Application Note:
Simplified offset stabilization of a low-noise 1 GHz oscillator

Summary: We utilize the **Octave Photonics Comb-Offset-Stabilization Module (COSMO)** to detect the carrier-envelope-offset frequency (f_{CEO}) of a **Menhir Photonics 1-GHz, 1550-nm oscillator** with less than 140 pJ of pulse energy (<140 mW average power). A **Vescent Photonics SLICE-OPL** offset-phase-lock controller provides the feedback signal to the oscillator and establishes a tight lock with only 0.26 radians of residual phase noise. Together, this demonstrates a simple method for building compact and reliable frequency comb sources at GHz repetition rates.

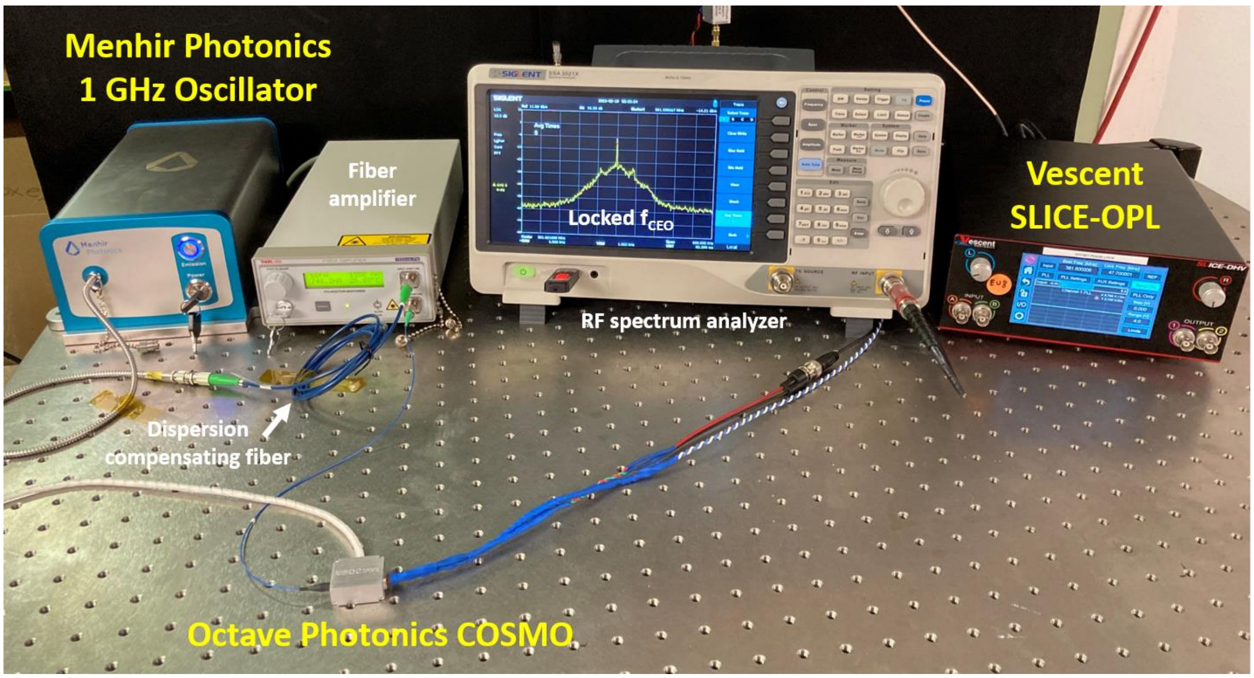

Figure 1. The experimental setup for carrier-envelope offset frequency (f_{CEO}) stabilization of a 1 GHz 1550-nm oscillator. The Menhir Photonics oscillator generates a 1 GHz pulse train at 1550 nm, which is fed into an erbium-doped fiber amplifier to increase the pulse energy. The amplified pulse train passes through a short section of dispersion compensating fiber and then enters the Octave Photonics Comb-Offset-Stabilization Module (COSMO) where f_{CEO} is detected. The f_{CEO} *signal* is then amplified, filtered, and fed into the Vescent SLICE-*OPL*, which provides a feedback signal to the laser. The locked f_{CEO} signal with coherent spike is seen on the RF spectrum analyzer.

Introduction: Laser frequency combs are essential optical-to-microwave converters for applications such as optical atomic clocks and high-resolution dual-comb spectroscopy. Frequency combs are based on femtosecond mode-locked lasers that have their repetition rate (f_{rep}) and carrier-envelope-offset frequency (f_{CEO}) stabilized. The repetition rate can easily be stabilized by detecting the pulse train with a photodetector and providing feedback to the laser oscillator. Detecting f_{CEO} is more difficult and is typically accomplished through f-2f self-referencing, where the spectrum is broadened to at least one octave via supercontinuum generation. The low frequency side of the spectrum is then frequency doubled in a second-harmonic-generation material and overlapped in time with the high-frequency spectrum on a photodetector, detecting the microwave f_{CEO}.

info@octavephotonics.com • OCTAVEPHOTONICS.COM
325 W South Boulder Rd Suite B1 • Louisville, CO 80027

While frequency combs operating near 100 MHz repetition rates are becoming an established technology, combs at GHz repetition rates open the door to exciting new applications but present several challenges. First, low-noise, reliable oscillators at >0.5 GHz repetition rate are difficult to construct using conventional laser architectures. However, today the MENHIR-1550 SERIES of 1550 nm oscillators offer ultra-low-noise performance at repetition rates from 100 MHz to 5 GHz using an extremely stable design. Second, the f-2f self-referencing process typically requires at least 1 nJ of pulse energy (>1 W average power at f_{rep} = 1 GHz) and involves careful alignment of the interferometer. The Octave Photonics COSMO is a compact one-box solution that allows f_{CEO} to be detected with less than 200 pJ (<200 mW at f_{rep} = 1 GHz) of pulse energy. Finally, since a 1 GHz repetition-rate frequency comb can have CEO frequencies ranging from DC to 500 MHz, the electronics required to provide fast feedback to the laser are not trivial. The new Vescent Photonics SLICE Offset Phase Lock (SLICE-OPL) box provides a straightforward off-the-shelf solution to stabilizing f_{CEO} at frequencies up to 10 GHz.

These three breakthrough technologies from Menhir Photonics, Octave Photonics, and Vescent combine to form a system where **a fully stabilized laser frequency comb can be constructed in minutes rather than days.**

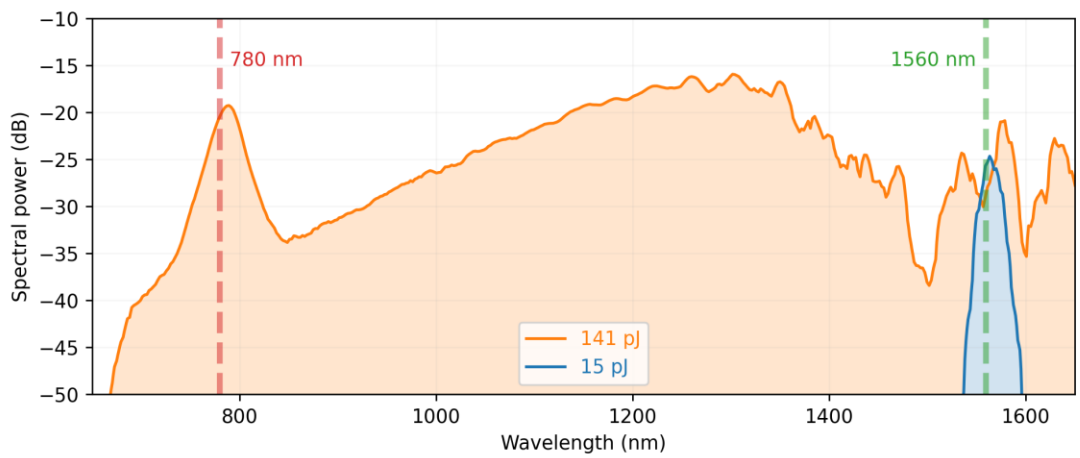

Figure 2. Supercontinuum generation from an Octave Photonics supercontinuum generation unit. Light at 780 nm is generated for pulse energies above 140 pJ (140 mW). Inside the COSMO, the light at 1560 nm is doubled to interfere with the supercontinuum light at 780 nm to detect f_{ceo}. (Note that the output of the supercontinuum device was packaged with 780-nm fiber, thus light at longer wavelengths is partially attenuated.)

Experiment: The optical system is composed of polarization-maintaining (PM) fiber components to simplify assembly and minimize thermal drifts. The output of the Menhir 1 GHz oscillator first passes through a 90-cm length of dispersion-compensating fiber (Thorlabs PMDCFA5) to compensate for the dispersion of other components in the system. The 1-GHz pulse train then passes through a Thorlabs EDFA100P amplifier, which is dispersion-compensated for use with femtosecond pulses. The light enters the Octave Photonics COSMO, which contains a supercontinuum generation waveguide, a second-harmonic-generation material, and an amplified photodetector. The electrical signal from the photodetector passes through a tunable-bandpass filter centered at ~380 MHz to select the CEO frequency and is then amplified with an additional RF amplifier (Mini-Circuits ZFL-1000LN+). This signal is connected to the Vescent SLICE-OPL, which provides feedback to the pump current of the MENHIR-1550 for f_{CEO} stabilization. The f_{CEO} spectrum and noise spectrum were recorded using a Siglent SSA3021X RF spectrum analyzer. The amplifier provides up to 180 mW of power, but we tune the amplifier pump current to provide 140 mW (140 pJ) to optimize the CEO signal.

Results: Inside the Octave Photonics COSMO, broadband supercontinuum is generated. The supercontinuum spectrum has a peak near 780 nm. Light near 1560 nm is frequency doubled to interfere with the light at 780 nm. To illustrate this concept experimentally, we first connected a packaged supercontinuum generation device to the output of the amplifier. Figure 2 shows how the narrow-band spectrum out of the amplifier is converted into an ultra-broad supercontinuum for pulse energies higher than about 140 pJ. Furthermore, this spectrum exhibits a strong peak near 780 nm.

Next, we connected the amplifier output to the COSMO device and tuned the amplifier to provide the strongest f_{CEO} signal. As expected, the signal was optimized at approximately 140 pJ. f_{CEO} was observed with approximately 36 dB signal-to-noise ratio (SNR) with 300 kHz resolution bandwidth (RBW) and with ~42 dB SNR at 100 kHz RBW (Figure 3, left). These SNRs are more than sufficient for a tight and reliable lock of f_{CEO}. Then, we connected the electrical f_{CEO} signal to the Vescent SLICE-OPL and started low-bandwidth feedback, which allowed us to lock f_{CEO} to an arbitrary RF frequency (Figure 3, right, blue curve). As we increased the gain on the feedback, we saw the center of the f_{CEO} peak narrow and the "coherent spike" appear in the center (Figure 3, right, orange curve). This indicates that we achieved a tight phase lock of f_{CEO}.

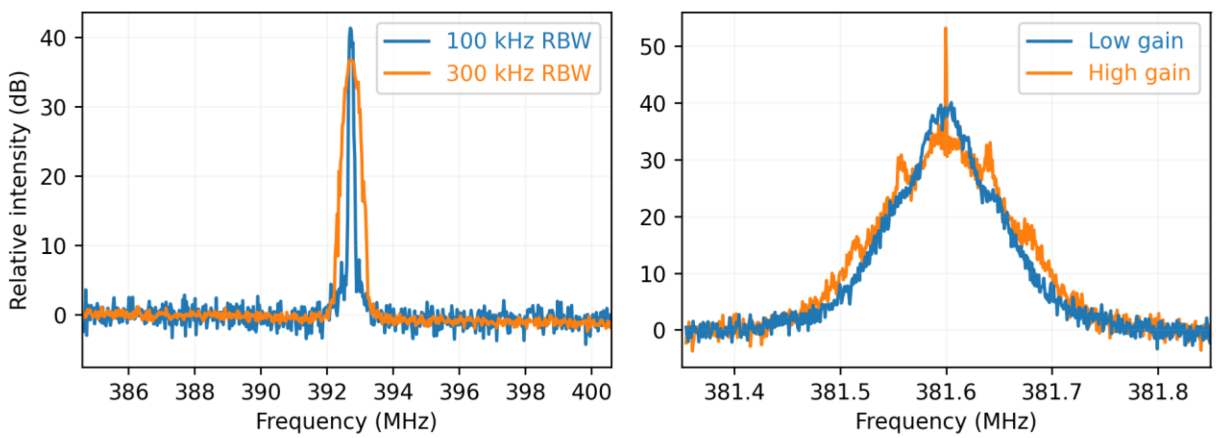

Figure 3. Carrier-envelope-offset frequency (f_{CEO}) peaks detected using the COSMO unit. (left) The unlocked peak shows a SNR of about 35 dB with 300 kHz resolution bandwidth (RBW) and about 42 dB with 100 kHz RBW. (right) With a low-gain lock, the position of the peak is locked, but the peak shape remains similar. When a high-gain lock is applied, the so-called "coherent spike" appears in the center of the peak, confirming a high-quality phase-lock between the f_{CEO} microwave signal and the SLICE-OPL internal synthesizer.

The observed in-loop residual phase noise in the f_{CEO} lock is shown in Figure 4, and confirms a strong suppression of the phase nose for frequencies lower than 40 kHz. The phase noise shown here is comparable to a previous experiment [Lesko2020] using a more conventional f-$2f$ interferometer and locking electronics. The integrated phase noise is 0.26 radians, which is also similar to the previous study, and confirms that we have obtained a very tight phase-lock of the CEO.

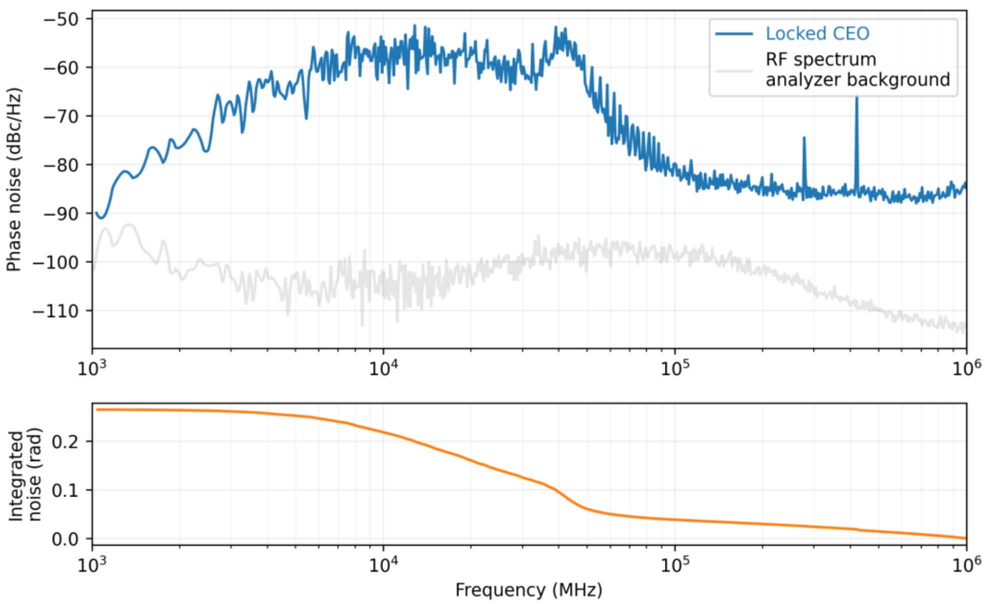

Figure 4. The in-loop phase noise of the locked f_{CEO}. (top) The noise spectrum of the locked laser shows that the phase noise is low for frequencies lower than the locking bandwidth of about 40 kHz. (bottom) The integrated phase noise shows that the total phase noise is about 0.26 radians.

Conclusion: We demonstrated how a carrier-envelope-offset-stabilized laser system can be easily constructed using commercial components, namely the MENHIR-1550 1-GHz laser from Menhir Photonics, the Comb-Offset Stabilization Module (COSMO) from Octave Photonics, and the SLICE-OPL locking electronics from Vescent Photonics. The phase noise of the lock is similar to previously reported results [Lesko2020] that used a more conventional carrier-envelope-offset detection scheme and locking electronics, demonstrating that this approach is capable of state-of-the-art performance with lower size, weight, and power requirements. By locking the repetition rate (in addition to the carrier-envelope-offset frequency) using similar off-the-shelf electronics, this system could function as an ultra-low-noise optical frequency comb at 1 GHz.

Links: Learn more at **menhir-photonics.com**, **octavephotonics.com**, **and** **vescent.com**.

References

Lesko2020 – Lesko et al., "Fully phase-stabilized 1 GHz turnkey frequency comb at 1.56 µm," *OSA Continuum* **3**, 2070-2077 (2020)

info@octavephotonics.com • OCTAVEPHOTONICS.COM
325 W South Boulder Rd Suite B1 • Louisville, CO 80027