Fiber laser-based frequency combs with high relative frequency stability

N. R. Newbury, W. C. Swann, I. Coddington, L .Lorini, J. C. Bergquist, S. A. Diddams
National Institute of Standards and Technology
325 Broadway
Boulder, CO USA
nnewbury@boulder.nist.gov

***Abstract*—We describe our current low-noise fiber-laser frequency comb and present measurements of its residual instability. Through a comparison with a Ti:Sapphire frequency comb, we measure residual fractional frequency instabilities (Allan deviation) of ~6×10^{-17} at 1 second and ~1.3×10^{-18} at 1000 seconds. This stability demonstrates that the performance of a fiber frequency comb can rival that of current Ti:sapphire frequency combs.**

I. Introduction

The development of fiber laser-based frequency combs [1-5] has followed along rapidly behind the initial development of solid-state Ti:Sapphire frequency combs.[6-8] In both cases, the basic principle of the frequency comb remains the same: a single optical or microwave reference is used to stabilize the individual modes of a passively mode-locked laser.

Fiber-based frequency combs can be relatively compact compared to solid-state frequency combs and cover a wavelength range that overlaps the optimum transmission window of optical fiber, the gain bandwidth of Er-based amplifiers, and the operating bandwidth of a wide array of fiber-optic components developed for telecommunications. However, the initial fiber frequency combs did not operate at the same level of performance as state-of-the-art Ti:Sapphire frequency combs. For applications in which the comb is locked to a microwave reference, the original fiber-comb performance was quite sufficient, since the average position of the comb line can still be counted far better than the instability of the microwave reference (typically ~10^{-13} at 1 second). However, to support future optical clocks, much lower residual instabilities of 10^{-15} at 1 second or lower are desired.

Fortunately, the limit to the residual stability of fiber-based frequency combs has continued to drop.[4, 9] Here, we present our latest experiment using a fiber-based frequency comb with sub-Hertz residual linewidths.[5] Through a comparison with a Ti:Sapphire frequency comb, we find residual instabilities (Allan deviations) of ~6×10^{-17} at 1 second and ~1.3×10^{-18} at 1000 seconds, which instabilities are comparable to those achieved with Ti:sapphire frequency combs.[10]

II. Fiber Comb

A. Configuration

Fiber laser frequency combs are based on passively mode-locked fiber lasers.[11] A number of different laser designs have been successfully used including figure-8 laser,[1] soliton [12] or stretched-pulse fiber ring laser,[13] and Fabry-Perot laser using a saturable absorber.[2] The exact configuration of the laser does not appear to be important, although it may affect the feedback bandwidth. All these lasers generate ~100 fs pulses of laser light at ~0.1 nJ of energy and repetition rates of ~100 MHz. The spectral width of the pulses can range from 20 nm to 80 nm depending on the laser configuration. In the frequency domain, the laser output is described by a comb of optical frequencies given by $\nu_n = nf_r + f_0$, where n is the mode number, f_r is the repetition rate, and f_0 is the offset frequency. By locking one comb mode ν_{nref} to an optical reference and the offset frequency, f_0, to an rf reference, the entire comb of lines is stabilized. In order to lock f_0 to a reference, it must first be detected. This detection is accomplished through the standard f-to-2f interferometer, which requires a full octave of bandwidth.[7] Therefore, the laser output must be externally spectrally broadened. Because the pulses are so short, the peak powers are significant and one would expect significant spectral broadening in optical fiber due to nonlinear effects. However, for current nonlinear fibers the pulse peak powers are not sufficient to generate a full octave of bandwidth. Therefore, the laser output is first amplified in a dispersion-managed erbium fiber amplifier. The output of the amplifier is then injected into a special highly nonlinear optical fiber that generates an octave-spanning supercontinuum. The development of this optical fiber was a critical step toward achieving fiber laser frequency combs.[14, 15]

Once the supercontinuum is generated, the offset frequency f_0 is detected by doubling the ~2 μm portion of the comb and heterodyning it against the ~1 μm end of the comb to generate an rf beat signal at f_0.[1, 7, 16] At this point, the comb can be stabilized by phase-locking f_0 to a rf source and one of the comb lines to an narrow-linewidth optical source, for example from an optical clock. However, before

1-4244-0647-1/07/$20.00 ©2007 IEEE

discussing the phase-lock, we briefly discuss the noise sources that perturb the comb linewidth.

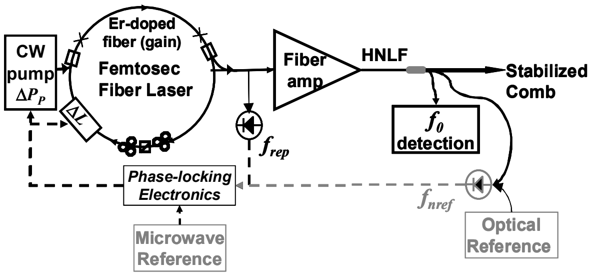

Figure 1. Basic schematic of a fiber laser frequency comb. The femtosecond fiber laser output is amplified and spectrally broadened in highly nonlinear fiber (HNLF). The offset frequency is phase-locked to a microwave reference. The remaining degree of freedom of the comb can be stabilized through (1) phase-locking the repetition rate to a microwave reference or (2) phase-locking one tooth of the comb to an optical reference (shown in gray). Solid lines represent fiber optic paths and dashed lines represent electronic signals.

B. *Noise Sources*

The performance of the fiber frequency comb is determined by the noise on the comb lines. The basic noise sources on the fiber frequency comb, listed in Fig. 2, can be divided into two groups: "intra-cavity" noise from perturbations of the circulating laser pulse within the laser cavity, and "extra-cavity" noise from supercontinuum broadening and photodetection that occurs outside of the laser cavity. Intra-cavity noise sources include environmental perturbations, pump-induced noise, and amplified spontaneous emission (ASE) from the intracavity gain, which is the source of the quantum-limited noise for mode-locked lasers. "Extra-cavity" noise sources include: ASE from the amplifier, amplitude noise to phase noise (AM to PM) conversion in the nonlinear fiber during supercontinuum generation, and environmentally-induced path length changes, and detection shot noise. These noise sources and their effect on the comb is discussed in much more detail in Ref. [17]

There are two critical, basic distinctions between the intra-cavity and extra-cavity noise. First, the comb performance is more sensitive to intra-cavity noise than extra-cavity noise. In general, this sensitivity, as measured by the linewidth or frequency jitter, arises from the fact that the same perturbation that might cause white phase noise outside the cavity will cause white frequency noise inside the cavity. Therefore, in terms of comb linewidth, it is the intra-cavity noise that dominates. Second, a given intra-cavity perturbation will cause correlated noise in f_r and f_0, denoted δf_r and δf_0, which give rise to perturbations across the (spectrally broadened) comb of $\delta\nu_n = n\delta f_r + \delta f_0$. (Intra-cavity perturbations will also change the pulse amplitude and carrier frequency, but these changes do not directly affect the comb frequencies except through extra-cavity amplitude-to-phase noise conversion or dispersion.) In other words, the effect of intra-cavity noise can be specified in terms of only two parameters, either δf_r and δf_0 or δf_r and n_{fix} (in the fixed-point picture [18, 19]) and can be captured within the simple model: $\nu_n = nf_r + f_0$. A given extra-cavity noise source, on the other hand, can vary from comb line to comb line in a complicated way.

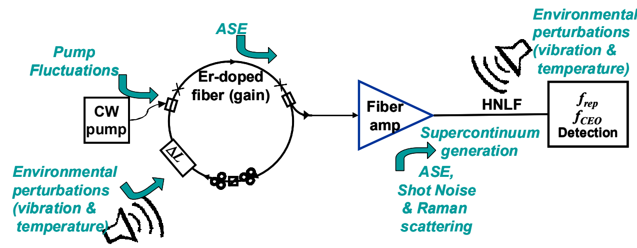

Figure 2. Perturbations to the comb arise from intra-cavity noise due to environmental perturbations, pump noise, and ASE from the gain medium. Perturbations to the comb also arise from extra-cavity noise due to environmental perturbations, noise generated during supercontinuum generation from ASE, shot noise and Raman scattering, and detection shot noise.

As discussed in Ref. [17], the power spectral density for the frequency fluctuations from each of the three intra-cavity noise terms has a different spectral shape as a function of Fourier frequency, f: The environmental noise causes "$1/f$" noise, the ASE-induced noise causes white frequency noise, and the pump-induced noise causes noise that is white in frequency up to a characteristic corner frequency, beyond which the noise rolls of as $1/f^2$. Fortunately, because the comb is defined by only two degrees-of-freedom, despite the fact there are at least three important noise terms, it is sufficient to feedback to only two points on the comb to remove the noise. It is customary to feedback to the pump power to stabilize the offset frequency and to the cavity length to stabilize one optical mode of the comb, as described in the next section.

C. *Phase-locking the comb*

The offset frequency is phase-locked to an rf synthesizer by feeding back to the pump laser power. By using phase-lead compensation (i.e., derivative feedback) in the feedback loop the feedback bandwidth can be extended considerably beyond the characteristic rolloff in the laser response.[13, 20] The end result is a tightly phase-locked offset frequency with < 1 radian phase excursions from the reference oscillator (corresponding to an instrument-limited linewidth).[13]

The second degree-of-freedom of the comb is stabilized by phase-locking one tooth of the comb to an optical reference, i.e., a narrow stabilized laser.[5, 21] This approach is shown as the grey line in Fig. 2. The optical reference laser might be stabilized to an optical cavity if only short-term stability is important. It might also be the output of an optical atomic clock if absolute stability is important. For a sub-hertz stabilized optical reference, we would like a tight phase-lock to the reference. This tight phase-lock can be accomplished by a high bandwidth piezo-electric fiber stretcher. [17] In that case, very narrow lines can be observed from a fiber laser frequency comb. With IMRA America, we have demonstrated instrument-limited residual linewidths of less than 100 mHz across the comb spectrum.[5] In essence, by phase-locking the comb to an optical reference, the stability and low phase noise of a single optical reference is transferred all the way across an optical span of 1 to 2 microns. Additionally, the repetition frequency of the comb is now extremely stable with a projected residual timing jitter of ~ 1 fs or less. This high phase coherence and low timing jitter can be exploited in a number of applications.

III. Comb Tests: A Coherent Network

In order to test the residual stability of the fiber comb, we constructed the coherent ring network shown in Figure 3 and described in more detail in Ref. [10]. Starting at the top, the output of a cavity-stabilized fiber laser at 1126 nm is transmitted over a 200 m, Doppler-cancelled fiber optic link to a self-referenced fiber-laser frequency comb located one floor up in the same building. The fiber-laser frequency comb is phase-locked to the 1126 light, faithfully transferring the stability and phase noise of this source across the comb, including the low-loss window of optical fiber. A second 1126 nm signal is similarly transmitted over a 300 m, Doppler-cancelled, fiber link to similarly phase-lock a self-referenced Ti:Sapphire laser-based frequency comb. To complete the loop, a 500 mW amplified cw fiber laser at 1535 nm is frequency-doubled in periodically-poled lithium niobate and phase-locked to the Ti:Sapphire frequency comb. The fundamental 1535 nm cw light is then transmitted over a 200 m, Doppler-cancelled fiber optic link to the fiber-laser frequency comb. The heterodyne beat between this cw 1535 nm signal and the nearest frequency comb tooth provides an open-loop measure of the stability, linewidth, and phase or timing jitter noise supported by the coherent network.

Figure 4 gives the measured residual stability on the 1535 nm beat signal. The quantity measured is actually the residual stability of the entire network including the fiber frequency comb, Ti:sapphire frequency and fiber cancellation phase-locks. Therefore, the measured stability represents an upper limit to that of the fiber frequency comb. The residual stability is consistent with noise generated from the roughly meter-long path lengths in fiber optics or air that are “out-of-loop” so that their path lengths are not compensated by one of the phase-locks.

IV. Conclusions

The fiber-laser frequency comb can provide comb lines that have residual phase noise of < 1 radian and residual stabilities below 10^{-18} with respect to an optical reference. Therefore, the fiber-laser frequency can serve as a viable alternative to the Ti:sapphire frequency comb for measurement of the next generation of optical clocks. The choice of the most appropriate comb technology can be made based on the desired wavelength coverage of the comb.

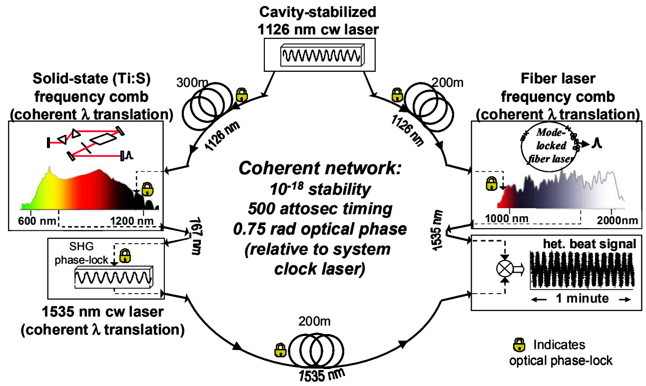

Figure 3. The coherent network for measuring the residual stability on the fiber-laser frequency comb.

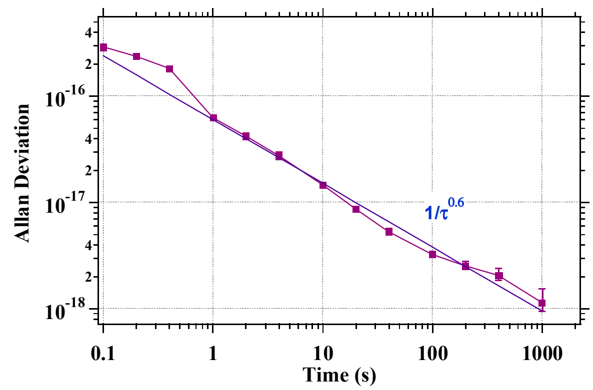

Figure 4. Fractional frequency uncertainty (Allan deviation) of the beat signal versus averaging time. Also shown is a fit with a $1/\tau^{0.6}$ slope. Data taken from Ref. [10]

References

[1] 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., vol. 29, pp. 250-252, 2004.

[2] 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., vol. 29, pp. 2467-2469, 2004.

[3] H. Hundertmark, D. Wandt, N. Haverkamp, and H. R. Telle, "Phase-locked carrier-envelope-offset frequency at 1560 nm," Opt. Express, vol. 12, pp. 770-775, 2004.

[4] 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, vol. 13, pp. 904-909, 2005.

[5] 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., vol. 31, pp. 3046-3048, 2006.

[6] T. Udem, R. Holzwarth, and T. W. Hänsch, "Optical Frequency Metrology," Nature, vol. 416, pp. 233-237, 2002.

[7] D. J. Jones, S. A. Diddams, J. K. Ranka, A. Stentz, R. S. Windeler, J. L. Hall, and S. T. Cundiff, "Carrier-envelope phase control of

femtosecond mode-locked lasers and direct optical frequency synthesis," Science, vol. 288, pp. 635-9, 2000.

[8] 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., vol. 31, pp. 1011-1013, 2006.

[9] H. Schnatz, B. Lipphardt, and G. Grosche, "Frequency metrology using fiber-based fs-frequency combs," presented at Conference on Lasers and Electro-Optics/Quantum Electronics and Laser Science Conference (CLEO) 2006 Technical Digest, Long Beach, CA, 2006.

[10] I. Coddington, W. C. Swann, L. Lorini, J. C. Bergquist, Y. L. Coq, C. W. Oates, Q. Quraishi, K. S. Feder, J. W. Nicholson, P. S. Westbrook, S. A. Diddams, and N. R. Newbury, "Coherent optical link over hundreds of metres and hundreds of terahertz with subfemtosecond timing jitter," Nature Photonics, vol. 1, pp. 283-287, 2007.

[11] L. E. Nelson, D. J. Jones, K. Tamura, H. A. Haus, and E. P. Ippen, "Ultrashort-pulse fiber ring lasers," Appl. Phys. B, vol. 65, pp. 277-94, 1997.

[12] B. R. Washburn, R. Fox, N. R. Newbury, J. W. Nicholson, K. Feder, P. S. Westbrook, and C. G. Jørgensen, "Fiber-laser-based frequency comb with a tunable repetition rate," Opt. Express, vol. 12, pp. 4999-5004, 2004.

[13] 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., vol. 31, pp. 1997-1999, 2006.

[14] J. W. Nicholson, M. F. Yan, P. Wisk, J. Fleming, F. DiMarcello, E. Monberg, A. Yablon, C. G. Jørgensen, and T. Veng, "All-fiber, octave-spanning supercontinuum," Opt. Lett., vol. 28, pp. 643-645, 2003.

[15] J. W. Nicholson, P. S. Westbrook, K. S. Feder, and A. D. Yablon, "Supercontinuum generation in UV irradiated fibers," Opt. Lett., vol. 29, pp. 2363-2365, 2004.

[16] F. Tauser, A. Leitenstorfer, and W. Zinth, "Amplified femtosecond pulses from an Er:fiber system: Nonlinear pulse shortening and self-referencing detection of the carrier-envelope phase evolution," Opt. Express, vol. 11, pp. 594-600, 2003.

[17] N. R. Newbury and W. C. Swann, "Fiber Laser Frequency Combs," Journal of the Optical Society of America B, pp. to be published, 2006.

[18] H. R. Telle, B. Lipphardt, and J. Stenger, "Kerr-lens, mode-locked lasers as transfer oscillators for optical frequency measurements," Appl. Phys. B, vol. 74, pp. 1-6, 2002.

[19] E. Benkler, H. R. Telle, A. Zach, and F. Tauser, "Circumvention of noise contributions in fiber laser based frequency combs," Opt. Express, vol. 13, pp. 5662-5668, 2005.

[20] J. J. McFerran, W. C. Swann, B. R. Washburn, and N. R. Newbury, "Suppression of pump-induced frequency noise in fiber-laser frequency combs leading to sub-radian fceo phase excursions," Appl Phys. B, vol. 86, pp. 219-227, 2007.

[21] A. Bartels, C. W. Oates, L. Hollberg, and S. A. Diddams, "Stabilization of femtosecond laser frequency combs with subhertz residual linewidths," Opt. Lett., vol. 29, pp. 1081-1083, 2004.