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First investigation of the noise and modulation properties of the carrier-envelope offset in a modelocked semiconductor laser

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We present the first characterization of the noise properties and modulation response of the carrier-envelope offset (CEO) frequency in a semiconductor modelocked laser. The CEO beat of an optically-pumped vertical external-cavity surface-emitting laser (VECSEL) at 1030 nm was characterized without standard f-to-$2f$ interferometry. Instead, we used an appropriate combination of signals obtained from the modelocked oscillator and an auxiliary continuous-wave laser to extract information about the CEO signal. The estimated linewidth of the free-running CEO beat is approximately 1.5 MHz at 1-s observation time, and the feedback bandwidth to enable a tight CEO phase lock to be achieved in a future stabilization loop is in the order of 300 kHz. We also characterized the amplitude and phase of the pump current to CEO-frequency transfer function, which showed a 3-dB bandwidth of ~300 kHz for the CEO frequency modulation. This fulfills the estimated required bandwidth and indicates that the first self-referenced phase-stabilization of a modelocked semiconductor laser should be feasible in the near future.

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Optical frequency combs from modelocked solid-state lasers have been a revolution in the field of high precision metrology by directly and coherently linking the optical and microwave parts of the electromagnetic spectrum [1–3]. Such stabilized frequency combs enable the measurement of optical frequencies with an extreme precision [4,5] and constitute a key element of novel optical atomic clocks that have surpassed the best microwave frequency standards in terms of fractional frequency stability [6,7].

Most comb applications today require self-referencing, i.e., the detection and stabilization of the carrier envelope offset (CEO) frequency f_{CEO} [1,8]. This has been achieved in various fiber laser systems [9] and solid-state lasers (Ti:sapphire [2] or diode-pumped solid-state lasers–DPSSLs [10,11]). Electronic feedback modulating the pump power of the femtosecond laser is the most common approach to phase-stabilize f_{CEO} to an external reference frequency [3]. Alternative methods have been demonstrated, which make use of an intracavity loss modulator enabling the modulation bandwidth to be extended beyond the gain lifetime limitation, such as a graphene electro-optic modulator [12] or an opto-optical modulation of a semiconductor saturable absorber mirror (SESAM) [13]. Other solutions are based on feedforward corrections applied to the CEO frequency [14] or passive CEO cancellation using a difference frequency generation (DFG) process [15].

Self-referencing modelocked lasers with a high repetition rate in the GHz range is much more challenging, as the CEO noise typically scales with the repetition rate [16], therefore requiring larger feedback bandwidths. In addition, the standard self-referencing method most often involves f-to-$2f$ interferometry to detect the CEO frequency [1]. This requires a coherent supercontinuum (SC) spectrum that covers at least one frequency octave, which is fairly challenging to achieve for some novel comb technologies that are presently being developed. The use of higher-order nonlinear processes, such as $2f$-to-$3f$ [1], slightly reduces the requirements in terms of spectral width of the SC spectrum, but at the expense of a higher complexity.

Among the emerging comb technologies, modelocked semiconductor lasers are promising for future low-cost high-volume production owing to the benefits of semiconductor manufacturing. Vertical external-cavity surface-emitting lasers (VECSELs) or modelocked integrated external-cavity surface-emitting lasers (MIXSELs) [17] can lead to compact and cost-effective frequency comb systems in the future. However, no such modelocked laser has ever been CEO-frequency-stabilized yet. The main reason is the insufficient peak power and too long pulse duration that have so far prevented the generation of a suitable SC spectrum for CEO detection.

A CEO beat signal from a semiconductor modelocked laser has been detected for the first time by Zaugg *et al.* after external pulse amplification and compression [18], but no further investigation has been reported since then. The 1038-nm VECSEL was first amplified to 5.5 W average power using a fiber amplifier, then the pulses were compressed to 85 fs to generate the necessary octave-spanning SC spectrum in a photonic crystal fiber (PCF). However, the detected CEO signal was not suitable for noise analysis or stabilization as the signal-to-noise ratio (SNR) of ∼15 dB (in a 100-kHz resolution bandwidth) was insufficient. Extra noise may have been induced in the amplification.

In this Letter, we present the first detailed characterization of the CEO frequency in a modelocked VECSEL, showing promising results for future self-referencing stabilization. For this purpose, we implemented a characterization method of the CEO beat that does not require f-to-$2f$ interferometry and therefore circumvents the need for a coherent octave-spanning comb spectrum that has not yet been achieved directly from the output of this laser. The information about the CEO noise and modulation response was obtained directly from the output of the oscillator, without any further spectral broadening, pulse compression, or amplification. We recently showed a proof-of-principle demonstration of this method implemented with an Er:fiber frequency comb for which the CEO beat was separately detected using an f-to-$2f$ interferometer for cross validation [19]. The method proved to be suitable to infer both the frequency noise spectrum of the free-running CEO beat and the transfer function of f_{CEO} for a modulation of the laser pump current. Here we report on the implementation of this method for the characterization of the CEO frequency of a modelocked VECSEL.

The investigated ultrafast laser oscillator was a prototype developed at ETH Zurich. The laser cavity had a semiconductor gain chip as folding mirror, and a SESAM and an output coupler (1% transmission) as end mirrors. It generated sub-300-fs pulses at around 1030 nm [20]. The VECSEL was pumped with up to 17 W of optical power from a commercially-available fiber-coupled 808-nm multimode pump diode. The average output power was 90 mW with a spectral width of ∼4 nm. The pump diode was driven in-parallel by a low-cost constant current source and a home-built voltage-current transducer providing a fast modulation channel for the pump power. A dedicated low-pass filter was implemented between the two current sources to avoid undesirable crosstalk. A 3-dB modulation bandwidth of the pump power of around 1 MHz was therewith achievable with this homemade transducer. Fast modulation capabilities of the pump power are important for future comb self-referencing with direct control of the CEO frequency via pump current modulation. The VECSEL repetition rate $f_{\mathrm{rep}} \approx 1.77$ GHz was phase-stabilized to a radio-frequency (RF) signal referenced to an H-maser for stable long-term operation at the required level of accuracy. This stabilization was implemented by a phase-locked loop operating at $5 \cdot f_{\mathrm{rep}}$ (∼8.85 GHz), with a feedback signal applied to a piezoelectric transducer (PZT) controlling the position of the output coupler within the VECSEL cavity.

The principle of the method applied to characterize the CEO beat without directly detecting it was recently presented in Ref. [19]. It requires an auxiliary continuous wave (cw) laser. Whereas a planar waveguide external-cavity laser with a very low frequency noise was used in our proof-of-principle experiment at 1.55 μm, this type of laser is not available at the 1030-nm emission wavelength of our VECSEL. Therefore, a distributed feedback (DFB) laser (Eagleyard) with a specified linewidth <2 MHz was used in the work reported here. Its frequency noise power spectral density (PSD) has first been measured to assess its suitability for this application. This was realized by heterodyning the laser with the SC spectrum generated in a highly nonlinear fiber from a fully-stabilized Er:fiber frequency comb (Menlo FC 1500-250). The SC spectrum was spectrally filtered using a fibered tunable bandpass filter with a bandwidth of ∼1 nm and amplified in a semiconductor optical amplifier (Innolume) before being combined with the auxiliary cw laser in a 90/10 fiber coupler. The resulting beat signal was bandpass filtered and its frequency noise was measured using a frequency discriminator [21] and a fast Fourier transform spectrum analyzer. The noise of the auxiliary DFB laser was the dominating contribution in this measurement, leading to the frequency noise spectrum displayed in Fig. 2.

The experimental setup for the characterization of f_{CEO} was implemented in a similar way as in our previous proof-of-principle demonstration. However, different RF components (filters, frequency dividers, amplifiers) were used to account for the different repetition rate and mode number N involved here. Basically, two RF signals were detected, corresponding to a harmonic $N_1 = 9$ of the repetition rate (at 15.92 GHz) and to the beat signal f_{beat} between one mode of the VECSEL (with a nominal mode number $N = N_1 \cdot N_2$) and the auxiliary laser, which was detected at a frequency of 14.96 GHz. In order to remove the contribution of the VECSEL repetition rate, these signals were processed and combined according to the general principle reported in Ref. [19] and to the detailed scheme displayed in Fig. 1(b). Finally, only a frequency-divided contribution of the CEO frequency fluctuations δf_{CEO} (division by a factor $N_2 = 18,288$ here) occurred in the noise of the output signal $\delta f_{\mathrm{out}} = \delta f_{\mathrm{CEO}}/N_2$. This signal also contained the frequency noise of the cw laser (divided by the same factor N_2), but it had a negligible impact as it was significantly lower than the noise of the free-running CEO beat (as shown in Fig. 2). Therefore, the CEO noise was retrieved by up-scaling by a factor N_2^2 the phase noise of the output signal measured with a phase noise analyzer (FSWP from Rohde & Schwarz). The assessed CEO frequency noise displayed in Fig. 2 is not affected by the noise of the auxiliary laser (apart from some isolated peaks) and was thus correctly retrieved. In order to verify the correctness of the CEO noise measurement and to check if the considered combination of signals resulted in the expected compensation of the repetition rate noise, we also measured the sum-frequency component signal at the mixer output as discussed in Ref. [19]. This signal contains two times the noise of the repetition rate and thus shows the same noise features as the repetition rate as displayed in Fig. 3, which enabled identifying the correct difference-frequency signal.

At frequencies higher than ∼10 kHz, the measured CEO noise was limited by the noise floor of the experimental setup, which resulted from an RF synthesizer used to frequency down-convert the signal of the harmonics of f_{rep}, as previously discussed [19]. Therefore, we extrapolated the $1/f$ noise of the CEO signal to higher frequencies (blue dashed line in Fig. 2) to

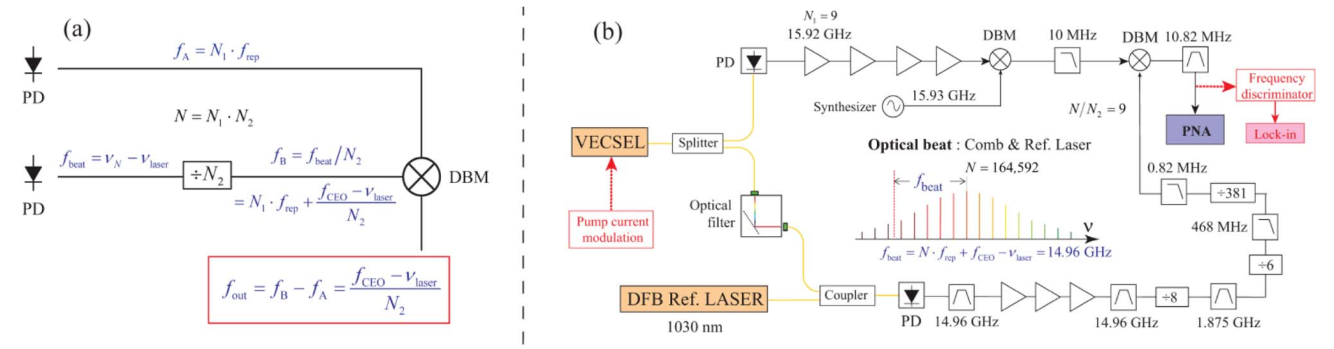

Fig. 1. (a) Basic principle of the proposed scheme to characterize the CEO beat without directly detecting it [19]. A high harmonic N_1 of the repetition rate (upper branch, signal f_A) is mixed with the heterodyne beat with a cw laser, frequency-divided by N_2 (lower branch, signal f_B), to produce a signal f_{out} that is exempt from the contribution of f_{rep}. PD: fast photodiode; DBM: double-balanced mixer. (b) Detailed experimental scheme realized for the implementation of the method with a modelocked VECSEL with $f_{rep} \approx 1.77$ GHz using an auxiliary DFB laser at 1030 nm. PNA: phase noise analyzer. All radio-frequency components except the narrow band-pass filters at ~15 GHz are standard off-the-shelf components. The frequency discriminator and lock-in amplifier are used for the transfer function measurement.

estimate the feedback bandwidth that would be required to achieve a tight CEO lock in a future self-referencing setup. From the crossing point of the extrapolated noise spectrum with the β-separation line [22], we assessed a full width at half maximum of the CEO beat of ~1.5 MHz (1-s observation time) and a corresponding required feedback bandwidth of ~300 kHz.

To assess if such bandwidth would be achievable using a direct modulation of the pump power via the pump current, we measured the modulation response of f_{CEO}. We used the same general setup as before, but demodulated the output signal using a frequency discriminator [21] and a lock-in amplifier referenced to the applied pump diode modulation using our fast modulation electronics. Figure 4 shows the measured amplitude and phase of the pump current to f_{CEO} transfer function. For comparison, we also measured the transfer function of the VECSEL output power for the same pump current

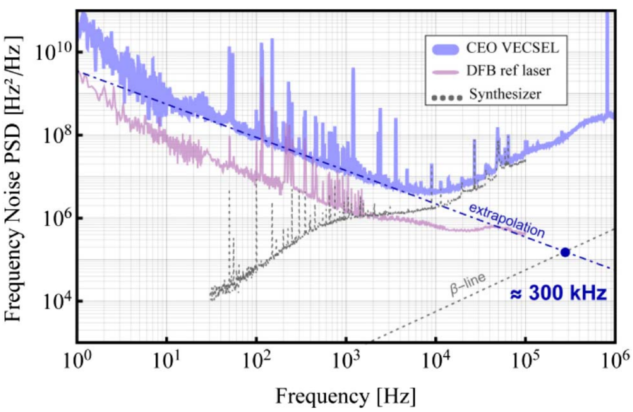

Fig. 2. Frequency noise PSD of the free-running CEO beat of the VECSEL assessed with the proposed method (thick light blue line). The thin light purple line represents the frequency noise PSD of the free-running cw laser used in this experiment. The CEO noise at frequencies higher than ~10 kHz is limited by the noise of a synthesizer used in the experiment (dashed grey line). Therefore, an estimation of the feedback bandwidth required for a future phase stabilization of f_{CEO} was assessed by extrapolating the $1/f$ noise (dashed blue line) up to its crossing point with the β-separation line [22].

modulation, as it generally has a similar behavior [23], which is indeed the case here. The amplitude of the transfer functions is constant up to at least 100 kHz, resulting in a 3-dB bandwidth of ~300 kHz for f_{CEO} modulation. At this frequency, the corresponding phase shift is approximately –90°. The CEO modulation capability of this VECSEL is significantly faster than usually encountered in DPSSLs or fiber lasers, resulting from the much shorter upper state lifetime in the semiconductor gain. The VECSEL CEO transfer function reported here is not limited by the carrier lifetime, which is much shorter, but by the cavity dynamics [23]. The fast modulation capability of the VECSEL is promising for a future self-referencing stabilization loop.

Finally, we also measured the frequency drift of f_{CEO} by recording the beat signal between an optical frequency reference ν_{laser} and one optical mode of the VECSEL (with f_{rep} stabilized to an RF synthesizer that was referenced to an H-maser). The optical reference was made of the cw DFB laser stabilized to a line of the SC spectrum of a commercial fully-stabilized Er:fiber frequency comb referenced to the H-maser. In this scheme, the

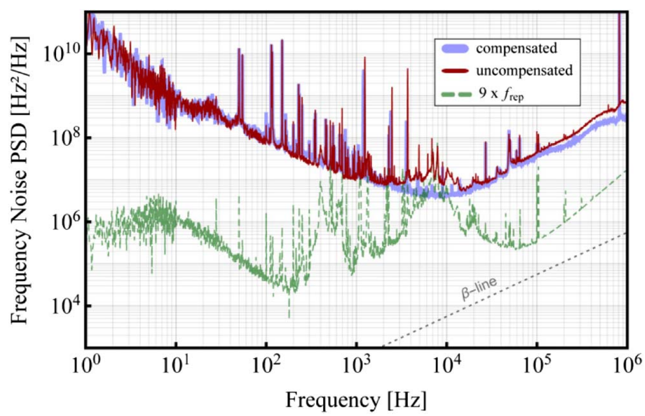

Fig. 3. Frequency noise PSD corresponding to the up-scaled noise obtained for the two signals at the mixer output (thick light blue line: compensated signal corresponding to the frequency-difference component; thin red line: uncompensated signal corresponding to the sum-frequency component) and comparison with the ninth harmonic signal of the repetition rate (thin dashed green line).

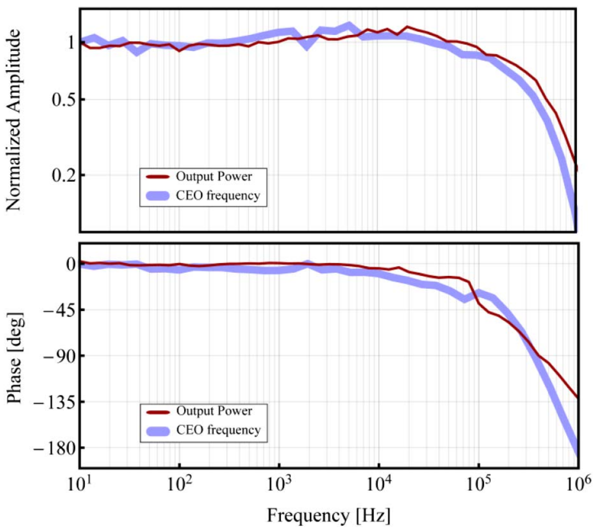

Fig. 4. Normalized amplitude (top) and phase (bottom) of the measured transfer functions of the VECSEL CEO frequency (thick blue line) and output power (thin red line) obtained for a direct modulation of the pump current. The phase of f_{CEO} has been offset by 180° to facilitate the comparison with the phase of the output power transfer function.

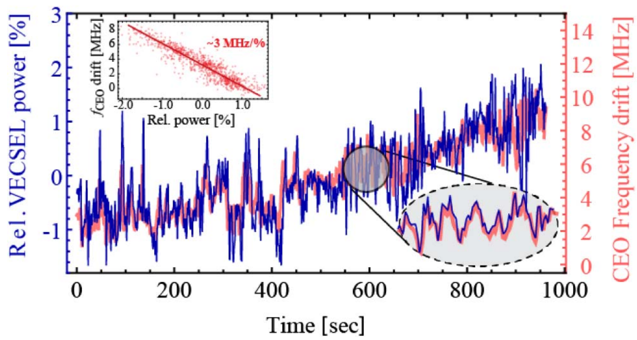

Fig. 5. CEO frequency drift (thick light red trace) measured by heterodyning the VECSEL emission with the DFB auxiliary laser frequency-locked to an Er:fiber comb fully-stabilized to an H-maser and comparison with the VECSEL output power (thin dark blue line). The inset in the right-bottom corner displays a zoom of the traces over 70 s, and the top-left inset shows the high correlation between the drift of f_{CEO} and the relative variations of the VECSEL output power with a slope of ~3 MHz/%.

slow frequency fluctuations of the beat signal only reflect the variations of the VECSEL CEO frequency, as all other frequencies (f_{rep}, ν_{laser}) were stabilized. A slow drift of ~8 MHz was observed in 15 min. Furthermore, we measured at the same time the relative variations of the VECSEL output power. A strong correlation was observed between the variations of f_{CEO} and the VECSEL output power as shown in Fig. 5. The intensity noise of the pump diode was likely responsible for this effect. Therefore, a feedback loop acting on the pump diode current is expected to be highly efficient for f_{CEO} noise reduction with a large bandwidth, enabling a tight CEO lock to be reached in future self-referencing experiments.

In conclusion, we reported the first thorough analysis of the noise and modulation properties of the CEO beat in a modelocked VECSEL. This was realized using a novel approach that we recently proposed to characterize the CEO beat without directly detecting it using standard f-to-$2f$ interferometry. Our results show that a modulation of f_{CEO} can be achieved by direct pump current modulation with a 3-dB bandwidth of around 300 kHz, which is comparable to the feedback bandwidth needed to achieve a tight CEO lock in a future self-referencing scheme estimated from our noise measurements. These results pave the way for the first self-referencing of a modelocked semiconductor laser, which is our next target.

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