Agile high-resolution linear interferometric method for carrier-envelope phase measurement

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A bandwidth-independent and linear interferometric method for the measurement of the carrier-envelope phase of ultrashort pulse trains is demonstrated. The pulses are temporally overlapped in a resonant multiple beam interferometer. From the position of the spectral interference pattern, the relative carrier envelope phase is obtained. Cross-calibration has been performed by *f*-to-2*f* interferometry in two independent experiments. The optical length of the interferometer has been actively stabilized, leading to a phase resolution of 70 mrad (rms), i.e., ≈λ/100 in CEO phase.

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Experiments in attosecond physics and ultraprecise frequency metrology [1] are critically relying on low-noise carrier-envelope phase (CEP) measurements of ultrashort pulses and subsequent low-jitter stabilization [2]. While recent methods for CEP stabilization have emerged into the single attosecond regime for Ti:sapphire lasers [3,4], this laser parameter is virtually inaccessible for a large class of lasers which either do not display sufficient near-octave spectral width or peak powers to satisfy the rather demanding constraints of *f*-to-2*f* interferometry [5] and other related methods [6]. In response to this blind spot of laser characterization, we have recently proposed and demonstrated a linear method of CEO phase detection, based on the combination of a multiple-beam and a two-beam interferometer [7]. Admittedly, however, our original proof of principle for pure linear optical CEP measurements was far from being practical, as it only allowed for time-averaged measurements only. In particular, interferometric stability of the set-up turned out to be a limiting factor in these measurements.

Here we introduce a significantly improved linear method for CEP measurements, relying solely on a multiple-beam interferometer and a spectrograph. This technique, which can be regarded as a simplified and robust successor of the double interferometer arrangement [7], offers not only the measurement of the pulse-to-pulse CEP shift, but appears to be fast enough to apply feedback to lasers with prohibitively low pulse energy for regular CEP stabilization schemes. Moreover, our scheme allows simultaneous monitoring of intracavity refraction and linear dispersion for a virtually unlimited range of mode-locked lasers, including monolithic designs where such insight is otherwise difficult to obtain [8].

When a single ultrashort pulse passes through a multiple beam interferometer (MBI), a pulse train with decreasing peak height will emerge from this interferometer. In the complementary spectral domain, this scenario gives rise to the appearance of spectral interference fringes. As each pulse in the produced train experiences an additional round trip in the MBI compared to its predecessor, the spacing of the spectral fringes, or more precisely their deviation from equidistance, is uniquely defined by the group delay dispersion of the multilayer mirrors forming the cavity [9], by the ambient air of the interferometer [10], and other sources of intracavity dispersion. If all sources of intracavity dispersion are avoided, however, one can reverse the situation. Using a dispersionless ring resonator with a total roundtrip group delay close to the temporal pulse spacing, a spectrally equidistant fringe pattern $\nu_i = \nu_0 + i\Delta\nu$ results that has only two degrees of freedom, i.e., the fringe spacing $\Delta\nu$ and an offset ν_0. While the former relates to the group delay mismatch between the laser cavity and the ring resonator, the latter uniquely defines the CEP between two subsequent laser pulses. Small residual GDD contributions can be removed by suitable calibration as long as they are static. Therefore, linear interference in a single ring resonator suffices, in principle, to completely characterize the CEP of a pulse train. All required information is readily retrieved from

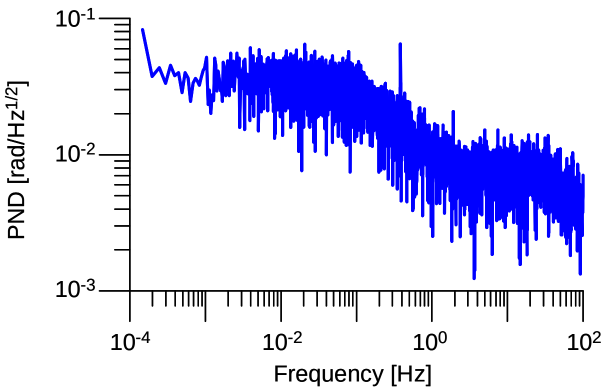

Fig. 1. Phase noise density of CEO phase measurement observed with active cavity length stability of the MBI. Phase was rescaled for 800 nm central wavelength.

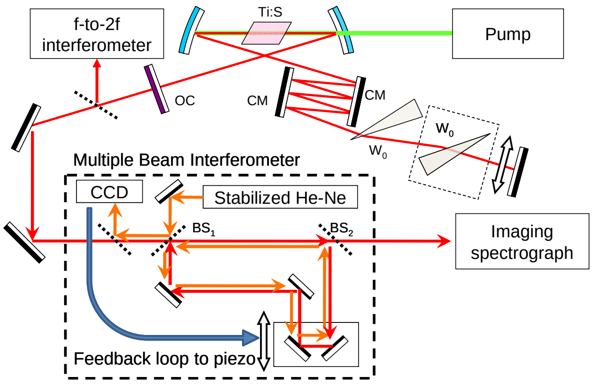

Fig. 2. Experimental setup.

the measured spectral interference pattern via Fourier processing [11]. As small changes in the repetition rate of the laser oscillator affect Δν equally well as a drift of the MBI, both resonators have to be either stabilized, or their drift has to be recorded with sub-fringe accuracy.

In our implementation, a ring with adjustable roundtrip time was designed to closely match the 87.4 MHz repetition rate of a mode-locked Ti:sapphire laser. Given the rather long interferometer, thermal drift and mechanical vibrations pose severe problems for our measurement application. For stabilization of the cavity length, a frequency stabilized He-Ne laser with sufficient coherence length was aligned collinearly with the ring resonator. Based on the observation of the interference pattern of the He-Ne laser, the optical path length inside the MBI was actively stabilized with a servo loop. We observe phase noise densities in the range from 5 to 50 mrad/Hz$^{1/2}$ (see Fig. 1.), from which we deduce a long-term stability of 70 mrad (rms) within one hour at 800 nm central wavelength. This stability corresponds to approximately 1/100 of a fringe.

The light source of the experiment was a commercial Ti:sapphire oscillator with a pulse duration of 10 fs, central wavelength at 803 nm, and a bandwidth of 70 nm. In the oscillator, chirped mirrors were used for dispersion compensation. A fused silica wedge pair was also inserted into the cavity for coarse CEP adjustment. A fraction of the beam was directed to a conventional quasi-common-path type *f*-to-2*f* interferometer [12] while the main part entered the MBI. The pulse train leaving the interferometer was sent a spectrograph, where the spectral interference patterns were recorded continuously (Fig.2). The CEO phase was deduced on the fly from the spectral position ν_0, the fringe spacing Δν and from the simultaneously recorded repetition rate f_{rep} of the oscillator.

The MBI was calibrated with the *f*-to-2*f* interferometer. To this end, we varied the CEP by sinusoidal translation of the intracavity fused silica wedge pair (w_0). The CEP

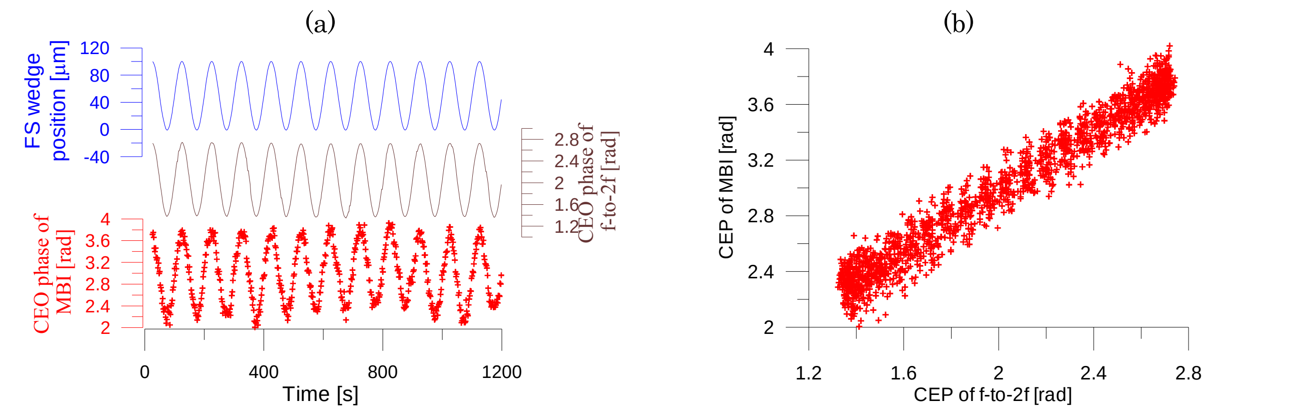

Fig. 3. CEP measurements. Shown are the position of the intracavity wedge (blue solid line), the CEP measured by *f*-to-2*f* interferometry (brown solid line) and the one measured with the MBI (red dots). (a) sinusoidal and (b) random movement of the wedge.

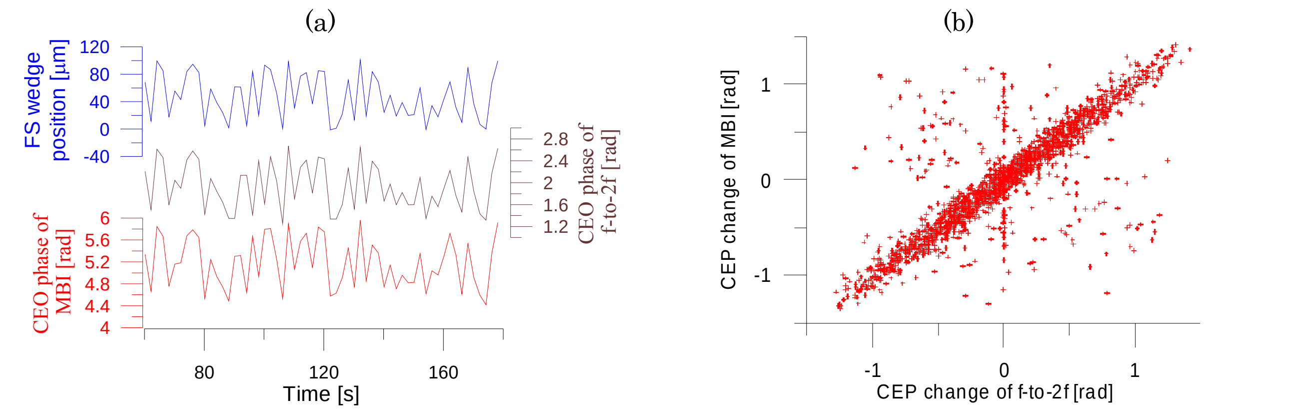

Fig. 4. Correlation between the phase as measured by the MBI vs. the one measured by *f*-to-2*f* interferometer. (a) sinusoidal and (b) random wedge movement.

was then simultaneously monitored with the MBI and the f-to-$2f$ interferometer. Figure 3(a) indicates a favorable agreement of the wedge position and the CEP measured with either method. Note that neither of the methods enables measurement of the absolute phase [13], hence there is phase shift between the results. A parametric plot of one phase shift measurement vs. the other is shown in Fig. 3(b). Both measurements are linearly correlated with a phase jitter of the MBI measurement of 145 mrad (rms).

In a second experiment we varied the wedge position in a random way. Again, the agreement between the wedge position and the measured CEP is excellent (Fig. 4(a)). For removal of slow thermal drift from the measured data, we plot the phase change between subsequent CEP measurement results rather than raw data (Fig. 4(b)). The linear correlation between the two methods appears now even more pronounced, and the residual jitter is markedly reduced to 117 mrad, as is expected due to the $1/f$ noise characteristics in Fig. 1. This type of analysis, however, inevitably produces a relatively small number of outliers due to phase unwrapping problems in the data analysis software. Both experiments therefore confirm an excellent suitability of our linear method for CEP measurements, with residual rms jitters well below 120 mrad.

In summary, we have demonstrated a novel linear optical and conceptually extremely simple method for CEP measurements. The method relies on multiple-beam spectral interferometry, requires no nonlinear optical effect, and can be implemented with a linescan camera or linear photodiode array. The method is therefore applicable for single milliwatt average powers and probably even below, and it is also not restricted to silicon detectors. Moreover, it can be directly employed even for picosecond lasers as long as their spectral coverage supports a few resolvable spectral fringes, as well as lasers in mid IR [14] or UV. These conditions are much less stringent than the octave coverage and 100 kW peak powers required for f-to-$2f$ interferometry. Nevertheless, the advantages of our method certainly come with the trade-off of a finite phase resolution. While we have been able to push the resolvable CEP change to around 120 mrad, further measures such as operation of the MBI in a vacuum chamber promise another order-of-magnitude improvement in this regard. Such measures appear extremely promising for CEP measurements on lasers with short cavities. In any case, as we have shown linear interferometry may serve to significantly augment the tool box for CEP characterization.

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