INRIM Sr Optical Clock: An Optically Loaded Apparatus for High-Stability Metrology

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***Abstract*—We report on the development of a new compact strontium optical lattice clock employing a 2D-MOT as cold atomic source. The clock system reliability is currently studied using the most abundant isotope, the bosonic ^{88}Sr. More than 10^5 ^{88}Sr atoms are loaded in the optical lattice at 813 nm at temperatures of few microKelvin. All the needed optical frequencies are stabilized to a zero-CTE high finesse optical resonator, and can be operated without frequency adjustments for weeks. The system shows the advantage of optical guiding and switching the atomic source to the clock spectroscopy region by demonstrating more than 17 s lifetime. First spectroscopy tests on the clock transition on ^{88}Sr atoms has been performed by magnetic-field induced spectroscopy.**

I. Introduction

The simple electronic structure and its commercial accessible cooling transitions made the Sr atom one of most used atomic species in AMO laboratories. Thanks to the long living intercombination and clock transitions, the Sr atom finds a successful application in the precision measurements field like optical clocks [1], [2], quantum control and quantum simulation [3], [4], searches of new physics beyond the standard model [5], and chronometric geodesy [6], [7].

In this work we present current status of the Sr optical atomic clock at INRIM. The latest results focus on the laser frequency stabilization system (Sec.II), atomic manipulation and preparation (Sec.III), and lattice trapping characterization (Sec.IV), and finally the first clock transition spectroscopy (V).

II. The frequency stabilization system

The INRIM Sr lattice clock is designed to implement a multiwavelengh frequency stabilization [8] to an optical cavity, replacing any additional atomic spectroscopy systems provided by heatpipes or hollow cathode lamps. It is based on a monolithic optical cavity made by ULE with high-reflectivity coating at three wavelengths ($922\,\mathrm{nm}$, $689\,\mathrm{nm}$ and $813\,\mathrm{nm}$) corresponding to the three main cooling and trapping wavelength, with peak finesse ($\sim$ 10000) for the narrow intercombination transition wavelength at 689 nm, which is also close to the clock transition at $698\,\mathrm{nm}$.

The temperature of cavity is actively stabilized to its zero-CTE point at $29.34\,^{\circ}\mathrm{C}$, which we measured by beating our 689 nm laser to an optical frequency comb stabilized by a H-maser.

The two cooling lasers at $922\,\mathrm{nm}$, for the $^1\mathrm{S}_0-{}^1\mathrm{P}_1$ first-stage cooling and detection transition, and $689\,\mathrm{nm}$, for the $^1\mathrm{S}_0-{}^3\mathrm{P}_1$ second-stage cooling transition, are frequency stabilized to the multiwavelength ULE cavity by means of the dual-sideband offset locking technique [9]. This modified version of the Pound-Drever-Hall (PDH) technique allows to tune the carrier frequency from the cavity resonance by shifting the modulation frequency Ω_{gap} while the PDH signal is extracted by demodulating the photodiode signal at the second sideband Ω_{PDH}.

The cavity drift is monitored with respect to the resonance transition $^1\mathrm{S}_0-{}^3\mathrm{P}_1$, in particular by looking at the red MOT shape [10]. From the adjustments of Ω_{gap} we infer an average drift rate of $0.1\,\mathrm{Hz/s}$. This low drift value allows us to prepare and manipulate ultra-cold samples of Sr atoms without any frequency adjustment for weeks.

The clock laser at $698\,\mathrm{nm}$ is also preliminarily frequency stabilized to the multiwavelength cavity, entering from the opposite side of the cavity with respect to the $689\,\mathrm{nm}$ laser with opposite polarization [11]. The $698\,\mathrm{nm}$ laser is locked to cavity with the standard PDH technique. A fast servo loop on the diode injection current yields a control bandwidth of 1.2 MHz, thus the laser stability is limited by the cavity length instability. We measured a short term instability of $\sigma_\nu \sim 2$ Hz at $1\,\mathrm{s}$ via virtual beatnote against an ultra-stable laser at the ytterbium clock transition wavelength. Similar instability affects the $689\,\mathrm{nm}$ laser.

III. Atomic sample preparation

The characterization of the 2D-MOT atomic source and the first cooling and trapping stage exploiting the strong ("blue") $^1\mathrm{S}_0-{}^1\mathrm{P}_1$ transition have been already described in a previous work [12]. A first magneto-optical trap (MOT) is loaded in in $410\,\mathrm{ms}$. A low intensity blue MOT phase of $6\,\mathrm{ms}$ is applied reducing the blue MOT saturation parameter $s = 0.26$. This low intensity MOT stage reduces the temperature of the blue MOT from $8(1)\,\mathrm{mK}$ to $2(1)\,\mathrm{mK}$. At the end of this first cooling stage, we collect $7\times10^6\,\mathrm{atoms}$.

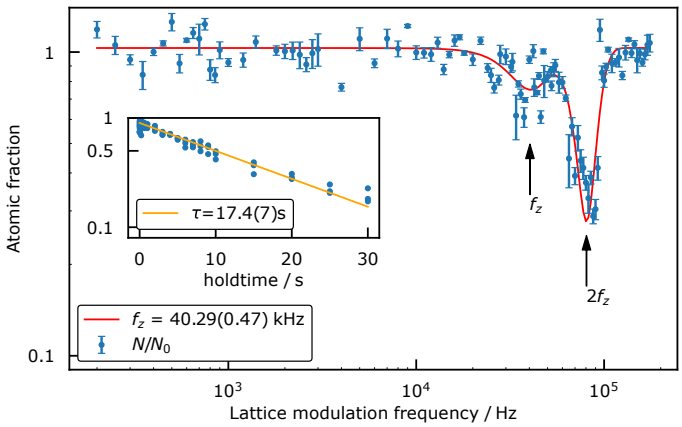

Fig. 1. Characterization of optical lattice. The main panel shows the fraction of survived atoms in the lattice as function of the AM modulation frequency under parametric excitation. The trap frequency signature is provided by a depletion of the atomic signal in the lattice at frequency of the main trapping frequency f_z and its parametric excitation resonance at $2f_z$. The inset shows the fraction of atoms as function of its hold time in the lattice.

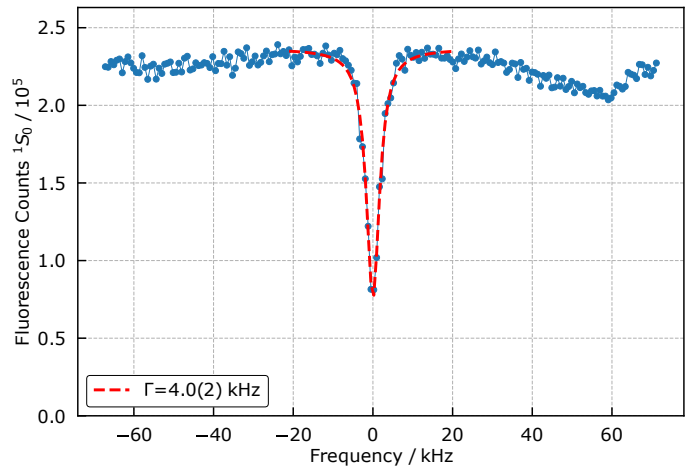

Fig. 2. Magnetic-induced clock spectroscopy on ^{88}Sr atoms in an optical lattice (B = 11 mT). The sideband spacing is about 60 kHz, while the mean vibrational quantum number can be found from the ratio of the lower to the upper sideband amplitude, which yields a value of $\langle n \rangle$ = 0.8, which indicates an average lattice temperature of 3(1) μK.

A second ("red") MOT cooling stage operating on the $^1S_0 - {}^3P_1$ intercombination transition is then employed for efficient loading in the optical lattice [10]. Optimal transfer from the blue to the red MOT is achieved with a initial FM modulation of 35 kHz, modulation depth of 3 MHz and shifted by -800 kHz from $^1S_0 - {}^3P_1$ transition. At the end of this broad-band stage, we trap 3.8×10^6 atoms at 11 µK, resulting in a transfer efficiency of 66 % from blue MOT to the broad-band red MOT. The transfer process from the blue MOT to the red broad-band MOT is obtained in 220 ms.

The final ultra-cold temperature of the atomic sample is reached switching to single frequency and adiabatically ramping down the beams' power from 13 mW to 10 µW in 30 ms. At the end of this stage, we trap 3.5×10^6 atoms below 1 µK. The transfer efficiency from blue MOT to the red MOT single frequency is 60 %.

The overall loading time for the blue MOT loading and also for the broad-band MOT loading can be further reduced and optimized. For all the manipulation, no repumpers are employed.

IV. Lattice trapping and characterization

First tests of trapping strontium atoms in an optical lattice in the Lamb-Dicke regime were performed.

The lattice trap is achieved with 600 mW of 813 nm laser input, and a waist of 50 µm overlapped at the red MOT atomic position. During the sample preparation, the lattice trap is always turned on. After 30 ms from red-MOT turn-off, more than 10^5 atoms remain trapped in the lattice at a temperature of 1.3 µK, obtained by time-of-flight ballistic expansion measurement.

The optical lattice was further characterized by measuring its lifetime and the trapping frequencies, as shown in Fig. 1. Here, the inset reports a lifetime of 17.4(7) s, enjoying the absence of a direct atomic source flux. The lattice trapping frequencies were measured by parametric excitation exerted by AM modulation of the lattice power (modulation index $\varepsilon = 1.5\,\%$ and pulse duration of 500 ms). The excitation spectrum is reported in Fig. 1, showing dips in the lattice population corresponding to the second and first harmonic of the axial trapping frequency at $f_z = 40.3(5)$ kHz, which corresponds to a lattice depth of $38.8(5)E_R$ and a Lamb-Dicke parameter of $\eta = 0.10(1)$.

V. First tests of magnetic-field induced spectroscopy of the Sr clock transition

Finally, first tests of clock spectroscopy in our apparatus are performed on the bosonic ^{88}Sr isotope, whose clock transition is doubly-forbidden and has to be induced by an external field, coupling the excited clock state to a dipole-allowed transition. Magnetic-field induced spectroscopy (MIS) [13] is the easiest and most common method to perform clock spectroscopy on the ^{88}Sr atom.

Figure 2 reports a MIS spectrum of the clock transition of ^{88}Sr atoms confined to an optical lattice. We employ the MOT coil pair to generate a bias magnetic field (up to 11 mT) along the vertical axis, nearly orthogonal to the lattice direction which induces the doubly-forbidden $^1S_0 - {}^3P_0$, while a dichroic mirror is used both as retro-reflecting mirror for the trapping light and as input coupler for the clock light at 698 nm. After the clock laser pulse, a probe pulse of 0.7 ms resonant to the strong $^1S_0 - {}^1P_1$ transition is applied to the atomic sample and its fluorescence is then collected by the CCD camera and processed. For long interrogation pulses and strong bias fields a strong depletion of the ground state population, much larger than 50%, is observed, in agreement with inelastic collisional losses for this particular atomic species [14], [15]. As shown in Fig.2, sideband spectroscopy data is in full agreement with time-of-flight and parametric excitation measurements.

VI. Conclusions

After few years since the start of this project [16], INRIM's Sr optical clock is ready to perform high-stability metrology in a new compact apparatus enjoying the high accuracy features granted by optical loading from a sideband-enhanced 2D-MOT atomic source [12]. The clock transition has been successfully observed in the Lamb-Dicke regime and reported here for the first time. Further stability and accuracy tests of the apparatus are currently on-going. This result also represents a preliminary step before switching to the strongly-coupled atom-cavity system needed to generate non-classical many-body states and study superradiance on the Sr clock transition [17].

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