Reducing the linewidth of fiber-laser frequency combs

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Abstract: Fiber laser-based frequency combs typically exhibit broad optical linewidths, particularly in the wings. These broadened linewidths originate from white amplitude noise on the pump laser, which can be eliminated to achieve sub-Hz offset frequency linewidths.

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The output of a mode-locked laser forms a comb of optical frequencies with a spacing set by the repetition rate, f_r, and an offset set by the carrier-envelope offset (ceo) frequency, f_{ceo}. Frequency combs have proven indispensable to optical frequency metrology,[1, 2] as well as showing promise for other applications. Frequency combs are generated with either a Ti:Sapphire mode-locked laser or, more recently, a fiber laser. Fiber laser-based frequency combs have practical advantages over Ti:Sapphire-based combs in that they are less expensive, more power-efficient, potentially more compact, and compatible with fiber optics.[3-5] However, they have historically exhibited significantly higher frequency noise. This high frequency noise needs to be reduced in order for fiber-laser combs to be useful for precision optical frequency measurements.

On long time-scales, or at low Fourier frequencies, the frequency noise on the comb can be removed by phase-locking both f_r and f_{ceo} to a reference. The resulting stabilized comb is then suitable for basic optical frequency metrology, where the frequencies are typically counted with a ~1 second gate time. However, the frequency noise is still present on shorter timescales (at higher Fourier frequencies). As a result, the nth comb line may have a center frequency that is very well defined as $f_n = nf_r + f_{ceo}$, but its linewidth can be quite large. For fiber laser-based combs, the most egregious effect on linewidth occurs for the f_{ceo} beat signal; this signal is typically generated by beating the high-frequency end of the comb (at 1 μm) with the doubled low-frequency end of the comb (at 2 μm).[6, 7] Presently, f_{ceo} widths are in the range of 100 kHz to 1 MHz. Interestingly, the comb linewidth near 1 μm is somewhat narrower, with typical widths of tens of kilohertz. Naively subtracting these linewidths yields a linewidth greater than 100 kHz for the comb at 2 μm, which is difficult to explain in the standard picture of the comb and has led to some speculation about the presence of excess noise. However, as shown below this subtraction is incorrect and, in fact, the linewidth at 2 μm is narrower than at 1 μm. Indeed, in recent work, Benkler *et al.* found no evidence for the presence of any excess noise, and, furthermore, demonstrated a method for circumventing the large frequency noise on the comb. [8]

The comb offset frequency is typically controlled by feeding back to the pump laser current, which modulates the pump power and thereby changes the offset frequency. The various mechanisms by which the pump power affects the offset and repetition frequencies in a fiber laser-based comb are elucidated in Refs. [9, 10]. Here we use the results of [9, 10] to explain the broad linewidth of f_{ceo} and the broad linewidth of the individual comb elements. We find that the 1480 nm pump laser exhibits amplitude noise that is white in frequency and considerably larger than expected from the pump current noise. This amplitude noise on the pump laser drives a “breathing-mode” motion of the comb about a “fixed point” frequency, f_{fix} at mode $n=n_{fix}$ (see Fig 1), so that the comb linewidth increases with the frequency offset from this fixed point. Fortunately, the fiber laser responds as a low-pass filter, with a cutoff frequency $\nu_{3\mathrm{dB}}$ of ~ten kilohertz, so that the pump-induced frequency noise is limited to low frequencies. Below $\nu_{3\mathrm{dB}}$, this “breathing-mode” noise results in white frequency noise on f_r, f_{ceo}, and the f_n. This white frequency noise explains the Lorentzian-like shape of the optical linewidths and f_{ceo} beat note. Moreover, it explains both the broad comb linewidth at 1 μm and the broader offset frequency linewidth.

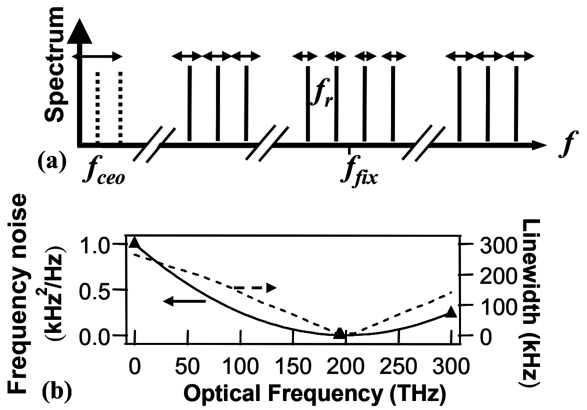

Fig. 1. (a) The breathing mode of the comb induced by pump power fluctuations. The fixed point is typically near the carrier frequency. (b) The frequency noise level, $S_n(0)$ (solid line, left axis) and the linewidth (dashed line, right axis) versus f_n. For these calculations, ν_{3dB} = 6 kHz and $S_{ceo}(0)$ = 61 dB Hz^2/Hz, corresponding to conditions at a 400 mA pump current. The black triangles are actual measured values of $S_n(0)$ for the $f_{ceo}, f_{n\_1064}, f_{n\_1536}$ and f_{n_1550} .

Figure 2 shows the experimental setup. A stretched pulse fiber laser.[11] 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_r and the beat signals for $f_{ceo}, f_{n\_1064}, f_{n\_1550}$, and f_{n_1536} (where f_{n_λ} indicates the comb line at wavelength λ) using a digital FFT. The parameters characterizing the comb response were measured giving:[10] $\nu_{3\text{db}} \approx$ 6 kHz, Pdf_r/dP = 320 Hz, where P is the pump power, and n_{fix}= (4.1±0.1)×10^6, corresponding to $c/(n_{fix}f_r)$ = 1460 nm.

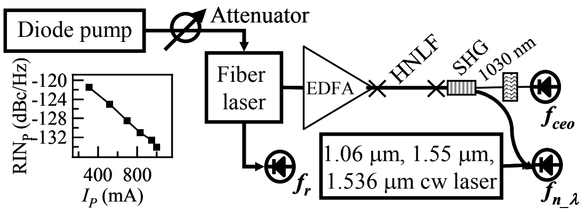

Fig. 2. The experimental setup for the measurements of $f_r, f_{ceo}, f_{n\_1064}, f_{n\_1.550}$, and $f_{n\_1.536}$ versus pump RIN. HNLF: highly nonlinear fiber, EDFA: erbium-doped fiber amplifier, SHG: second harmonic generation. Inset: The measured pump RIN versus current.

By beating the comb with a cw laser, we determined the power spectral density S_n of the frequency noise on the n$_{\text{th}}$ comb tooth. According to Figure 1, we expect the noise to increase quadratically with (n-n_{fix}). Figure 3 shows the measured frequency noise on both the ceo frequency (equivalent to the comb tooth at zero frequency) and the comb tooth at 1.064 µm. The frequency noise rolls off at $\nu_{3\text{db}}$, as expected. The relative level of the frequency noise between the comb line at n=0 (the ceo beat) and the comb line at 1.064 µm is 8.5 dB, as expected from our values for the fixed point. Note that Figure 3 shows the frequency noise spectrum and not the linewidths. The linewidths can be calculated from the frequency noise. If this white frequency noise extended to infinity, rather than to a finite $\nu_{3\text{db}}$, the resulting field spectra would be Lorentzian with a width of $\pi S_{1.06\mu m}$ and πS_{ceo}. Instead the rolloff in the frequency noise results in substantially narrow linewidths of $\pi(S_{1.06\mu m}\nu_{3\text{db}})^{1/2}$ and $\pi(S_{ceo}\nu_{3\text{db}})^{1/2}$. (See Fig. 1b for a comparison of frequency noise and optical comb linewidth). The white floor on the frequency noise is still under investigation but may be related to the quantum limit. At low Fourier frequency, other environmental effects will cause large frequency noise, but this noise is more easily removed through feedback.

The offset frequency can be actively stabilized to an rf reference through feedback to the pump power, however standard proportional-integral feedback is of limited effectiveness since the feedback response and noise both roll off at ν_{3dB} = 6 kHz. Because our laser showed no relaxation oscillations at the 6 kHz rolloff, however, we were able to use a phase-lead compensated feedback to extend our system's bandwidth to 50 kHz, reducing the frequency noise by an additional 38 dB at ν=1 kHz and the in-loop linewidth to less than 1 Hz (see Fig. 4). The signal-to-noise ratio (SNR) near the carrier is 45 dBc/Hz. Similar sub-hertz linewidths and SNR were observed by Hartl *et al.*[5] using a different laser design. The corresponding integrated ceo phase noise is

$\delta\phi_{ceo}^2 = \int_0^{100kHz} \nu^{-2} S_{ceo}(\nu)\, d\nu = (1.3\ \mathrm{rad})^2$. The pulse-to-pulse phase jitter may be higher, depending on the white phase noise floor, but these levels are promising for time-domain applications. Additionally, by phase-locking f_{ceo}, we also remove noise on the repetition rate of the laser. In fact, with f_{ceo} locked, the phase noise of the free-running f_r is superior to that of a high-quality rf synthesizer for Fourier frequencies greater than 5 kHz.

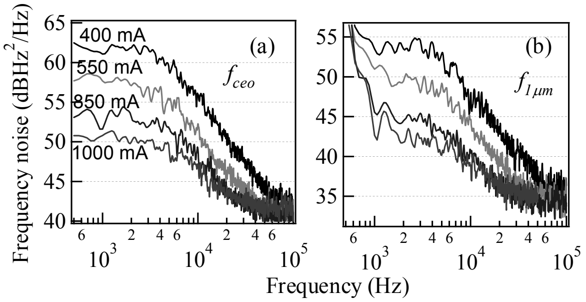

Figure 3: Measured frequency noise on (a) the ceo frequency, S_{ceo} and (b) the 1.064 μm comb line, S_{n_1064} as a function of increasing pump laser current (and therefore decreasing pump laser RIN). Scales are offset by the expected 8.5 dB.

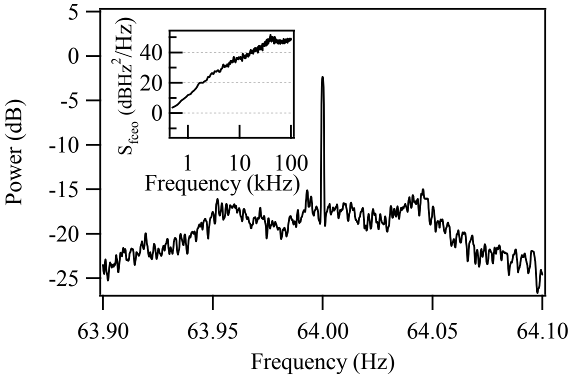

Figure 4: Phase-locked f_{ceo} beat signal using phase-lead compensation showing the coherent carrier. Inset: Corresponding frequency noise. (Compare to Fig. 3.) Servo bumps at ~50 kHz are evident.

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