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Dual Frequency Comb Sampling of a Quasi-Thermal Incoherent Light Source

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Abstract: Dual, coherent frequency combs are used to measure the spectrum of an incoherent, quasi-thermal source through Fourier spectroscopy. The source spectrum is acquired over 1 THz bandwidth with an absolute frequency accuracy set by the combs.

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One of the intriguing new applications of frequency combs is to the field of Fourier transform infrared spectroscopy (FTIR) [1-4]. To date, all comb-based spectroscopy systems have interrogated a passive sample, for example of a gas, where one comb probes the sample and the resulting complex spectrum is acquired by a second “local oscillator” (LO) comb that has a slightly different repetition rate. This system can be viewed as the analog of standard FTIR spectrometer, where the pulse train from one comb replaces the light in the fixed arm and the pulse train from the second comb replaces the light in the delayed arm of the Michelson interferometer. Here it is demonstrated that this dual-comb system can be reconfigured to measure the spectrum of an incoherent source in a manner analogous to standard passive FTIR systems. Just as with the previous spectroscopy demonstrations, this comb-based passive FTIR system has the advantages of a fast scanning rate, high frequency resolution, and a frequency accuracy that can reach kilohertz or even hertz levels depending on the underlying reference. However, due to its coherent single-mode detection and the photon statistics inherent to any thermal source, the signal-to-noise ratio of a single interferogram is limited to unity. Nevertheless, it is possible to generate spectra with reasonable signal-to-noise ratios through coherent signal averaging. This approach is interesting in terms of calibration of spectrometers or for precision measurements of frequency shifts in absorption lines across an incoherent spectrum.

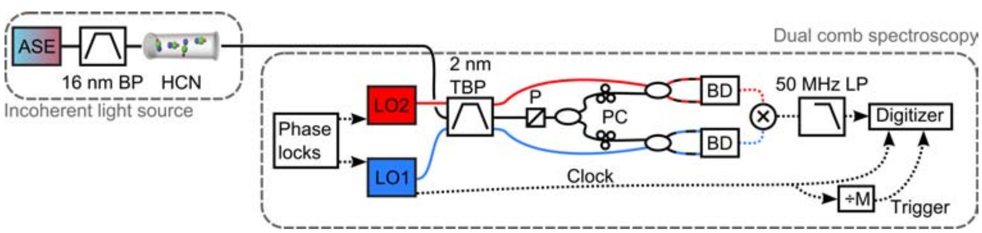

Fig. 1: Setup to measure the spectrum of an incoherent source with high frequency accuracy by sampling the spectrum in time with two asynchronous frequency combs. 16 nm BP: 16 nm wide bandpass, TBP: tunable BP, P: polarizer, PC: polarization controller, BD: balanced photodetector, LP: lowpass, *M*: number of pulses per frame, LO: local oscillator (frequency comb). Solid lines are fiber optic paths, dotted lines are electrical paths.

The experimental setup is shown in Fig. 1. An amplified spontaneous emission (ASE) Er-fiber source serves as the quasi-thermal light source. Its output is spectrally filtered to 16 nm and passed through a cell of Hydrogen Cyanide (HCN) gas to add sharp spectral features. The dual-comb system is then used to measure the autocorrelation of the quasithermal ASE field, and therefore its spectrum, as follows. The pulse train of each LO comb is separately combined with the ASE light and the resulting overlap of the ASE electric field and the LO comb pulse is detected in a balanced detector. The detected voltage is proportional to the ASE field sampled by the comb pulses. Because the ASE light is incoherent, this voltage will be random. However, the phase-locks between the two LO sources are arranged such that the pulses from the two sources are optically coherent but have slightly different repetition rates, f_{r1} and f_{r2}. As a result, the pulse train from one source will slowly walk through the pulse train from the other source. The sampled voltages from the two pulse trains are then acquired as series of relative effective time delays; their product, generated by a mixer in Fig. 1, is exactly the autocorrelation of the ASE electric field (i.e., interferogram), modified by the spectral envelope of the comb pulses. This interferogram is generated repeatedly at a rate equal to the difference in comb repetition rates, Δf_r , at an effective time step $\Delta\tau = f_{r1}^{-1} - f_{r2}^{-1}$, over an effective time span of f_{r1}^{-1}.

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As mentioned earlier, the statistics of the quasithermal source result in a time-domain signal-to-noise (S/N) ratio of unity for a single interferogram. The corresponding spectral S/N is $1/\sqrt{R}$, where R is the number of resolved frequency points. To achieve useful S/N, two things are done. First, the data are sequentially acquired in 2 nm increments with a tunable filter. Second, at each filter setting, the signal is averaged over many interferograms. To average without excessive digitization, Ref. [5] is followed as described hereafter. Each comb is phase-locked to a pair of cavity-stabilized lasers at 1535 nm and 1560 nm. (In addition the optical frequency of the 1560 nm laser is measured with a third self-referenced frequency comb allowing for hertz level frequency calibration of the combs and of the final spectrum.) Adjusting the phase-locks such that LO1 and LO2 have exactly M and $M+1$ comb lines, respectively, between the two locking points, ensures that each sequential interferogram will have exactly M data points and repeat with exactly the same phase, so that they can simply be added together.

In this case, the two LOs have repetition rates of f_{r1} = 100.023 MHz and f_{r2} = 100.026 MHz, giving M = 31834, Δf_r = 3142 Hz, an effective sampling time step of $\Delta\tau$ = 0.3 ps, and an effective time span of 10 ns. The minimum spectral resolution is 100 MHz = 0.003 cm^{-1}. The spectral range $1/\Delta\tau$ = 3.2 THz, corresponding to the difference between the two cavity-stabilized cw lasers, is significantly larger than the 250 GHz bandpass; therefore the determination of the absolute frequency is straightforward.

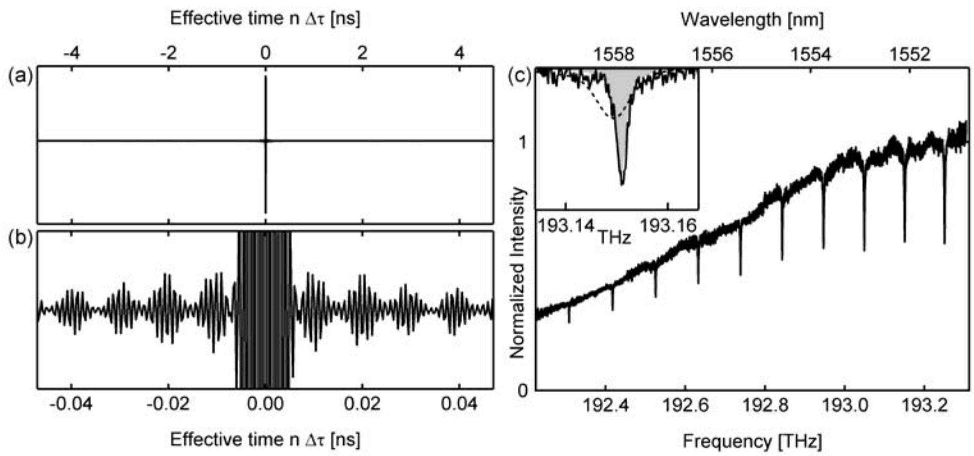

Fig. 2: (a) High signal-to-noise interferogram (autocorrelation) containing 31834 points over an effective time window of ± 5 ns at a bandpass filter setting of 193.05 THz (1552.9 nm). (b) Expanded view of the interferogram at 30x the vertical scale and 100x the horizontal scale. The oscillations on both sides of the centerburst correspond to HCN absorption lines. (c) Spectrum over 1 THz obtained by concatenating spectra averaged for 4 minutes at seven different filter positions. Inset: Comparison of the passive FTIR spectrum (solid line) to the OSA spectrum (dashed line) and reference truth data obtained with a swept cw laser and wavelength meter (grey fill). All vertical scales are linear.

Fig. 2 shows measured data demonstrating the system capabilities. The single interferogram of Fig. 2 (a) was acquired over 1 hour and represents over 10^7 averaged interferograms. The time-domain S/N ratio is 3016, corresponding to a S/N of 0.95 per individual interferogram, which is close to the upper limit of S/N=1 for a thermal photon source. Fig. 2 (c) shows a spectrum obtained by concatenating several measurements at different tunable bandpass positions after removing the filter shape. In this case, each of the seven measurements was averaged to an S/N of about 700 for about 4 minutes. Finally, the inset demonstrates the superior frequency accuracy and resolution of this method over those of a standard optical spectrum analyzer.

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