Status and Perspectives of INRIM Sr Cavity-Enhanced Optical Clock

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***Abstract*—We report on the status of the strontium optical lattice clock at INRIM and its development towards a cavity-enhanced optical frequency standard exploiting quantum techniques. We have recently developed a novel method to perform high-fidelity spectral purity transfer based on serrodyne optical frequency shifting. We estimated the phase noise induced by the modulation setup by developing a novel composite self-heterodyne interferometer. The consequent short-term stability of our clock is presented, showing collision-limited interaction time in the bosonic ^{88}Sr clock. We also outline the progress towards a cavity-enhanced optical lattice clock. We present a numerical study on collective spin-squeezed states produced by QND continuous measurement of a lossy cavity and its relevance for a Sr optical lattice clock.**

I. Introduction

The Sr optical lattice clock (OLC) at INRIM has been conceived to host and test new technical and conceptual solutions for both transportable and quantum-enhanced OLCs [1]. It employs a cold atomic source for optical loading of the ultracold Sr frequency discriminator [2], and a multiwavelengh frequency stabilization system including the clock laser which dramatically simplifies OLC apparatus [3]. OLC operation has been successfully demonstrated on ultracold ^{88}Sr atoms by magnetic-field induced spectroscopy [4]. Our optical clock has shown a long-term frequency instability as low as $4 \times 10^{-14}/\sqrt{\tau}$, limited by the short local oscillator coherence time. The ultimate goal of our apparatus is to exploit a high-finesse optical cavity with high atom-light cooperativity to generate non-classical collective atomic states which surpass the quantum-projection noise limit [5].

In this work we present the current status and the perspectives of our OLC experiment. In particular, we describe the improvement on the short-term stability of our clock laser by spectral purity transfer enabled by serrodyne modulation of the clock laser beam sent to the multiwavelength cavity for frequency stabilization [6]. We describe the serrodyne modulation setup, the spectral purity transfer system (Sec.II) and its impact on the coherence time of our atomic frequency reference and the short-term clock stability (Sec.III). While the new science cell hosting the cavity-enhanced system is under construction, we performed a numerical study on collective spin-squeezed states produced by QND continuous measurement of a lossy cavity [7] and its relevance for a Sr optical lattice clock (Sec.IV). Finally, we outline some perspectives for our experiment in Sec.V.

II. Serrodyne phase modulation for spectral purity transfer

We implement serrodyne modulation in an optical frequency standard to perform spectral purity transfer between two ultrastable optical frequencies. Relying on an optical frequency comb (OFC) as a transfer oscillator [8], we phase lock a $698\,\mathrm{nm}$ ultrastable laser [3] to a superior ultrastable laser source at $1156\,\mathrm{nm}$ employed in a ^{171}Yb optical lattice clock [9]. Our broadband optical frequency shifter is based on serrodyne modulation of a waveguide EOM in a cavity-stabilized ultrastable optical frequency standard. We have imparted optical shifts between 50 and 750 MHz with efficiencies exceeding 60% and low spurious harmonic generation thanks to a previously untested NLTL component (Picosecond 7100). We assessed the phase jitter added by the serrodyne modulation setup.

We designed a composite self-heterodyne interferometer based on an AOM operating in the Raman-Nath (RN) regime. It consists of two Mach-Zehnder interferometers (MZIs) generated by a beam impinging on the AOM, where the common reference arm is the unshifted AOM's 0th diffraction order, while the 1 and -1 diffraction orders yield two separate MZIs' beatnote frequencies. While one MZI comprises the fiber EOM with serrodyne modulation, and the other is only affected by its optical path fluctuations, both experience the AOM phase noise. However, mixing their beatnotes, it is possible to obtain an RF signal f_m that cancels the anticorrelated AOM phase noise contribution, thus beating the noise wall due to the AOM driver noise. Exploiting RN heterodyne interferometry, the measured phase jitter is lower than $3 \times 10^{-3}\,\mathrm{rad}$ after $1\,\mathrm{s}$ integration time, which is more than one order of magnitude lower than state-of-the-art optical oscillators [10].

Then we achieved low-noise optical phase lock of a 698 nm laser to a 1156 nm laser through a OFC transfer oscillator by feeding back the virtual beatnote frequency deviations to the serrodyne frequency shifter. We observed phase-locking between the two lasers, reaching a white phase noise floor of

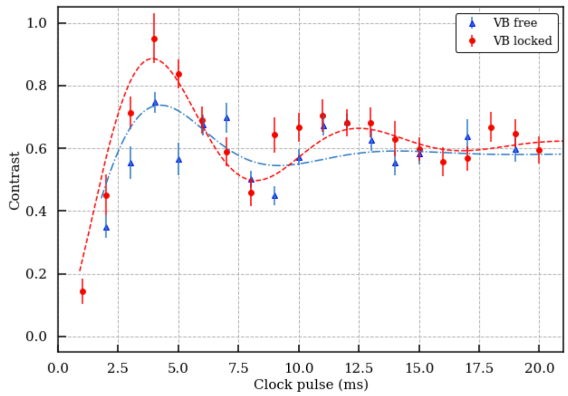

Fig. 1. Rabi oscillations of the ^{88}Sr clock transition with an without phase-locked loop on the virtual beatnote (VB).

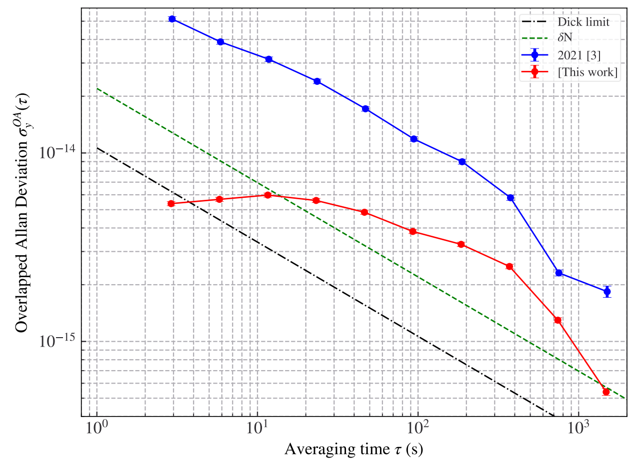

Fig. 2. Interleaved frequency instability of the ^{88}Sr clock after SPT compared with the earliest result [3].

$-80\,\mathrm{dBrad^2/Hz}$ up to $10\,\mathrm{kHz}$, limited by the bandwidth of the fiber noise cancellation servo.

III. Sr OLC atomic coherence and instability

The first operation of the Sr optical lattice clock (OLC) at INRIM was performed with ^{88}Sr as frequency discriminators and using the multiwavelength cavity as short-term frequency reference for our clock laser. This resulted in successful operation of the clock for few hours without unlocks and down-times, reaching a long-term frequency instability as low as $4 \times 10^{-14}/\sqrt{\tau}$, limited by the short local oscillator coherence time. It has been characterized by measuring Rabi oscillations, as shown in Fig. 1, where a coherence time of about 10 ms is observed.

By using the virtual beatnote as new frequency reference and serrodyne modulation for phase lock to the Yb laser, we observed an increase of visibility of a factor 2, as show in figure. First tests of interleaved stability show a new instability level of $2.2 \times 10^{-14}\,1/\sqrt{\tau}$, with a Dick limit five times lower, as reported in Fig. 2. Because of low detection efficiency, we are constrained to operate with a relatively high number of atoms ($\sim 5 \times 10^4$ atoms). This limits now the clock stability because of line broadening [11].

IV. Spin-squeezing generation in cavity-coupled atomic ensembles with continuous measurements

In order to understand the ultimate metrological advantage in employing our cavity-enhanced OLC setup, we performed a numerical study about the generation of spin-squeezed states by coupling three-level atoms to an optical cavity and continuously measuring the cavity transmission in order to monitor the evolution of the atomic ensemble [7]. Using microscopic simulations of the full dynamics, we show that one can achieve significant spin-squeezing even without the continuous feedback that is proposed in optimal approaches [12]. We distinguish between different squeezing regimes and characterise the dependency of squeezing generation on the various parameters which characterise the system configuration.

We mainly focus on Λ-type atomic level configurations [13], but show how our results can be adapted to V-type configurations which are relevant to our apparatus.

We identify an ideal regime of the initial parameters, i.e. atom-cavity coupling, cavity detuning, external driving rate, and cavity decay constant, in which the achieved squeezing depends solely on the atomic ensemble size. In this regime the metrological gain does not reach Heisenberg scaling as for schemes employing continuous feedback [12], but is is comparable to the scaling for other squeezing methods (e.g. One-Axis Twisting [14]) with the advantage of relying on a much simpler experimental configuration that does not require a strict feedback control of the atomic system.

V. Outlook and Perspectives

The Sr OLC at INRIM is progressing towards state-of-art optical clocks. The newly realized transfer oscillator scheme promises to boost the stability and the coherence of the system, which will be fully exploited in the cavity-enhanced setup. The broadband optical frequency shift allowed by serrodyne modulation will easily be used for other Sr isotopes, with both metrological and fundamental applications.

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