Coherent Measurements with Fiber-Laser Frequency Combs

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Abstract: The coherent and broad spectral output of fiber-laser frequency combs can be exploited for a variety of high-resolution measurements outside of conventional frequency metrology. We will discuss recent measurements in spectroscopy, ranging, and telecommunication components.

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1. Introduction

Single-frequency or swept lasers serve as the optical source in a wide variety of high-resolution systems including laser spectroscopy, coherent range/Doppler laser RADAR (LIDAR), and high-speed telecommunication test and measurement systems. The ultimate goal of these systems is to gain information by measuring a modulation on the laser carrier signal. In the case of spectroscopy, one is interested in the attenuation of the laser after passing through a sample. In the case of LIDAR, one is interested in the delay or frequency shift of the light. Finally, in the case of telecom test and measurement, one is interested in the intentional or unintentional modulation effects of active or passive components in the network. In all these cases, the system bandwidth is a critical parameter. However, with single frequency lasers, the instantaneous bandwidth is limited to that of the detection electronics; higher bandwidths can only be achieved by sweeping the laser, a process which is often time-consuming and noisy. Coherent fiber-laser frequency combs provide an interesting source to circumvent these issues and provide a rapid, broad bandwidth measurement.

Fiber-laser frequency combs were initially developed to support optical frequency metrology and follow directly from the original development of Ti:Sapphire-based frequency combs [1, 2]. The comb is formed by stabilizing the output of a femtosecond fiber laser. (See Ref. [3, 4] and references therein.) In the frequency domain, this stabilized femtosecond laser produces a comb of frequency lines, resembling a very large (>100,000) collection of cw lasers. In the time domain, it produces a train of optical pulses that can be very short and have very low carrier phase and timing jitter [3-5]. The frequency comb has been used extensively for frequency metrology and is not the limiting factor in comparisons of even the best performing optical clocks [6].

Here, we will discuss our recent experiments exploring other applications for fiber-laser frequency combs outside of frequency metrology. In essence, this coherent broadband laser source can replace coherent single frequency lasers in high-resolution measurements systems. The resulting modulation of the frequency comb can then be measured by mixing it with a second phase-coherent frequency comb. As discussed below, this detection scheme can be viewed equivalently as coherent linear optical sampling, multi-heterodyne detection, or simply an electric-field cross-correlation [7-11].

2. Dual Coherent Laser Sources

Following earlier work [8-10], we have setup a high-resolution sensing system using two coherent frequency combs, as shown in Figure 1 [11]. In order to realize truly coherent optical sampling with this approach, the signal and LO sources must be fully phase coherent, with less than a radian of *relative*, pulse-to-pulse optical phase jitter over the measurement period. This requirement differs substantially from the requirements on the comb in optical frequency metrology, where the comb must be phase-coherent on long time scales with a single rf or optical clock. In that case, the required long-term absolute phase coherence is achieved by relying on a self-referenced detection of the offset frequency, a method which usually requires generating a full octave of bandwidth from the comb. Here, we only require a relative, short-term phase coherence. Therefore, rather than using self-reference detection, we phase-lock both lasers to two narrow-linewidth cw lasers which gives us more flexibility in the output power spectrum while still providing the necessary tight relative phase coherence between the sources. Interestingly, while frequency metrology for optical clocks often uses only a few teeth of the frequency comb, we actually use many teeth for the high-resolution sensing applications discussed here

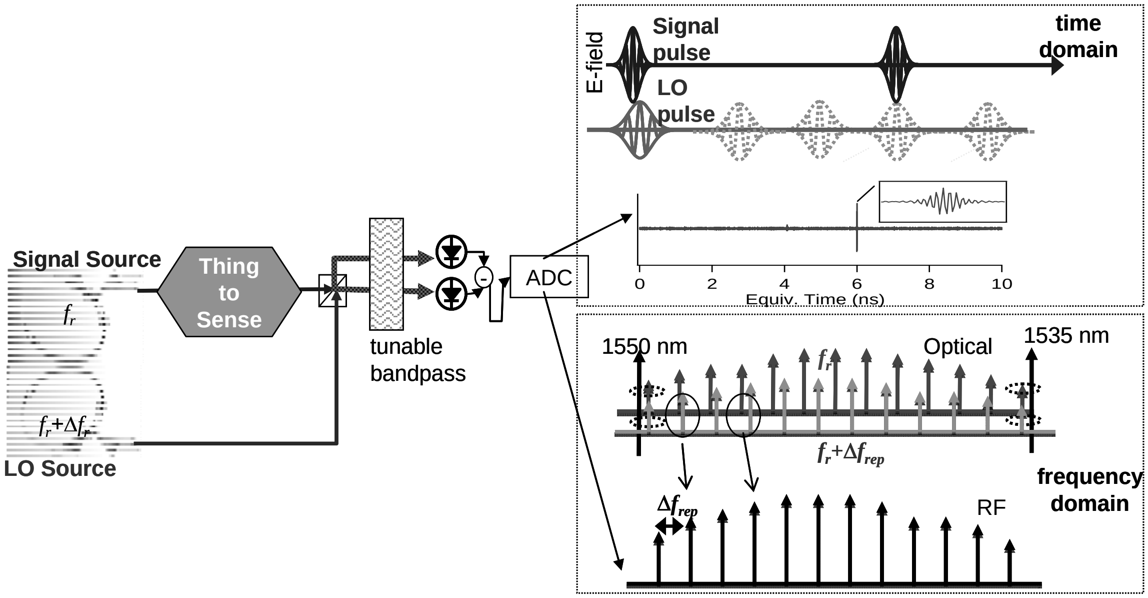

Figure 1: Basic setup for coherent measurements using dual coherent frequency combs. The repetition rate of the two lasers is nominally 100 MHz, and they differ by Δf_{rep}*~1-5 kHz. In the time domain, the LO pulse train slowly "walks" through the return pulse to generate a measurement of the returning electric field. In the frequency domain, the LO pulse acts as a massively parallel heterodyne receiver to generate an rf comb. The phase and amplitude of each rf comb tooth reflects the phase and amplitude of the modified signal comb.*

3. Coherent Spectroscopy

As a demonstration of the potential of this technique for coherent spectroscopy, we have used it to measure the full coherent spectrum of one of the rovibrational bands of Hydrogen Cyanide gas [11]. The source comb is passed through the gas sample and we detect the relative change in both the amplitude and phase of each comb tooth. Since the frequencies of the comb modes are well known, there is no uncertainty in the frequency axis for the spectral measurement. Perhaps more importantly, the system uses heterodyne detection and therefore has greater potential sensitivity than conventional broadband direct detection techniques.

4. High Precision Ranging

This same system can be used for precision range measurements. In earlier work, we used a single frequency comb to measure the range to an object to ~ 50 μm resolution [12]. However, for this earlier work, the range ambiguity was quite small. By using two distinct frequency combs, as shown in Fig. 1, we can now measure the range at arbitrary distance from the source. The concept is perhaps most easily considered in the time domain where it can be viewed as a "time-of-flight" measurement. In this view, one source outputs a stream of pulses that reflect off the target, while the second local oscillator source provides a precise linear time gate for measuring the return time [13]. We will present some preliminary measurements of high-resolution ranging in the laboratory setting.

5. Telecom device characterization

Telecommunication systems are operating at higher and higher modulation frequencies and with greater complexity phase-modulation formats. In order to operate at their highest data transmission, future systems are pushing the limits of the various components and the links themselves. Linear optical sampling provides a highly sensitive means of directly measuring the high-speed optical waveform [7]. We have taken some preliminary measurements using the coherent linear optical sampling depicted in Fig. 1, with the modification that one comb is replaced by a modulated optical waveform. These data can be used, for example, to characterize the performance of a high-speed, phase modulator [14].

5. Conclusion

Frequency combs have revolutionized optical frequency metrology. They have the potential to bring equivalent improvements in resolution and sensitivity to a variety of other applications. Here, we discuss three such applications: precision spectroscopy, precision ranging, and precision characterization of telecom components.

6. References

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