Supplemental Document

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Hybrid phase-matching for optical parametric amplification of few-cycle infrared pulses: supplement

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Supplementary materials

Technical details of the OPCPA:

An implementation of this concept is shown in Figure 2. A Ti:Sapphire oscillator (Rainbow II, Femtolasers GmbH) generates broadband pulses carried at a central wavelength of 780 nm. The broad oscillator bandwidth is necessary for the stabilization of the carrier-envelope phase (CEP), performed using a feed-forward technique (CEP4, Femtolasers). A dichroic beam splitter is used to separate the spectral region around 1030 nm for amplification in a fiber. After setting the repetition rate to 3 kHz, the pulses enter a Yb:YAG thin-disk regenerative amplifier. This amplification technique efficiently reduces thermal lensing and self-focusing in the gain medium [27] and has been proven to efficiently work as a pump for OPCPAs [5] [28] [29]. The outgoing beam has a power of 50 W, after subsequently being compressed to 1.4 ps with a grating compressor. The remaining oscillator output, centered at 780 nm, is amplified in a 9-pass cryo-cooled Ti:Sapphire amplifier (Femtopower, Femtolasers GmbH). These pulses are compressed to 25 fs, using a transmission grating based compressor, the output of which provides 2.5 W at 3 kHz. The amplified pulses are split, using a dielectric beam-splitter with 95% reflectivity. The reflection is used for attosecond metrology experiments. The 5% transmission (125 mW) is coupled into a 28-cm-long hollow core fiber (HCF) with a 140 µm inner diameter, filled with krypton gas at a pressure of 1.5 bar to produce broadband white-light (WL) pulses whose spectrum spans from 500 nm to 1000 nm. After being compressed using chirp mirrors, the OPCPA seed is generated via intra-pulse DFG, performed in BBO, and its amplification is done in two stages: a PPLN and a combination of type-I and type-II BBO.
The BBO used for DFG is provided by Castech, the PPLN for the first amplification stage by HC Photonics and the two BBOs by Bluebean Optical Tech. The beam mode is detected using a pyrocam by Spiricon and the spectrum recorded using a NIRQuest spectrometer (Ocean Optics).

One of the challenges faced when building an OPA is the choice of seed and pump spot size on the crystals. Once the seed spot sizes are defined, the pump spots can be changed by changing the magnification of the telescopes. The spatial overlap in the stages can be manually improved by adjusting the pump mirrors, while keeping the seed alignment fixed. The temporal overlap between pump and seed in each crystal can be controlled by delay stages positioned along the pump path. This eliminated the need for extra optics in the seed beam path and, as the pump beam has a larger diameter, the system is more stable against small fluctuations when the stages are moved.

CEP measurements: A type-I BBO, set after the 30 cm long HCF, is used to generate enough second harmonic to have good contrast in the spectrometer when it interferes with the fundamental in the spectrometer (Maya, Ocean Optics). To show that the fringes seen are CEP dependent, the AOPDF has been set such that the CEP is flipped from 0 to pi every 800 shots. The one hour long continuous CEP and the flipping CEP measurement are shown below in Figure 1, (a) and 1 (b) respectively.

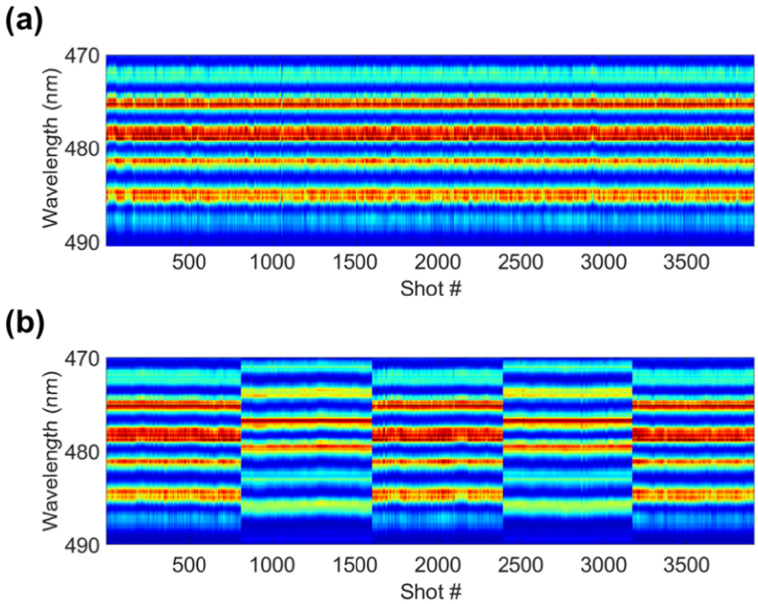

Fig. 1. The CEP stability has been measured via an f-2f interferometer. (a) The CEP has a standard deviation of 64.7 mrad over one hour of continuous measurement. In (b) it is shown how the CEP value can be actively controlled with the AOPDF, repeatedly applying a π phase shift.