Applications of Highly Coherent Femtosecond Fiber Lasers

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Abstract: Coherent, broadband fiber lasers produce pulse trains with <1 femtosecond relative timing uncertainty and <1 mHz relative frequency uncertainty. These sources can advance many applications including optical frequency metrology, ranging LIDAR, and broadband molecular spectroscopy.

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1. Introduction

The output of a femtosecond fiber laser can be both spectrally broadened and stabilized, thereby providing a broadband coherent source in the near infrared. In the frequency domain, the result is a frequency comb with frequency stabilities at the millihertz level (relative to the reference), while in the time domain, the result is an optical pulse train with sub-femtosecond relative timing jitter [1, 2]. This coherent source can be used for high-resolution measurements in a range of areas including frequency metrology, ranging, vibrometry, and spectroscopy. We will discuss the performance of these sources and some recent work exploring their applications.

2. Optical Frequency Metrology

Originally, frequency combs were developed to support optical frequency metrology for optical atomic clocks [3, 4]. The first combs were based on solid-state femtosecond lasers, but fiber-based systems were soon available as well (see [2] and references therein). Figure 1 shows the basic configuration of a stabilized femto-second fiber laser and the resulting frequency comb output. The frequency comb can be phase-locked to either an rf or optical reference [5,6]. If locked to a Cesium microwave clock, the frequency comb provides a precise spectral ruler, where each comb tooth frequency is known with respect to the microwave clock. It can therefore be used to measure the absolute frequency of an optical clock. If locked to an optical atomic clock, the frequency comb provides an even more stable spectral ruler and can be used to measure the relative frequency of a second optical clock. In all cases, the fiber frequency comb is sufficiently stable that it contributes negligible uncertainty to the optical frequency measurement [5, 7].

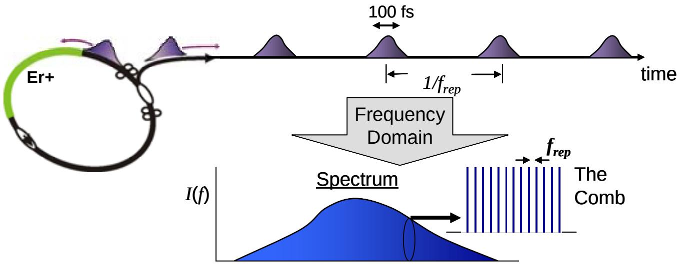

Figure 1: A femtosecond fiber laser will put out a train of pulses in time at a repetition frequency $f_{repetition}$. Because the pulses are short, their spectrum is broad. Because the pulses are repetitive in time, the spectrum is actually composed of a series of discrete lines.

3. Coherent Spectroscopy

The use of combs for optical frequency metrology is critical for optical clocks. However, it is interesting that this particular application actually uses only a few teeth of the frequency comb. Most of the frequency comb teeth do not participate in the measurement. On the other hand, other high-resolution sensing applications can benefit from the full comb output. Following earlier work [8, 9], we have recently demonstrated a multi-heterodyne technique for measuring the full coherent output of a frequency comb [10]. This basic technique, shown in Figure 2, allows us to measure the relative amplitude and phase between two frequency combs. If one comb is passed through a sample, for example, we can then measure the full amplitude and phase spectrum of the sample. 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 direct detection techniques. We will discuss recent high-resolution measurements of the HCN gas spectrum.

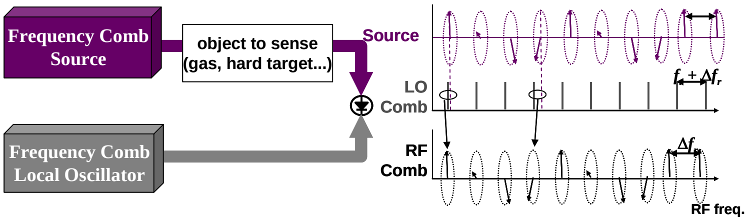

Figure 2: Basic concept behind multiheterodyne spectroscopy. The two combs are slightly offset in repetition rate. As a result, their heterodyne signal leads to an rf comb, where there is a one-to-one mapping between the optical comb teeth and the rf comb teeth. Note that both the amplitude and phase of the optical signal is measured.

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 [11]. However, for this earlier work the range window was quite small. By using two distinct frequency combs, as shown in Fig. 2, 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 [12]. The timing accuracy can be as low as femtoseconds since it is measured in the optical. We will present some preliminary measurements of high-resolution ranging in the laboratory setting.

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 two such applications of precision spectroscopy and precision ranging.

6. References

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