Broadband, Frequency Comb Spectroscopy

Ian Coddington, William C. Swann, Nathan R. Newbury
Optoelectronics Division, NIST
325 Broadway, Boulder,CO 80305
ian@nist.gov

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 spectroscopy.

OCIS codes: (140.3510) Lasers, fiber; (300.6310) Spectroscopy, heterodyne; (320.7090) Ultrafast lasers

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 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 pulse. We recently demonstrated that this system can 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].

The stabilized femtosecond frequency comb was originally developed as a powerful tool for frequency metrology [2,3], providing stable and well known frequencies over much of the optical spectrum (see figure. 1). The challenge for spectroscopy is to simultaneously address between a hundred thousand and a million individual comb lines. Expanding on earlier work by Kielman *et. al.* [4,5] we demonstrate that this separation can be done by heterodyning the frequency comb with a second comb of slightly different frequency spacing. The result of this heterodyning is a radio frequency (rf) comb where each tooth corresponds to the heterodyne beat between a single optical tooth from each comb.

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 heterodyne signal is really a mapping of the full electric field, meaning that both optical amplitude and optical phase are simultaneously retrieved. Finally, 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.

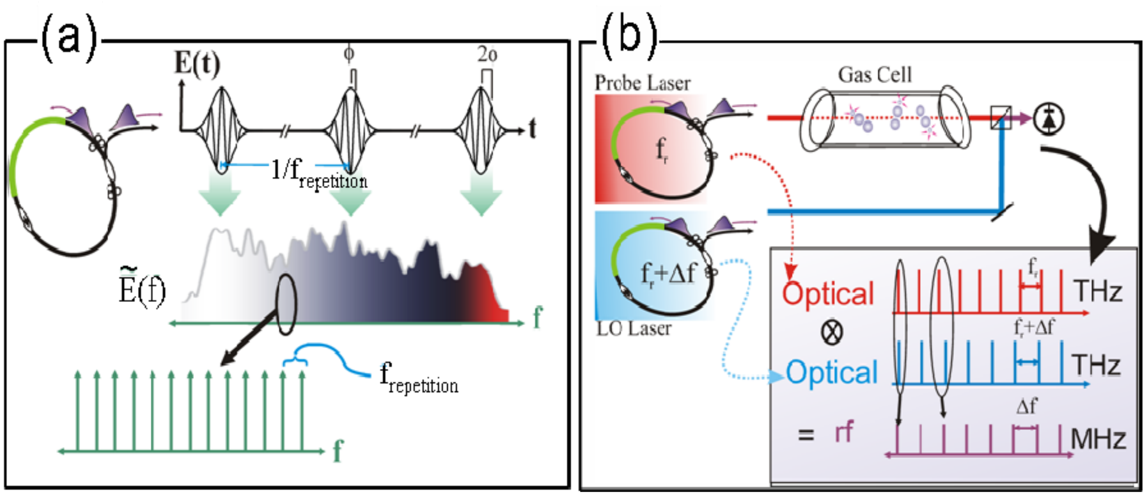

Figure 1: (a) A femtosecond fiber laser will put out a train of pulses in time at a repetition frequency $f_{repetition}$. The spectrum of each pulse extends over 125 nm and can be further broadened in nonlinear optical fiber, but retains the "comb" structure. (b) Basic concept behind multiheterodyne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

2. Experiment

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, 100,016 kHz and 100,017 kHz, cause the slight frequency mismatch necessary for our rf mapping detection scheme.

Figure 1(b) shows the experimental configuration for using two frequency combs to measure the optical response of a system. Here we emphasize the spectroscopic applications, but in principle one could use this system to query the optical response of a number of systems such as telecom components or nonlinear materials. In addition to the beam path shown in figure 1(b) we also incorporate a dummy path containing no cell. This path allows us measure the background amplitude and phase profile of the combs, which is later subtracted out.

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 [1,6,7].

Figure 2(a) shows the resulting phase and transmittance spectrum of our HCN cell. Across the figure there are 50,000 data points, each corresponding to the phase shift and absorption experienced by a single comb tooth.

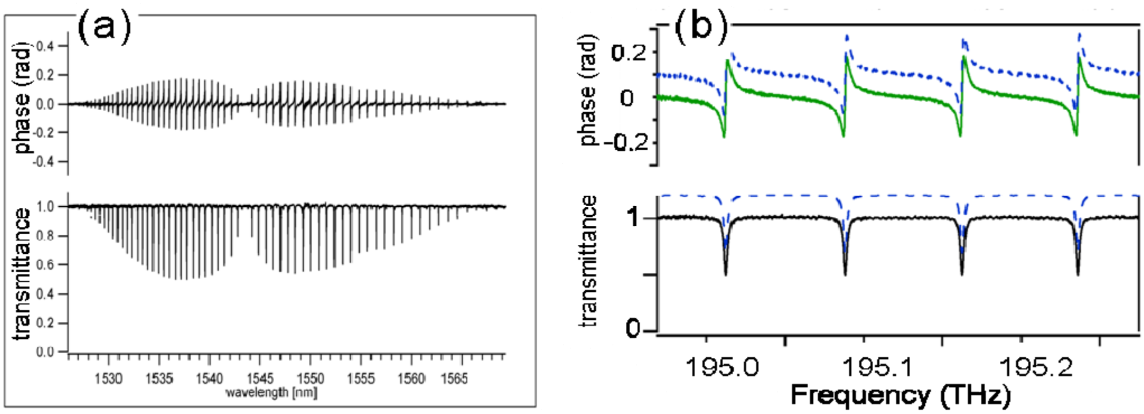

Figure 2(a) Measured phase and absorption spectrum for hydrogen cyanide (HCN). In total the measurement spanned from 1492 nm to 1618 nm or 155,000 individual frequency comb lines. For clarity only the data showing HCN absorption bands is shown. (b) Expanded view, data is in excellent agreement with previously published values [8] (dotted lines offset for clarity).

3. 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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