Ultimate quantum noise limit of frequency comb measurements: can we read out optical clocks with 10^{-20} precision?

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Since the advent of frequency combs in the early 2000s, the precision of optical clocks has dramatically improved. The latest generation of optical lattice clocks [1] was demonstrated to exhibit a relative precision of 2.5×10^{-19}. Continuously operating such a clock over the age of the universe, a timing error of only 100 ms would accumulate. Therefore, such clocks have the prospect of eventually replacing the current primary frequency standards, enabling fundamental tests, e.g., for providing evidence for a drift of elementary constants, and may also allow construction of a new generation of gravitational wave detectors. However, in either of these applications, it is of paramount importance to reliably count clock cycles. As frequencies in the 100 THz range are far beyond the capabilities of even the most advanced electronic circuits, optical frequency combs are required to mitigate the problem of measuring the optical clock frequency. Rather than measuring one unknown optical frequency directly, one actually counts three microwave frequencies. To this end, one has to measure the comb spacing and the beat frequency between clock frequency and a neighboring comb mode. For an absolute measurement of an unknown frequency, one additionally requires monitoring the carrier-envelope phase (CEP), and the latter is typically the most cumbersome of the three measurements. Most frequency combs demonstrated to date are laser-based light sources, exhibiting both technical noise mechanisms as well as quantum noise. While technical noise contributions are often narrowband and may be eliminated by suitable filtering, broadband spontaneous emission inside the laser imposes a fundamental barrier, which is commonly referred to as Schawlow-Townes noise. In a mode-locked laser, there is an additional timing noise mechanism. The latter immediately affects the measurement of comb spacing, but is typically too faint to cause any significant degradation of a frequency comb measurement. The case is different for Schawlow-Townes noise, which manifests itself in a $1/f$ flicker-noise mechanism [2], see Fig. 1.

At first sight, it appears puzzling that two independent measurements of the CEP slowly dephase on the multi-second time scale. Splitting the comb signal into two, one would intuitively expect that independent counting of the CEP signal in two independent f-$2f$ interferometers can only lead to identical results. This somewhat simplistic experience independent phase shifts in either interferometer due to Schawlow-Townes noise, giving rise to a quantum-noise induced phase difference between

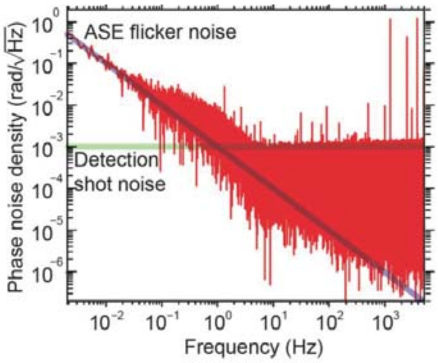

Figure 1. ASE-induced $1/f$ noise and shotnoise detection floor for the example of a CEP stabilized Ti:sapphire laser. This measurement was acquired out-of-loop of a CEP stabilized laser, which was stabilized with the feed-forward technique. In-loop and out of- loop measurement slowly dephase on a scale of many seconds.

the two frequency channels in either interferometer. Given that quantum noise contributions are statistically independent after beam splitting, this mechanism causes a random phase walk between the signals in the f and the $2f$ arm of both interferometers, i.e., a limitation sets in with the dissemination of the signal, even if the clock is perfectly stable. Moreover, given that Schawlow-Townes noise causes linewidths in the sub-hertz range, it actually appears not overly surprising that dephasing effects only set in at multi-second time scales (cf. Fig. 1).

This rather slow dephasing effect has also been observed and confirmed by several independent research groups [2-4] with nearly identical $1/f$ behavior. This flicker noise causes a drift mechanism, which becomes a limiting factor when relative precisions below $\sim 10^{-20}$ are to be addressed. Similarly, thermal drift has always been limiting quartz oscillators. Our findings indicate that precision prospects of optical frequency is not unlimited either, and it seems that we are going to feel limiting effects in the near future. In other words: similar to Moore's law in electronics, any exponential growth behavior so far met a game stopper, and it seems that Schawlow-Townes noise may exactly act as the latter for precision frequency metrology.

References

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