Introduction

In the last 50 years, laser science has progressed from the first demonstration of a laser [1, 2] to a research field that has tremendous impact on other fields in science as well as our everyday life. Utilization of the unique properties of laser light is diverse and ranges from highly sophisticated tools in experimental physics to core components in contemporary telecommunication networks. Such applications are the driving force behind the continuous progress of laser science and have initiated the development of novel laser concepts.

Apart from laser sources emitting a continuous wave, the generation of pulsed laser light has attracted much attention. To a large part, this interest is due to the fact that laser pulses enable the study of rapid dynamic processes in nature that cannot be accessed electronically. For example, the dynamics of chemical bonds during the course of a chemical reaction can be temporally resolved with femtosecond laser pulses (1 fs = 10^{-15} s) [3]. The strive for enhancement of the temporal resolution in such studies has led to the invention of the technique of mode locking [4, 5]. The basic concept of mode locking is phase-synchronization of laser cavity modes, which are equally spaced in frequency. While originally in competition with other methods for the generation of laser pulses, mode locking has succeeded in the generation of the shortest laser pulses. This success has culminated in the production of only 4.5 fs long laser pulses directly from a laser [6]. These laser pulses encompass less than two optical cycles in their intensity half width.

With ever decreasing pulse duration, the traditional description of a pulse via its slowly-varying intensity envelope breaks down as the relative phase between carrier and the maximum of the intensity envelope starts to play a role. This quantity is called the carrier-envelope phase. The breakdown of the slowly-varying envelope approximation appears most markedly in high-harmonic processes [7, 8] and is utilized for the synthesis of attosecond pulses in the extreme ultraviolet (1 as = 10^{-18} s) [9]. Since there is no mechanism locking the carrier-envelope phase of a pulse in the generation process, the carrier-envelope phase evolves freely in a train of pulses from a mode-locked laser. The evolution is dominated by a constant drift, with deviations only caused by external perturbations of the mode-locking process. In the frequency domain, the carrier-envelope phase drift corresponds to an offset of the comb of the synchronized cavity modes from zero. While this fact was already realized in the late 70s [10], there was no practical way of controlling the offset of the frequency comb of a mode-locked laser, i.e., the electric field evolution in a pulse train, until much later. For the first time a self-referencing measurement technique for the comb offset, termed f–$2f$ interferometry, was demonstrated in 1999 [11, 12]. The availability of this measurement scheme has revolutionized the field of frequency metrology [13, 14], where broadband frequency combs produced by few-cycle lasers are now widely used as optical clockwork [14, 15] replacing the formerly used complicated and inflexible frequency chains [16]. Frequency comb based metrology setups have gained such a high degree of precision that the question of a potential drift of fundamental constants can be addressed today [17].

Both attosecond physics and frequency metrology require a controlled evolution of the carrier-envelope phase in a pulse train. Currently, the most widespread technique for achieving this goal is phase locking of the comb offset to a stable reference using a phase-locked loop. Feedback is applied to the laser by manipulating the difference between the intracavity group and phase velocity. Most often this is achieved by modulation of the pump of the mode-locked laser, which alters the nonlinear pulse propagation inside the gain medium. The residual jitters between carrier and envelope that have been achieved with such phase-locked loops are on the order of only 100 as.

In order to progress beyond current achievements of carrier-envelope phase stabilization, however, clarification of the origin of the residual carrier-envelope phase jitter is required. The work presented in this thesis investigates whether the origin of the residual jitter is merely of a technical nature or if there is a fundamental physical limitation.

Outline

After a general introduction presented in Chapter 1, improvements of the existing technology are devised in Chapter 2. It is shown that a common-path layout of f–$2f$ interferometers removes spurious technical noise by more than 40%. In addition, a two detector arrangement for carrier-envelope phase retrieval of amplified laser pulses reducing the impact of shot noise is demonstrated. Both investigations give insight into mechanisms that currently limit carrier-envelope phase stabilization. In Chapter 3, a novel approach to stabilization is demonstrated, which replaces the feedback concept by a feed-forward scheme. In contrast to feedback based carrier-envelope phase stabilization, the feed-forward scheme is capable of generating zero-offset frequency combs, is unconditionally stable and does not require any manipulation of important laser parameters. Moreover, with the achieved 20 as residual temporal jitter between carrier and envelope, the feed-forward carrier-envelope phase stabilization clearly outperforms the feedback method promising to be a substantial leap ahead for frequency metrology and attosecond physics. Finally in Chapter 4, analysis of the obtained stabilization results reveals that in Kerr-lens mode-locked lasers the residual carrier-envelope phase jitter lies below the level expected for the conversion of pump laser shot noise into carrier-envelope phase noise. In search for an explanation for this remarkable finding, a feedback based squeezing, a soliton induced photon-number squeezing and a quantum non-demolition like light power measurement is discussed. The feedback based squeezing and the quantum non-demolition like measurement of the intracavity power are identified as the probable origins of the observed sub-shot-noise signatures of the carrier-envelope phase jitter. Application of this sub-shot-noise sensitivity may enable the limitations in current high-sensitivity interferometric measurements to be overcome.