Fiber-laser frequency comb: An explanation for the offset frequency linewidth

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Abstract: Fiber laser-based frequency combs typically exhibit broad optical linewidths in the wings of the frequency comb. We find these broadened linewidths originate from white amplitude noise on the pump laser.
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Fiber laser-based frequency combs [1-4] have some potential practical advantages over their more developed Ti:Sapphire laser-based counterparts [5]; they are less expensive, more power-efficient, and potentially more compact. However, the optical linewidths of the individual frequency comb lines are orders-of-magnitude broader than in Ti:Sapphire-based systems, where sub-Hz linewidths are possible [6]. These broad optical linewidths are most evident in the linewidth of the offset frequency beat, which is typically ~100-200 kHz. The fiber frequency comb is still adequate for frequency metrology since the line center of the broad frequency comb lines are well-defined through phase-locking to an rf reference [3]. However, for extremely precise optical frequency metrology or optical coherence measurements on short time scales, these broad linewidths are a potential drawback. A final issue with the broad linewidths is their apparently odd wavelength dependence. While the offset beat between the 1 μm and doubled 2 μm comb light is ~150 kHz wide, the comb linewidth near 1 μm is 10's of kHz wide. Naively subtracting these linewidths yields a >100 kHz linewidth of the comb at 2 μm, which is difficult to explain in the standard picture of the comb. However, as shown below this subtraction is incorrect and, in fact, the linewidth at 2 μm is narrower than at 1 μm. Furthermore, in agreement with [4], we find no violation of the standard expression for the frequency of the *n*th comb line, $f_n = nf_{rep} + f_o$, where f_{rep} is the repetition frequency and f_o is the offset frequency.

The comb offset frequency is typically controlled by feeding back to the current of the pump laser, 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 [7, 8]. Here we use the results of [7, 8] to explain the broad linewidth of the offset frequency f_o 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 (see Fig 1b) so that the comb linewidth increases with frequency difference from this fixed point. Fortunately, the fiber laser responds as a low-pass filter, with a cutoff frequency of ν_{3dB} ~10's of kHz, so that the pump-induced frequency noise is limited to low frequencies. Below ν_{3dB}, this "breathing-mode" noise results in white frequency noise on f_{rep}, f_o, and the f_n. This white frequency noise explains the Lorentzian-like shape of the optical linewidths and f_o beat note. Moreover, it explains both the broad comb linewidth at 1 μm and the broader offset frequency linewidth.

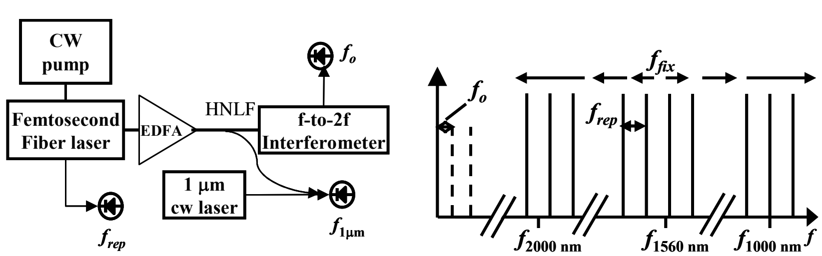

Fig. 1. a) Schematic of the system used for the measurements of f_{rep}, f_o and the beat at 1 μm. The femtosecond fiber laser was in stretched-pulse mode and operated at $f_r \approx 50$ MHz [9], HNLF: highly nonlinear fiber, EDFA: erbium-doped fiber amplifier. b) Schematic of the breathing-mode noise induced by the ASE-driven pump noise.

Figure 1a shows the experimental setup. We first established the response of the femtosecond laser to pump power fluctuations by modulating the pump power and measuring the corresponding modulation of f_{rep} and f_o [8]. From these data, we find a fixed point corresponding to 1.49 μm ± 3%. The sensitivity of the repetition rate to the pump power, P, is given by Pdf_{rep}/dP =320 ± 10 Hz and the 3-dB rolloff ν_{3dB} = 7.5 kHz. With the laser response characterized, we examine the effect from the pump relative intensity noise (RIN_P). The pump RIN is shown in Fig.

2a along with the resulting amplitude noise on the fiber laser, which shows the expected 7.5 kHz rolloff from the response dynamics. Through the sensitivity of the repetition frequency to pump fluctuations, $P df_{rep}/dP$, this RIN gives rise to frequency noise on the repetition frequency that is flat with a value of $\delta f_{rep}^{\;2} = (320)^2 \times \mathrm{RIN}_P$ (Hz^2/Hz) out to the 7.5 kHz rolloff. The corresponding phase noise falls off as the square of the Fourier frequency and results in the wings of the rf spectra shown in Fig 2b.

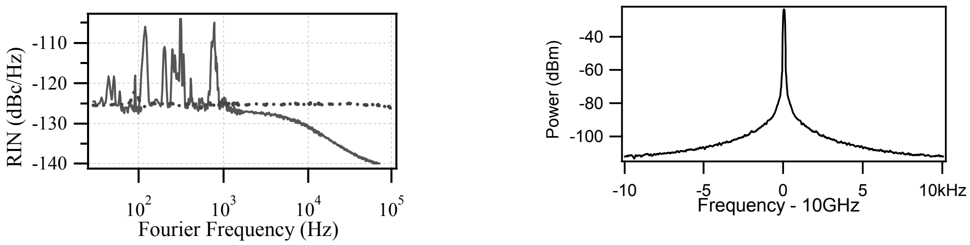

Fig. 2. a) Relative intensity noise (RIN) of the pump laser (dashed) and the femtosecond fiber laser (solid). The RIN of the pump current source is -138 dBc/Hz. The spikes in the laser are mainly vibrationaly induced. b) RF spectrum of the repetition rate at the 10 GHz harmonic with a 300 Hz bandwidth. The wings result from the pump-induced noise.

This noise on the repetition rate also appears on the individual comb lines, increasing quadratically as one moves away from the fixed point at 1.49 μm (see Fig 1b). Specifically, the frequency noise on the comb lines at a vacuum wavelength, λ, is $\delta f_\lambda^{\;2} = (f_\lambda - f_{fix})^2(\delta f_{rep}/f_{rep})^2$ and the frequency noise on the offset frequency (effectively the comb line at zero frequency) is $\delta f_0^{\;2} = (f_{fix})^2(\delta f_{rep}/f_{rep})^2$. (Note that additional environmental affects will still produce a finite linewidth at the fixed point frequency.) The measured power spectral densities of $\delta f_{1.06\mu m}^{\;2}$ and $\delta f_0^{\;2}$ in Hz^2/Hz are shown in Fig 3a. Clearly evident is the $20\ \mathrm{Log}(f_{fix}/(f_{1.06\mu m} - f_{fix})) = 8$ dB difference in the noise. If this white frequency noise extended to infinity, rather than 7.5 kHz, the resulting field spectra would be Lorentzian with a width of $\pi \delta f_{1.06\mu m}^{\;2}$ and $\pi \delta f_o^{\;2}$. Instead the rolloff in the frequency noise results in substantially narrow linewidths that can be either measured or calculated numerically from the noise power spectra. The measured field spectra are shown in Fig 3b with linewidths of 150 kHz and 60 kHz for f_o and $f_{1.06\mu m}$ respectively.

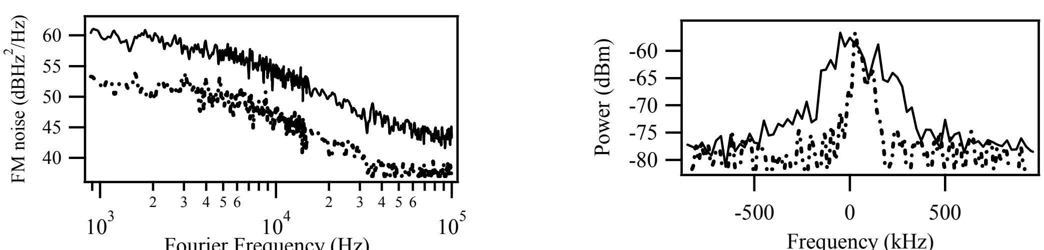

Fig. 3. a) Frequency noise power spectral densities for f_o (solid) and $f_{1\mu m}$ (dashed) for the RIN levels of Fig. 2a. b) The corresponding field spectra.

Since the linewidths are induced by technical noise on the pump laser, they can be reduced by reducing the pump RIN, the magnitude of the laser response [7], or the laser response bandwidth. Indeed by reducing the RIN we have lowered the offset frequency linewidth to 50 kHz.

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