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

EPJ Web of Conferences 41, 10005 (2013)
DOI: 10.1051/epjconf/20134110005

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_{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 anti-reflection 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 $p + s / i$ pulses. These pulses were typically observed at mW-level average powers and output coupled through curved mirror M1.

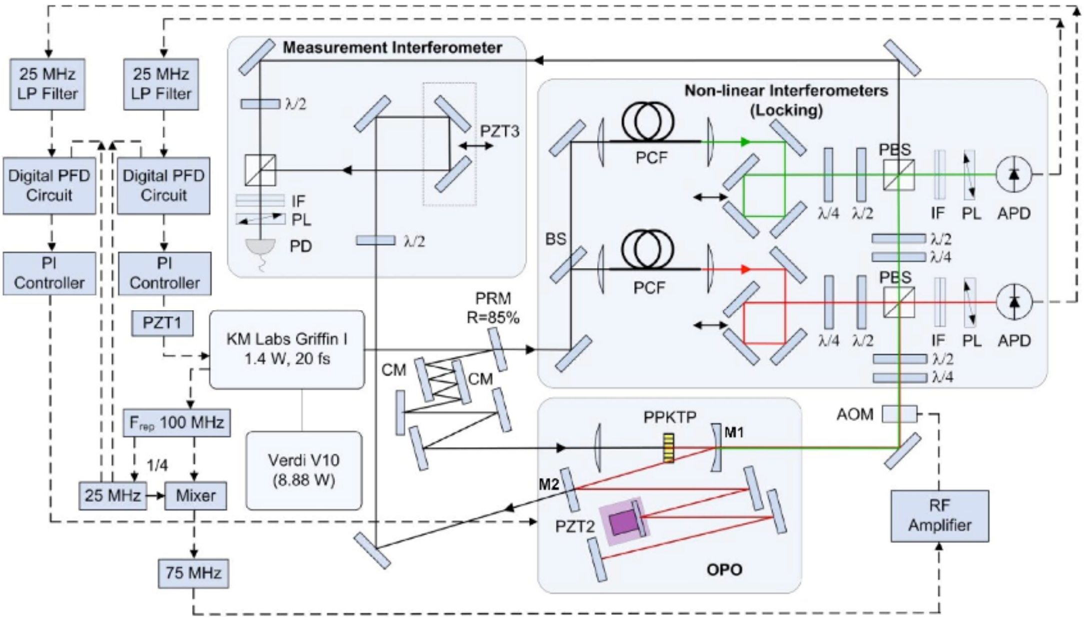

Fig. 1. Optical (solid lines) and electronic (dashed lines) layout. APD, avalanche photodide; BS, beam splitter; CM, chirped mirror; IF, interference filter; PBS, polarizing beam splitter; PD, silicon photodiode; PI, proportional integral amplifier; PL, polarizer. See text for other label definitions.

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 $f^{i}_{CEO} = f^{p}_{CEO} - f^{s}_{CEO}$ 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 $f^{p}_{CEO} - 2f^{s}_{CEO}$ was obtained by interfering the 530-nm SHG signal (2*s*) pulses with the other supercontinuum. Locking both beat frequencies to zero causes $f^{p}_{CEO} = f^{s}_{CEO} = f^{i}_{CEO} = 0$ Hz, making all of the pulses listed in Table 1 mutually coherent.

Table 1. Output wavelengths from the pump and OPO.

Wavelength (nm)	400	456	530	642	800	1060	3260
Origin	$2\omega_p$	$\omega_p + \omega_s$	$2\omega_s$	$\omega_p + \omega_i$	ω_p	ω_s	ω_i
CEO frequency	$2f^{p}_{CEO}$	$f^{p}_{CEO} + f^{s}_{CEO}$	$2f^{s}_{CEO}$	$f^{p}_{CEO} + f^{i}_{CEO}$	f^{p}_{CEO}	f^{s}_{CEO}	f^{i}_{CEO}

CEO-locking to 0 Hz was achieved by blue-shifting the $p + i$ and 2*s* 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 2*s* 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_{REP} with sidebands at $\pm f_{REP}/4$. Consequently, either beat frequency can be locked to $f_{REP}/4$ or $3f_{REP}/4$, with no electronic means of distinguishing between the two scenarios, giving a total of 4 possible locking combinations, only one of which will achieve $f_{CEO}^{p} = f_{CEO}^{s} = f_{CEO}^{i} = 0$. 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 μm. 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 2*s* 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.

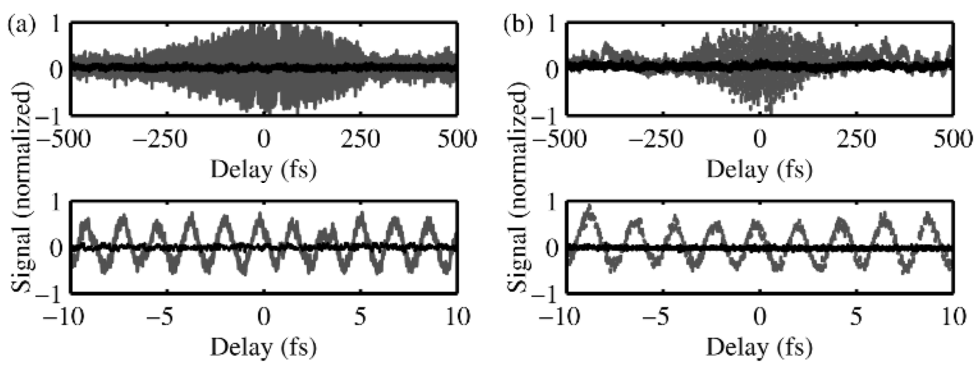

Fig. 2. Interferograms showing simultaneous phase coherence between 532-nm and 670-nm OPO outputs and a pump super-continuum. (a) Photodiode signal at 532 nm (2*s*) with locking on (grey) and off (black); (b) photodiode signal at 670 nm (*p* + *i*) with locking on (grey) and off (black).

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

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