Stable frequency comb derived from a narrowband Yb-fiber laser: pre-chirp management for self-referenced f_{CEO} stabilization

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Abstract: We demonstrate the feasibility of implementing frequency combs from a narrowband (5-nm, 415-fs transform-limited pulse) laser, paving the way for large line-spacing frequency combs based on multi-GHz lasers which emit long (>200 fs) pulses.

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Many applications demand laser frequency combs with line spacing >10 GHz such that each individual comb-line can be accessed [1]. This requirement has stimulated research efforts in developing femtosecond lasers with >1 GHz repetition rate. Most of these lasers are relative narrowband with pulse durations far exceeding 100-fs. In implementing a self-referenced frequency comb, stabilization of carrier-envelope offset frequency (f_{CEO}) is rather challenging, which normally involves supercontinuum (SC) generation inside a highly nonlinear fiber. A high-quality SC with excellent coherence is crucial to f_{CEO} locking that ensures a stable frequency comb. The SC coherence is primarily determined by the input pulse duration coupled into the nonlinear optical fiber; pulses of 100 fs (or even shorter) are normally required [2]. Indeed, most demonstrated frequency combs are based on lasers with direct output of <100 fs pulses. Since multi-GHz lasers generate long output pulses (≥ 200 fs), the following question naturally arises: is it possible to fully stabilize relatively narrowband lasers to achieve frequency combs, and are therefore frequency combs with multi-GHz line spacing feasible from the modelocked lasers? In this paper, we address this question by demonstrating a self-referenced frequency comb (see Fig. 1) based on a narrowband 280-MHz Yb-fiber oscillator.

Fig. 1. Fully stabilized frequency comb based on a 280-MHz narrowband Yb-fiber oscillator. OSC: oscillator, AOFS: acousto-optic frequency shifter, PD: photo-detector, CL: collimating lens, PBC: polarization beam combiner, WDM: wavelength division multiplexer, YDF: Yb-doped fiber, ISO: isolator, DM: dichroic mirror, PCF: photonic crystal fiber, PPLN: periodically poled lithium niobate, APD: avalanche photo-detector.

The 280-MHz Yb-fiber oscillator is intentionally mode-locked with 5-nm bandwidth, corresponding to 415-fs transform-limited pulses. The pulses, after pre-chirped with a pair of diffraction gratings (Box 1 in Fig. 1), are amplified (up to 1.3-W average power) and spectrally broadened in two Yb-doped fiber amplifiers (YDFAs, Box 2), and then compressed with another grating pair (Box 3). To achieve compressed pulses with the best quality, we varied the grating pair separation in Box 1 to optimize the pulse pre-chirp prior to the amplification [3].

Because SC generation is extremely sensitive to the intensity noise of the driving pulses [4], we measured the relative intensity noise (RIN) of the amplified pulses at different pre-chirp settings. Figure 2(a) shows the integrated RIN from 100 Hz to 10 MHz as a function of the group-delay dispersion (GDD) for pre-chirping the oscillator pulses. Indeed, the

integrated RIN reaches a minimum of 0.075% at the pre-chirp GDD of -0.09 ps^2 (indicated by the red circle in Fig. 2(a)). As a comparison, it increases to 0.093% at the pre-chirp GDD of 0.01 ps^2 (green circle in Fig. 2(a)). With the pre-chirp GDD of -0.09 ps^2 where the minimum RIN is achieved, the compressed pulses reach the minimum duration as well. The red curve in Fig. 2(b) shows the optical spectrum after the amplifier was broadened from 5 nm to $>15 \text{ nm}$; such a broadened spectrum accommodates a transform-limited pulse of 90 fs. We measured the resulting compressed pulse using an autocorrelator and the autocorrelation trace is shown in Fig. 2(c) as the red curve. As a comparison, the autocorrelation trace of the transform-limited pulse calculated from the broadened spectrum is plotted in the same figure as the blue dashed curve.

Fig. 2. (a) Amplified pulse instability measured at different pre-chip into YDFA (b) Measured spectra after YDFA, (c) Measured autocorrelation of the compressed pulse.

The compressed pulses with $\sim 2\text{-nJ}$ pulse energy are coupled into 40-cm photonic crystal fiber (3.2- μm core diameter, zero-dispersion wavelength at 945-nm) for SC generation. A 1f-2f interferometer (Box 4 in Fig. 1) generates f_{CEO} beat signal with the $\sim 40\text{dB}$ signal-to-noise ratio. The f_{CEO} is stabilized using an acousto-optic frequency shifter (AOFS) [5,6]. We have obtained the locking bandwidth of $>150\text{-kHz}$ and the integrated RMS phase noise of 0.64-rad from 1 Hz to 10 MHz (Fig 3(a)); we achieved an f_{CEO} line-width of $<10\text{-Hz}$ with the resolution bandwidth (RBW) of 0.2-Hz (Fig 3(b)).

Fig. 3. (a) Power spectral density (PSD) and the RMS integrated phase noise; unlocked (black), locked (red), Phase error integrated from 1 Hz to 10 MHz (blue), (b) Measured f_{CEO} linewidth (x-axis: $f_{\text{CEO}} - 190 \text{ MHz}$) with 1 kHz RBW; Inset with 0.2 Hz RBW.

We demonstrate the feasibility of implementing frequency combs from a narrowband (5-nm bandwidth, corresponding to 415-fs transform-limited pulses) laser, which is of particular importance for realizing large line-spacing frequency combs based on multi-GHz oscillators usually emitting long ($>200 \text{ fs}$) pulses. Optimization of the pre-chirping led to the shortest compressed pulses with the minimum RIN, which is critical for the subsequent SC generation that determines the SNR of the f_{CEO} beat-note. Currently we are working on employing the technique demonstrated in the paper to fully stabilize a 3-GHz Yb-fiber laser to achieve a self-referenced 3 GHz frequency comb.

References

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