CW laser with time-bandwidth limited resolution over a wide spectral range. In our current configuration, the system has an update rate of 300 μs and provides both an intensity spectrum at 100 MHz resolution and, for sufficiently narrow sources, an electric field spectrum at 3 kHz resolution (=1/300 μs) with kHz-level accuracies, set by our cavity-stabilized optical reference.

This approach will allow for precision frequency metrology of both continuously swept and frequency-hopped CW lasers systems and can provide useful information on the dynamics of these lasers. In addition, the ability to produce, and measure, complicated CW optical waveforms has a number of interesting applications. In spectroscopy, or metrology of telecommunication components, one can tailor the frequency profile versus time of the laser for maximum sensitivity by jumping between spectroscopic features of interest while still maintaining calibration [5, 6]. Mode hops of the laser can be monitored. Similarly, this system could be an enabling technology for coherent lidar systems by allowing for metrology of precise optical frequency waveforms both including, and beyond, fm linear sweeps [7].

The experimental setup is shown in Fig. 1. The pulse trains from two comb sources, acting as local oscillators (LO1, LO2), are separately combined with the CW laser under test. The LO combs are phase locked to the same fixed CW optical reference so that they are optically coherent (<0.5 radian residual phase noise) but have slightly different repetition rates, f_{r1} and f_{r2}. As a result, the pulse timing from LO1 will slowly shift with respect to LO2 and they will effectively sample the CW field at the separated times t and $t+\Delta t$ for a range of Δt's. Multiplication of the two series of digitized signals from each LO comb yields an autocorrelation measurement of the CW electric field in much the same way as a scanning Michelson interferometer or wavelength meter. The Fourier transform of the autocorrelation yields an intensity spectrum with resolution equal to the comb repetition frequency and accuracy equal to that of the frequency comb referencing (*provided* a tight mutual coherence is maintained between the LOs). The acquisition period for a single autocorrelation is$1/\Delta f = 1/(f_{r1} - f_{r2})$ and equals 300 μs in our case. Here, one can see the strength of the dual comb spectrum analyzer, as an equivalent wavelength meter would require a scanning mirror moving at 5000 m/s.

In addition to the autocorrelation spectrum with 100 MHz resolution, the direct heterodyne signal between the laser with the nearest comb tooth of either LO gives the laser electric field spectrum with a time bandwidth limited resolution of 3 kHz. A third sampling channel compares the CW laser to a duplicate of LO2 that is frequency shifted by $\sim f_{r2}/4$ with an acousto-optic modulator (AOM.). This third channel allows continuous monitoring of the heterodyne signal in regions where the heterodyne signal against the unshifted LO2 is close to zero or Nyquist frequency [8], greatly expands the ambiguity range of the autocorrelation spectra, and allows determination of the sign of the heterodyne signals from the autocorrelation spectra without recourse to a Hilbert Transform.

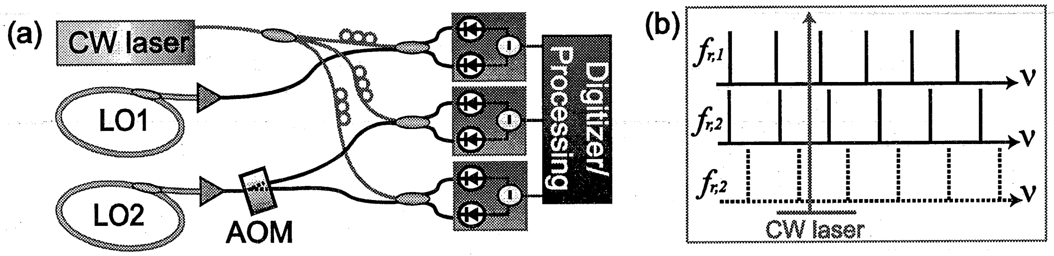

Figure 1. (a) Experimental setup. The CW laser beats against two LO frequency combs with different repetition rates as well as a frequency-shifted version of one of the frequency combs. (b) Frequency domain diagram showing the measurement concept. The relative linewidth of the comb teeth must be narrow. However the CW laser can be very broad and rapidly changing.

To demonstrate the system, we measure an external cavity diode laser (ECL) swept in a nonlinear pattern over 28 nm (see Fig 2a). For much of the ramp the laser is swept with a mechanical motor that broadens the linewidth beyond 100 MHz over 300 μs, and only the "coarser" autocorrelation spectrum is meaningful. At various times, the motor is stopped (e.g. for a measurement) and the heterodyne signal yields the laser frequency spectrum at high resolution, as shown in Fig. 2b and 2c. Because the frequency measurement is absolute (to within 25 nm ambiguity, which is well outside the *a priori* knowledge of the laser frequency), there is no need to continuously track the CW laser; every individual 300 μs measurement is completely independent and does not rely on previous measurements. Here we digitize data for 300 μs every 1.5 ms. A comparison of this system and a conventional self-referenced frequency comb stabilized to a maser [9] validate the frequency accuracy to 3 kHz for a fixed CW laser.

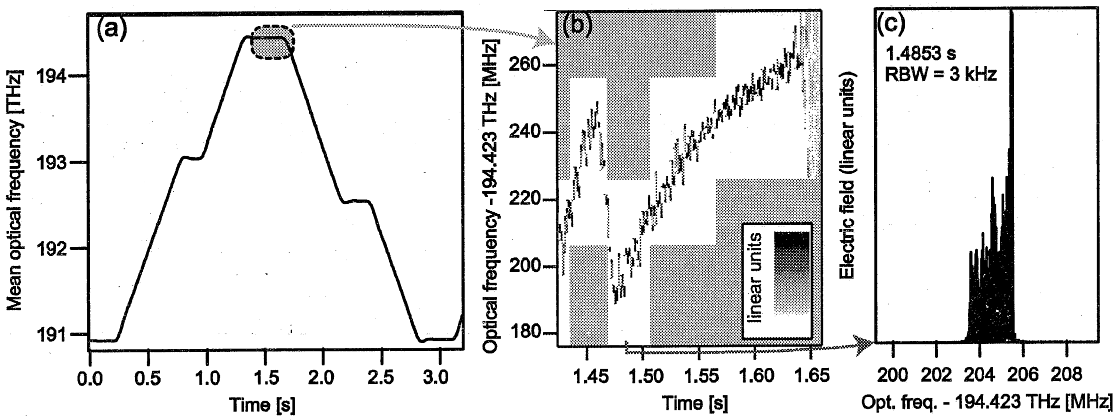

Figure 2: Measurements of the instantaneous spectrum of a swept external cavity laser diode (ECL). (a) ECL mean optical frequency versus time over the sweep from the autocorrelation measurement at 100 MHz resolution. (b) Expanded view showing the frequency spectrum versus time of the ECL laser measured from the heterodyne signal with the LO2 comb. White regions show the Nyquist limited measurement region for a single comb set by the comb repetition rate; assuming the instantaneous bandwidth is less than ~$f_{r2}/4$, one simply selects the heterodyne signal from either the shifted or unshifted LO2 comb for continuous monitoring. At 1.64 seconds the tuning motor is engaged and the instantaneous bandwidth exceeds f_{r2}. The autocorrelation spectral measurement, at 100 MHz resolution, is still valid and the laser frequency is measured as shown in (a). (c) The electric field spectrum of the CW laser at a given time slice from (b).

In conclusion we have demonstrated a technique for analyzing laser spectra at a high update rate, accuracy and resolution over broad bandwidth. This capability far exceeds conventional techniques and can be both a versatile diagnostic tool as well as enabling the use of arbitrary CW waveforms for different sensing applications.

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