WC4.3 (Invited)
17:00 – 17:30

Measuring Optical Waveforms with Fiber Frequency Combs

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Abstract: A stabilized frequency comb provides a broadband array of highly resolved comb lines. Using a multiheterodyne technique, we measure the amplitude and phase of every comb line, allowing for massively parallel, high-resolution optical sampling.

1. Introduction

One can think of a stabilized frequency comb as a train of femtosecond pulses that are effectively the sum of a hundred thousand or more, evenly spaced, single frequency lasers (often referred to as comb teeth). This melding offers an alluring combination: the frequency precision, stability and resolution of continuous wave lasers coupled with the enormous bandwidth and time resolution of femtosecond pulses. These combs are an interesting alternative to swept cw laser measurement system offering greater bandwidth and far greater timing jitter/phase stability. We recently demonstrated that combs have be used for massively parallel spectroscopy in which 150,000 comb teeth spanning 120 nanometers are used to record the absorption and phase spectra of a hydrogen cyanide (HCN) gas sample [1], with greater resolution, speed and accuracy than conventional techniques. However, this comb based measurement is far more general and has a number of additional applications including ultra precise and rapid distance metrology or phase sensitive telecom pulse sampling [2].

The stabilized femtosecond frequency comb was originally developed as a powerful tool for frequency metrology [3,4], providing stable and well known frequencies over much of the optical spectrum (see figure. 1). However, to take advantage of the power of the frequency comb for more general application one must overcome the challenge of simultaneously addressing between a hundred thousand and a million individual lines of the frequency comb. Expanding on earlier work in the THz regime [5,6,7] we address these lines by heterodyning the frequency comb with a second comb of slightly different frequency spacing. The resulting heterodyne signal is a radio frequency (rf) comb where each tooth corresponds to the heterodyne beat between a single optical tooth from each comb.

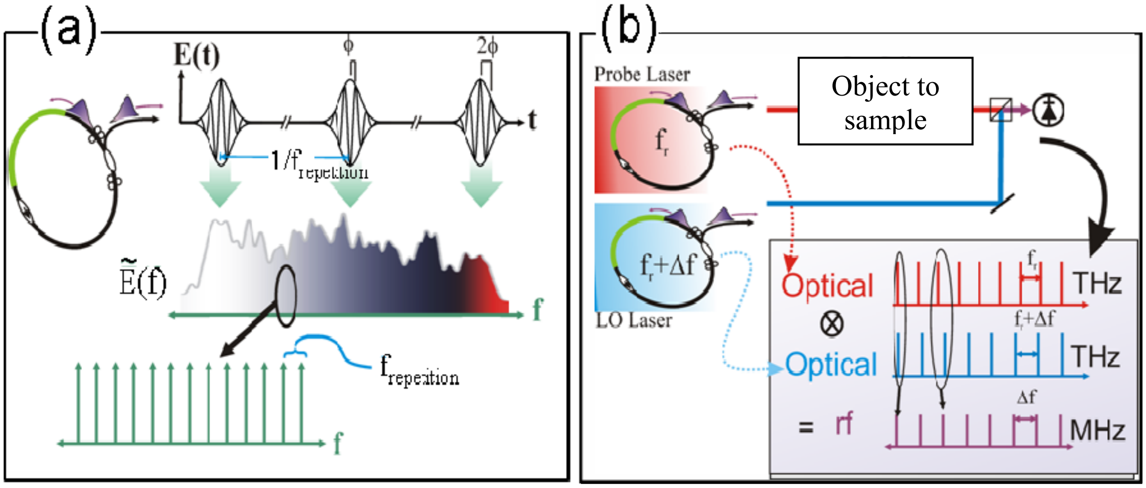

Figure 1: (a) A femtosecond fiber laser will put out a train of pulses in time at a repetition frequency $f_{repetition}$. The spectrum of each pulse extends over 125 nm and can be further broadened in nonlinear optical fiber, but retains the "comb" structure. (b) Basic concept behind multiheterodyne measurement. 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.

The advantage of this multiheterodyne scheme is at least four-fold. First, the mapping of optical combs into the rf allows for the straightforward retrieval of each comb line by use of a single photodiode and a fast digitizer. Secondly, the mapping also allows for near perfect knowledge of absolute frequency (1 Hz level). Thirdly, the use of heterodyne detection allows for the detection of very weak signals and the rejection much technical noise. We were able to retrieve data with as little as twenty picowatts per comb tooth. Finally, the heterodyne signal is really a mapping of the full electric field, meaning that both optical amplitude and optical phase/time delay are simultaneously retrieved for each comb tooth. As a corollary the time domain signature of the optical pulses are recovered as well.

For this experiment we use a pair of erbium fiber based femtosecond frequency combs. Each comb has a bandwidth of roughly 125 nm centered around 1550 nm. The repetition rates (tooth spacing) of the two combs are nominally 100 MHz and differ by 1-5 kHz, depending on application. Because we resolve comb teeth in frequency/time, it is critical to have a high degree of stability between the two frequency combs or else the signal washes out. We achieve this stability by stabilizing each comb to the same pair of single frequency lasers located at 1535 nm and 1550 nm. This is sufficient to stabilize the two degrees of freedom in a frequency comb and allows us to achieve a linewidth of less than one hertz between the two combs. More information on this technique can be found in Refs [1,8,9].

Figure 1(b) shows the experimental configuration for using two frequency combs to measure the optical response of a system. The object under test can range from a gas sample, a telecom component or an open space LIDAR path. In addition to the beam path shown in figure 1(b) we also incorporate a reference path which allows us measure the background amplitude and phase profile of the combs so that the response if the object under test can be isolated.

Figure 2 shows data from two applications: rapid broadband spectroscopy (frequency domain), and rapid high resolution ranging (time domain). In both applications data can be acquired a very high rates with an accuracy that pushes or exceeds the limits of conventional technology as one would expect from frequency combs.

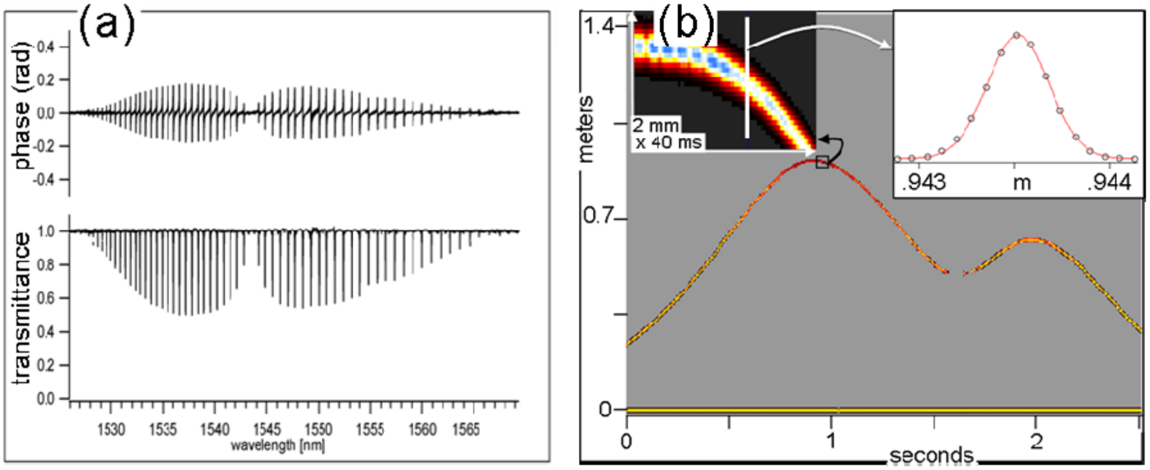

Figure 2(a) Measured phase and absorption spectrum for hydrogen cyanide (HCN). In total the measurement spanned from 1492 nm to 1618 nm or 155,000 individual frequency comb lines. For clarity only the data showing HCN absorption bands is shown. (b) Precision ranging of a moving reflector in the time domain. This technique allows for 20 μm range resolution with a 5 kHz update rate allowing for real time tracking of the target. Resolution can be increased below 200 nm with longer averaging time.

References

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