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Carrier-envelope offset frequency stabilization in a femtosecond optical parametric oscillator without nonlinear interferometry

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By exploiting the correlation between changes in the wavelength and the carrier-envelope offset frequency ($f_{CEO}$) of the signal pulses in a synchronously pumped optical parametric oscillator, we show that $f_{CEO}$ can be stabilized indefinitely to a few MHz in a 333-MHz repetition-rate system. Based on a position-sensitive photodiode, the technique is easily implemented, requires no nonlinear interferometry, has a wide capture range and is compatible with feed-forward techniques which can enable $f_{CEO}$ stabilization at loop bandwidths far exceeding those currently available to OPO combs.

The stabilization of the carrier-envelope offset frequency ($f_{CEO}$) in a femtosecond frequency comb normally proceeds by first detecting this frequency using heterodyne nonlinear interferometry, then comparing it with a reference to provide an error signal which is used in a suitable intra-/extra-cavity control loop [1]. With the exception of directly generating a zero-offset comb by difference-frequency mixing [2], this remains the only possible route to stabilizing $f_{CEO}$ in a laser comb. The situation in a synchronously pumped optical parametric oscillator (OPO) is subtly different. The offset frequency of such an OPO comb is controlled by adjusting the cavity length of the oscillator by fractions of a wavelength, exploiting the principle that a one-wavelength change in the roundtrip resonator length modifies the carrier-envelope phase by $2\pi$. In this paper we take advantage of the fact that this slight cavity-length change of $\Delta L$ modifies the roundtrip resonator length according to [7],

$$\Delta L = \frac{1}{2\lambda} \left( \frac{d^2 n}{d\lambda^2} \right)^{-1}$$

where the nonlinear crystal has a refractive index of $n$ and a thickness of $t$. Combining (1) and (2) leads to the relationship between wavelength and $f_{CEO}$.

$$\Delta f_{CEO} = \frac{f_{REP}}{\lambda} \frac{d^2 n}{d\lambda^2}$$

The mid-band wavelength in a femtosecond OPO containing only a nonlinear crystal and dispersionless mirrors tunes with the roundtrip cavity length according to [7],

Our demonstration employs a 333-MHz PPKTP-based OPO, already described in detail elsewhere [3]. The signal wavelength of this OPO is monitored by using a position-sensitive photodiode onto which a line spectrum of the second-harmonic signal pulses is imaged. Position sensitive detectors (PSDs) have been used for a number of years as sensors within wavelength-stabilization feedback loops for synchronously pumped OPOs [4, 5] and generate an output voltage which varies smoothly and monotonically with signal wavelength. Operated under appropriate conditions, PSDs can provide a voltage which responds linearly to the position of an incident beam, with sub-µm positional accuracy being possible when a low-noise (< 0.01%) bias-current source is used [6]. Importantly, the illuminating spot can have a diameter far greater than the PSD resolution, because which responds linearly to the position signal, responds only to the integrated center of illumination on the detector [6].

Before introducing the details of the experimental demonstration we first present the formal basis of $f_{CEO}$ stabilization using wavelength control in a femtosecond OPO. The mid-band roundtrip cavity phase in the OPO resonator changes with cavity length as $\Delta \phi = \frac{2\pi}{\lambda} \lambda$, while the envelope phase is held constant by the arrival time of the pump pulses (the same principle which is responsible for the OPO repetition frequency always tracking that of the pump). Consequently, a cavity-length change of $\Delta L = \lambda$ modifies the roundtrip carrier-envelope phase by $2\pi$, which is observed as a change in $f_{CEO}$ equal to $f_{REP}$; the repetition frequency. Formally, this can be written as:

$$\Delta f_{CEO} = \frac{f_{REP}}{\lambda}$$

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$$\Delta f_{CEO} = \frac{f_{REP}}{\lambda} \frac{d^2 n}{d\lambda^2}$$
In our experimental demonstration we employ a simple Littrow spectrometer design [8] to image the spectrum of the second-harmonic signal pulses onto the PSD. For a spectrometer with a focal length \( f \), a grating period \( D \) and Littrow angle \( \theta \), it can be shown that,

\[
\Delta f_{CEO} = 4D\cos\theta \frac{f_{CEO}}{f} \frac{d^2n}{dx^2} \Delta x
\]

where \( \Delta x \) is the uncertainty in the central spot position reported by the PSD. Implementing \( f_{CEO} \) stabilization by using wavelength control therefore requires a small \( f_{CEO} \) which is achieved when the OPO crystal dispersion is low and the spectrometer parameters (\( D, \theta \) and \( f \)) are chosen to favour a high spectral dispersion on the PSD. Naturally, the lowest error in \( f_{CEO} \) is obtained when the uncertainty in the spot position is small, however this parameter depends not only on the PSD and its drive circuitry, but also on the spatial extent of the imaged line spectrum. PSDs exhibit highly nonlinear behavior at their edges so, if the line spectrum extends into the outer regions of the sensor, \( \Delta x \) can quickly increase. For this reason—and somewhat counter intuitively—configuring a spectrometer with too high a spatial dispersion is counterproductive because the benefits of higher spectral resolution are outweighed by the increased positional error in the PSD signal. Figure 1 shows the measured response function of the 6-mm-long PSD used in this work (First Sensor, ODS-6 SMD), illustrating a central linear region of about 1.5 mm, bordered by two highly nonlinear regions. A linear fit to the central region (red line) shows a 20-µm error in the vertical intercept, which we use as the value for \( \Delta x \).

The optical arrangement is illustrated in Fig. 2. Multi-milliwatt second-harmonic generation (SHG) of the signal pulses was provided by a 50-µm-long quasi-phasematched grating poled in series with the main 1-mm-long OPO grating. The SHG light exited mirror M3 as a collimated beam before entering a Littrow spectrometer configured with a 1800 lines/mm grating (\( D = 555 \) nm) and a lens whose focal length was varied over the range \( f = 35 – 500 \) mm. The OPO was operated at signal wavelengths in the range from 1250–1350 nm (tuning spectra are presented in Fig. 3), and in this configuration the Littrow angle for the SHG light was 35.8°. The OPO was operated as a ring resonator, so the pulses travelled only once through the 12-mm PPKTP crystal during each roundtrip. The carrier-envelope offset frequency, \( f_{CEO} \), was monitored by heterodyning the sum-frequency pump + signal pulses with a corresponding wavelength in the pump supercontinuum. This supercontinuum was produced by sampling 10% of the Ti:sapphire pump power and launching it into a 30-cm length of photonic crystal fibre with a core diameter of 2-µm and a zero dispersion wavelength of 740 nm (NKT, NL-2.0-740). Normally it is this heterodyne signal which is compared with a reference signal in a phase-frequency detector circuit to derive an error signal for cavity length stabilization [9, 10], but in the context of the work here it simply provided a metric for the quality of the \( f_{CEO} \) stabilization achieved by using only wavelength control.

![Fig. 1. Dependence of the PSD signal on the position of a HeNe spot as it was scanned across the aperture of the device. The graph is plotted with the dependent variable (PSD signal) on the horizontal axis to produce a vertical intercept that corresponds to a positional uncertainty. The solid line is a linear fit to the data in the range 2.5–40 mm and has a slope (uncertainty) of 0.321 (0.010) and an intercept (uncertainty) of 3.107 (0.019).](image)

![Fig. 2. Layout of the OPO and wavelength-feedback loop.](image)

![Fig. 3. Signal spectra recorded from the OPO as the cavity length was tuned over a length of 655 µm using a piezo-electric transducer (PZT).](image)

The stability of \( f_{CEO} \) was evaluated by measuring its Allan variance by counting its frequency with averaging times of between 1 s and 100 s. An example of raw time-series data acquired over a 100-s observation window and with an averaging time of 1 s is shown in Fig. 4. These data exhibit a standard deviation of 0.59 MHz and an Allan variance of 0.54 MHz.

![Fig. 4. Time-series data showing the carrier-envelope offset frequency of the OPO signal pulses averaged over 1-s intervals during a total observation time of 100 s.](image)
The observed levels of stability can be compared with the value predicted from Eq.(4) by using the actual system parameters. Taking $\Delta s = 20 \mu m$ and $f = 200$ mm gives $\Delta f_{CEO} \approx 3.6$ MHz, which is broadly consistent with the short-term stability observed in experiment. Furthermore, the data in Fig. 6 suggest that the long-term stability could be significantly improved by tighter control of the temperature of the OPO system in order to decouple it from larger excursions in the lab temperature (around +/- 0.5 °C).

One of the significant benefits of controlling $f_{CEO}$ by using wavelength stabilization is the intrinsically broad capture range for locking. Typical radio-frequency (RF) locks typically require the $f_{CEO}$ beat signal to lie within a limited band of frequencies close to the reference frequency before the associated RF components (bandpass filters, amplifiers, comparators etc.) will function correctly. Wavelength stabilization has no such constraints, with the PSD signal available across the entire OPO tuning range. In Fig. 7 (multimedia available) we illustrate the acquisition of the $f_{CEO}$ lock, which occurs in a milliseconds. Fig. 7(a) shows the RF spectrum from 0 – 350 MHz, showing signals at $f_{CEO}$, $f_{REP}$, $f_{CEO}$ and $f_{REP}$. Before stabilization $f_{CEO}$ in 100 seconds can shift across a range of 100 MHz (indicated in green), but after dosing the wavelength stabilization loop (indicated in red) $f_{CEO}$ was stabilized to a value of approximately 10 MHz. The resolution bandwidth was 100 kHz and the vertical divisions are 10 dBm. A 15 second visualization of the excursions in $f_{CEO}$ is presented online for both the free-running and locked cases (see Visualization 1).

A further important opportunity provided by wavelength stabilization of $f_{CEO}$ is its compatibility with high-bandwidth feed-forward techniques [11,12]. This approach employs an acousto-optic modulator driven by a frequency equal to a constant minus $f_{CEO}$ to produce a diffracted beam which is dynamically corrected for deviations in the comb offset, at bandwidths orders of magnitude faster than intracavity modulation techniques [1]. Unlike most laser frequency combs, typical free-running OPO combs do not possess the passive $f_{CEO}$ stability to be compatible with feed-forward correction, however pre-stabilization of $f_{CEO}$ using wavelength control immediately confers the necessary stability on $f_{CEO}$ to make extra-cavity correction possible.

In summary, we have demonstrated a new method for stabilizing the carrier-envelope offset frequency of a femtosecond optical parametric oscillator frequency comb. The approach is easily implemented using low-cost components, requires no nonlinear interferometry, offers long-term stability to the few-MHz level (or ~1% of $f_{REP}$), has a wide capture range and is compatible with feed-forward techniques which can enable $f_{CEO}$ stabilization at MHz loop bandwidths.

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