Towards optical attosecond pulses: broadband phase coherence between an ultrafast laser and OPO using lock-to-zero CEO stabilization

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Towards optical attosecond pulses: broadband phase coherence between an ultrafast laser and OPO using lock-to-zero CEO stabilization

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Abstract: The carrier-envelope-offset frequencies of the pump, signal, idler and related sum-frequency mixing pulses have been locked to 0 Hz in a 20-fs-Ti:sapphire-pumped optical parametric oscillator, satisfying a critical prerequisite for optical attosecond pulse synthesis.

1 Introduction

Nonlinear $\chi^{(2)}$ media provide frequency-conversion bandwidths of 1 – 2 PHz, sufficient to support sub-500-as optical fields, offering a radically different route to this temporal regime than attosecond pulses produced by high-harmonic generation. Sum-frequency-mixing (SFM) and second-harmonic-generation (SHG) within a femtosecond optical parametric oscillator (OPO) provide a practical means of creating the short parent pulses needed to coherently synthesize sub-femtosecond pulses over a wide visible bandwidth. A major obstacle is that the parent pulses produced by these processes are normally mutually incoherent because their carrier-envelope-offset (CEO) frequencies are all different combinations of those of the pump ($p$), signal ($s$) and idler ($i$) pulses. Previously, we demonstrated coherent pulse synthesis between the SHG pulses from an OPO and those of its Ti:sapphire pump laser by locking the CEO frequencies of both sources to a common value [1]. This approach can be generalized to allow pump and OPO pulses at multiple wavelengths to be made coherent by locking their CEO frequencies to 0 Hz [2]. Here we describe how this approach was applied to achieve broadband phase coherence between a pump laser and multiple outputs from an OPO, spanning $>0.6$ PHz in bandwidth [3].

2 Experimental configuration and CEO stabilization of pump and OPO

In the experimental arrangement (Figure 1) a Ti:sapphire laser producing 20-fs 100-MHz ($f_{\text{REP}}$) pulses at 800 nm was used to synchronously pump a PPKTP OPO. The 0.5-mm PPKTP crystal was coated on one face with a high-reflectivity NIR coating and on the other with a broadband antireflection visible-NIR coating. The OPO oscillated at 1060 nm and was tunable over 980 nm – 1200 nm. Table 1 lists the outputs generated by non-phase-matched SHG of the $p$ and $s$ pulses and
SFM between the $p + s$ pulses. These pulses were typically observed at mW-level average powers and output coupled through curved mirror M1.

A fraction (15%) of the pump light was used for CEO stabilization via two nonlinear interferometers (see Figure 1) in which 2 photonic crystal fibers (PCFs) generated independent pump supercontinua. The idler CEO frequency $f_{CEO}^{i} = f_{CEO}^{p} - f_{CEO}^{s}$ was obtained by interfering the 642-nm $p + i$ SFM pulses with one supercontinuum after a 10-nm bandwidth interference filter. Similarly, a beat frequency at $f_{CEO}^{p} - 2f_{CEO}^{s}$ was obtained by interfering the 530-nm SHG signal ($2s$) pulses with the other supercontinuum. Locking both beat frequencies to zero causes $f_{CEO}^{p} = f_{CEO}^{s} = f_{CEO}^{i} = 0$ Hz, making all of the pulses listed in Table 1 mutually coherent.

**Table 1.** Output wavelengths from the pump and OPO.

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>400</th>
<th>456</th>
<th>530</th>
<th>642</th>
<th>800</th>
<th>1060</th>
<th>3260</th>
</tr>
</thead>
<tbody>
<tr>
<td>Origin</td>
<td>$2\omega_p$</td>
<td>$\omega_p + \omega_s$</td>
<td>$2\omega_s$</td>
<td>$\omega_p + \omega_i$</td>
<td>$\omega_p$</td>
<td>$\omega_s$</td>
<td>$\omega_i$</td>
</tr>
<tr>
<td>CEO frequency</td>
<td>$2f_{CEO}^{p}$</td>
<td>$f_{CEO}^{p} + f_{CEO}^{i}$</td>
<td>$2f_{CEO}^{i}$</td>
<td>$f_{CEO}^{p} + f_{CEO}^{s}$</td>
<td>$f_{CEO}^{p}$</td>
<td>$f_{CEO}^{s}$</td>
<td>$f_{CEO}^{i}$</td>
</tr>
</tbody>
</table>

CEO-locking to 0 Hz was achieved by blue-shifting the $p + i$ and $2s$ pulses before the nonlinear interferometers by an acousto-optic modulator (AOM) driven at $3f_{REP} / 4$. The AOM can be considered to red-shift the $p + i$ and $2s$ modes by $f_{REP} / 4$, and for this reason we referenced the detected beat frequencies to $f_{REP} / 4$. The resulting error signal was used to control the $p$ and $s$ CEO frequencies via 2 piezoelectric transducers (PZTs). In this way the CEO frequencies of all the pulses on the optical bench were locked to 0 Hz.
3 Results and discussion

When locked, optical heterodyning at the avalanche photodiode (APD) in each nonlinear interferometer produces a frequency at $f_{\text{REP}}$ with sidebands at $\pm f_{\text{REP}}/4$. Consequently, either beat frequency can be locked to $f_{\text{REP}}/4$ or $3f_{\text{REP}}/4$, with no electronic means of distinguishing between the two scenarios, giving a total of 4 possible locking combinations, only one of which will achieve $f_{\text{CEO}}^p = f_{\text{CEO}}^i = f_{\text{CEO}}^s = 0$. Phase coherence was therefore confirmed by implementing a measurement interferometer (Figure 1) in which light from the second PCF, which contained a strong 530-nm component and a weaker 642-nm component, was interfered with visible light exiting one of the OPO folding mirrors. The OPO beam path was modulated using a PZT stage (PZT3) with a frequency of 1.4 Hz and a displacement of 400 $\mu$m. The beams were combined and passed through an appropriate interference filter before being detected on a silicon photodiode.

With the CEO frequencies of the pump and OPO correctly locked we observed fringes between the pump super-continuum pulses and the $p + i$ and $2s$ pulses, indicating complete coherence (Figure 2, grey lines). When either CEO frequency was unlocked no fringes were observed, indicating a lack of coherence between the pulses (Figure 2, black lines). Observing interference at two distinct wavelengths shows that all CEO frequencies have been locked to 0 Hz and confirms phase-coherence across the complete ensemble of pump and OPO pulses.

![Interferograms showing simultaneous phase coherence between 532-nm and 670-nm OPO outputs and a pump super-continuum. (a) Photodiode signal at 532 nm ($2s$) with locking on (grey) and off (black); (b) photodiode signal at 670 nm ($p + i$) with locking on (grey) and off (black).](image)

4 Conclusions

Phase coherence between a femtosecond OPO and its pump laser across a 0.6-PHz bandwidth was achieved by locking the CEO frequencies of all participating pulses to 0 Hz, confirmed by time-domain interferometry. This broadband output can be used to synthesize sub-cycle optical waveforms through direct interference of their electric fields.

5 References