Application Note: Ultra-low-noise frequency comb offset stabilization with stability better than 10^{-20}

Summary: The **Octave Photonics Comb-Offset-Stabilization Module (COSMO)** provides a compact method to detect the carrier-envelope-offset frequency (f_{CEO}) of a laser frequency comb. To assess the stability of the locked f_{CEO}, we use one COSMO to measure the f_{CEO} of an **Ultra-Low-Noise (ULN) Frequency Comb from Menlo Systems (FC1500-250-ULN)** and verify the fidelity of the phase-lock loop using a second COSMO that is outside the feedback loop. After measuring operation for more than 12 hours, we find that the signals from the two COSMO units agree to better than $1\mathrm{x}10^{-17}$ at 1 second and better than $1\mathrm{x}10^{-20}$ at 1,000 seconds. This level of performance is compatible with the most demanding applications.

Introduction: Ultra-high stability laser frequency combs are critical for building optical atomic clocks, enabling the operation of quantum computers, and constructing quantum-based sensors. Menlo Systems is at the forefront of the development and manufacturing of the most stable frequency combs demonstrated to date [1], enabling record-breaking optical clocks stabilities [2] and the synthesis of the most stable microwave signals [3]. In order to stabilize a laser frequency comb, it is necessary to detect and lock the carrier-envelope offset frequency (f_{CEO}). Menlo Systems frequency comb systems use traditional *f-2f* interferometry to detect f_{CEO}, whereas the actuation to stabilize f_{CEO} within the figure 9 fiber oscillator [4] is permitted by a proprietary intra-cavity EOM [5], allowing ultra-low-noise operation.

The Octave Photonics COSMO provides a compact spectral broadening and *f-2f* interferometer solution for detecting the f_{CEO} signal [6, 7]. Additionally, the COSMO allows f_{CEO} to be detected with exceptionally low pulse energies, enabling lower power consumption or higher repetition rate lasers. While the COSMO utilizes the proven technique of *f-2f* interferometry, it differs from traditional f_{CEO} detection schemes in that it utilizes a nanophotonic waveguide [8-11] for the supercontinuum generation process. Additionally, while uncommon, any f_{CEO} detection apparatus could introduce excessive noise into the locked system. Thus, it is necessary to verify that any new f_{CEO} detector can provide low-noise detection of the f_{CEO}.

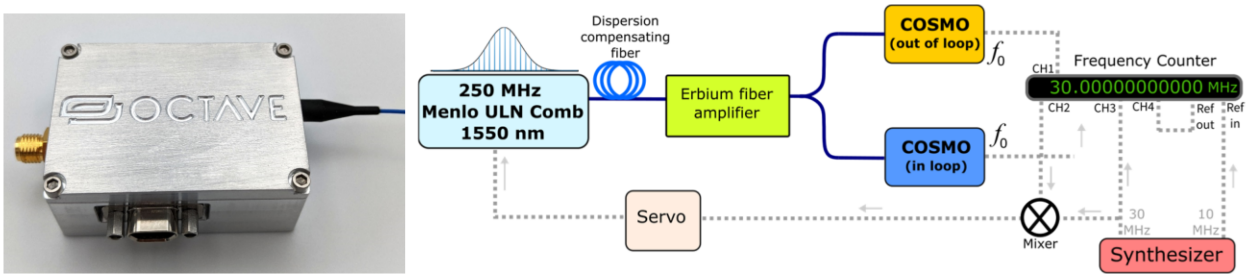

Figure 1. Experimental setup. (left) The comb offset stabilization module (COMSO) receives pulses from the fiber on the right and generates the f_{CEO} signal on the SMA connector on the left. (right) The experimental setup for testing the stability of the Menlo Ultra-Low-Noise (ULN) frequency comb using two COSMOs.

Here we use one COSMO as part of the feedback loop to lock the f_{CEO} of an Ultra-Low-Noise (ULN) laser frequency comb from Menlo systems. Another out-of-loop COSMO is used to verify the stability of the f_{CEO}. By comparing the stability of the two signals, we find that the COSMO allows the comb to reach a level of stability comparable to that obtained using a traditional *f-2f* interferometer. Thus, the COSMO can be used to stabilize a Menlo Systems frequency comb system for applications such as state-of-the-art optical atomic clocks, which demand the highest level of comb performance.

Experiment: The Menlo ULN laser produces an optical pulse train at 250 MHz and a center wavelength of approximately 1550 nm. The pulses pass through polarization-maintaining dispersion compensating fiber in order to compensate for the dispersion of downstream components and ensure compressed pulses at the COSMO. The rest of the fiber components utilize polarization-maintaining fiber (PM1550), ensuring robust operation against environmental instabilities. The pulses then pass through an erbium-doped fiber amplifier (Thorlabs EDFA100P). The light is then split with a 50:50 fiber splitter, and half of the light is directed to each COSMO. After accounting for losses, the power at the input to each COSMO device is approximately 45 mW (pulse energy 180 pJ), approximately a factor of 5 lower than is required for supercontinuum generation and *f-2f* self-referencing using traditional highly nonlinear fibers.

The f_{CEO} signal from the in-loop COSMO is mixed with a 30 MHz signal from an RF synthesizer (Holzworth 9002A), providing an error signal. This signal is sent to a high-performance servo (Vescent Photonics D2-125), which provides feedback to the laser, locking f_{CEO} to the 30 MHz reference. The signal from the in-loop COSMO is fed to a zero-dead-time frequency counter (K+K FXE). The counter is operated as a lambda counter with a 1 second gate time and referenced to a 10 MHz signal from the same RF synthesizer. The 10 MHz reference signal from the counter and the 30 MHz signal from the synthesizer are also connected to the counter to provide estimates of the measurement floor induced by the counter and the synthesizer respectively. Finally, the signal from the out-of-loop COSMO is connected to the frequency counter to verify the stability of the f_{CEO} signal.

Results: If both COSMOs function with high stability, the f_{CEO} recorded by each unit should be similar. Indeed, as shown in Figure 2b, the in-loop and out-of-loop COSMOs record values for the f_{CEO} that are nearly identical. In the modified Allan deviation (Figure 2c), the out-of-loop COSMO obtains approximately 8x10^{-18} at 1 second and 8x10^{-21} at 1000 seconds. At times longer than about 1000 seconds, our measurement is limited by the stability of the synthesizer used.

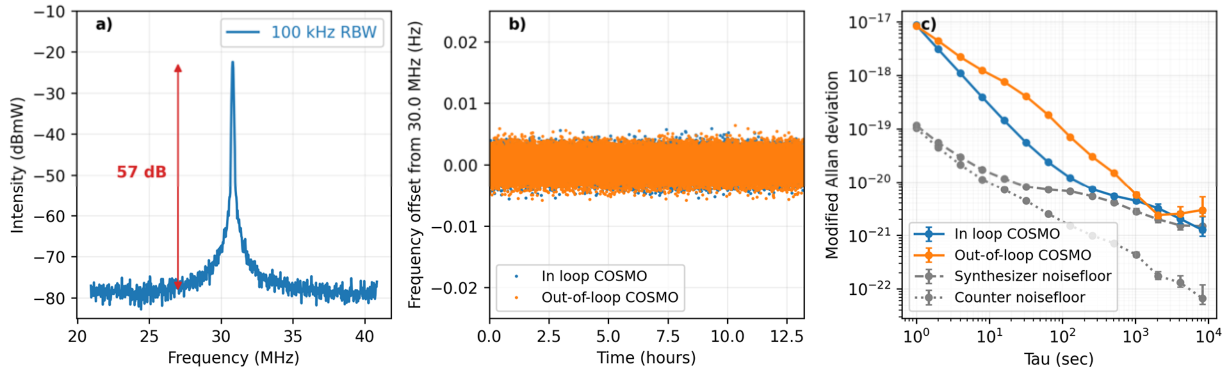

Figure 2. Stabilization and out-of-loop verification of f_{CEO} using the COSMO. a) The unlocked f_{CEO} recorded with the COSMO has a high signal-to-noise ratio, enabling tight locking of f_{CEO}. b) The f_{CEO} frequencies recorded by the two COSMOs show nearly identical stability over the course of 13-hour period. c) the modified Allan deviation shows that the f_{CEO} of the comb has been stabilized to a level compatible with ultra-high-stability measurements of optical clocks.

At shorter times, it is likely that these measurements were limited by fiber path length fluctuations and that the intrinsic stability of the f_{CEO} provided by the COSMO is better than presented here. While it might be expected that the in-loop and out-of-loop COSMOs should provide *exactly* the same f_{CEO} measurement, this is not the case due to the fact that pulses must travel through different optical fibers to reach the in-loop COSMO versus the out-of-loop COSMO. There are ~1.5 meters of fiber between the splitter and each COSMO, so the total fiber-length difference between the two COSMOs is 3 meters. Thus, we attribute the small difference between the measurements to small path-length changes in the optical fiber.

Conclusion: Here we have measured the fractional frequency stability of the carrier-envelope-offset frequency of a Menlo Systems Ultra-Low-Noise (ULN) frequency comb system making use of the Octave Photonics COSMO. By using two separate COSMO devices, we make an out-of-loop measurement of the comb stability, verifying the ability of the COSMO to detect the carrier-envelope offset with extreme precision. The level of fidelity reached in the control of the offset frequency with the COSMO supports precision frequency measurements using ULN combs at a level of 10^{-20} at 1,000 seconds.

Links: Learn more at octavephotonics.com, and menlosystems.com.

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