Chapter 1
Self-Referenced Scheme for Direct Synthesis of Carrier-Envelope Phase Stable Pulses with Jitter below the Atomic Time Unit

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Abstract A method for stabilizing the carrier-envelope phase of mode-locked oscillators is introduced. Other than previous concepts that exerted feedback action directly on the oscillator, our novel feed-forward concept employs an acousto-optic frequency shifter after the oscillator to correct the phase drift. This novel method is shown to simultaneously provide superior residual phase jitters and long-term performance, enabling previously considered impossible experiments in attosecond physics.

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1.1 Introduction

The ability to measure and control the relative phase between carrier and envelope of a light pulse is one of the key inventions that made attosecond pulse generation possible [1–5]. Inside a laser oscillator, the envelope of the pulses propagates at the group velocity whereas the underlying carrier propagates at the phase velocity. In all intracavity dispersive media, in particular inside the laser gain crystal, both propagation velocities differ, which gives rise to a slippage of the envelope relative to the carrier. Given a per-roundtrip phase slippage $\Delta\phi_{\mathrm{CE}}$, one computes a slippage rate

$$f_{\mathrm{CE}} = \frac{\Delta\phi_{\mathrm{CE}}}{2\pi} f_{\mathrm{rep}}, \tag{1.1}$$

with f_{rep} being the repetition rate of the laser oscillator. Computing phase and group velocities for a typical Ti:sapphire few-cycle laser with about 2.5 mm crystal length, one computes a $\Delta\phi_{\mathrm{CE}}$ on the order of 1,000 rad. It is important to understand that integer multiple phase shifts of 2π exactly reproduce the initial electric field transient. Therefore only the fractional sub-cycle part of $\Delta\phi_{\mathrm{CE}}$ enters into the carrier-envelope phase dynamics. However, it also becomes clear that even the tiniest variation in crystal temperature or atmospheric conditions inside the laser cavity will have a measurable effect on f_{CE}. Assuming that the total phase shift between carrier and envelope changes by only one part in 10^6, (1.1) indicates a 15 kHz change of f_{CE}, i.e., dephasing between carrier and envelope occurring on the microsecond scale. These considerations make it immediately clear that a stabilization of f_{CE} needs to be extremely agile, capable of reacting to perturbations within a few microseconds.

1.2 Traditional Stabilization Scheme

All approaches towards stabilizing the carrier-envelope frequency rely on the heterodyne measurement scheme originally proposed in [1]. In its most common implementation, this scheme heterodynes fundamental frequency components $f_i = f_{\mathrm{CE}} + i f_{\mathrm{rep}}$ from the blue edge of an octave-spanning spectrum with frequency-doubled components $2f_j = 2f_{\mathrm{CE}} + 2j f_{\mathrm{rep}}$ from the infrared edge. Measuring the difference frequency between f_i and $2f_j$ with $2j = i$ gives access to f_{CE}, with the rf beat note signal being measurable directly by a photo diode. This scheme is referred to as f-$2f$ scheme. Another commonly used variant of the heterodyne scheme is the 0-f scheme that employs beating of fundamental frequency components from the red edge of the comb with difference frequency components generated within the frequency comb itself [6]. The latter method has the advantage of being less demanding in terms of bandwidth, often obviating the need for additional external broadening of the laser spectrum in a photonic crystal fiber.

Either of the above measurement schemes delivers a radio frequency signal with frequency f_{CE}. All methods for stabilizing this frequency so far enforced a phase lock between f_{CE} and a reference signal that was typically derived from the laser repetition rate f_{rep}. Using a phase-locked loop for stabilizing f_{CE} comes with two fundamental issues. First, it is difficult to stabilize f_{CE} to zero, i.e., the case of exactly identical electric field transients of subsequent pulses. At exactly zero frequency, the heterodyne scheme fails to provide unambiguous information on the sign of an intracavity phase distortion. Several more elaborate schemes have been proposed to overcome this difficulty [7, 8]. Second and probably more importantly, a feedback scheme requires some means for controlling the carrier-envelope frequency of the oscillator. At first sight, this requirement does not appear to be overly restrictive, as f_{CE} varies virtually with all mechanical and environmental parameters of the laser. However, as discussed above, the feedback mechanism needs to be very fast with at least several kilohertz bandwidth to be able to compensate the rapid fluctuations of f_{CE}. Even though many different feedback mechanisms have been explored, the bandwidth requirements strongly favor electro-optic or acousto-optic modulation of the pump power, which allow for modulation bandwidths of hundreds of kilohertz or more. Nevertheless, there is still a caveat with this fast feedback mechanism: pump power modulation will not only change the carrier-envelope frequency via nonlinear index changes inside the laser crystal, but it will also affect pulse duration, peak power, and the repetition rate of the laser. To date, there is no known side-effect-free feedback mechanism for the carrier-envelope frequency.

In conclusion, the proven traditional feedback method for stabilizing f_{CE} comes with a series of drawbacks that render long-term stabilization difficult. In particular, there is always a trade-off between the precision of a servo loop and the phase capture range, i.e., the largest phase distortion that the servo loop can handle without dropping out of lock or suffering a cycle slip. Many highly stabilized pump lasers exhibit rare needle-like fast transients in their output power, which make it necessary to extend the capture range of the phase detector well beyond 2π. Nevertheless, mapping a large phase range on to, e.g., a 10 V range also increases the susceptibility of the electronics towards voltage noise. In the following, we will discuss a scheme that overcomes all these limitations and allows for long-term stabilization without sacrificing phase stability on short time scales.

1.3 Feed-Forward Scheme

The setup of the feed-forward scheme is depicted in Fig. 1.1. Rather than acting back upon the laser oscillator, we directly employ the measured offset of the frequency comb f_{CE} and shift each and every line within it by this amount [9, 10]. For this purpose, we employ an acousto-optic frequency-shifter (AOFS) that we drive directly with the amplified f_{CE} signal. In the first diffraction order of the AOFS, we therefore generate a zero-offset comb with all individual frequencies being integer

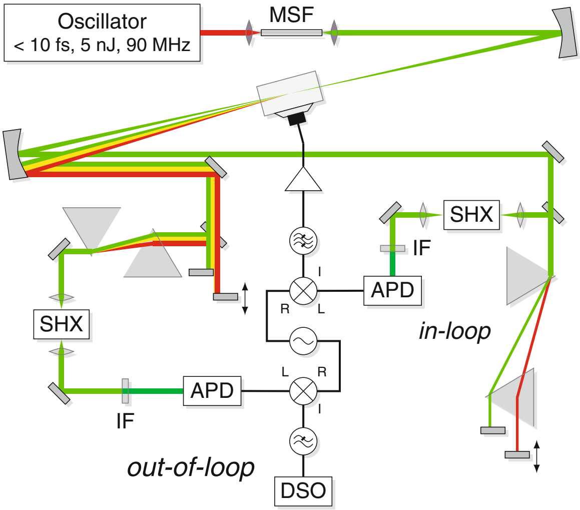

Fig. 1.1 Set-up employed for the out-of-loop characterization of residual CEP jitter. *SHX*: periodically poled lithium niobate crystal phase matched for frequency doubling 1,064 nm; *IF*: interference filter at 532 nm; *APD*: avalanche photodiodes; *MSF*: microstructured fiber; *DSO*: digital storage oscilloscope

multiples of the repetition rate, i.e., $f_i = i f_{\mathrm{rep}}$. Consequently, all pulses in the pulse train exhibit identical electric field transients. Apart from automatically providing an offset-free comb, the servo bandwidth of our system is only limited by the travel time of the acoustic wave from the actuator to the interaction zone with the laser beam. Given the high speed of sound in silica, we computed a microsecond lag in the AOFS, allowing a bandwidth well in excess of 200 kHz. Compared to the best reported bandwidths of feedback schemes [11] of about 50 kHz, this about fivefold increased bandwidth encompasses typical parasitic laser power modulations stemming from the primary switching power supplies of the pump lasers.

We tested the stabilization with the scheme depicted in Fig. 1.1. In these experiments, the laser was deliberately stabilized not to zero offset. This avoids the phase ambiguity at exactly zero offset frequency as well as $1/f$ noise issues. Measured phase noise spectra are shown in Fig. 1.2. Integrating over the entire frequency range we measure a total rms phase noise of 45 mrad. Subtracting internal noise contributions generated in our electronics, we deduce a residual timing jitter between carrier and envelope of 12 as (5 s–0.2 μs). This number is a factor 2 smaller than the atomic unit of time, which is normally considered a limit for the fastest transient events in atomic and molecular physics. Using a more elaborate scheme than depicted in Fig. 1.1, we have recently been able to further push residual timing jitter down to 8 as, i.e., a phase jitter of 20 mrad [13].

The residual carrier-envelope phase jitters of the feed-forward schemes have to be compared with the best obtained values of the feedback scheme, which lie in the range of about 100 mrad [12]. Therefore, the feed-forward scheme improves the obtainable precision of carrier-envelope phase stabilization by about a factor five. Moreover, the feed-forward scheme cannot fall out of lock, at least as long as there is a detectable beat signal. Even after brief interruption of the input signal, the stabilization immediately restores itself. We ran overnight tests and

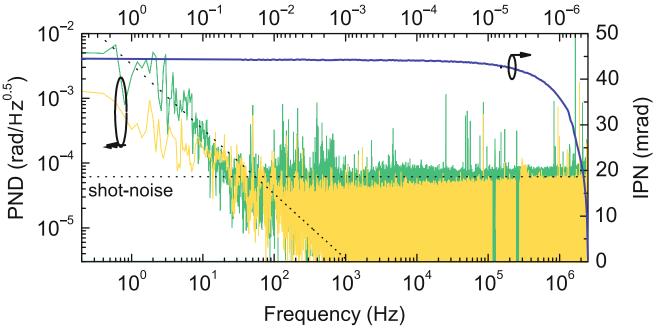

Fig. 1.2 Residual phase noise of the feed-forward stabilized Ti:sapphire oscillator. *Black curve*: integrated phase noise of the stabilized oscillator, amounting to a total of 45 mrad over the entire frequency range. *Dark gray curve*: spectral phase noise density of the stabilized oscillator. *Light gray curve*: background measurement

observed more than 12 h of phase-stable operation of the laser without any need for readjustment or the appearance of dropouts. Therefore the feed-forward scheme enables unprecedented precision without compromising the phase capture range.

Despite the obvious advantages of using an AOFS for phase stabilization, this scheme also appears to exhibit some disadvantages over the traditional scheme. One possible issue is angular dispersion inside the diffracted beam. We found, however, that this potential problem is readily compensated for by introducing a BK7 prism with 18° apex angle inside the stabilized beam path [6]. A second possible issue is caused by a slow drift of f_{CE}, translating into beam pointing variations and changing the period of the acousto-optic index grating, which will also cause a slow drift of the phase of the stabilized pulses. In our experiments we found stabilization of the carrier-envelope frequency to within 100 kHz around the center frequency completely sufficient to suppress all these undesired drift effects [13]. Compared to stabilization within a phase-locked loop, such a stabilization is much less demanding and removes all long-term drift effects that may otherwise appear on a time scale of some ten minutes and above.

1.4 Conclusion

The feed-forward scheme offers a row of advantages over traditional carrier-envelope phase stabilization schemes. Most importantly, it combines locking precision and long-term stability in an unprecedented way. Moreover, the scheme comes without complicated servo controllers that may fall out of lock, which is particularly cumbersome for the heavy statistics often required in attosecond physics. We therefore believe that feed-forward stabilization will widely replace feedback schemes in stabilized chirped-pulse amplifier chains. A precision beyond the atomic unit of time together with added statistical capabilities appear to enable previously impossible experiments in attosecond physics.

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