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Characterizing the carrier-envelope offset in an optical frequency comb without traditional *f*-to-2*f* interferometry

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We present a new method to measure the frequency noise and modulation response of the carrier-envelope offset (CEO) beat of an optical frequency comb that does not make use of the traditional f-to-$2f$ interferometry. Instead, we use an appropriate combination of different signals to extract the contribution of the CEO frequency without directly detecting it. We present a proof-of-principle validation realized with a commercial Er:fiber frequency comb and show an excellent agreement with the results obtained using a standard f-to-$2f$ interferometer. This approach is attractive for the characterization of novel frequency comb technologies for which self-referencing is challenging, such as semiconductor mode-locked lasers, microresonator-based systems, or GHz repetition rate lasers.

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Optical frequency combs from mode-locked lasers have revolutionized the field of optical metrology in the last decade. They provide a direct and coherent link between the microwave and optical frequency domains, enabling the measurement of optical frequencies with extreme precision. A frequency comb constitutes a frequency ruler in the optical spectral domain [1], which is characterized by two radio frequencies (RF), the repetition rate f_{rep}, and the carrier-envelope offset (CEO) frequency f_{CEO}. The repetition rate corresponds to the spacing between the comb modes, and f_{CEO} represents the global frequency shift of the comb spectrum from the origin. Therefore, the frequency ν_N of each comb mode depends only on three parameters (N is the mode number):

$$\nu_N = N \cdot f_{\mathrm{rep}} + f_{\mathrm{CEO}}. \qquad (1)$$

Many applications require a fully stabilized comb, where both f_{rep} and f_{CEO} are phase-locked. Whereas the stabilization of f_{rep} is fairly direct by controlling the cavity length using a piezo-electric transducer, the detection and stabilization of f_{CEO} are more challenging. The standard self-referencing method [2] requires an octave-spanning spectrum that is usually obtained by spectral broadening in a nonlinear medium such as a highly nonlinear fiber, a photonic crystal fiber or an integrated waveguide. Other methods that are less demanding in terms of spectral width of the comb spectrum were based on optical frequency dividers in the early days of frequency combs [3] or make use of higher-order nonlinear processes, such as $2f$-to-$3f$ [4,5].

The ability to achieve a tight phase-lock of the CEO beat strongly depends on its free-running frequency noise and on the capability to control f_{CEO} using a suitable actuator with a sufficient bandwidth. The standard method involves modulating the pump power of the femtosecond laser, which is realized by a direct modulation of the injection current in diode-pumped solid-state lasers (DPSSLs) or fiber lasers.

Today, there is a strong demand for novel compact and cost-effective frequency comb systems. One highly promising technology relies on semiconductor lasers, such as vertical external cavity surface emitting lasers (VECSELs) or mode-locked integrated external cavity surface emitting lasers (MIXSELs) [6]. Such lasers are promising for future low-cost high-volume production, but no CEO stabilization has ever been demonstrated so far based on this technology, as a consequence of their insufficient peak power. Very recently, the only CEO beat ever detected from a semiconductor mode-locked laser has been reported [7], which required external pulse amplification and compression. So far, no stabilization attempt or noise analysis has been presented, which is most likely due to the insufficient signal-to-noise ratio achieved for the CEO beat. Before such a mode-locked laser can be fully phase stabilized, it would be valuable to get first insights on its CEO noise level. In addition, knowing the response of f_{CEO} to a modulation of the pump power is a key requirement for the future phase-stabilization of f_{CEO}. This is the case for many other novel laser systems.

In this Letter, we suggest and validate a new method to characterize the CEO beat, which does not involve self-referencing, but instead assesses its properties indirectly from an appropriate combination of different signals. Another technique that does not involve nonlinear interferometry to measure f_{CEO} was suggested by Osvay *et al.* based on spectrally and spatially resolved multiple-path interferometry [8]. This method was able to determine f_{CEO}, but with a precision of a few MHz only, and did not provide any information on the CEO noise spectrum. In contrast, the approach reported here is applicable to the characterization of the CEO beat in terms of frequency noise and modulation response. It is particularly attractive for laser systems for which the self-referencing method is not yet achievable. We should stress that this approach does not target f_{CEO} stabilization and, thus, does not intend to replace the powerful self-referencing concept for CEO phase-stabilization.

As a proof-of-principle demonstration, we implemented the proposed method with a commercial Er:fiber frequency comb and compared the results with the use of traditional f-to-$2f$ interferometry to validate this new approach. The experimental method that we propose here does not require a direct detection of the CEO beat, but indirectly assesses its properties from an appropriate combination of signals that is schematized in Fig. 1(a). These signals are mixed in such a way that the contribution of f_{rep} cancels out, giving access f_{CEO} only. The method emulates the use of a frequency comb as a transfer oscillator [9] to compare two distant optical frequencies without contribution of the comb noise. Here the concept is modified to combine a high harmonic N_1 of f_{rep} with the signal obtained from the heterodyne beat f_{beat} between a comb line N and a narrow-linewidth continuous-wave (CW) laser. Very limited information about the properties of f_{CEO} could be directly obtained from this beat signal, as it simultaneously contains contributions of f_{CEO} and $N \cdot f_{\mathrm{rep}}$. Even if f_{rep} is locked to an RF reference, its contribution to the noise of the beat signal is generally not negligible compared to the noise of f_{CEO}, at least out of its locking bandwidth. The different approach reported here enables suppressing the contribution of f_{rep} and, thus, assessing the properties of f_{CEO} over a much wider range, both in terms of frequency noise and modulation response. This is a key benefit of the reported approach.

The basic principle of the method is schematized in Fig. 1(a) and consists of the combination of two signals. The CW laser frequency ν_{laser} and the comb repetition rate are adjusted so that the index N of the comb line that beats with the laser can be factorized as $N = N_1 \cdot N_2$. On one side, the heterodyne beat frequency $f_{\mathrm{beat}} = (\nu_N - \nu_{\mathrm{laser}})$ is detected using a fast photodiode and is frequency-divided by the large integer number N_2 to produce a signal at a much lower frequency f_{B} (lower branch in Fig. 1). On the other side, a high harmonic signal $f_{\mathrm{A}} = N_1 \cdot f_{\mathrm{rep}}$ is detected (upper branch of the scheme). The two signals, f_{A} and f_{B}, are mixed to generate the difference frequency $f_{\mathrm{out}} = f_{\mathrm{B}} - f_{\mathrm{A}} = (f_{\mathrm{CEO}} - \nu_{\mathrm{laser}})/N_2$, in which the contribution of f_{rep} cancels out for a proper choice of the sign of the heterodyne beat signal. Therefore, only the noise of f_{CEO}/N_2 remains, provided that the noise of the CW laser is sufficiently low to have a negligible contribution. Besides the difference frequency component $(f_{\mathrm{B}} - f_{\mathrm{A}})$, the mixer output also contains the sum frequency component $(f_{\mathrm{B}} + f_{\mathrm{A}})$, and great care is needed to select the proper signal for the characterization of f_{CEO} (this will be discussed at the end of this Letter).

Figure 1(b) displays the detailed experimental setup implemented to validate this method using a commercial Er:fiber frequency comb (FC1500 from MenloSystems, Germany). Its repetition rate was tuned to $f_{\mathrm{rep}} \approx 250.45$ MHz in this experiment, and the CEO beat was detected using a standard common-path f-to-$2f$ interferometer for comparison. In the experimental setup, we used a high harmonic $N_1 = 60$ of f_{rep} at $f_{\mathrm{A}} \approx 15$ GHz, which was detected using a fast photodiode (model 1434 from Newport, with 25 GHz bandwidth), filtered with a narrow-band filter (model TIC-15GB10-01 from Techniwave with ∼70 MHz bandwidth) and amplified to a level of ∼0 dBm. As a reference CW laser, we used a planar-waveguide external cavity laser at 1557.4 nm (model ORION from Redfern Integrated Optics, Inc.) with a free-running linewidth of a few kilohertz only (over a timescale of 1–10 ms). The laser had a negligible contribution to the measured noise, as shown in Fig. 2. Alternatively, the laser can be stabilized to a high-finesse ultra-stable optical cavity to improve its frequency stability and further reduce its optical linewidth, but this was not necessary here.

The beat signal f_{beat} was detected at a high frequency of ∼15 GHz using a fast photodiode (model DSC40S from Discovery Semiconductors, Inc., with 14 GHz bandwidth). After proper filtering with a narrow-band filter (model TWRWC14.95GFC01 from Techniwave with ∼70 MHz bandwidth) and subsequent several stages of amplification to a level of around −12 dBm, this signal was frequency divided by the large number $N_2 = 12,800$, leading to a signal at $f_{\mathrm{B}} \approx 1.2$ MHz. This division was performed in three subsequent steps using

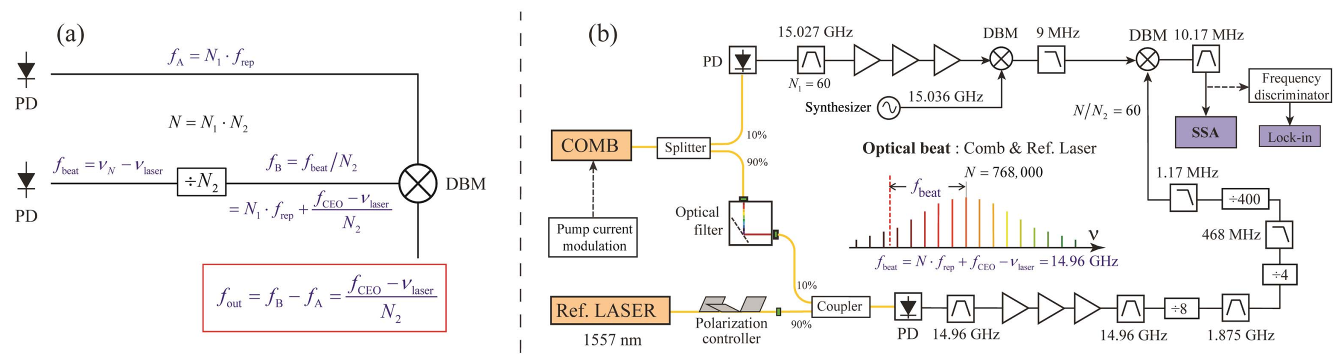

Fig. 1. (a) Basic principle of the proposed scheme to characterize f_{CEO} without directly detecting it. A high harmonic N_1 of f_{rep} (upper branch, signal f_{A}) is mixed with the beat note with a CW laser, frequency divided by N_2 (lower branch, signal f_{B}), to produce a signal f_{out} that is exempt of the contribution of f_{rep}. PD: fast photodiode; DBM: double-balanced mixer. (b) Detailed experimental scheme realized for the proof-of-principle implementation of the method with a commercial Er:fiber frequency comb with $f_{\mathrm{rep}} \approx 250$ MHz using a narrow-linewidth CW laser at 1557.4 nm. SSA: signal source analyzer. All RF components except the narrow-bandpass filters at ∼15 GHz are standard off-the-shelf components.

off-the-shelf frequency pre-scalers (÷8, 4, and 400, respectively) with proper filtering in between. As the signals in the two branches of the setup had a very different frequency ($f_A \approx 15$ GHz versus $f_B \approx 1.2$ MHz), their direct combination in a frequency mixer was not possible due to the impracticality to isolate and analyze the adequate signal among the two close components at the mixer output (15 GHz ± 1.2 MHz). In the present implementation of the method, we proceeded differently by first frequency downconverting the high harmonic $N_1 \cdot f_{rep}$ with the signal of a low-noise synthesizer (Rohde & Schwarz SMF100A) tuned to the frequency $f_{synth} = N_1 \cdot f_{rep} + 9$ MHz. The resulting downconverted signal at 9 MHz was then combined with the frequency-divided signal $f_B = f_{beat}/N_2$ in a double-balanced mixer to produce two signals at $(f_{synth} - f_A \pm f_B)$. The contribution of f_{rep} was canceled out in the properly selected signal. After bandpass filtering, the resulting RF signal at ~10 MHz contained only the contributions of f_{CEO} and of the CW laser, both divided by the large integer number N_2. This signal was analyzed using a signal source analyzer (SSA, Keysight E5052B) for phase noise measurements, or processed by a phase-locked loop (PLL) frequency discriminator [10] and a lock-in amplifier to measure the transfer function of f_{CEO} when the current of the pump diode of the mode-locked laser was modulated by a small-amplitude sine waveform.

The frequency noise power spectral density (PSD) of the CEO beat assessed using our experimental setup is displayed in Fig. 2, where it is compared to the CEO noise spectrum directly obtained from the output of the f-to-$2f$ interferometer. An excellent agreement is observed between the two measurements up to an offset frequency of ~10 kHz, which demonstrates the suitability of the proposed method. At higher frequency, the measurement is limited by the noise of the 15 GHz synthesizer used for frequency downconverting the high harmonic $N_1 \cdot f_{rep}$, which is also displayed in Fig. 2 (measured with Keysight E5052B and E5053A). In this proof-of-principle demonstration, the available CW laser at 1557.4 nm

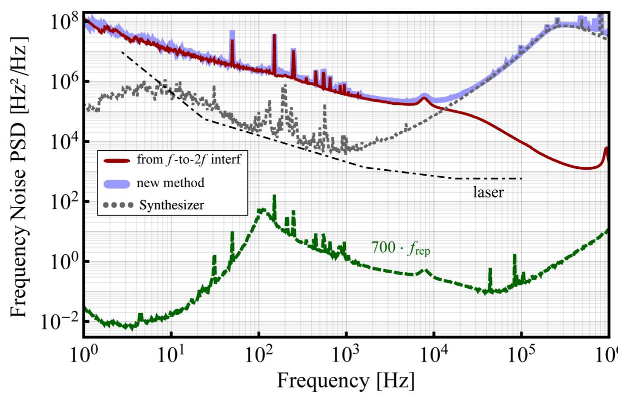

Fig. 2. Frequency noise spectrum of the free-running CEO beat of an Er:fiber comb measured with the proposed method (thick light blue line) and comparison with the CEO noise directly measured from an f-to-$2f$ interferometer (thin dark red line). The dotted gray line represents the noise floor of the measurement introduced by a frequency synthesizer, and the dashed-dotted line displays the typical frequency noise PSD previously measured for the free-running CW laser used in this experiment [11]. The residual contribution of f_{rep} in the measured signal resulting from its imperfect cancellation is also displayed (green dashed line).

did not lead to an exact cancellation of f_{rep} in the output signal f_{out}. The targeted comb mode number $N = N_1 \cdot N_2 = 768,000$ would have required a repetition rate of 250.65 MHz, which was not achievable with our frequency comb. Alternatively, the nominal comb repetition rate of 250 MHz would have requested a CW laser wavelength of 1561.4 nm to achieve a perfect cancellation of the repetition rate. With our experimental conditions of $f_{rep} = 250.45$ MHz and $\nu_{laser} = 192.5$ THz, the output signal f_{out} still contained a contribution of $\sim 0.055 \cdot f_{rep}$, corresponding to a residual contribution of $\sim 700 \cdot f_{rep}$ when scaled up by the factor $N_2 = 12,800$. However, this residual contribution is completely negligible as shown by the independently measured noise of f_{rep} also displayed in Fig. 2. This demonstrates that the proposed method is not too challenging to be implemented, as it is not necessary to exactly fulfill the condition $N = N_1 \cdot N_2$. The comb repetition rate was locked in these noise measurements to minimize the residual contribution resulting from its imperfect cancellation. However, it turns out that this residual contribution would be negligible even for a free-running f_{rep}.

In addition to the characterization of the CEO noise, our experimental setup was also applied to measure the frequency modulation response of f_{CEO} to a small modulation of the frequency comb pump current. The knowledge of this transfer function is an important step to assess the possibility to achieve a tight CEO lock in a stabilization loop using the common method of pump current modulation. In this experiment, we applied a sine modulation to the input voltage of the pump driver, and the output signal f_{out} was demodulated using a PLL frequency discriminator [10]. A lock-in amplifier was used to measure the amplitude and phase of the change of f_{CEO} induced by the modulation. The pump current modulation was kept small, typically <1 mA for an average current in the order of 800 mA. The result of this measurement is shown in Fig. 3, where it is compared to the result directly obtained from the CEO beat detected in the f-to-$2f$ interferometer using the same measurement principle. Here, also, an excellent agreement is obtained, both in terms of amplitude and phase.

To cross-check the operation of our novel method, we also measured the transfer function for the other frequency component in the output signal. In practice, this was realized by simply shifting the synthesizer frequency f_{synth} without changing any filter in the setup to exchange the sign of the output signal ($f_A + f_B$ instead of $f_A - f_B$), but it could also be achieved by tuning the CW laser. As modulating the pump current does not only affect f_{CEO}, but also f_{rep} [12], the contribution of the repetition rate modulation Δf_{rep} in this uncompensated signal is doubled (i.e., it contains $120 \cdot \Delta f_{rep}$) instead of being canceled. The result is also displayed in Fig. 3, where the transfer function of $60 \cdot f_{rep}$ (measured from the 60th harmonic of f_{rep} at ~15 GHz in the upper branch of the setup of Fig. 1) is shown as well for comparison.

We performed a similar cross-check for the CEO noise measurement using the other frequency component in the output signal (Fig. 4). The noise measured at low frequency was unchanged as the repetition rate stabilization led to a much weaker contribution to the beat signal than the free-running CEO. At frequencies higher than ~30 Hz, a significant difference was observed between the two curves, which confirmed that the contribution of f_{rep} in the measured signal was efficiently suppressed. If the measurements of the uncompensated signal

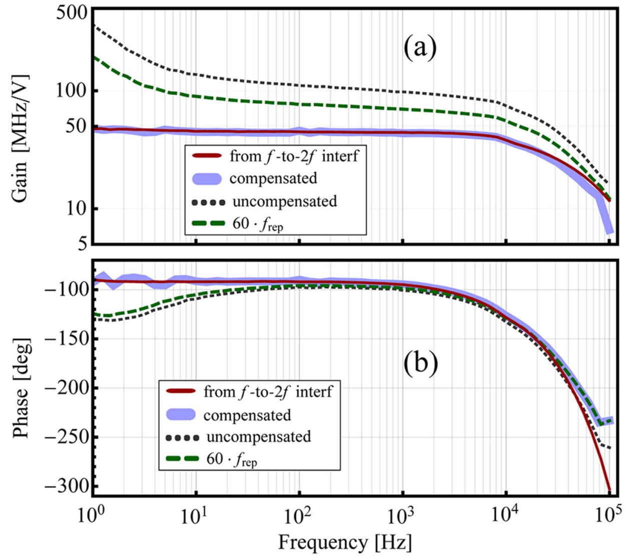

Fig. 3. Transfer function [amplitude (a) and phase (b)] of f_{CEO} measured with the proposed method (thick light blue line) for a modulation applied to the input voltage of the pump driver and comparison with the curve directly measured from the CEO beat (thin dark red line). The signal corresponding to the other frequency component at the output of the mixing process is also shown (uncompensated signal, dotted black line). This signal contains $120 \cdot \Delta f_{rep}$ and is compared to the transfer function measured directly for $60 \cdot f_{rep}$ from the high harmonic of the repetition rate at ∼15 GHz (green dashed line).

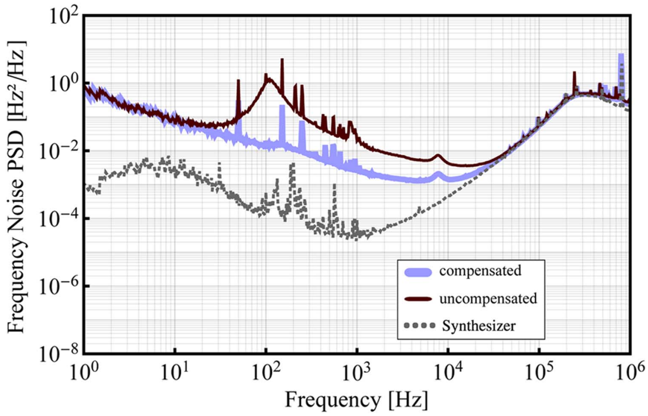

Fig. 4. Comparison of the signals measured for the two signs of the heterodyne beat between the CW laser and the comb line, corresponding to the cases where the contribution of f_{rep} is either suppressed (compensated) or doubled (uncompensated). The noise of the raw signals is displayed here (i.e., not rescaled by the factor N_2).

shown in Fig. 3 for the transfer function and in Fig. 4 for the noise spectrum do not bring any additional information about the properties of f_{CEO}, they constitute important inputs to ensure the correctness of the results. It is not relevant for the measurements reported here that aimed at comparing the results of the novel method with the standard self-referencing technique. However, a practical verification performed by measuring both signals at the mixer output becomes important when no CEO beat is available. This will be the case in future implementations of the method with novel comb technologies.

In conclusion, we demonstrated a new method to characterize both the frequency noise and the transfer function of the CEO beat in a frequency comb without directly detecting f_{CEO}, e.g., using a standard f-to-$2f$ interferometer. The method was validated with an Er:fiber comb at 1560 nm, and an excellent agreement was obtained with the CEO properties directly measured from the CEO beat at the output of an f-to-$2f$ interferometer. The results of this Letter pave the way to using this approach for the characterization of mode-locked lasers for which the generation of a CEO beat by f-to-$2f$ interferometry is challenging, such as GHz mode-locked DPSSLs, microresonator-based systems, or novel semiconductor mode-locked lasers which is our next target.

In the current implementation of the repetition rate compensation scheme reported here, a limitation to the measurable CEO noise arose from a frequency synthesizer used for frequency downconversion of the high harmonic of f_{rep} before its subtraction from the frequency-divided beat signal. We expect this limitation to be removed and the setup to be improved with the use of a single sideband (SSB) mixer that would enable us to directly mix the signals from the two branches of our setup ($f_A \approx 15$ GHz and $f_B \approx 1.2$ MHz, respectively) and analyze the resulting signal without using the 15 GHz synthesizer. With this update, we expect to lower the noise floor of the system, resulting in the possibility to measure the frequency noise PSD of the CEO beat in a wider frequency range.

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