In-Situ Measurement of Intensity-Dependent Carrier-Envelope Phase Changes in Hollow Fiber Compression

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Abstract: We report on a single-shot, in-situ interferometric method for measuring intensity-dependent phase changes in laser pulse propagation. With this method, the impact of hollow fiber compressors on phase stability was characterized.

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The availability of carrier-envelope phase (CEP)-stabilized few-cycle femtosecond pulses is essential in attosecond experiments. Since gain narrowing limits the shortest pulse duration achievable from chirped pulse amplifiers (CPAs) to typically 20-30 fs, one has to resort to post-compression schemes. Hollow fiber compression (HFC) [1] is an efficient and versatile method for generating intense few-cycle pulses in the visible and near infrared spectral range [2-4]. The CEP stability of the pulses emerging from fiber compression has been assessed in several measurements [5-7]. However, only the overall CEP drift accumulating throughout the entire system including the HFC has been measured so far. Here, we propose and demonstrate a very simple and robust method for measuring the nonlinear intensity-dependent CEP changes emerging exclusively within the HFC.

The phase shift experienced by an optical signal can be detected via linear interference with a reference replica. In our approach, dubbed In-situ Single-shot Interferometry (ISI), a small, co-propagating replica of each pulse that is coupled into the fiber is generated by means of a thin birefringent plate. The orientation of the plate in the plane perpendicular to the beam determines the amount of energy coupled into the pulse replica, while the delay between main pulse and replica is determined by the thickness of the plate and the optical properties of the crystal. For a linearly polarized pulse, the replica will also be linearly polarized, its polarization perpendicular to that of the main pulse. The main pulse experiences self-phase modulation in the gas-filled hollow fiber, whereas the replica will propagate linearly, provided that its intensity is sufficiently low. One can verify that that replica does not undergo spectral broadening (i.e., does not undergo SPM) by investigating its spectrum at the fiber output. Since the Kerr effect-induced refractive index changes are highly adiabatic, they will have no effect on the replica as long as it does not overlap in time with the main pulse. Phase shifts in the replica caused by refractive index changes due to the recombination of the free electrons resulting from ionization by the main pulse can be ruled out by using a pre-pulse replica. Alternatively, a post-pulse replica with a delay larger than the typical plasma recombination time can be used just as well. A polarizer and a spectrograph are used to detect linear spectral interference between the main pulse and its replica at the output of the HFC. Fourier analysis of the single-shot spectral interferogram yields the phase difference between the main pulse and the reference replica, accumulated along the common beam path. This phase difference corresponds to the nonlinear phase shift experienced by the main pulse.

The experiment is schematically shown in Fig. 1a). CEP-stabilized pulses from a 6 mJ, 1 kHz Ti:sapphire multipass amplifier (Femtopower PRO HE CEP, Femtolasers) with 25 fs duration pass a 1.5 mm-thick calcite plate oriented such as to produce a weak, orthogonally polarized replica with a temporal separation of 900 fs. The pulses are coupled into a hollow fiber with a diameter of 320 µm and 1 m length operating in the pressure gradient (PG) regime [8]. After recollimation, the pulses coupled into a spectrometer by means of a beam splitter. A polarizer placed before the device is adjusted for maximum contrast of the resulting interference fringes. The spectrometer recorded single-pulse interference patterns at a repetition rate of 500 Hz.

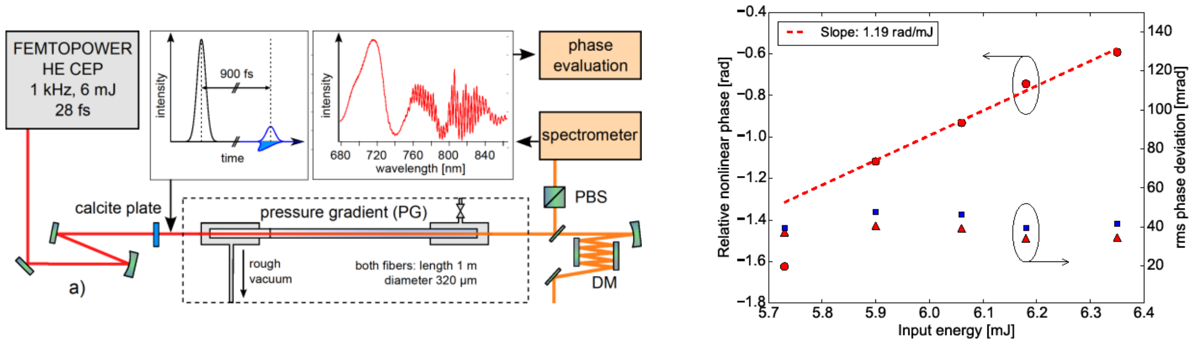

Figure 1: a) Experiment setup. See text for details. PBS: polarizing beam splitter cube; DM: dispersive mirror compressor. b) Mean phase change and phase jitter emerging in the HFC. Red circles: mean phase extracted by ISI. Red triangles: rms CEP jitter extracted from the same dataset. Blue squares: rms CEP jitter calculated from shot-to-shot energy fluctuation. The leftmost data point was omitted in the fit, its lower value probably due to decreased gas pressure in the fiber.

We first performed a measurement with the fiber under vacuum, in order to assess the noise floor of the ISI technique. The CEP noise contribution from the evacuated HFC amounted to 6 mrad rms over 105 shots (200 s) at the full input energy of 6 mJ, most likely limited by the signal-to-noise ratio of the spectrometer. Applying a backing pressure of approximately 1.5 bar helium, the output spectra corresponding to a bandwidth-limited pulse duration of 3.9 fs and an energy of 2.1 mJ were generated. The rms phase noise detected with the ISI method increased to 40 mrad for the same measurement time. Monitoring the mean phase shift emerging in the HFC with the ISI method while slightly varying the input pulse energy, we determined a coupling constant of 1.19 rad/mJ (see Fig. 1b)). In order to allow a consistency check, the pulse-to-pulse energy fluctuations were simultaneously measured with a photodiode in front of the HFC. The phase jitter calculated with the previously determined coupling constant agrees with the value indicated by ISI to within 10 %. For changes in backing gas pressure, a coupling constant on the order of 100 mrad/% relative pressure change was determined. Due to the low precision of the pressure measurement available, this value provides but a coarse estimate. However, since the leakage rates and backing pressures drifts usually encountered in HFC systems are slow, we conclude that pressure-related CEP changes are limited to slow, monotonous drifts. We found that phase values retrieved from the ISI measurement are independent of which pulse – main or probe – passes the fiber first, demonstrating that long-life (>1 ps) plasma-related effects do not affect the measurement.

In-situ single-shot interferometry (ISI) was applied for measuring the CEP-drift emerging due to nonlinear propagation in a pressure-gradient hollow fiber compressor. The measurement will provide guidelines for the energy up-scaling of phase-preserving hollow fiber compressors and can be employed as an additional feedback mechanism for CEP stabilization over extended periods of time in systems equipped with HFCs. Detailed frequency analysis of the HFC phase noise as well as experiments aiming at a comparison to phase measurements carried out with conventional f-to-2f interferometers are under preparation.

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