Characterizing phase fluctuations of fiber oscillators by using external optical cavities

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Abstract: We experimentally characterize amplitude and phase fluctuations of a femtosecond fiber oscillator close to the standard quantum limit (SQL). A passive optical cavity is employed to convert frequency noise to relative intensity noise (RIN) with close to quantum-limited sensitivity. The noise properties of the investigated oscillator reach the SQL (by 3dB) at 0.1 microsecond timescales.
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To apply femtosecond oscillators to high precision metrology and quantum optics, their noise properties are required to be quantum limited at a given detection frequency [1, 2]. Typically, Titanium sapphire oscillators are employed. However, they are usually limited to laboratory setups due to cost and instabilities. In contrast, fiber oscillators are low cost and robust but little is known about their noise properties at high sideband frequencies. Direct phase noise measurements of fiber lasers require complex methods, such as the f-to-2f method succeeding super-continuum generation, which is based on nonlinear effects. A passive – yet indirect - phase noise measurement can be achieved by locking an external optical cavity to a laser and analysis of the error signal [3]. Even if this approach is relatively easy to implement; in practice, it is highly perturbed by electronic noise sources.

In this contribution, we propose and experimentally demonstrate a method that detects phase noise of ultrafast fiber lasers close to the standard quantum limit. The technique is readily applicable to any laser source and is based on analyzing the reflection from a passive cavity, a system known to contain all noise information of a light state [4]. Specifically, in the reflection from passive cavities phase noise translates to RIN - which is a well established characterization method for CW lasers [5]. Here, we extend the technique to ultrafast lasers by noting that CEO phase noise is dominating timing jitter by several orders of magnitude. The method overcomes the drawback of the previous error signal method and achieves sensitivity close to the quantum limit.

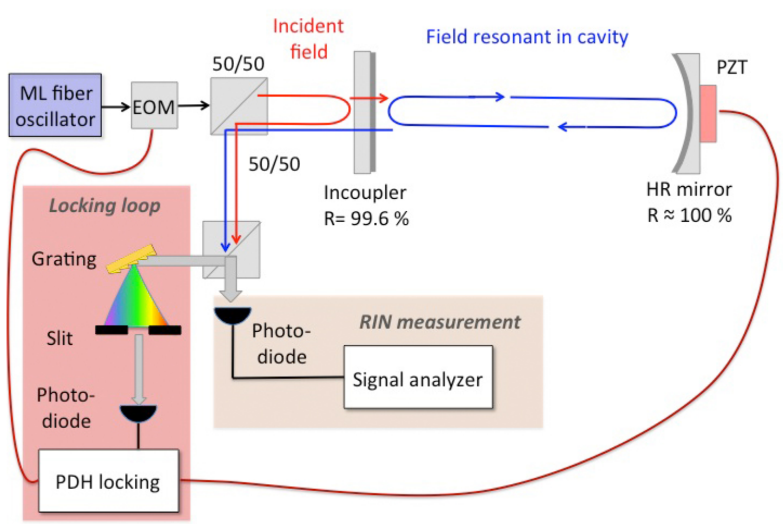

Fig. 1. Schematic of the experimental setup of locking an external optical resonator to the fiber oscillator.

Figure 1 shows a schematic of the experimental setup. The Yb-doped fiber oscillator to be characterized is of stretched-pulse type and is mode-locked by a saturable-absorber mirror. The center wavelength of the spectrum is about 1035 nm. The laser possesses a measured total net GDD of 0.012 ps^2. The repetition rate is 75 MHz. The high stability of the fiber laser cavity manifests itself in low repetition rate fluctuations, which is measured to be –80dBc at 100 Hz sideband frequency. An external resonator cavity is locked to the fiber laser by using the Pound-Drever-

Hall (PDH) technique. An electro-optical modulator imprints a 5 MHz phase modulation on the laser output. From the cavity reflection only the central part of the spectrum is used for the derivation of the PDH error signal. By controlling the position of a piezo-actuated mirror, stable locking is achieved over a timespan > 10 min. To keep the design of the external resonator as simple as possible, we chose a semi confocal resonator with 300 MHz free-spectral-range. The cavity´s resonance linewidth $\delta\nu$ is about 200 kHz and can be regarded as a lower frequency detection boundary for the herein proposed characterization technique. The beam that is reflected from the locked cavity is analyzed in terms of RIN by using a signal analyzer. Two cases are considered: First, the RIN measurement with the beam-path inside the cavity blocked, and second, a measurement with a locked cavity.

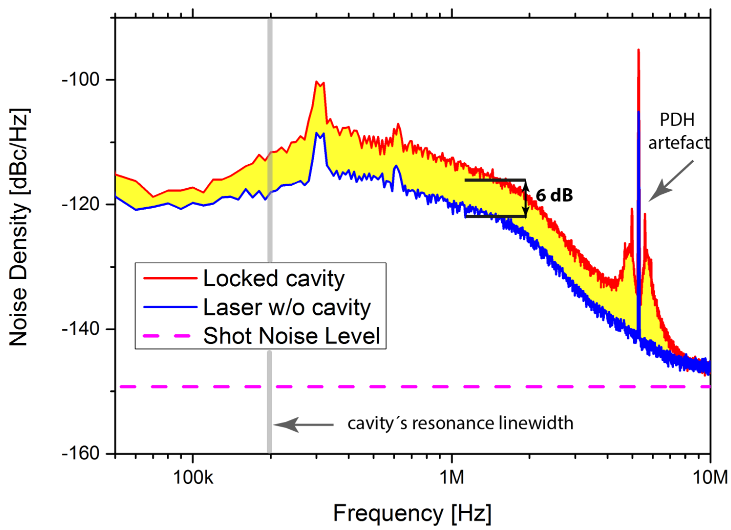

Fig. 2. Noise density of the laser without the effect of the cavity filter (blue curve) and for the case of the locked cavity (red curve). The additional noise is given by the difference (yellow area). The grey vertical line highlights the external resonator´s linewidth.

Figure 2 shows the effect of the cavity on the RIN measurement. When the beam path inside the cavity is blocked, the incoupling mirror acts as a normal mirror and we perform a conventional RIN measurement of the fiber oscillator. The high levels of RIN, which are up to 30dB above the SQL, are due to the RIN of the pump diodes. An independent balanced detector measurement allows a presentation of the data with respect to the SQL. If the cavity is locked, the laser phase noise is partially converted to amplitude fluctuations resulting in an increased RIN by 6 dB. This effect decreases for frequencies below the cavity´s linewidth of 200 kHz and also depends on the electronic locking point. Above 8 MHz the two measurements collapse and are close to the standard quantum limit. Consequently, both amplitude and phase noise reach close to quantum limited properties. From the slope of the RIN´s increase, estimation of the absolute level of CEO phase noise is possible [6].

In conclusion, the reflection of a laser output from a locked external cavity can be used to characterize phase (i.e. also frequency) noise of ultrafast lasers with high sensitivity. The advantages of the method are as follows: it is a passive technique and there is no need for generation of octave spanning spectra as compared to the f-to-2f method. Also, by converting phase noise to RIN, a standardized and quantitative comparison among different laser sources (including laser amplifier chains) is possible. The method can also be extended to a spectrally resolved analysis. And by designing a fiber oscillator with a pump diode exhibiting low RIN, quantum limited properties can be reached well below 8 MHz. This will render fiber oscillators to be robust and inexpensive sources suitable for quantum optical applications.

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