Digitally controlled precision optical frequency comb

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***Abstract*— We discuss the implementation and relative frequency stability of a compact rack-mounted fiber-based optical frequency comb system fully controlled digitally. Such a system allows for frequency comb operation in embedded experimental setups where high stability and accuracy are required.**

***Keywords*— Time and frequency metrology, optical frequency comb, FPGA, digital electronics, phase-locked loop**

I. Introduction

The compact integration of optical frequency combs is highly desired for a growing number of applications, such as transportable optical clocks for geodesy measurements [1,2], RADAR, LIDAR, and optical free-space time and frequency transfer [3]. All those applications require the development of optical frequency combs that are compact, robust, low noise and accurate outside the laboratory. While fiber-based optical frequency combs have been demonstrated to be a good candidate for applications in hostile environments in terms of robustness and small form factor, the control of its degrees of freedom (carrier envelope frequency f_{ceo} and repetition rate f_{rep}) usually relies on expensive and bulky analog circuits, as well as large electronics to drive requisite actuators such as PZTs or EOMs. Here, we present an optically-referenced fiber-based optical frequency comb system controlled and stabilized by low latency phase locked loops incorporating digital PID loop filters based on a single FPGA (Field programmable Gate Arrays), allowing in-loop stability performance in the optical domain of better than a few parts in 10^{18} for an averaging time of 1 s. The in-loop phase noise error of f_{ceo} and f_{beat} servo-locking shows a promising potential for many applications in precision metrology.

II. Optical frequency comb system

The full system, including the fiber comb, EDFA, the f-2f interferometer, and the electronics control of the comb, is enclosed in a 2U rack unit (see Figure 1) making the system extremely relevant for applications requiring the comb to be transportable.

The femtosecond oscillator consists of an 80 MHz repetition rate Er fiber laser. Its output is split in three branches for the detection of the repetition rate, the detection of f_{ceo} through an EDFA and f-2f interferometer, and a beatnote detection unit for the detection of a beatnote between the comb and a CW laser reference. Presently the system offers one optical output at 1550 nm and 3 RF outputs, for monitoring of f_{ceo}, f_{rep} and f_{opt}. Additionally the system has an input for a microwave reference such as GPS, or microwave atomic clock such as a maser or rubidium clock.

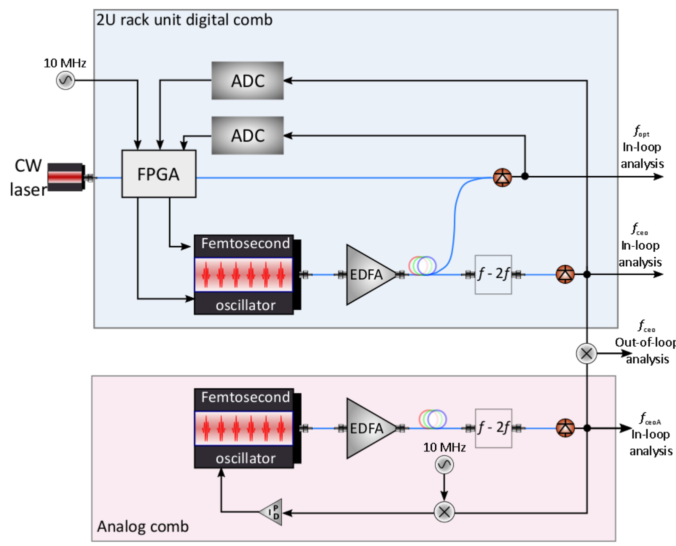

Figure 1: Experimental setup to characterize the residual noise and stability of the digital servo-locks. See text for details. EDFA: Erbium Doped Fiber Amplifier; ADC: Analog to Digital Converter; FPGA: Field Programmable Gate Arrays.

Due to the use of digital electronics, the system can be fully monitored by a web application or a tablet interface developed in order to control the laser state, the stabilization of the comb and real-time diagnostic. The system allows plug and play operation and it usually takes just a few minutes to operate the comb from turn on to a fully optically referenced frequency comb.

I. Preliminary results

The carrier envelope offset frequency is locked on an RF reference while the repetition rate is optically locked through the beatnote between a CW laser at 1550 nm and a comb tooth. The digital phase locked loops allow for a maximum feedback bandwidth of around 100 kHz, limited by the latency of the implemented FPGA. We have measured the in-loop phase noise error of the carrier frequency f_{ceo} and the optical lock of f_{opt}. To evaluate the fidelity of the digital locking architecture we have also compared the phase errors from the digital phase lock with conventional analog servo locking on an auxiliary frequency comb [4] (see Figure 1). The resulting out-of-loop measurement for f_{ceo} is limited by the noise added by the digital lock (then similar to the in-loop noise). The results are depicted on Figure 2. The digital phase error exhibits a plateau at around < 10^{-6} rad^2/Hz within the loop bandwidth. Due to quantization noise resulting from the 14 bit ADCs (Analog to Digital Converters), the digital lock does not exhibit the $1/f$ phase noise evolution as familiar from analog circuitry. This limitation can potentially be overcome by using ADCs with a higher number of bits. For microwave generation applications, scaled to 10 GHz, the system would be compatible for an optical frequency division setup with a phase noise floor of around -150 dBc/Hz when integrated with an ultra-low noise compact optical cavity [5] and digital synthesis schemes [6].

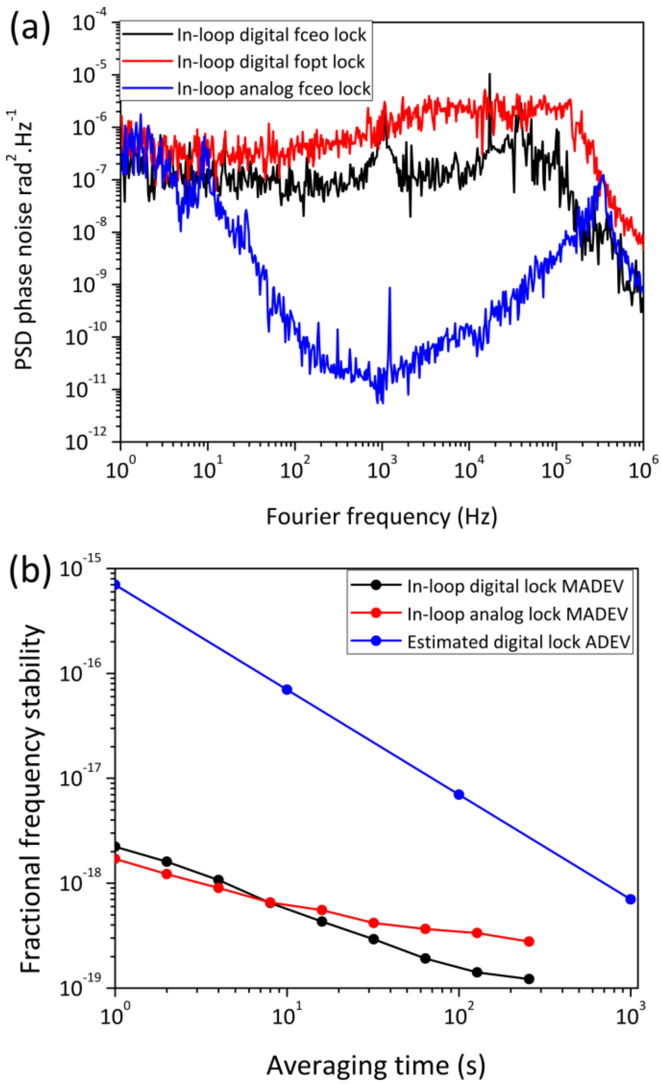

Figure 2: (a) Power spectral density of phase noise of the in-loop digital lock (red curve), the in-loop digital f_{opt} lock (black curve) and the in-loop analog f_{ceo} lock (blue curve). (b) Fractional frequency instability in term of modified Allan deviation (Λ-type counter or 1ms gate time) of the analog (black) and digital lock (red) and an estimation of the Allan Deviation (blue).

We have also measured the fractional frequency stability in terms of modified Allan deviation (1 ms gate time or lambda-type counter). It shows a very good stability of 2×10^{-18} at an averaging time of 1 s averaging on $\sqrt{\tau}$ due to the dead time of the frequency counter, competitive with conventional analog PIDs [7]. Due to the phase noise floor between 1 Hz and 100 kHz at 10^{-7} rad^2/Hz we estimate, from the power spectral density of phase noise, an Allan Deviation (in a 100 kHz measurement bandwidth) limited to 7.10^{-16} at 1 s averaging time and averaging on τ. However, this stability is very interesting for precision optical clock applications. Nevertheless, a full out-of-loop measurement with an additional CW laser will have to be carried out to check any systematic frequency offset as we have not taken into account any non-common optical and electrical paths outside the loop. The accuracy of such a system for its integration with a transportable optical atomic clock will be the eventual figure of merit.

In conclusion we have achieved a record in-loop frequency stability of just a few parts in 10^{18} level for a digital frequency comb with only 14 bit of resolution, demonstrating the large potential of fiber-based combs with digital electronics for low noise compact and robust systems for precision metrology applications. Further studies will be devoted to reducing the in-loop phase noise error and the implementation of software for full automation of the system in conjunction with optical clock systems and microwave frequency synthesis to anticipate a redefinition of the SI second.

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