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Optical lattice clocks towards the redefinition of the second

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Abstract. Nowadays atomic optical lattice clocks can perform frequency measurements with a fractional uncertainty at the 10^{-18} level in few hours of measurement, outperforming the best caesium (Cs) standards operated in the world. Since the definition of the unit of time is based on Cs, a worldwide debate about the need to promote the redefinition of the second on a optical reference is under-way. At INRIM (Istituto Nazionale di Ricerca Metrologica) we developed an optical lattice clock based on ytterbium atoms and compared it against a Cs fountain. These results are an important contribution to the debate.

1. Introduction

The time unit, i.e. the second, is one of the base units in the International System of Units (SI). Its definition is based on the atomic transition between two hyperfine levels of the caesium (Cs) atom ground state [1]. Cs frequency standards [2], or Cs clocks, are in charge of the second realization: they generate a microwave whose frequency matches the second definition requirements, being able to excite Cs atoms on the mentioned atomic transition. This microwave can thus be used to calibrate all other oscillators.

Atomic clocks can also be based on other atomic transitions. Nowadays, among the best performing clocks there are optical lattice clocks, which use optical atomic transitions as frequency reference. World best optical lattice clocks currently provide frequency measurements with ultimate fractional uncertainties at the level of 10^{-18} after 3 hours of measurement [3, 4]. Best performing Cs standards are instead showing fractional uncertainties of about 2.3×10^{-16} after 9 days of continuous measurement [5].

The interest in developing optical frequency standards is due to their high quality factor Q, with respect to the one of Cs standards. The quality factor is defined as $Q = f/\Delta f$, where f is the frequency of the reference atomic transition (clock transition) and Δf is the clock transition linewidth. Since Δf is similar in both microwave and optical standards, the five order of magnitude higher frequency of an optical radiation with respect to a microwave lets perform frequency measurements at higher resolution.

Optical clocks need to be calibrated by measuring their oscillator frequency against a Cs standard. This comparison is currently possible through the use of the optical frequency comb

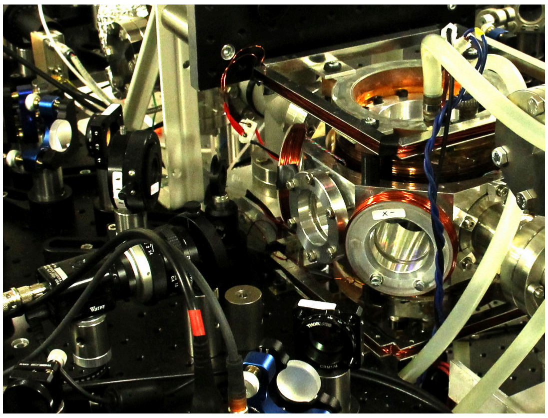

Figure 1. Picture of the INRIM ^{171}Yb optical lattice clock vacuum chamber.

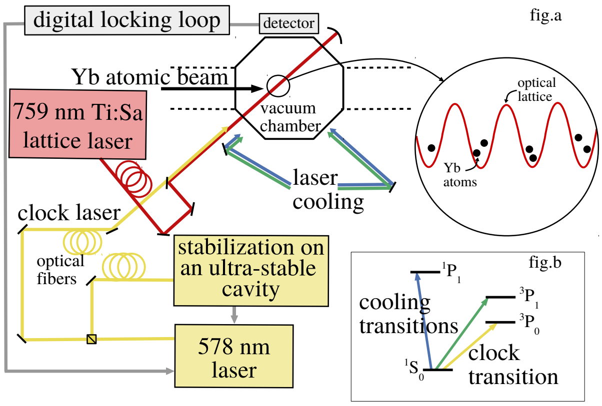

Figure 2. (a) Scheme of the INRIM ^{171}Yb optical lattice clock experimental set-up (b) Yb atomic transitions relevant for the clock operation.

[6], which bridges the frequency gap between the two oscillator frequencies. This process leads on one hand to the use of optical clocks as a secondary representation of the second, but on the other end the comparison is limited by the Cs clocks uncertainty budget. The large discrepancy between the performances of optical and microwave standards has thus opened the way for a worldwide ongoing discussion about the need to change the SI definition of the second [7].

Beyond the metrological purpose of the optical clocks research field, the availability of accurate optical frequency standards has an important impact on fundamental physics research. For instance, radioastronomy has significantly benefited from the possibility to accurately synchronize radio-antennas for very long baseline interferometry [8]. Relativistic geodesy has also been affected by the availability of accurate frequency standards, which are sensitive detectors of gravity variations [9]. Finally, optical clocks can be used to investigate the variation of fundamental constants, such as the fine structure constant [10].

At the Istituto Nazionale di Ricerca Metrologica (INRIM), in Italy, we developed and fully characterized an ^{171}Yb optical lattice clock [11]. An absolute frequency measurement has been performed against the INRIM Cs fountain clock, which is the Italian primary frequency standard.

2. The Ytterbium-171 optical lattice clock

The ^{171}Yb optical lattice clock uses as atomic frequency reference the transition between the $^1S_0$ (ground state) and the $^3P_0$ states at 578 nm. The local oscillator is a yellow laser, whose linewidth is required to be 1 Hz for probing the narrow clock transition. This is accomplished thanks to a frequency stabilization scheme based on an ultra-stable optical Fabry-Pérot cavity (see Fig. 2) [12].

The clock transition is a good frequency reference if it is completely unperturbed or if frequency shifts of the transition due to perturbations are well controlled, i.e. are measured accurately. In order to realize such controlled environment, atoms need to be wisely prepared for the interrogation process. Firstly, a cloud of Yb atoms inside a vacuum chamber (see Fig. 1) are laser cooled down to microkelvin temperatures [13], exploiting radiation pressure from laser beams interacting with blue and green Yb transitions (see Fig. 2). Atoms have to be cold in order to be afterwords successfully loaded in the potential wells of an optical one-dimensional lattice, generated as a laser standing wave (see Fig. 2). Thanks to the strong confinement, the atomic transition Doppler frequency shift is suppressed. Moreover, the trapping lifetime of the atoms in the lattice, usually longer than 1 s, allows long interrogation pulses. Furthermore, this spatially confining technique lets trap thousands of neutral atoms: the interrogation of this atom sample leads to a high resolution signal. Finally, the frequency shift caused by the interaction between the lattice laser and the atoms is cancelled at the first order by selecting appropriately the lattice wavelength. At this so-called *magic wavelength*, the two clock states are shifted by the same amount, keeping the clock transition unperturbed [14]. For Yb, the magic wavelength has been experimentally determined to be 759 nm [11, 15, 16].

Thousands of atoms in the lattice sites are thus ready to be interrogated by the clock laser (see Fig. 2). In the process, a single laser pulse of duration within 60 ms and 100 ms interacts with the atoms: if the laser is resonant, atoms will be excited along the clock transition, otherwise a computer controlled loop move the laser frequency closer to resonance, locking it to the atomic reference.

Since residual atoms perturbations are present, the systematic frequency shifts generated by these effects have to be evaluated and applied to the clock frequency as a correction term. While the physical parameter leading to the frequency shift is under control, the shift measurement is performed by comparing two Yb clock frequency measurements where the parameter under test has been changed. This is done by interleaving two frequency measurements in the two different operating regimes. For example, interleaving a clock cycle with a high number of atoms in the lattice with a clock cycle with a low number of atoms in the lattice allows to evaluate the frequency shift due to atomic collisions, which are proportional to the atomic density of the interrogated sample. The uncertainty of frequency shift measurements performed with this method is statistically limited by the measuring time, thus the physical effects concerned are not limiting issues. If the effect perturbing the atoms is not controlled, the frequency shift evaluation can be performed indirectly by measuring correlated quantities. The uncertainty of such evaluations would depend on the knowledge about the effect and the capacity to set-up the required specific experiment; as a result, these effects would probably contribute to the total uncertainty to a greater extent. The total uncertainty coming from residual frequency shift measurements represents the clock accuracy limit.

The ^{171}Yb optical lattice clock developed at INRIM has been recently characterized with a fractional uncertainty limit of 1.6×10^{-16} [11]. Main contributions to the uncertainty budget are the second order shifts due to the atoms interaction with the lattice laser and the shift generated by the black body radiation. Both effects are under investigation in order to be tackled properly. Concerning the latter for example, at the National Institute of Standards and Technology (NIST, USA) researchers decided to enclose atoms in a black body chamber into vacuum, in order to have a high degree of control of the black body temperature affecting atoms [17], while at RIKEN (Japan) researchers decided to interrogate atoms in a cryogenic environment [3], directly cancelling the black body radiation source.

3. Absolute frequency measurement of the ^{171}Yb clock transition

^{171}Yb clock transition, among other atomic transitions, has been recommended as a secondary representation of the second by the International Committee for Weights and Measures (CIPM) [18], which is in charge of the establishment of the international metrological conventions. This recommendation follows the availability of ^{171}Yb clock frequency measurements performed independently around the world [19 - 22]. At INRIM a direct absolute frequency measurement of the Yb clock transition against the INRIM Cs fountain clock as been performed [11]: the measurement value results to be 518 295 836 590 863.59(31) Hz, which is in agreement with the recommended value for ^{171}Yb [18]. This is the first direct measurement of the ^{171}Yb clock transition at this level of uncertainty. This measurement further confirm previous measurements and contribute to reaffirm the ytterbium transition as an interesting candidate for the redefinition of the SI second.

4. Conclusions

Optical clocks nowadays are outperforming Cs clocks by many order of magnitude both in term of accuracy and stability, raising the question about a redefinition of the SI second based on an optical atomic transition. Many different optical transitions, both in the visible and in the UV region, are being investigated. The ^{171}Yb transition has been already measured in many independent experiments with an high accuracy; at INRIM we demonstrated an ^{171}Yb optical lattice clock with a fractional uncertainty limit of 1.6×10^{-16} and we measured its frequency against the Cs Italian primary frequency standard with a fractional uncertainty of 5.9×10^{-16}. In addition, ytterbium has the potential to see further increased the control of its perturbations thanks to its atomic structure and properties. Thus, Yb clocks are competitive in the world scenario in the fullfilment of the requirements leading to the SI second redefinition.

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