Elimination of pump-induced frequency jitter on fiber-laser frequency combs

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Optical frequency combs generated by femtosecond fiber lasers typically exhibit significant frequency noise that causes broad optical linewidths, particularly in the comb wings and in the carrier-envelope offset frequency (f_{ceo}) signal. We show these broad linewidths are mainly a result of white amplitude noise on the pump diode laser that leads to a breathing-like motion of the comb about a central fixed frequency. By a combination of passive noise reduction and active feedback using phase-lead compensation, this noise source is eliminated, thereby reducing the f_{ceo} linewidth from 250 kHz to <1 Hz. The in-loop carrier-envelope offset phase jitter, integrated to 100 kHz, is 1.3 rad.

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The output of a mode-locked laser in frequency space comprises the individual laser modes separated by the repetition rate of the laser. These modes form a comb of optical frequencies that can be stabilized to an rf or optical reference to serve as an indispensable tool for optical frequency metrology.[1,2] Originally developed with Ti:sapphire lasers, frequency combs have been recently demonstrated with mode-locked fiber lasers. They are less expensive, more power efficient, more compact, and compatible with fiber-optic technologies.[3–6] However, fiber-laser combs exhibit significantly higher frequency noise and broader optical comb lines than those of Ti:sapphire-laser-based combs; this higher noise level ultimately limits their performance for experiments that require short-term stability and must be circumvented, as discussed by Benkler *et al.*,[7] or removed, as discussed here.

The optical linewidths of fiber-laser frequency combs are particularly large at the wings of the comb; the linewidth near 1 μm is typically 30–100 kHz, and the linewidth of the carrier-envelope offset (ceo) frequency, f_{ceo}, is typically 100–300 kHz. [f_{ceo} is alternately described as either the mode extrapolated to zero optical frequency or the beat frequency between the doubled long-wavelength (2 μm) and short-wavelength (1 μm) ends of the comb.] These broad linewidths have been observed since the first detection of f_{ceo} in a fiber laser system[8,9] and persist even for phase-locked systems, which is an indication that the underlying noise extends to high Fourier frequencies. (A notable exception is the comb of Hartl *et al.*,[6] for which the locked f_{ceo} linewidth is below 1 Hz.) As with any laser, environmental perturbations will broaden the comb linewidths, but these perturbations fall off rapidly with higher Fourier frequencies and do not explain the large linewidths. Similarly, the quantum-limited noise[10] from amplified spontaneous emission (ASE) is low and does not explain the linewidths.

In this Letter, we identify a major contributor to the broad linewidths: white amplitude noise on the pump laser. When coupled with the sensitivity of the laser to pump fluctuations,[11,12] this amplitude noise drives a breathing-mode motion of the comb about a fixed point,[7] typically near the center frequency of the laser output. We reduce this frequency noise by 12 dB by directly reducing the pump noise. Since the laser responds as a simple low-pass filter, we further reduce this noise using phase-lead compensation in the feedback to the pump power to stabilize f_{ceo}, reducing its linewidth from 250 kHz to below 1 Hz, and the ceo phase noise jitter to 1.3 rad, a promising value for future time-domain applications.

The output of a fiber-laser frequency comb typically covers from 1 to 2 μm, with the frequency of individual comb teeth given by $f_n(t)=nf_r(t)+f_{\mathrm{ceo}}(t)$, where f_r is the laser repetition frequency. Pump laser noise causes linearly correlated noise on both f_r and f_{ceo} across this comb through a variety of mechanisms.[11,12] This linearly correlated noise is best described using the "elastic-tape" model,[7,13] as it results in a breathing motion of the comb about one single fixed comb tooth [see Fig. 1(a)]. From the expression for $f_n(t)$, the fixed point for changes in the pump power, P, is $n_{\mathrm{fix}} \equiv -(\mathrm{d}f_{\mathrm{ceo}}/\mathrm{d}P)/(\mathrm{d}f_r/\mathrm{d}P)$ and is typically near the center of the laser output.[11,12] If

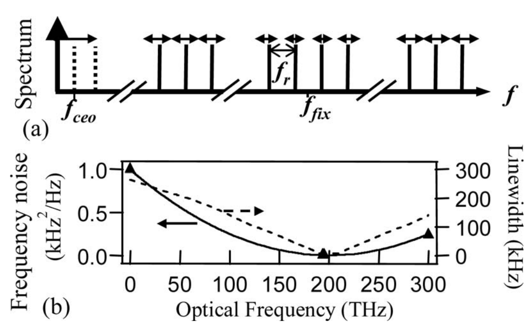

Fig. 1. (a) Breathing mode of the comb about the fixed point induced by pump-power fluctuations; the length of the double arrow indicates the magnitude of the jitter. (b) Frequency noise level, $S_n(0)$ (solid line, left axis) and the linewidth, Δf_n (dashed line, right axis), versus f_n, assuming $f_{\mathrm{fix}}=c/1460$ nm, $\nu_{3\,\mathrm{dB}}=6$ kHz, $S_{\mathrm{ceo}}(0)=60$ dB Hz^2/Hz (=1 kHz^2/Hz), corresponding to 400 mA pump current. The black triangles are actual measured values of $S_n(0)$ for f_{ceo}, f_{n_1064}, f_{n_1536}, and f_{n_1550}.

the pump fluctuates slowly by $\delta P(t)$, the frequency of the nth comb mode fluctuates by $\delta f_n(t)=(n-n_{\text{fix}})\delta f_r(t)$, where the repetition-rate fluctuation is $\delta f_r(t)=\delta P(t)\mathrm{d}f_r/\mathrm{d}P$.

Noise is typically described by a power spectral density (PSD) versus Fourier frequency ν, which gives the frequency noise per hertz bandwidth. From the above expression, the pump-induced frequency noise PSD of the nth mode is $S_n(\nu)=(n-n_{\text{fix}})^2\, S_r(\nu)$, where $S_r(\nu)$ is the PSD of the repetition rate. From Ref. 11, the laser response to pump-power changes will fall off as a low-pass filter with a cutoff frequency $\nu_{3\text{ dB}}\sim 5$ to 15 kHz. Therefore, the pump-induced frequency noise PSD on f_n is

$$S_n(\nu) = (n - n_{\text{fix}})^2\left(\frac{P\mathrm{d}f_r}{\mathrm{d}P}\right)^2\left[\frac{RIN_P}{1+(\nu/\nu_{3\text{ dB}})^2}\right]\left[\frac{\text{Hz}^2}{\text{Hz}}\right], \tag{1}$$

where RIN_P is the relative intensity noise of the pump (and the third parenthetical term is the corresponding laser RIN). There are other contributions to the frequency noise PSD, in particular from environmental perturbations, which will dominate for n near n_{fix} or at low $\nu<1$ kHz and must be dealt with through appropriate feedback. However, for $n \gg n_{\text{fix}}$ or $n \ll n_{\text{fix}}$ and at $\nu>1$ kHz, the pump-induced noise dominates. In particular, the frequency noise PSD of f_{ceo} (the tooth at $n=0$) is $S_{\text{ceo}}(\nu)\equiv S_{n=0}(\nu)=n_{\text{fix}}^2 S_r(\nu)$. The quadratic increase in noise with separation from the fixed point (see Fig. 1) is unavoidable and not a result of the supercontinuum generation in the nonlinear fiber.

Typically the comb linewidth, Δf_n, rather than the frequency noise, S_n, is measured (either directly for f_r and f_{ceo}, or by heterodyning a comb tooth with a narrow-linewidth cw laser for f_n.) The linewidth of an individual comb mode, $\exp[2\pi i f_n t + i\delta\theta(t)]$ is directly related to the phase noise, $\delta\theta(t)$, which has a PSD of of $\nu^{-2}S_n$. For white frequency noise ($\nu_{3\text{ dB}}\rightarrow\infty$), the linewidth is simply $\Delta f_n=\pi S_n(0)$ Hz. Here, however, the frequency noise does roll off at a finite Fourier frequency, $\nu_{3\text{ dB}}=5-15$ kHz. Nevertheless, provided that $\Delta f_n<\pi\nu_{3\text{ dB}}$, as is the case for f_r, it is still true that $\Delta f_n=\pi S_n(0)$. If instead $\Delta f_n>\pi\nu_{3\text{ dB}}$, as is the case for f_{ceo} or in the wings of the comb, we numerically determine instead that $\Delta f_n\sim\pi[S_n(0)\nu_{3\text{ dB}}]^{1/2}$ Hz.

Equation (1) suggests four possible approaches to reducing $S_n(\nu)$. First, the laser can be designed such that either $\mathrm{d}f_r/\mathrm{d}P\rightarrow 0$ or $\mathrm{d}f_{\text{ceo}}/\mathrm{d}P\rightarrow 0$.[11,12] Second, $\nu_{3\text{ dB}}$ can be reduced, although it is constrained to exceed the bare gain relaxation rate.[11] Third, the pump RIN can be reduced. Fourth, one can use phase compensation to extend the feedback bandwidth to pump power well beyond $\nu_{3\text{ dB}}$. These last two approaches are pursued here.

A stretched-pulse erbium-doped fiber laser was used in these experiments (Fig. 2).[14] It was pumped by 100 mW of 1480 nm light and produced ~10 mW of output power with a spectral width of 80 nm and a comb tooth spacing (f_{rep}) of 50 MHz. The system was arranged to monitor f_{rep}, f_{ceo}, f_{n_1064}, f_{r_1550}, and f_{n_1536} (where f_{n_λ} indicates the comb line at wavelength λ) using a digital fast Fourier transform spectrum analyzer. The parameters characterizing the comb response were measured, giving[12] $\nu_{3\text{ db}}\approx 6$ kHz, $P\mathrm{d}f_r/\mathrm{d}P=-320$ Hz, and $n_{\text{fix}}=(4.1\pm 0.1)\times 10^6$, corresponding to $c/(n_{\text{fix}}f_r)=1460$ nm.

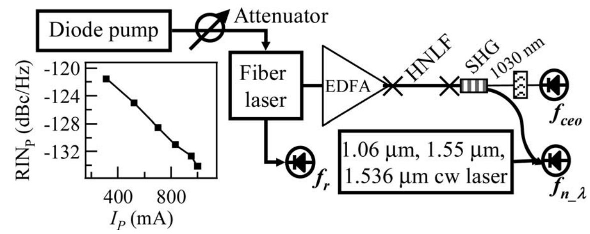

Fig. 2. Experimental setup for measurements for f_r, f_{ceo}, f_{n_1064}, f_{n_1550}, and f_{n_1536} versus pump RIN. HNLF, highly nonlinear fiber; EDFA, erbium-doped fiber amplifier; SHG, second-harmonic generation. Inset, measured pump RIN versus current.

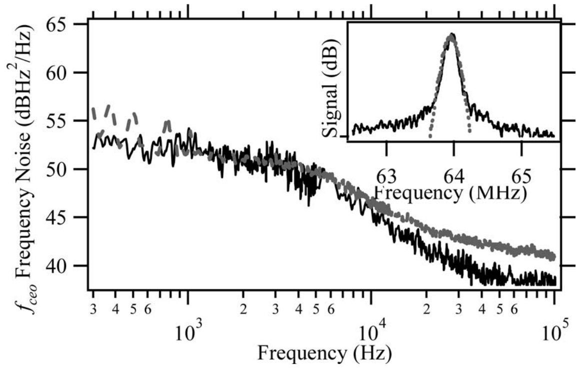

Fig. 3. Measured S_{ceo} (solid line) and expected S_{ceo} (dashed gray line) calculated from scaling the measured laser RIN by $n_{\text{fix}}{}^2(P\mathrm{d}f_r/\mathrm{d}P)^2=(P\mathrm{d}f_{\text{ceo}}/\mathrm{d}P)^2$. (The floor results from the RIN measurement limit.) Inset, measured f_{ceo} line shape (solid line) and the calculated line shape (dashed gray line) obtained from only the pump-induced frequency noise.

The only commercially available pump diode lasers with sufficient power to pump fiber-laser frequency combs are Fabry–Perot diode lasers that are Bragg grating stabilized to 980 nm or, in our case, 1480 nm. Unfortunately, these lasers exhibit a RIN of ~−125 dBc/Hz, extending well beyond 100 kHz,[15] far above the RIN of a quiet current supply. In addition, these lasers exhibit a 1460 nm ASE peak that is not absorbed by the Er gain as strongly as the 1480 nm pump light, yielding additional RIN on the laser through mechanisms similar to mode partition noise.

The measured laser frequency noise on f_{ceo}, S_{ceo}, and the noise calculated from Eq. (1) using the measured n_{fix}, $\mathrm{d}f_r/\mathrm{d}P$, and the laser RIN agree well (Fig. 3). (The laser RIN, rather than pump RIN, was used to include the effects of the 1460 nm ASE peak.) Furthermore, the inset of Fig. 3 shows good agreement between the measured and calculated line shapes, indicating that pump-induced frequency noise dominates.

Empirically, we find that both the RIN and the 1460 nm ASE drop dramatically with increasing pump current, I_P. This lower RIN can be exploited by simply increasing I_P and adding an attenuator to fix the power into the laser at 100 mW. Figure 4 shows that the frequency noise at f_{ceo}, S_{ceo}, and that at f_{n_1064}, S_{1064}, do indeed drop with increasing pump current (decreasing RIN_P). Furthermore, there is a $20\log_{10}(|n_{1064}-n_{\mathrm{fix}}|/n_{\mathrm{fix}})=8.5$ dB offset between the two, as expected from Eq. (1) (recalling that $S_{\mathrm{ceo}}\equiv S_{n=0}$). Similar agreement is found with S_r, S_{n_1536}, and S_{n_1550} [see Fig. 1(b)]. The ~16× noise reduction with increasing pump current results in a 4× reduction in the linewidths since $\Delta f_n \propto [S_n(0)]^{1/2}$ at these noise levels. At 1 A, the noise approaches a white-noise floor, possibly related to the quantum-limited noise.[10]

Typically f_{ceo} is stabilized through feedback to the pump power.[3–6] Unfortunately, standard proportional-integral feedback is of limited effectiveness since the feedback response and noise both roll off at $\nu_{3\,\mathrm{dB}}=6$ kHz. As noted above, one can take advantage of the low-pass roll-off of Eq. (1) by using phase-lead compensated feedback to extend the bandwidth to 80 kHz. This reduces the frequency noise by an additional 38 dB at $\nu=1$ kHz and the in-loop linewidth to <1 Hz (Fig. 5). The signal-to-noise ratio (SNR) near the carrier is 57 dBc/Hz. Similar subhertz linewidths and signal-to-noise ratio were

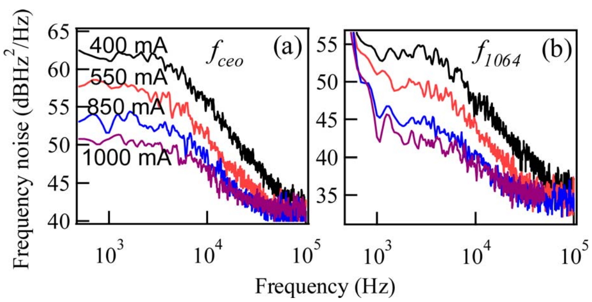

Fig. 4. (Color online) Measured frequency noise on (a) the ceo frequency, S_{ceo} and (b) the 1 μm comb line, S_{n_1064} at $I_P=400$ mA, 550 mA, 850 mA, and 1 A.

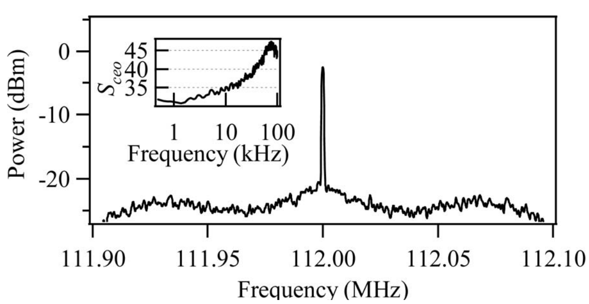

Fig. 5. Phase-locked f_{ceo} beat signal at 1 kHz resolution bandwidth (rbw) and $I_P=1000$ mA. The coherent peak remains below at a 0.3 Hz rbw (compare with Fig. 3, inset). Inset, corresponding frequency noise with servo bumps at 80 kHz [compare with Fig. 4(a)].

observed by Hartl *et al.*[6] using a different laser design. The corresponding integrated ceo phase noise is $\delta\phi_{\mathrm{ceo}}^2=\int_0^{100\,\mathrm{kHz}}\nu^{-2}S_{\mathrm{ceo}}(\nu)d\nu=(1.3\ \mathrm{rad})^2$. The pulse-to-pulse ceo phase noise may be higher, depending on the white phase noise floor, but these levels are promising for time-domain applications. While other environmental and ASE-induced noise sources remain, hertz-level fiber comb linewidths do seem possible. Finally, phase locking f_{ceo} in this way reduces the phase noise of the unlocked f_r to below that of a high-quality rf synthesizer for $\nu>5$ kHz.

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