Characterization of flicker noise contributions to the carrier-envelope phase stabilization of femtosecond lasers

Youjian Song* (1), Minglie Hu(1), and Günter Steinmeyer(2)
(1) Ultrafast Laser Lab, School of Precision Instruments and Opto-electronics Engineering, Tianjin University, 300072 Tianjin, China
(2) Max Born Institute, 12489 Berlin, Germany

In the last decade, carrier-envelope phase (CEP) stabilized passively mode-locked lasers have become an indispensable tool in a variety of fields ranging from optical frequency metrology to attosecond physics. This method enables counting of optical frequencies in the 100 THz range and is currently discussed for the definition of a new frequency standard to deduce the SI unit of the second. The relative precision of these measurements has reached a value of $<10^{-15}$, which makes the second the most precisely determined unit in the SI system. Moreover, the residual timing jitter between carrier and envelope amounts to < 10 attoseconds and constitutes the best temporal synchronization ever obtained. While methods for CEP stabilization have been substantially refined over the years, careful verification measurements of the obtained phase stability with a second independent interferometer always revealed a flicker noise contribution, which amounts to about 1 mHz/Hz$^{1/2}$ for Ti:sapphire based frequency combs and is about 100-1000 times larger for fiber-laser based combs. While this noise contribution does seem to play a role at the 10^{-15} precision level, it will eventually hinder further improvement in frequency metrology.

Figure 1 (a) shows the experimental setup employed for out-of-loop characterization of the residual CEP noise of a stabilized Ti:sapphire laser. Measurements were carried out with a monolithic *0-f* interferometer. Figure 1(b) shows characteristic two-sided CEP noise densities $S_\phi^{CEP}(f)$, which features a *1/f* behavior at low Fourier frequencies. The observed *1/f* CEP noise corresponds to white carrier envelope offset (CEO) frequency noise at levels $S_f^{CEO}(f) \approx 1mHz/\sqrt{Hz}$ or larger at low Fourier frequencies, see Fig. 1 (c). The observed white noise is indicative of a quantum origin.

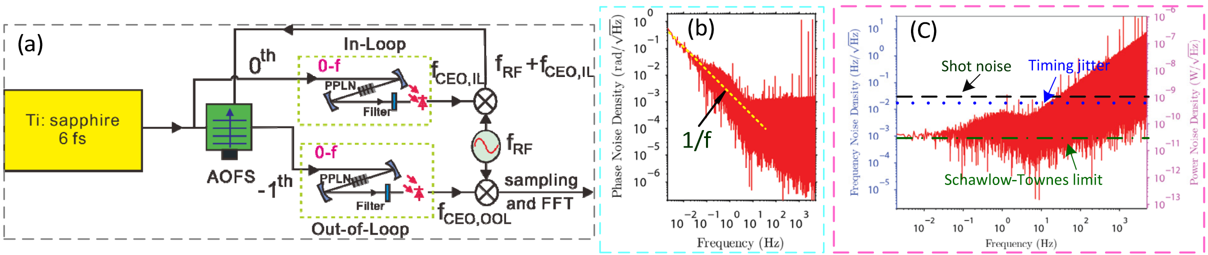

Fig. 1 Characterization and modeling of flicker noise in CEP stabilization of a Ti:sapphire laser.

We carefully analyzed various quantum noise based scenarios to explain the origin of the *1/f* noise signature. It should be noted that the measured noise level is substantially below the effect expected from intracavity laser shot noise, see the dashed line in Fig. 1 (c). ASE directly contributes to CEP noise through pulse train timing jitter and central frequency fluctuation. Timing jitter causes a breathing of the comb. The impact of timing jitter on f_{CEO} is shown as dotted line in Fig. 1 (c). This breathing-type deformation is contrasted by pure translational jitter of the comb. For the latter case, the resulting frequency noise is known as the Schawlow-Townes limit, which corresponds to the dashed-dotted line in Fig. 1 (c). We conclude that the observed flicker noise mostly stems, in fact, from quantum noise. We will further present an analytical model to fully explain the impact on quantum noise on the CEP of a laser and discuss consequences for frequency metrology and attosecond physics.