Flywheel oscillator for atomic fountain clocks using ultra-stable lasers and a fiber-based optical frequency comb

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***Abstract*—We demonstrate the use of a fiber-based femtosecond laser locked onto an ultrastable optical cavity to generate a low-noise microwave reference signal. Comparison with both a cryogenic sapphire oscillator (CSO) and a titanium-sapphire-based optical frequency comb system exhibit a stability of about 3×10^{-15} between 1 and 10 s. The microwave signal from the fiber system is used to perform Ramsey spectroscopy in a state-of-the-art cesium fountain clock. The resulting clock is compared to the CSO and exhibits a stability of $3.5\times10^{-14}\ \tau^{-1/2}$.**

I. Introduction

Ultra-stable laser light is a key element for a variety of applications ranging from optical frequency standards (1,2), tests of relativity (3), generation of low phase noise microwave signals (4), to gravitational wave detection (5).

Essential to this experiment was the implementation of two very low vibration sensitivity optical cavities (6). We have designed and realized these optical cavities, with fused silica mirror substrates to reduce the thermal noise. The vibration sensitivity has been measured to be below 1.5×10^{-11} ms^{-2} in each direction. The measured frequency instability of the beat-note signal between two cw fiber lasers at 1542 nm stabilized on to our two independent ultrastable cavities has been shown to be below 2×10^{-15} at 1s (7). Transfer of the stability of such an optical reference to the microwave domain by use of a titanium sapphire-based optical frequency comb has been demonstrated with a residual instability of 6.5×10^{-16} at 1s (4).

State-of-the-art microwave atomic fountain clocks, when limited by quantum projection noise (QPN) [8], exhibit a short-term stability well below 10^{-13} at 1 s integration time. However, the intrinsic phase noise of the microwave signal used as interrogation oscillator for these atomic standards degrades performances from the fundamental QPN limit via the Dick effect [9]. Therefore, the realization of extremely low noise microwave oscillators is of prime importance for frequency standards to reach high stability.

II. Experiment

A. Aims

The aim of this experiment was to provide a low noise microwave flywheel oscillator as interrogation oscillator for the LNE-SYRTE atomic fountain clocks. By locking a self-referenced optical frequency comb onto the ultra-stable laser light, we can generate a low phase noise microwave signal by photodetection of the comb's repetition rate. We have used this high-quality microwave reference as the flywheel oscillator for the LNE-SYRTE atomic fountain clocks.

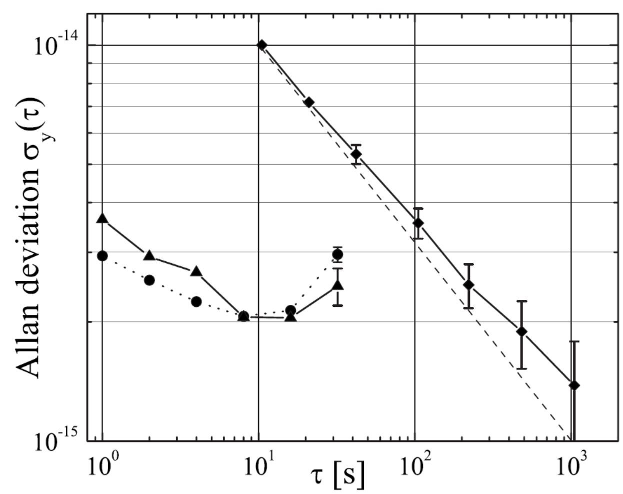

Fig. 1. Circles: Fractional frequency instability (Allan standard deviation) vs integration time of the microwave signal generated by the Er-doped fiber comb against the CSO at 11.932 GHz. Triangles: Er-doped fiber comb vs Ti:Sa femtosecond fiber comb. Diamonds: Er-doped fiber comb locked onto the FO2 atomic signal, compared against the CSO (quadratic drift removed). The latter instability scales as $3.5\times10^{-14}\ \tau^{-1/2}$ (dashed line).

B. Set-Up

As a first step, we compared the microwave signals generated by two different frequency combs, each locked on to an independent optical reference cavity. One of the combs is a ~770 MHz repetition rate Ti:Sa femtosecond laser locked on a 1062.5 nm ultra-stable laser cavity, the second one is a ~250 MHz repetition rate Er-doped fiber-based system locked on a 1542 nm ultra-stable laser cavity. Once locked onto the optical reference cavity, the repetition rate f_{rep} (and all its harmonics) reproduces its ultrahigh stability transferred to the microwave domain.

As a second step, a 11.932 GHz low noise microwave signal from the fiber-based system was used as a replacement of the LHe cryogenic sapphire oscillator (CSO) signal in our frequency synthesis system to drive the FO2 fountain. The cost of operation and maintenance associated with cryogenic cooling make it desirable to find an alternative technique; optical ultrastable reference cavities offer a reliable and low maintenance high spectral purity source. The flywheel is steered using a digital synthesizer driven by the frequency corrections of the FO2 fountain. The resulting microwave reference is then measured at 11.932 GHz against the 11.932 GHz signal from the CSO using a high resolution counter.

In a further experiment, the Er-doped fiber comb's repetition rate harmonic near 11.932 GHz was sent to the CSO/FO2 fountain laboratory 300 m away, and was compared to the 11.932 GHz CSO signal there.

III. RESULTS

The Allan deviation of the beat-note signal between the Er-doped fiber comb and the Ti:Sa femtosecond fiber comb at 9.2 GHz is below $5\text{x}10^{-15}$@1s (400 Hz BW, Fig. 1). A phase noise measurement of this beatnote is shown in Fig. 2.

The obtained frequency instability obtained using the microwave flywheel is slightly below $6\text{x}10^{-14}\,\tau^{-1/2}$ (Fig. 1). In the same operating conditions using the CSO as interrogation oscillator the frequency instability is $4\text{x}10^{-14}\,\tau^{-1/2}$.

The Allan deviation of the beat-note signal of the Er-doped fiber comb against the CSO/FO2 fountain laboratory is also shown in Fig. 1. These performances, among the very best for microwave sources, along with the reliability and robustness of the fiber-based system, qualifies it as an excellent microwave source for long-term operation of atomic fountain clocks. Further details of these experiments can be found in reference [10].

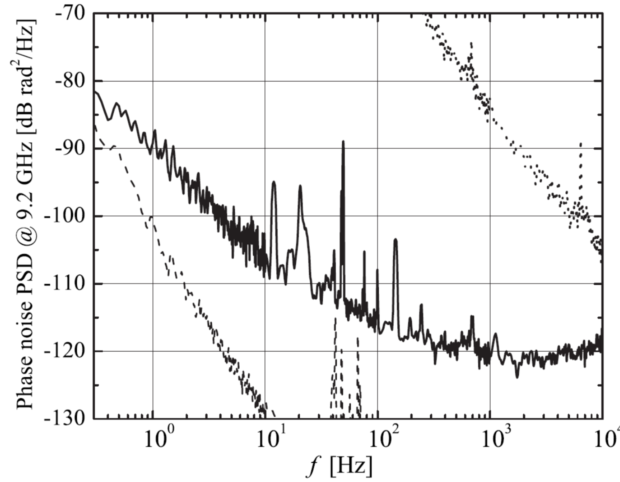

Fig. 2. Phase noise power spectral density at 9.2 GHz of the beatnote between the microwaves generated by the Er-doped fiber comb and the Ti:Sa femtosecond fiber comb. Dotted line is obtained for a free running Er-doped fiber comb. Dashed line: two ultrastable lasers locked onto 1542 nm independent reference cavities (scaled to 9.2 GHz). Degradation from optical to microwave is attributed mainly to amplitude to-phase noise conversion below ~1 kHz and to limited servo gain above ~1 kHz.

IV. CONCLUSION

The continuously operated fiber femtosecond optical frequency comb stabilized to an ultra-stable laser has the potential to replace the CSO as a flywheel, removing the use of cryogenics and providing an ultra-stable reference both in the optical and the microwave domain.

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