Narrow linewidth fiber laser frequency comb

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Abstract: Fiber laser frequency combs can provide a series of optical lines that span the spectrum from 1 to 2 μm. By tightly locking the frequency comb to an optical reference, it is possible for these comb lines to exhibit residual linewidths below 1 Hz, with correspondingly high residual stabilities. We present the current design of our narrow-linewidth frequency comb and discuss some applications that are possible with such a coherent source.

Introduction

Since their inception, frequency combs have revolutionized the fields of optical metrology,[1-3] and show increasing promise in a wide range of other applications such as spectroscopy, frequency transfer, and remote sensing. The first combs were based on Ti:Sapphire mode-locked lasers that operated in the visible spectral region.[1, 2] These were closely followed by fiber-based combs that operated in the near-infrared region.[4-6] These fiber combs were based on femtosecond (FS) fiber lasers [7] and made use of common telecommunications fiber components. The architecture of these combs include, in general, a FS mode-locked laser, which acts as a seed oscillator, followed by a piece of highly-nonlinear fiber (HNLF), which, through supercontinuum generation, broadens the seed oscillator's less than 100 nm wide output comb spectrum into a comb covering more than a full octave of spectral width. The temporal output of the comb is a train of optical pulses; in frequency space the spectrum appears as a series of regularly spaced frequencies separated by the repetition rate of the laser. One remarkable feature of this comb is that only two degrees of freedom (DOF) are required to stabilize every one of the ~10^6 modes across the comb spectrum. It is the precise control of these two DOFs that allow us to obtain the sub-hertz linewidths of the comb modes, with respect to the reference.[8, 9]

In general, the comb modes can be described by the simple formula, $f_n = nf_r + f_{ceo}$, where f_r is the repetition rate and f_{ceo} is the so-called carrier envelope offset (CEO) frequency. When locked to a microwave reference, f_r and f_{ceo} are stabilized. For the work described here, we lock to an optical reference. In that case, one comb mode at $n = n_{ref}$ with frequency f_{nref} is stabilized to the optical reference, while f_{ceo} is stabilized to a microwave reference (which can be referenced back to the comb repetition rate for a fully self-referenced comb, although this is rarely needed in practice.)

The comb

The layout of our comb is shown in Figure 1.[6] It is composed of a ring-configuration FS laser with a nonlinear polarization saturable absorber used to sustain modelocking.[7] The output of this laser is amplified to ~60 mW through an erbium amplifier and then passes through ~20 cm of HNLF, which provides the spectral broadening, covering over a full octave from ~ 1 um to over 2.2 um.[10] The HNLF output passes through a collinear f-to-2f frequency doubler,[5] where comb light at 2074 nm is frequency doubled to 1037 nm so that it overlaps fundamental comb light at 1037 nm. The heterodyne beat note between the doubled and fundamental spectra at 1037 nm provides the carrier-envelope offset (CEO) frequency, which is one of the DOFs required to stabilize the comb. [1, 2] [11]

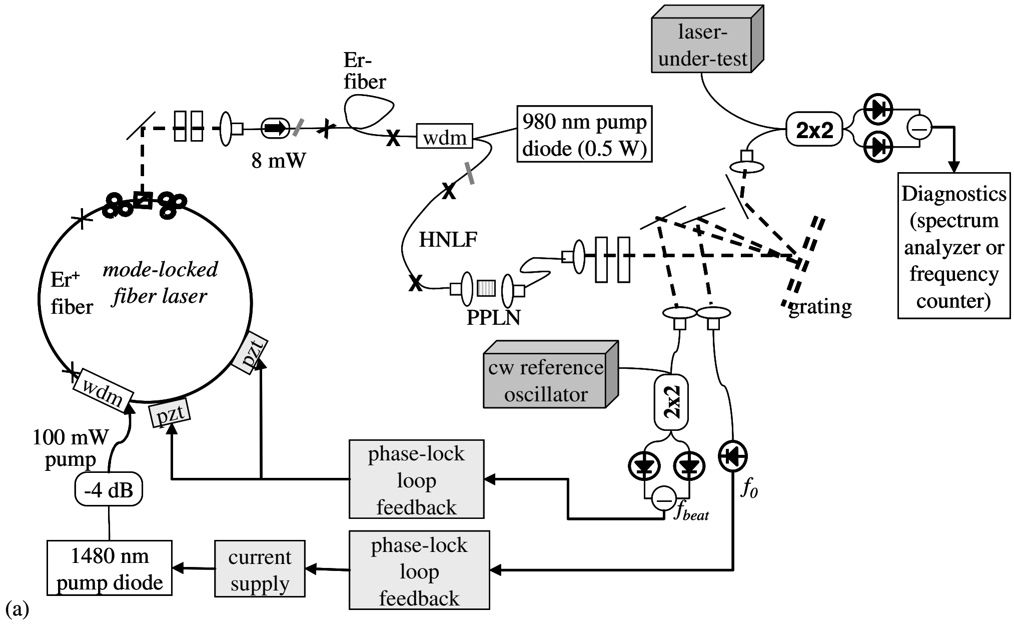

Figure 1: Layout of the fiber-laser frequency comb from Ref. [6].

We use two techniques to reduce the noise on the CEO lock, which is dominated by the transfer of amplitude noise on the pump to frequency noise on the CEO frequency.[9] First, the relative intensity noise on the pump decreases as the pump output current is increased, so we operate the pump at its maximum rated output and attenuate the pump light to the desired level for proper oscillator operation. This has the effect of reducing the noise contribution from the pump below that that would be obtained were the pump merely operated at the power necessitated by the oscillator. Second, to increase the bandwidth of the CEO lock beyond what is given naturally by the roll-off in the gain response of the oscillator's gain fiber, we use a phase-lead technique. The resulting CEO frequency is narrowed up to sub-hertz linewidths and sub-radian phase excursions.[12] Figure 2 shows the unlocked and the phase-locked CEO frequency. This beat note appears as an instrument-limited linewidth delta function on top of a noise pedestal, as indicative of a healthy phase lock.

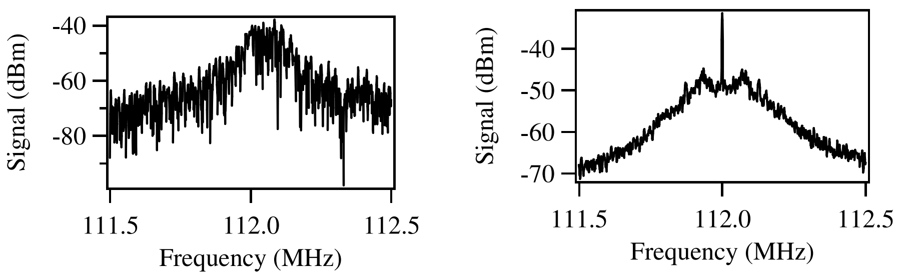

Fig 2: Unlocked and locked fceo signal. The coherent peak in the locked signal occurs when the integrated phase noise drops below 1 radian.

To substantially reduce the noise on the comb lines, we must also lock a single comb tooth to a stable, Hertz linewidth continuous wave (cw) optical reference[13]. This approach has the advantage of transferring the stability of the cw reference to the comb directly in the optical regime. This approach is well suited for applications of the comb in supporting up and coming optical clocks by transferring the clock signal over great distances on fiber as well as transferring the signal to other spectral regimes.[14] To increase the bandwidth of our optical lock we use a pair of piezo transducers; one has a low bandwidth (~1kHz) and high dynamic range for taking out length drifts and low frequency noise and the other has a bandwidth out to ~30 kHz (but lower dynamic range) and removes high frequency noise.[6] Figure 3 shows the unlocked and phase-locked optical beat frequency between the comb and a cavity-stabilized 1535 nm fiber laser.

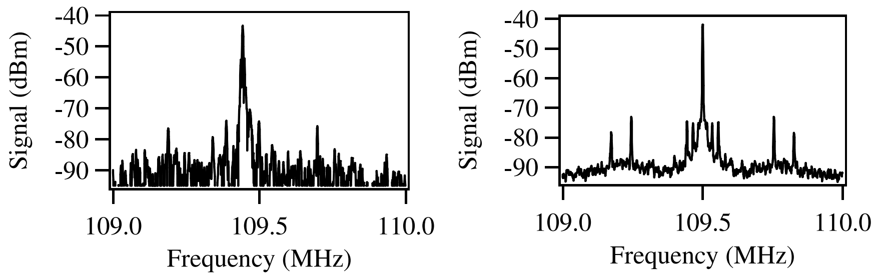

Fig. 3: Unlocked and locked optical beat note between a comb line and a cavity-stabilized laser at 1550 nm.

Applications: Support of optical clocks

The most immediate application of a fiber laser frequency comb of narrow linewidth is to optical frequency metrology. The low phase noise of the combs implies a high residual stability with respect to the reference source. To verify that the fiber frequency comb could support measurements of very high stability, we recently conducted experiments on a coherent fiber optic network that combined the fiber laser frequency comb, a Ti:sapphire frequency comb, several cavity-stabilized cw lasers, and several Doppler-cancelled fiber optic links.[14] The two frequency combs provided nodes of the network where the optical frequency of the source could be translated from 1.1 μm to 760 nm (in the case of the Ti:Sapphire comb) or from 1.1 μm to 1.535 μm (in the case of the fiber frequency comb). We found that the phase noise of light propagated around the fiber network and across the spectrum could be predicted by the various phase-locks in the network down to about 10 Hz Fourier frequency. Below 10 Hz, length noise on short "out of loop" paths within the system cause excess noise on the beat signal. An Allan deviation plot shows a fractional frequency instability of $\sim 6 \times 10^{-17}$ at one second, dropping to $\sim 2 \times 10^{-18}$ at 1000 seconds. This stability is more than adequate for transferring stable optical signals, such as might be encountered in optical clocks and frequency transfer, coherent communications, and other applications.

Applications: Spectroscopy and Remote Sensing

The stabilized comb, as demonstrated, is ideally suited for applications where both broad spectral coverage and well defined optical frequencies are required. One such application is coherent range/Doppler Light Detection and Ranging (LIDAR); the broad spectrum provides very fine range resolution, while the narrow lines provide high Doppler sensitivity. We have conducted some initial experiments on a laboratory-based range-Doppler LIDAR.[15] A drawback of the approach taken in this initial work is that it had only a limited range of regard. To solve this problem, one can use two phase-locked frequency combs; one comb acts as a transmitter while the other acts as a local oscillator (LO). The LO can be tuned to overlap the return signal, allowing for a much wider range of regard.

A second application is spectroscopy, where the comb's broad coverage guarantees overlap with many interesting spectral features, and the accurately defined comb line locations give absolute information on the location of these features. One way to use frequency combs for spectroscopy is to follow a technique originally developed in the microwaves and later used in the terahertz regime. [16, 17] The basic idea is to transfer the comb spectrum into the radiofrequency (RF) domain. This is accomplished by combining the output of two optical combs, operating at slightly different repetition rates but otherwise phase-locked together, into a single signal. In the RF domain, this signal appears as a comb of RF lines separated by the difference in repetition frequency of the two combs. Each tooth in this RF comb represents a beat signal between two particular comb teeth at a very well known optical frequency. This approach does require two stabilized frequency combs of very narrow linewidth, but the detection is quite simple – a single photoreceiver is needed rather than an entire spectrometer.

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