Towards a Sr Optical Lattice Clock at ROA

First implementations

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***Summary*—We present an overview of recent implementations achieved on the ongoing Spanish project for the construction of a stationary strontium optical lattice clock at ROA for frequency metrology**

Keywords—frequency chain; optical frequency comb; ultrastable cavity; Zeeman slower

I. Introduction

Optical atomic frequency standards are at the vanguard of frequency metrology and their performances have led to an improvement of two orders of magnitude, both in stability and accuracy, with respect to the best primary frequency standards [1-3].

The increased number of institutions implementing optical atomic clocks and the clocks' enhanced uptimes are creating a worldwide, robust and reliable clock network. This, followed by the latest SI units' revision in 2018, paves the way for a near-future redefinition of the SI second [4].

ROA, as the Designated Institute for Time and Frequency metrology in Spain, has recently started to build up an optical lattice clock based on ^{87}Sr atoms. Along this line, an entirely new optical infrastructure has been built in order to host this new frequency standard, where a frequency chain between the new optical oscillators and the microwave frequency standards has been built and stays operational. Additionally, first actions in order to face the coming cold atom stages are currently being carried out.

Here we describe the experimental work performed on the optical frequency comb, which is at the heart of the frequency chain, together with a second ultrastable cavity characterization and study of the deceleration of the atoms with a Zeeman slower before being loaded in a magneto-optical trap.

II. Methods/Results

One of the key technologies for implementation of optical clocks are optical frequency combs. In Fig. 1 is shown how our comb is optically referenced to a laser at 1542 nm (master laser), which is locked to an ultrastable cavity (USC1), constituting our operational optical reference system (ORS1). In order to remove the unavoidable drift of the USC1, we have phase locked a second laser (slave laser) to the master one in order to induce an opposite drift via a computer-controlled DDS which not only sets an arbitrary RF frequency offset but also allows its real-time modification. This optical drift is quantified by comparison of the 37th harmonic repetition rate of the comb (f_{rep} = 250 MHz) against a dielectric resonator oscillator (DRO) at 9.2 GHz phase locked to the 100 MHz output from our master H-maser, whose fractional drift is negligible ($< 2\times10^{-20}$/s).

We have additionally built a second ultrastable laser at 1396 nm that is locked to a very high finesse (> 400 000) cavity (USC2) equipped with crystalline mirrors, following the scheme depicted in Fig. 2. This second optical reference system (ORS2) will act as the future clock laser at 698 nm once frequency doubled.

Finally, we present a preliminary modeling for the atom loading via a permanent magnets Zeeman slower [5] to the under study magneto-optical trap.

III. Discussion/Interpretation

We show that a residual frequency drift on the slave laser lower than 30 mHz/s is easily obtained with this technique which is later on transferred to the comb. To illustrate and show that this counter-drift method is also applicable to non ultrastable lasers, we open the PDH lock of our master laser on purpose to leave it free running. A drift reduction of 10 times on the slave laser was achieved as shown in Fig. 3. This eases both the use of narrow filters on the comb-based measurements and the requirements for the future fiber link at ROA for an ultrastable frequency dissemination and optical clocks comparisons.

The former drift observation has been possible thanks to the direct comparison of the f_{rep} against our H-maser, which follows UTC. To avoid being limited by the frequency meter resolution we have rescaled the signal (and its noise) of the 100 MHz maser output to 9.2 GHz via the DRO in order to compare it to 37×f_{rep} (≈ 9.25 GHz). The stability comparison can be seen on Fig. 4a (purple curve), where the H-maser seems to be limited by a factor 2 at 1 s by the microwave link bringing the signal to the comb laboratory and it is clearly dominated by the drift of the ORS1 (red curve) after 100 s of integration time.

Our USC2 features a finesse > 410 000, measured using the cavity ring-down method. After characterizing its zero-crossing we have achieved a fractional stability < 3 × 10^{-15} at 1 s (green curve on Fig. 4b), whose flicker noise is unknown yet as it is hidden by the ORS1. Neither the power lock nor the acoustic and thermal shielding were in place. A third independent ultrastable laser will be needed in order to the see the expected stability improvement.

The Zeeman slower prototype is based on the configuration of interleaved magnets layers around the atomic propagation axis not only to build a magnetic field gradient as close as possible to the theoretically ideal one but also to reduce the number of magnets used in the arrangement. Thus, it impacts the slowing efficiency, the weight, and the dimensions of the apparatus. In Fig. 5 both the magnetic field along the Zeeman axis and the velocity space diagram have been simulated for an optical power of 70 mW, laser beam waist of 7 mm and an initial velocity capture of the Sr atoms corresponding to 466 m/s.

IV. Conclusions

We describe in this paper the optical frequency chain built at ROA with a low drift frequency comb which can be further improved by optimizing the algorithm in charge of the drift corrections, and a second ultrastable laser that provides redundancy and reliability. The latter will also act as the Sr clock laser for the atoms spectroscopy.

We show the approach we follow so as to implement a permanent magnets Zeeman slower with no electrical power, free of water cooling system, no induced thermal noise and reduced dimensions, easy to integrate on the ongoing and future portable optical clocks.

References

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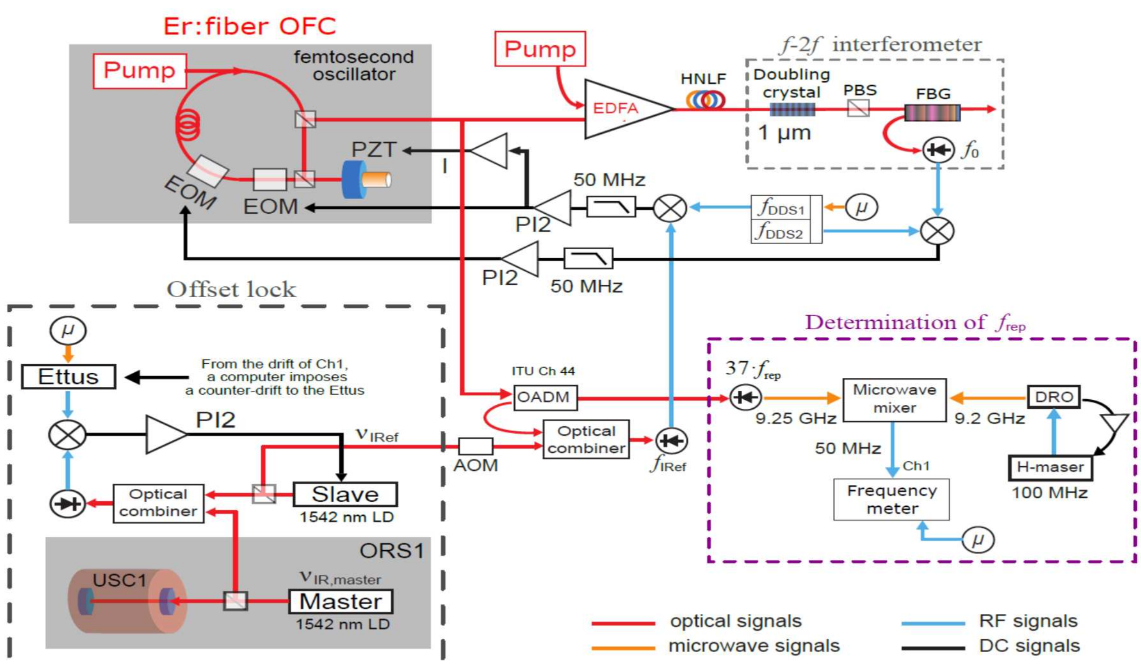

Fig. 1: Phase lock of the Er:fiber comb to an ultrastable cw laser at 1542 nm. Bottom left plot (grey dash line): offset lock of the slave IR laser (ν_{IRef}) to the master IR laser ($\nu_{\mathrm{IR,master}}$) for the counter-drift of ν_{IRef}. Bottom right plot (purple dash line): repetition rate of the comb (f_{rep}) determination by comparison with a H-maser. AODM: optical add and drop module, AOM: acousto-optic modulator, DRO: dielectric resonator oscillator, EOM: electro-optic modulator, FBG: fiber Bragg grating, HNLF: highly non linear fiber, OFC: optical frequency comb, ORS: optical reference system, PBS: polarized beam splitter, and PZT: piezo-electric ceramic.

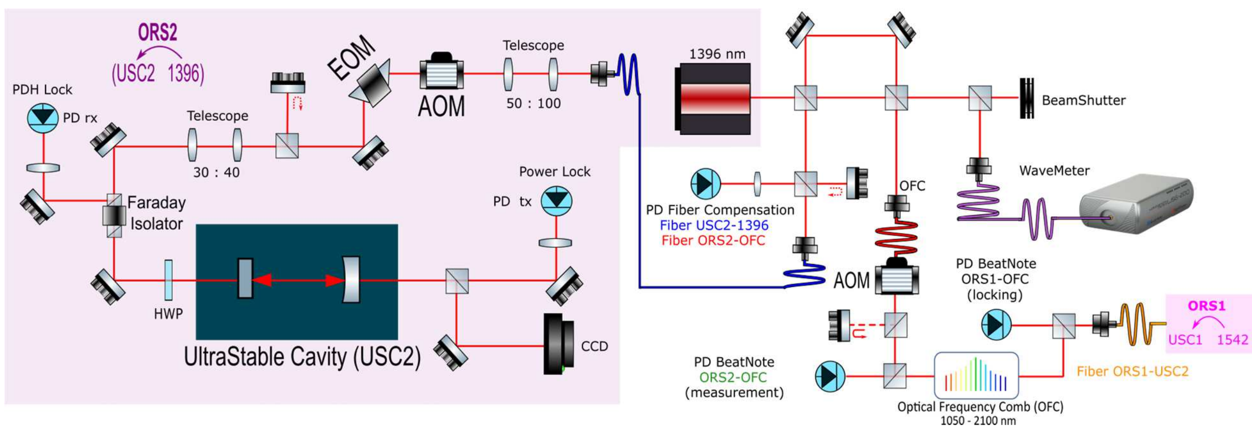

Fig. 2: On the left is shown the PDH lock scheme used to phase lock a 1396 nm laser to a high finesse cavity with crystalline mirrors (USC2), i.e, our second optical reference system (ORS2). On the right, the light distribution of the 1396 nm laser to the cavity setup, wavemeter and optical frequency comb (OFC). Acousto-optic modulators (AOMs) used for active fiber noise compensation.

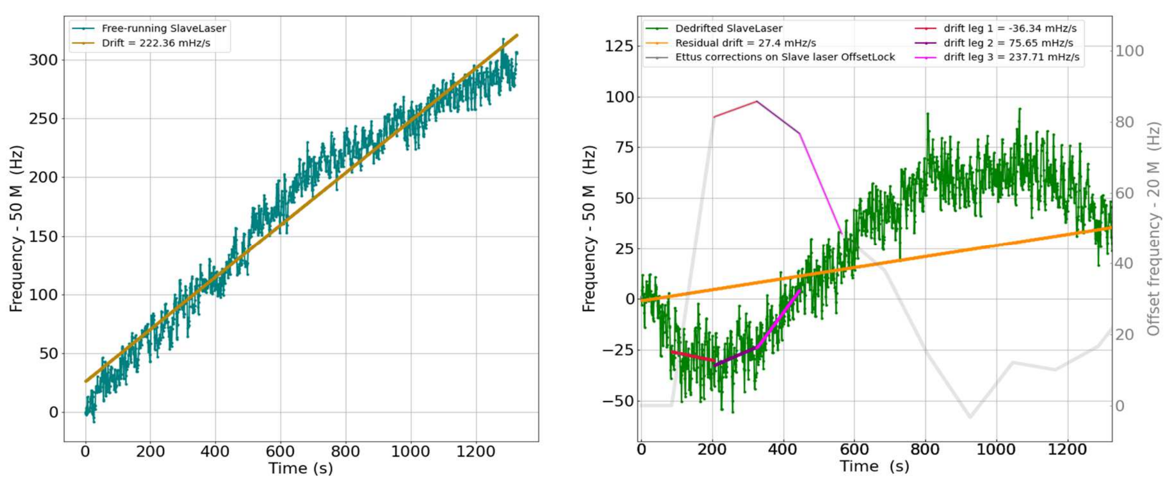

Fig. 3: Left plot: slave laser, offset locked to a free-running master laser, with an averaged drift > 220 mHz/s. Right plot: residual drift < 30 mHz/s of the slave laser after drift corrections on the computer-controlled DDS (Ettus) used in the offset lock setup (see grey dash lined plot in Fig. 1).

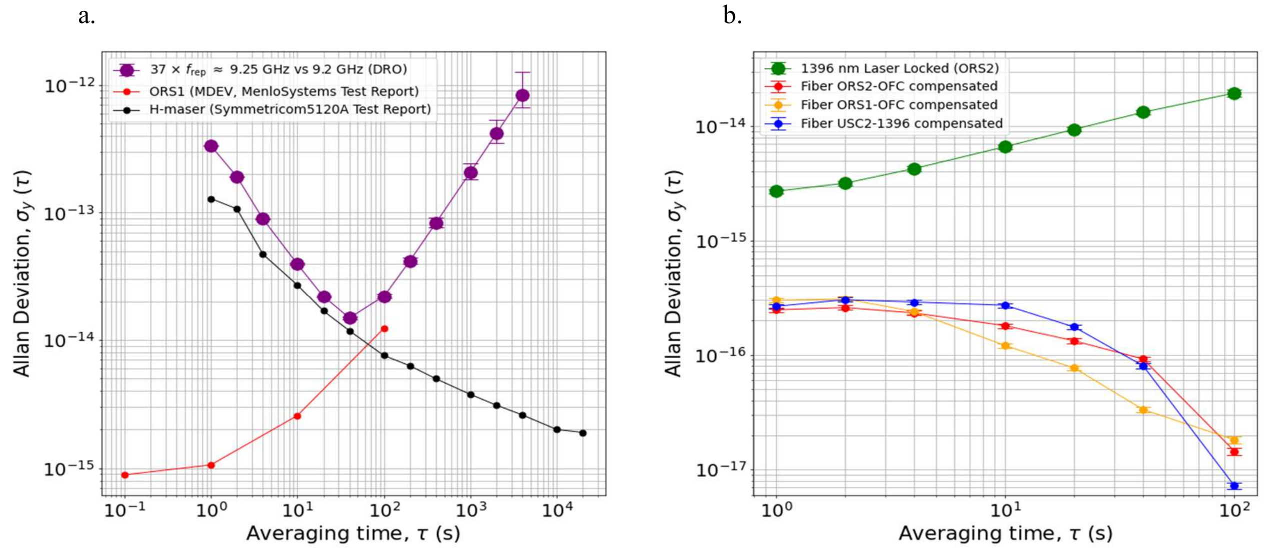

Fig. 4: a. Comparison of the master H-maser against the ORS1 (purple curve). Corresponding H-maser and ORS1 fractional stabilities (black and red curves) taken from their respective manufacturer test reports. b. ORS2 fractional stability of 2.7×10^{-15} at 1 s. The different fibers involved are compensated and the red, orange and blue curves correspond to out-of-loop measurements. All stabilities shown are in Pi mode.

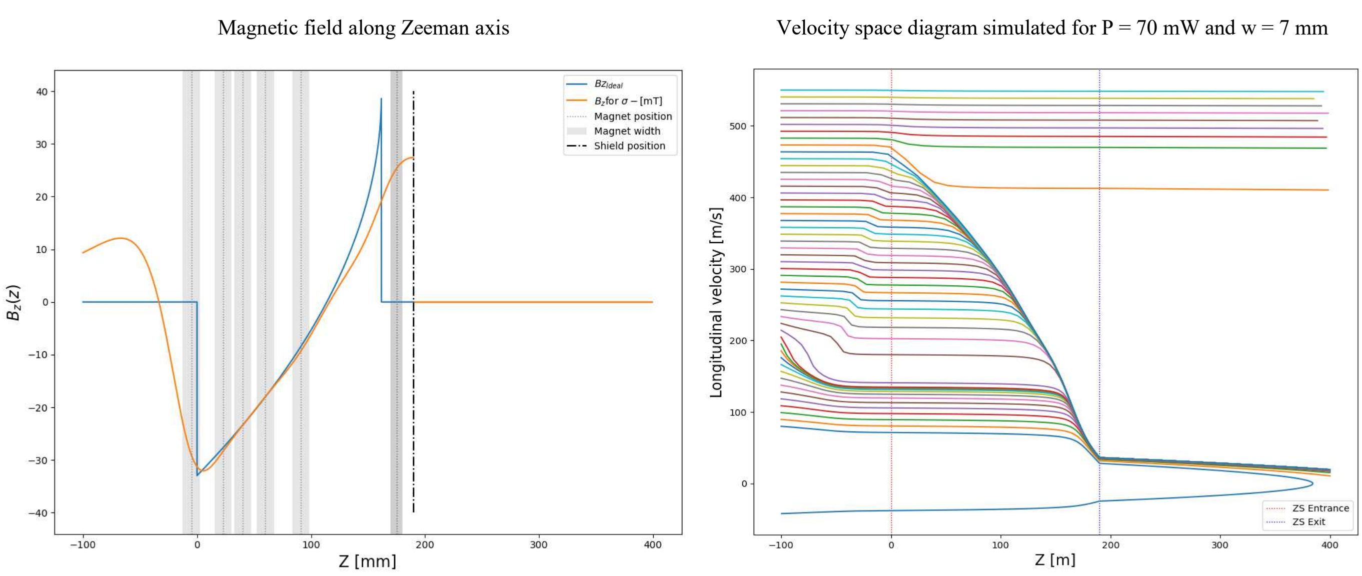

Fig. 5: Simulations of the magnetic field along the Zeeman axis (left) and velocity space diagram (right). The Zeeman slower design is based on 3 fully related parameters: 1/ a velocity capture of 466 m/s, being the higher velocity the apparatus is able to cool down, 2/ the maximum (des)acceleration, defined by the cooling laser optical power of 70 mW, and 3/ the length of the Zeeman slower, defined as the minimum distance to stop atoms at v = 0 m/s, which corresponds to 190 mm for the present case.