

Fiber-laser frequency combs

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Abstract: We discuss the contributions to the linewidth and frequency noise of the individual modes of a mode-locked fiber laser. Much of this noise can be suppressed through feedback to form a stable frequency comb.

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Fiber laser-based frequency combs [1-4] are based on stabilizing the output of a passively mode-locked, femtosecond fiber laser [5], following the basic concepts and techniques developed for the original Ti:Sapphire frequency combs [6, 7]. The system is most easily considered in the frequency domain, where the laser output is described in terms of the individual laser modes. The modes are separated by the repetition rate of the laser (equivalent to the time it takes the laser pulse to travel around the laser cavity). Through the passive mode-locking mechanism in the laser cavity, the participating laser modes have a definite phase relationship, and a frequency determined by the simple relationship $\nu_n = n f_r + f_0$, where n is the mode number, f_r is the mode spacing set by the laser repetition rate, and f_0 describes the translational motion of the comb in frequency space. A fiber-laser frequency comb is typically defined as this mode-locked laser output, with two important modifications. First, the laser output is spectrally broadened in a highly nonlinear fiber so that the comb of mode lines covers from about 1 to 2 μm or further. Second, the modes, ν_n , are phase-locked to a reference so that they remain fixed in frequency space. Fortunately, this phase-locking does not require individually stabilizing each individual laser mode; instead, it requires phase-locking only two degrees of freedom of the comb. For example, f_r and f_0 can be phase-locked to a single microwave reference, allowing a phase-coherent connection between the microwave domain and optical domain. Alternatively, one mode f_n can be phase-locked to an optical reference and f_0 to zero to link an optical reference to the microwave domain or another optical reference.[1, 8, 9] One of the most basic functions of the fiber-laser frequency comb is to faithfully translate the stability and phase noise of the microwave or optical reference across the entire comb of optical modes. For very narrow, highly stable, optical references, it can be challenging to avoid introducing any excess noise and only recently has the fiber-laser frequency comb demonstrated performance approaching, but still not rivaling, that of the Ti:sapphire frequency comb.[1]

How well the fiber-laser frequency comb follows the reference source depends on two factors: first, the magnitudes of the excess noise sources that disturb the comb and, second, the effectiveness of the feedback mechanisms used to remove this excess noise. Here we summarize the main sources of noise that perturb the frequency comb, the minimization of that noise through appropriate system design, and the effectiveness of the feedback to the laser. Figure 1 summarizes the basic configuration of the frequency comb and the various noise sources that can perturb the comb.[10]

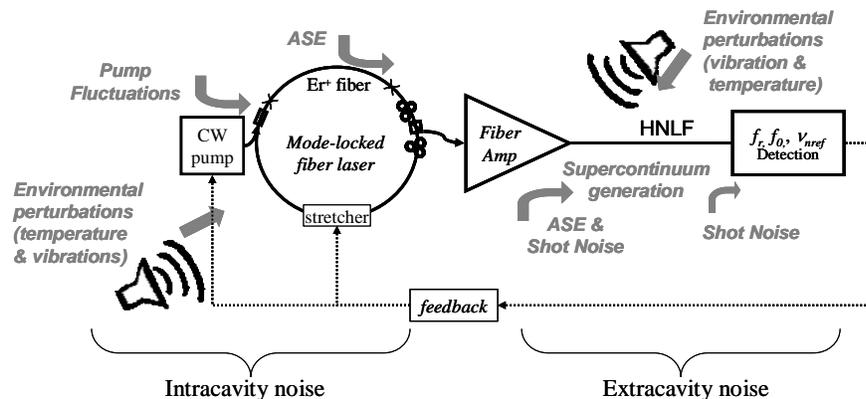


Fig 1: Schematic of a fiber laser frequency comb comprised of a mode-locked fiber laser, amplifier, highly nonlinear fiber and detection. The components after the laser broaden the output to cover an octave of bandwidth[11] and permit detection of the offset frequency through f-to-2f self-referenced detection.[7] The main noise sources acting on the laser (intracavity noise) and after the laser (extracavity noise) are shown. Feedback to the pump power and cavity length are used to stabilize the frequency comb.

The noise can be divided into two separate categories as shown in Fig. 1: (1) Intracavity noise that perturbs the mode-locked laser itself, and (2) Extracavity noise that perturbs the pulse train after it has left the laser source. Intracavity noise sources perturb the comb by causing correlated noise in the comb spacing and offset frequency. This noise can be characterized by including time-dependence in the simple equation governing the comb positions $\nu_n(t) = n f_r(t) + f_0(t)$, where t is time. Sources include environmental effects, pump noise (both “1/f” pump noise and white pump noise), [12, 13] and intra-cavity amplified spontaneous emission, [14, 15] which is responsible for the quantum-limited noise of a mode-locked fiber laser. The effect of these noise sources on the comb is best-described using the “fixed-point” framework [16] as shown in Fig. 2. Intracavity noise can be strongly suppressed through feedback to the laser, yielding a system with phase and timing jitter below the quantum limit. Extracavity noise is typically at a much lower level than intracavity noise, but can in principle vary strongly across the spectrum and cannot always be strongly suppressed through feedback. Extracavity noise sources include environmental perturbations, shot noise, and excess noise generated during supercontinuum formation in the highly nonlinear fiber. [17] The effect of these last two extracavity noise sources is generally to add a white phase noise floor to the comb, as depicted in Fig. 2. The effect of this noise can be quantified in terms of the comb linewidth, or more usefully in terms of the frequency noise power spectral density on each comb tooth.

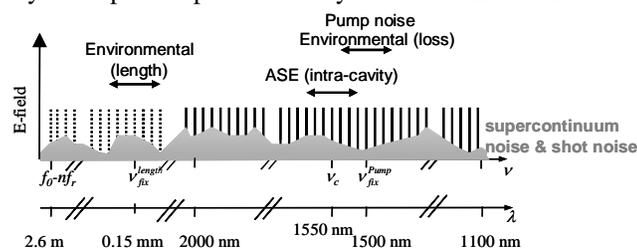


Fig. 2: Schematic illustrating the effect of various noise sources on the frequency comb output of a mode-locked fiber laser. Each noise source can be described in terms of its fixed point and the magnitude of the stretching motion it engenders about that fixed point.

By feeding back to the cavity length, we can remove most of the noise from environmental perturbations. By feeding back to the pump power by use of phase-lead compensation [12] we can effectively remove most of the noise caused by pump noise and cavity ASE, at least within the feedback bandwidth. The result is a comb with very low residual phase noise of ~ 1 radian or less and very good frequency stability. [1]

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