Narrow Linewidth 1.5 μm sources and the Thermal Limit

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Abstract: A measured 1 Hz linewidth between a cavity-stabilized, 1535 nm cw fiber laser and the 1535-nm tooth of a stabilized fiber frequency comb is below the thermodynamic limit of the frequency comb.

Narrow linewidth, coherent optical sources have numerous applications in optical clocks and remote sensing since they support much more sensitive frequency measurements than do rf sources. Phase-locking a cw laser to a stable optical cavity, using the well established Pound-Drever-Hall technique,[1] generates linewidths as low as 0.1 Hz.[2, 3] Such stabilized lasers are particularly important in developing highly precise optical clocks; as a result, most operate at wavelengths compatible with these clocks. However, lasers in the 1550 nm telecommunications band can be similarly narrowed, and here we report, to our knowledge, the first Hertz-level linewidth, cavity-stabilized laser at 1535 nm. Pulsed, mode-locked lasers can be similarly stabilized to form frequency combs with narrow linewidth comb teeth. First demonstrated with Ti:Sapphire systems,[4-6] this technology has also migrated to the 1550 nm telecommunication band and narrow-linewidth fiber-based frequency combs have been demonstrated [7-9] In Ref. 7, the relative linewidths of two fiber frequency combs were compared by referencing them to the same free-running cw laser. In Ref. 9, the linewidth of the fiber frequency comb was effectively compared to that of a Ti:Sapphire comb referenced either to the same underlying cw reference or to a distinct, separate cw reference. Here, we directly verify that the absolute comb tooth linewidth is of order 1 Hz by comparing the fiber frequency comb, phase-locked to a narrow cw laser at 1126 nm, with an independent cavity-stabilized laser at 1535 nm. Just as the cavity-stabilized lasers have a fundamental linewidth limited by the thermal cavity noise,[10] the fiber frequency comb has a fundamental linewidth limited by thermal noise of the femtosecond fiber laser's fiber-optic cavity.[11, 12] However, stabilizing the fiber frequency comb to a cavity stabilized laser brings the noise below this thermal limit.

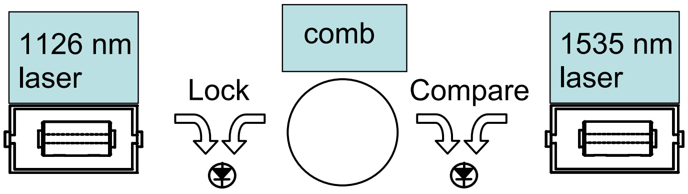

Fig. 1. Schematic of the setup for independently comparing a cavity-stabilized laser at 1535 nm and a cavity-stabilized laser at 1126 nm. The fiber frequency comb coherently translates the signal at 1126 nm to 1535 nm.

A schematic of the experiment is shown in Fig. 1. Cavity-stabilized 1126 nm laser light[2, 3] was sent over a Doppler-cancelled fiber link to the fiber frequency comb. Tightly phase-locking the comb to this stabilized 1126 nm light transferred the stability across the comb, as in Ref. 9. A separate cw fiber laser at 1535 nm was independently stabilized to an optical cavity, forming a narrow linewidth "probe." This probe was then heterodyned against a comb tooth at 1535 nm. Figure 2 shows the resulting heterodyne beat signal at two different rf spans. Interestingly, the "locked" beat signal between the comb and the 1126 nm light actually has a broader pedestal than does the measured beat signal between the comb and the independent 1535 nm laser. This somewhat counter-intuitive result arises because the comb tooth at 1126 nm suffers from both pump-induced and ASE-induced jitter, whereas the comb tooth at 1535 nm does not.[8] Both comb teeth are subject to frequency jitter from fluctuations in the cavity length, which dominates at low Fourier frequency, and therefore the two signals are very similar over the narrower band of Fig. 2a. Here, both signals show an instrument limited width of 1 Hz, measured over 2 seconds.

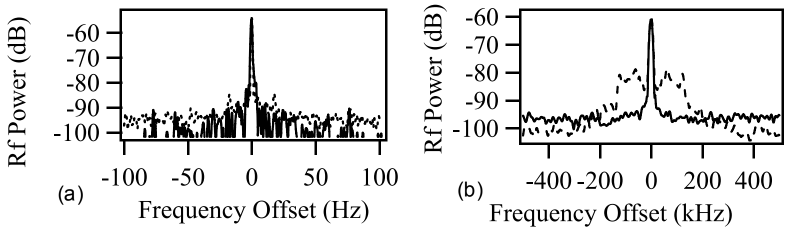

Fig. 2. Beat note between the cavity-stabilized laser and the comb mode at two different rf spans. The resolution bandwidths are 1 Hz and 1 kHz, respectively. Dashed line: 1126 nm beat note. Solid line: 1535 nm beat note.

A fundamental limit to the noise on the cavity-stabilized lasers arises from the thermal fluctuations in the cavity length.[10] Similar fundamental thermal fluctuations act on the single-mode optical fiber that makes up the cavity of the femtosecond fiber laser, which underlies the fiber frequency comb. The thermal fluctuations are given by $\Delta T^2 = kT^2/\left(\rho C V\right)$, where T is temperature, k is Boltzmann's constant, C is the specific heat, ρ the density and V is the mode volume. The power spectral density of the corresponding fiber length and resulting phase fluctuations has been derived.[11, 12] Interestingly, this fundamental thermal limit is much more relevant in determining the basic linewidth limitation near 1550 nm for cw fiber lasers than is the much smaller Schalow-Townes limit. Similarly, for the femtosecond fiber laser, these thermal fluctuations provide a fundamental limit to the free-running linewidth of the comb near 1550 nm. (Far from 1550 nm, the fundamental linewidth of the frequency comb is dominated instead by both pump-induced and ASE-induced fluctuations.[8]) Fig. 3 compares the frequency noise power spectral density for the free-running and phase-locked fiber comb at 1535 nm, as measured against the cavity-stabilized laser. Also plotted is the frequency noise contributed by the fundamental thermal limit of the fiber cavity. The noise of the free-running comb is considerably higher than this fundamental thermal limit; phase-locking the femtosecond fiber laser to the 1126 nm cavity-stabilized laser brings the noise below the fundamental thermal limit over a significant part of the lock bandwidth.

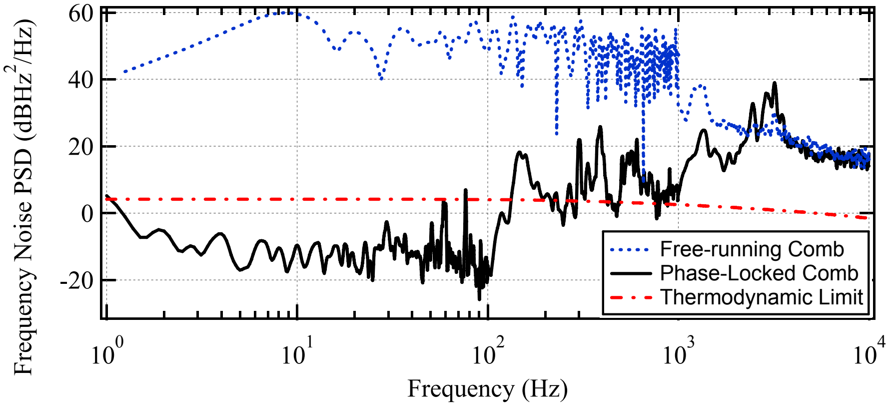

Fig. 3. Phase power spectral density for the fiber frequency comb line at 1535 nm with the comb unlocked (dashed line) and locked (solid line). The dotted-dashed line is the expected thermal limit for the fiber-laser cavity.

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