Residual stability of a fiber-based frequency comb

W. C. Swann, I. Coddington, L. Lorini, J. Bergquist, S. A. Diddams and N. R. Newbury
National Institute of Standards and Technology, 325 Broadway, Boulder, CO 80305
email: swann@boulder.nist.gov, phone: 303-497-7381, fax: 303-497-3387

Abstract: We present measurements of the residual frequency stability across a fiber frequency comb by comparison through a Ti:sapphire frequency comb. We find 6×10^{-17} stability at one second and 1×10^{-18} at 1000 seconds.

OCIS codes: (140.3510) Lasers, Fiber; (120.3930) Metrological Instrumentation.

Femtosecond frequency combs have revolutionized the field of optical metrology and will enable the practical use of optical clocks.[1] The recent advent of robust and compact fiber-laser based frequency combs in the 1 to 2 micrometer region, which employ reliable, readily available and inexpensive telecom components,[2-5] has simplified the task of transferring comb wavelengths within the 1550 nm band. Implicit in the task of transferring optical clock frequencies at very high stabilities is the need to establish the relative stability of both the fiber frequency comb and any fiber link that it is transferred over. To this end we have investigated the frequency stability across a fiber laser frequency comb over times between 0.1 and 7400 seconds. Our results demonstrate a factor of ~20 improvement over previous fiber comb stabilities[5, 6] and show that the stability performance of these combs is comparable to that of mainstay Ti: Sapphire combs.[7]

Our Er:fiber comb is based on a stretched-pulse passively mode-locked ring resonator with a 50 MHz repetition rate.[8] The output is amplified and passed through a piece of highly nonlinear fiber, producing an octave of comb light spanning over 1 to 2 micrometers. The offset frequency is detected with a collinear f to 2f interferometer[4] and stabilized through feedback to the pump power by use of a phase-lead technique for extended feedback bandwidth.[9] We stabilize the second comb degree of freedom by locking a comb tooth to a cavity stabilized laser at 1126 nm.[10] We then measure the known frequency of a stabilized laser at 1535 nm against a comb tooth to determine the residual stability of the fiber frequency comb.

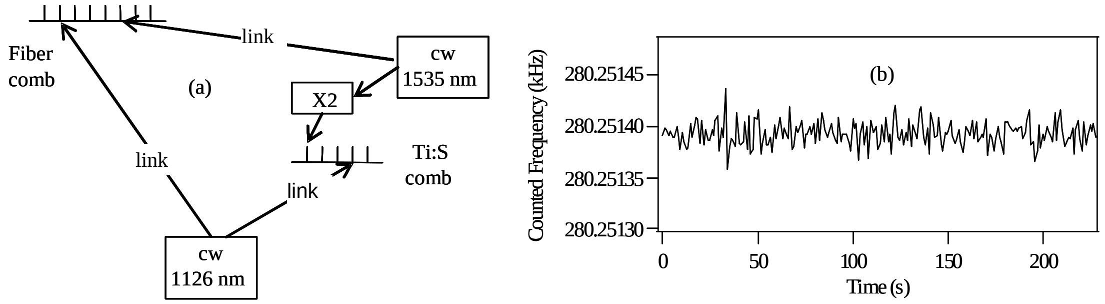

Figure1 (a): The fiber comb, 1126 nm cw laser, and 1535 nm cw source with associated doubling and Ti:Sapphire transfer comb, are in three different labs and connected using Doppler cancelled fiber links. (b): Example of counted data for a 1 second gate time.

Our measurement system, shown in Fig. 1(a), is laid out over three labs linked by over 700 m of optical fiber. Each fiber link is stabilized by use of a Doppler cancellation technique.[11] The cw 1126 nm light is split, and one part passes through a link to the fiber comb and provides the above-mentioned stabilization. The other part passes to a separate laboratory where it provides stabilization for a Ti: Sapphire comb.[12] Locked to this comb at 767.5 nm is a frequency-doubled 1535 nm cw fiber laser. This 1535 nm light, thus stabilized, is transferred through a third link where it is compared to the fiber comb. A heterodyne beat note between this 1535 nm light and an adjacent comb tooth is obtained by use of a balanced detector; it is the stability of this beat note that is of interest.

This beat note at 1535 nm is counted, along with the repetition rates and optical and offset frequency locks of both combs, by use of 11-digit frequency counters referenced to a common microwave source. (This source also references the various synthesizers used in other parts of the system.) Counter gate times between 0.1 and 30 seconds are used, and a total of over 2 hours of data was obtained. A sample of the count data at one second is shown in Fig. 1(b). Knowledge of the various mode numbers and offset lock signs and frequencies of the two combs, as well as the offset lock frequencies of the links, allow the expected beat note to be calculated (by extendedprecision calculations). The measured beat note agrees with the predicted value to within 2.2 parts in 10^{19}, averaged over 7400 seconds (~ 2 hours).

The Allan variance of the beat note, displayed in Fig.2, represents the combined stability of the fiber comb and all other components involved. The variance shows a stability of $\sim 6 \times 10^{-17}$ at one second and falls off roughly as $1/\tau^{0.6}$ across the entire span, where τ is the measurement time ranging between 0.1 and 1000 seconds. It is interesting to compare this measured stability with the predicted stability from the various in-loop measurements of the phase-locked frequencies. For both the Ti:Sapphire and fiber-laser frequency combs, the offset frequency lock and lock to the 1126 nm light show counter-limited stabilities (at one second) of 1- to 3×10^{-18}. Similar counter-limited stabilities are measured for the in-loop fractional frequency noise on the individual fiber optic links. Based on these results, one might expect a stability of our measured beat note of $\sim 6 \times 10^{-18}$ at worst, or 10 times lower than observed. As already noted in tests of the Ti:sapphire frequency comb,[7] the discrepancy can be explained by thermally induced drifts in short sections of out-of-loop fiber or air paths located immediately before the combiners that provide the beat signals. Indeed, measurement of the out-of-loop noise of one of the links returned a fractional noise of 1.7×10^{-17}, and similar levels are expected for out-of-loop sections in other parts of the system.

We can consider the temperature fluctuations that would be responsible for our observed Allan deviation at one second. If we assume a thermo-optic expansion coefficient $\Delta L_{opt}/L_{opt}$ of $\sim 1\times 10^{-5}$ / °C for optical fiber, an out of loop fiber path of ~ 3 m, and that the observed $\sim 6 \times 10^{-17}$ deviation at one second is caused by a fractional frequency noise power spectral density given by fiber length fluctuations of $\sim 10^{-32} / \sqrt{\text{Hz}}$, we find a temperature "noise" of ~ 0.1 mK / $\sqrt{\text{Hz}}$ that falls off as $1/f$, where f is the Fourier frequency. This noise could be reduced or eliminated if these out-of-loop sections were shortened. However, our current system demonstrates that the fiber-based combs are suitable for comparison of optical clock frequencies at high stability levels.

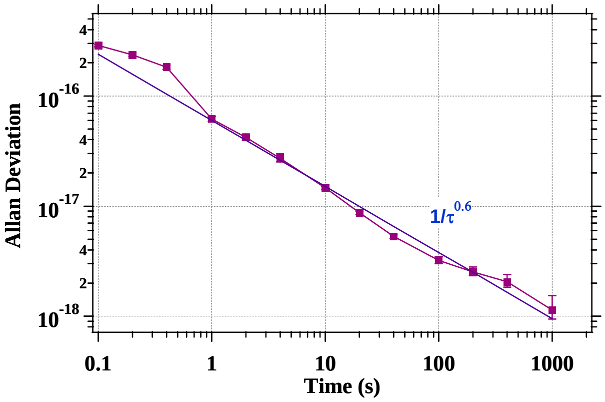

Figure 2: Allan deviation of optical beat signal (squares and line) versus measurement time. Also shown is a fit with a $1/t^{0.6}$ slope.

References:

1. T. Udem, R. Holzwarth, and T. W. Hänsch, "Optical Frequency Metrology," Nature **416**, 233-237 (2002).
2. W. C. Swann, J. J. McFerran, I. Coddington, N. R. Newbury, I. Hartl, M. E. Fermann, P. S. Westbrook, J. W. Nicholson, K. S. Feder, C. Langrock, and M. M. Fejer, "Fiber-laser frequency combs with sub-hertz relative linewidths," Opt. Lett. **31**, 3046-3048 (2006).
3. B. R. Washburn, S. A. Diddams, N. R. Newbury, J. W. Nicholson, M. F. Yan, and C. G. Jørgensen, "Phase-locked erbium-fiber-laser-based frequency comb in the near infrared," Opt. Lett. **29**, 250-252 (2004).
4. T. R. Schibli, K. Minoshima, F.-L. Hong, H. Inaba, A. Onae, H. Matsumoto, I. Hartl, and M. E. Fermann, "Frequency metrology with a turnkey all-fiber system," Opt. Lett. **29**, 2467-2469 (2004).
5. P. Kubina, P. Adel, F. Adler, G. Grosche, T. W. Hänsch, R. Holzwarth, A. Leitenstorfer, B. Lipphardt, and H. Schnatz, "Long term comparison of two fiber based frequency comb systems," Opt. Express **13**, 904-909 (2005).
6. H. Schnatz, B. Lipphardt, and G. Grosche, "Frequency metrology using fiber-based fs-frequency combs," in *Proceedings of Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference (CLEO) 2006 Technical Digest*, (Optical Society of America, 2006) CTuH1.
7. L.-S. Ma, Z. Bi, A. Bartels, L. Robersson, M. Zucco, R. S. Windeler, G. Wilpers, C. Oates, L. Hollberg, and S. A. Diddams, "Optical frequency synthesis and comparison with uncertainty at the 10^{-19} level," Science **303**, 1843-1845 (2004).
8. K. Tamura, E. P. Ippen, H. A. Haus, and L. E. Nelson, "77-fs pulse generation from a stretched-pulse mode-locked all-fiber ring laser," Opt. Lett. **18**, 1080-1083 (1993).
9. J. J. McFerran, W. C. Swann, B. R. Washburn, and N. R. Newbury, "Elimination of pump-induced frequency jitter on fiber-laser frequency combs," Opt. Lett. **31**, 1997-1999 (2006).
10. B. C. Young, F. C. Cruz, W. M. Itano, and J. C. Bergquist, "Visible lasers with subhertz linewidths," Phys. Rev. Lett. **82**, 3799 (1999).
11. J. C. Bergquist, W. M. Itano, and D. J. Wineland, in *International School of Physics "Enrico Fermi"*, W. Hansch and M. Inguscio, Eds. North-Holland, Amsterdam, 1992.
12. T. M. Fortier, A. Bartels, and S. A. Diddams, "Octave-spanning Ti:sapphire laser with a repetition rate >1 GHz for optical frequency measurements and comparisons," Opt. Lett. **31**, 1011-1013 (2006).