High Resolution Spectroscopy Using Fiber-Laser Frequency Combs

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Abstract

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. 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, focusing on recent work applying them to high-resolution spectroscopy.

Introduction

Optical sensing can provide information on a wide variety of systems. For example, LIDAR can provide information on both distance and velocity, while spectroscopy can provide information on the structure of an atom or molecule. In many of these situations, the resolution of the measurement is limited by the quality of the source. For example, high resolution ranging requires accurate timing, high resolution velocity measurements require accurate frequency measurements, and spectroscopy requires an intense and stable light source. Stabilized, broadened femtosecond fiber lasers can meet many of these requirements simultaneously.[1, 2] Originally, these sources were developed primarily for their important application to frequency metrology; they provide a stable, known frequency comb against which to measure optical clock frequencies.[3-5] Figure 1 shows the basic configuration of a stabilized femto-second fiber laser and the resulting frequency comb output. However, as has been widely recognized, these sources can also be exploited for high-resolution sensing. We have conducted some preliminary laboratory measurements exploring the use of these sources for high-resolution ranging, vibrometry, and spectroscopy measurements.[6-8]

Experimental Setup

Figure 2 shows the basic experimental configuration for using two frequency combs to prove the optical response of a system. The setup in Fig. 2 emphasizes spectroscopy and uses the technique of multiheterodyne spectroscopy to "read out" the amplitude and phase change of each comb tooth after it passes through a gas sample.[8-10] However, we note that the gas cell could be replaced by any material or even by a reflective surface (with some change in the experimental topology) if one wanted to measure range or distance.

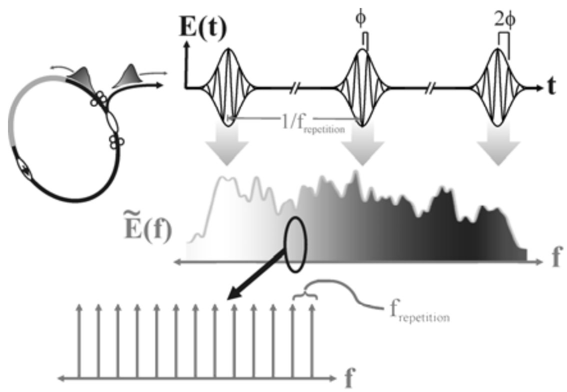

Figure 1: A femtosecond fiber laser will put out a train of pulses in time at a repetition frequency $f_{repetition}$. The spectrum can be broadened in nonlinear optical fiber, but retains the "comb" structure.

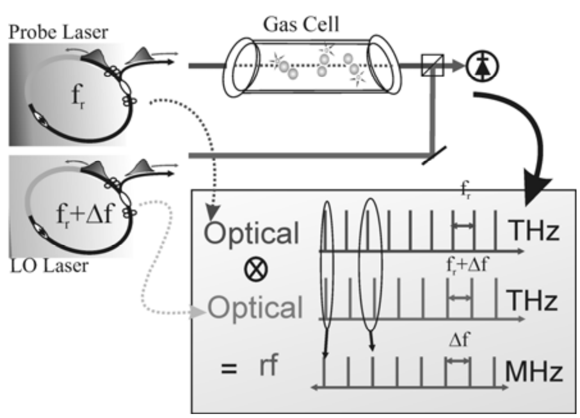

Figure 2: Basic concept behind multiheterodyne spectroscopy. The two combs are slightly offset in repetition rate. As a result, their heterodyne signal leads to an rf comb, where there is a one-to-one mapping between the optical comb teeth and the rf

comb teeth. Note that both the amplitude and phase of the optical signal is measured.

Results

As shown in Figure 2, the both the amplitude and phase of the transmitted light are available from this technique. Figure 3 shows the measured amplitude and phase of a section of spectrum across Hydrogen Cyanide (HCN), by use of a cell filled with 25 Torr of the gas. (These results are discussed in much more detail in Ref. [8]). HCN was chosen since it has a number of absorption lines in the 1550 nm region and is in fact used as a calibration source in many telecommunication systems.[11] The dips in the spectrum correspond to the absorption lines, while the overall shape corresponds to the optical filter used in selecting this portion of the spectrum. For the data of Figure 3, only a small (1 THz) sample of the spectrum is measured, but the spectrum of the source extends over a broader range, and the full spectrum can be stitched together from data similar to these.[8] We will also discuss the sensitivity and accuracy expected with this novel type of spectroscopy as well as current limitations.

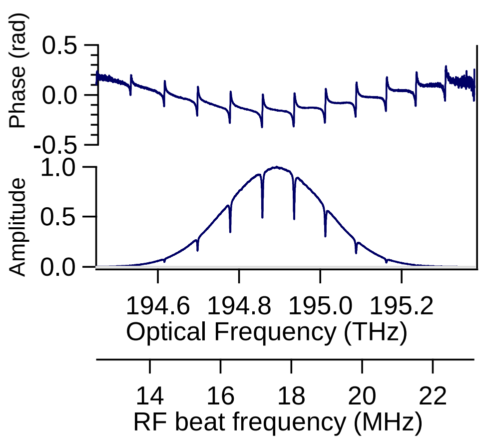

Figure 3: Example spectroscopic measurement on a 25 Torr cell of HCN gas covering about 1 THz in the optical. The samples occur at 100 MHz intervals. The absorption from many molecular lines is visible along with the corresponding phase shift.

Conclusion

Stabilized femtosecond fiber lasers can produce broadband coherent light that can be exploited in a number of high-resolution measurements. Originally, these combs found their main application in optical frequency metrology, but they should find many other applications as well in other areas of high-resolution measurements. We discuss a few of these other areas, demonstrating in particular the application of these sources to broadband, high-resolution spectroscopy.

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