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Ytterbium optical lattice clock at INRIM

Marco Pizzocaro*†, Filippo Bregolin*‡, Gianmaria Milani*†, Benjamin Rauf*†, Pierre Thoumany*†,
Giovanni Antonio Costanzo*†, Filippo Levi* and Davide Calonico*

*Istituto Nazionale di Ricerca Metrologica (INRIM), Physic Metrology Division,
Str. delle Cacce 91, 10135 Torino, Italy.
Email: m.pizzocaro@inrim.it
†Politecnico di Torino, Dipartimento di Elettronica e Telecomunicazioni,
C.so duca degli Abruzzi 24, 10125 Torino, Italy
‡Università di Torino, Dipartimento di Fisica,
Via Giuria 1, 10125, Torino, Italy

Abstract— **We present an optical lattice clock based on ytterbium ^{171}Yb atoms developed in the laboratories of INRIM. In the experiment, we cool and trap ytterbium atoms in a two stage magneto-optical trap (MOT) (at 399 nm and 556 nm for the first and second stage, respectively). Atoms are then transferred in a horizontal, one-dimensional optical lattice at the magic wavelength (759 nm). Here the clock transition at 578 nm is probed by a laser stabilized on an ultra-stable cavity. We describe the generation of all the laser sources, the physic package and the operation of the clock. Lasers at 399 nm, 556 nm and 578 nm are obtained, with different techniques, using non-linear crystals starting from infrared sources. The clock laser is stabilized using a high finesse notched ULE cavity. The lattice is made with a titanium-sapphire laser. The aluminum vacuum chamber is designed for wide optical access and its temperature is measured by 8 thermistors for blackbody shift evaluation. Our system allows for fast loading of the lattice with 1×10^4 atoms trapped in the lattice in 250 ms. We obtained preliminary spectroscopy results and we locked the clock laser to the atomic line. Future perspectives are discussed.**

I. INTRODUCTION

Among other the clock transition $^1S_0 - {}^3P_0$ at 578 nm of ytterbium ^{171}Yb neutral atom is recommended as secondary representations of the SI second reflecting the measurements made at National Institute of Standards and Technology (NIST) [1], [2], at the National Metrology Institute of Japan (NMIJ) [3] and at the Korea Research Institute of Standards and Science (KRISS) [4]. Figure 1 show the Ytterbium transitions relevant for clock operations. Note that ^{171}Yb is fermionic with nuclear spin $I = 1/2$ and further hyperfine structure is present. Ytterbium is easy to cool and trap in a double stage magneto-optical trap (MOT) exploiting the strong transition at 399 nm $^1S_0 - {}^1P_1$ (linewidth 29 MHz) and achieving microkelvin temperatures with the weaker transition at 556 nm $^1S_0 - {}^3P_1$ (linewidth 182 kHz). Ytterbium can then be loaded in an optical lattice at the magic wavelength (759 nm). A repumper at 1389 nm resonant with the $^1P_0 - {}^3D_1$ transition can be used to pump atoms from the clock state $^3P_0$ to the ground state $^1S_0$.

We are developing a ytterbium optical lattice clock based on ^{171}Yb. The experimental setup and the laser ensemble are complete while the characterization of the clock is under way. In the following we will describe the physic package, the laser ensemble and the operation of our clock as well as first spectroscopy results and future perspectives.
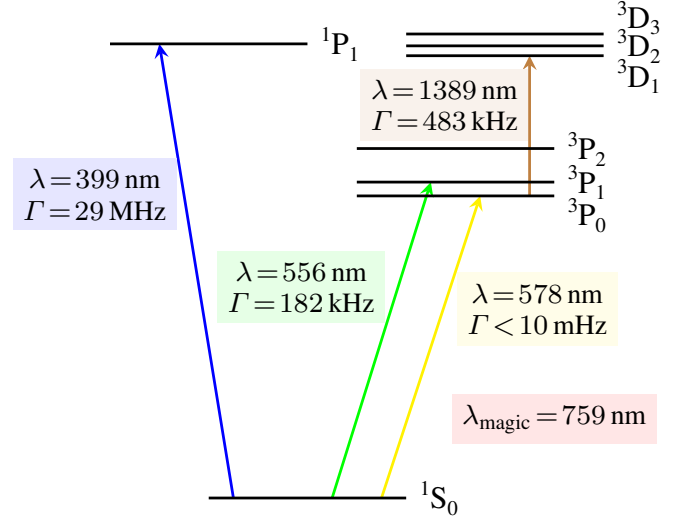

Fig. 1. Ytterbium levels relevant for clock operations

II. EXPERIMENTAL SETUP

A. Physic package

Figure 2 shows a scheme of the physic package and of the vacuum chamber. The atomic source is an effusion oven at 400 °C that produces a collimated atomic beam. Atoms are trapped in a custom aluminum chamber with indium-sealed viewports, designed for wide optical access. The chamber is designed without a Zeeman slower. Instead the distance between the trapping region and the atomic source is made as short as possible to maximize the atomic flux. During operation the chamber is kept in ultra-high vacuum (pressure $< 10^{-9}$ mbar) by two ion pumps and one non-evaporable getter pump.

The water-cooled MOT coils are outside the vacuum chamber, in the vertical direction. Three pairs of Helmholtz coils are used to compensate the stray magnetic field. Eight thermistors are placed on the aluminum vacuum chamber for blackbody shift evaluation.

B. Laser ensemble

The 399 nm radiation is obtained by second harmonic generation (SHG) from a 798 nm titanium-sapphire (Ti:sapphire)
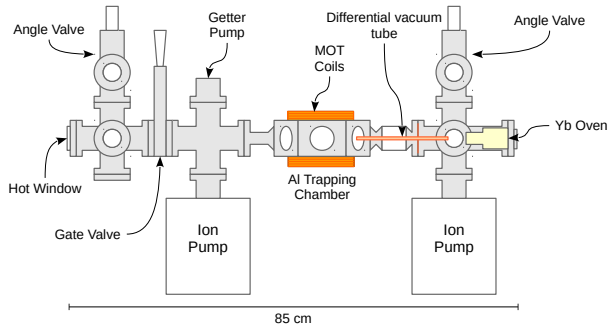
Fig. 2. Schematics of the physic package.

Fig. 3. Experimental setup for the lattice clock.

laser using a lithium triborate (LBO) crystal in an enhancement cavity [5]. The Ti:sapphire laser has an output power of $1.1\,\text{W}$ pumped by a $8\,\text{W}$ solid state pump laser at $532\,\text{nm}$. Up to $0.9\,\text{W}$ has been obtained but a typical output of $0.5\,\text{W}$ at $399\,\text{nm}$ is used for the experiment. The frequency can be locked to the atomic resonance of any ytterbium isotopes by transverse spectroscopy on an auxiliary atomic beam. Polarization-maintaining optical fibers deliver the $399\,\text{nm}$ light to the atoms for the first stage MOT, the slower beam and the detection probe beam.

The $556\,\text{nm}$ radiation is obtained by SHG from $1112\,\text{nm}$ amplified, ytterbium doped fiber laser using a single-pass periodically-poled potassium titanyl phosphate (PPKTP) crystal. Typically $10\,\text{mW}$ of $556\,\text{nm}$ light are obtained starting from $1.0\,\text{W}$ of infrared light. The frequency of the $556\,\text{nm}$ laser is locked to the resonance of a Corning Ultra Low Expansion glass (ULE) cavity, with acousto-optic modulators (AOMs) bridging the gap to the frequency of ^{171}Yb. The green laser is sent to the second stage MOT by polarization-maintaining optical fiber.

The lattice is made by a Ti:sapphire laser pumped by a solid state pump laser at $10\,\text{W}$. An AOM is used as an optical isolator and for power-stabilization. Typically $1\,\text{W}$ of light is send to the atoms using a polarization-maintaining optical fiber.

The clock laser at $578\,\text{nm}$ is obtained by sum frequency generation (SFG) in a waveguide periodically-poled lithium niobate (PPLN) crystal using an erbium fiber laser at $1030\,\text{nm}$ and a neodymium-doped yttrium aluminium garnet (Nd:YAG) laser at $1319\,\text{nm}$ [6]. The output power is typically $4\,\text{mW}$. The frequency is stabilized using the Pound-Drever-Hall technique on a $10\,\text{cm}$ ultra-stable cavity made by ULE, with fused-silica mirrors and ULE rings. The temperature of the cavity is stabilized by a double stage control with Peltier elements to the point of zero coefficient of thermal expansion of ULE. The temperature control is a digital implementation of the powerful Active Disturbance Rejection Control (ADRC) technique [7]. The clock light is delivered to the cavity, to the atoms and to a fiber comb by compensated optical fiber links.

A solid state laser at $578\,\text{nm}$ is under development. The radiation is obtained using a co-doped $\text{LiLuF}_4:\text{Dy}_3\text{Tb}_3$ fluoride crystal pumped by $450\,\text{nm}$ diode laser. [8]. This new compact system with its unique direct emission at $578\,\text{nm}$ could replace the current laser in the future.
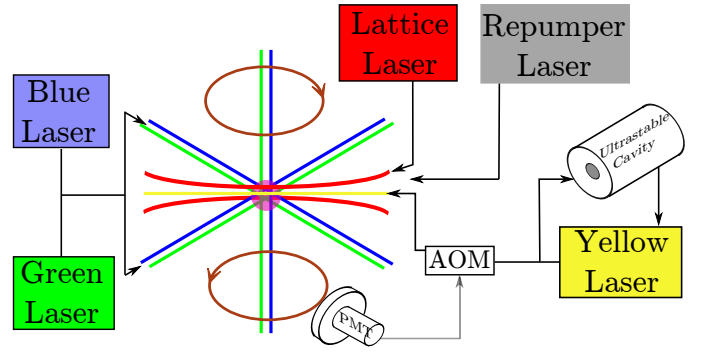
A pigtail distributed feedback laser at $1389\,\text{nm}$ is used as repumper from the clock state to the ground state. It has an output on the atoms of $10\,\text{mW}$ and a frequency variation $< 100\,\text{MHz}$. The power is enough to power-broadened the ytterbium line to $300\,\text{MHz}$ so that active frequency stabilization is not needed.

C. Clock cycle

The clock experimental setup is sketched in fig. 3. First ^{171}Yb atoms are trapped in a $399\,\text{nm}$ MOT from the atomic beam. The six laser beams have a total power of about $30\,\text{mW}$ with a $1/e$ radius of $1\,\text{cm}$ and a detuning of $-20\,\text{MHz}$. The magnetic field gradient is $0.4\,\text{T/m}$ along the vertical axis. A seventh beam, with a power of $50\,\text{mW}$ and a detuning of $-360\,\text{MHz}$ is focused counter-propagating to the atomic beam and acts as a slower. There is no dedicated magnetic field to make a Zeeman slower but we exploit the leaking field of the MOT coils. With the slower beam, we can capture up to 4×10^7 ^{171}Yb atoms. For clock operations, we capture typically 1×10^6 atoms in $150\,\text{ms}$ of $399\,\text{nm}$ MOT.

The second stage $556\,\text{nm}$ MOT is loaded from the $399\,\text{nm}$ MOT with an efficiency up to the $70\,\%$ simply turning off the $399\,\text{nm}$ beams. The $556\,\text{nm}$ beams have a total power of $2\,\text{mW}$, a $1/e$ radius of $0.5\,\text{cm}$ and are left on during the first stage. In $60\,\text{ms}$ we apply 3 stages at different frequency, intensity and magnetic field gradient to maximize the fraction of atoms transferred in the lattice. The first stage ($30\,\text{ms}$) is tuned to maximize the number of atoms in the $556\,\text{nm}$ MOT and has a magnetic field gradient of $0.25\,\text{T/m}$. The second stage ($20\,\text{ms}$) the frequency is brought closer to resonance and the magnetic field reduced to $0.18\,\text{T/m}$ to minimize the atoms temperature, that is reduced to $10\,\mu\text{K}$. The lifetime of this stage is $3\,\text{s}$. In the third stage ($10\,\text{ms}$) the magnetic field gradient is increased back to $0.25\,\text{T/m}$ and the frequency is tweaked to maximize the number of atoms in the lattice.

The lattice laser is delivered to the atoms by polarization-maintaining optical fiber and is focused by an achromatic lens to a waist of $45\,\mu\text{m}$. The laser is retro-reflected by a curved mirror to form a lattice with a depth of 300 recoil energies for $1\,\text{W}$ of power. The lattice is horizontal. We trap typically up to 5×10^3 atoms in the lattice while the maximum number of atoms we trapped was 3×10^4. Lifetime of atoms in the lattice is $3.0\,\text{s}$.

Atoms in the lattice are probed by the clock laser at $578\,\text{nm}$. The clock laser is collimated with a waist of $200\,\mu\text{w}$ collinear
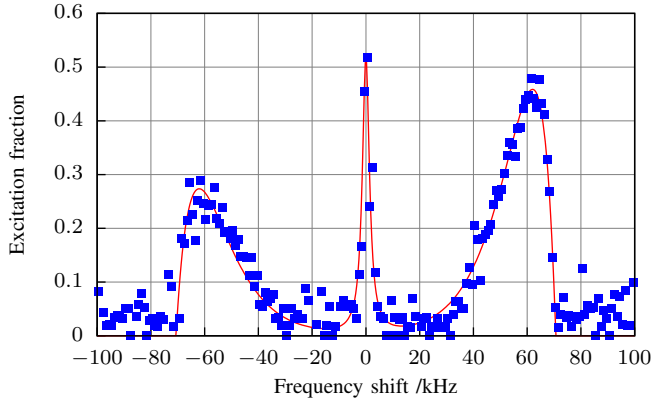
Fig. 4. Spectroscopy signal as a function of the 578 nm laser frequency from 1×10^4 atoms showing the sideband structure of the lattice. Red line is a fit of the sidebands.

to the lattice and is sent to the atoms trough the lattice back-reflector, that is transparent at this wavelength. The lattice and clock polarization are aligned vertically. Other than the 578 nm light, all other radiations are stopped by mechanical shutters during spectroscopy.

The spectroscopy of the atoms is performed by detecting with a photomultiplier tube the fluorescence from the atoms by 3 pulses of resonant light at 399 nm of the duration of 1 ms. The first pulse measures the atoms left in the ground state. The second pulse is used to subtract the background from scattered light and the atomic beam. After the second pulse the repumper laser at 1389 nm is used to pump back atoms from the clock state to the ground state in 12 ms. Then the third pulse detect the number of excited atoms.

Atoms can be prepared for interrogation in around 250 ms. We used clock pulses (Rabi pulses) of typically 50 ms to 100 ms. Total cycle length with detection is between 350 ms to 450 ms.

III. FIRST SPECTROSCOPY RESULTS

Figure 4 show the spectroscopic signal from 1×10^4 atoms in the lattice, while interrogated by $100\,\mu W$ pulses of 578 nm light of 100 ms. From the fit of the shape of the sidebands (red line in the figure) we can deduce a trap frequency of 70 kHz (consistent with a depth of 300 recoil energies) and an atomic temperature of $5\,\mu K$.

Applying a vertical magnetic field during spectroscopy reveals the hyperfine structure of the ytterbium clock line (fig. 5). The clock line is the average of the two π transitions, whose separation changes by 20 Hz/mT. In this figure the polarization of the clock laser was tilted respect to the vertical to show the also the σ transitions.

We used the spectroscopy signal to lock the frequency of the clock laser to the atoms using an AOM.

IV. CONCLUSIONS

We have show the status of the ytterbium optical lattice clock at INRIM. The experimental setup is complete and we achieved first spectroscopy results. In the next step we will
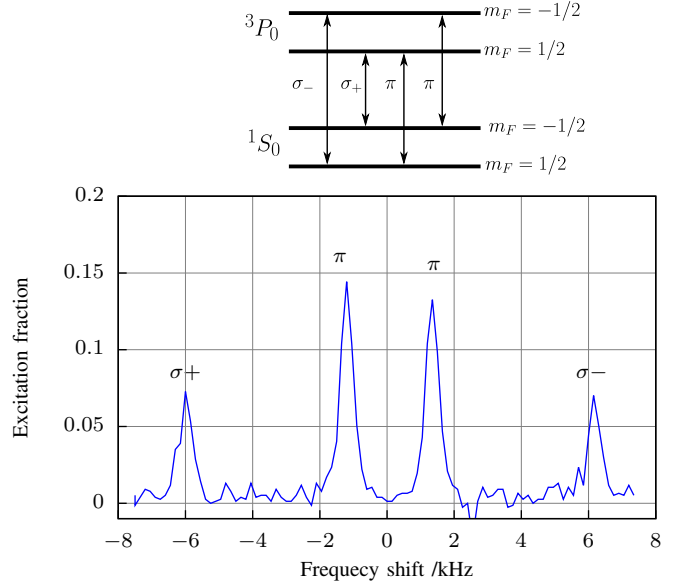

Fig. 5. Hyperfine structure and spectrum of the ytterbium clock transition with a magnetic field applied.

finish the characterization of the clock and measure its absolute frequency respect to the cryogenic fountain IT-CsF2 [9].

Moreover our ytterbium lattice clock is part of the EMRP project "International Timescales with Optical Clocks" [10], where a comparison campaign with other clocks is planned, both local and remote. The clock will be part of a proof-of-principle relativistic geodesy experiment. It will be compared to a transportable strontium clock developed at PTB moved to the Laboratoire Souterrain de Modane (LSM) in the Fréjus tunnel. The comparison will be made through a optical fiber link and with a transportable frequency comb developed at NPL at LSM. General relativity predicts a frequency shift of 10^{-16}/m and we should measure the 1000 m elevation difference between the two clocks at the decimeter level within a few hours.

As well, the Yb clock is part of the project AQUASIM, aiming to compare INRIM's clock to a ytterbium degenerate Fermi gas experiment at European Laboratory for Non-Linear Spectroscopy (LENS) in Florence [11]. The connection will exploit the already existing optical fiber link between the two laboratories [12] and will be useful for studies of collisions physics and quantum simulations.

REFERENCES

[1] N. D. Lemke, A. D. Ludlow, Z. W. Barber, T. M. Fortier, S. A. Diddams, Y. Jiang, S. R. Jefferts, T. P. Heavner, T. E. Parker, and C. W. Oates, "Spin-1/2 optical lattice clock," *Phys. Rev. Lett.*, vol. 103, no. 6, p. 063001, Aug 2009.

[2] N. Hinkley, J. A. Sherman, N. B. Phillips, M. Schioppo, N. D. Lemke, K. Beloy, M. Pizzocaro, C. W. Oates, and A. D. Ludlow, "An atomic clock with 10^{-18} instability," *Science*, vol. 341, no. 6151, pp. 1215–1218, 2013.

[3] M. Yasuda, H. Inaba, T. Kohno, T. Tanabe, Y. Nakajima, K. Hosaka, D. Akamatsu, A. Onae, T. Suzuyama, M. Amemiya, and F.-L. Hong, "Improved absolute frequency measurement of the ^{171}yb optical lattice clock towards a candidate for the redefinition of the second," *Applied Physics Express*, vol. 5, no. 10, p. 102401, 2012.

[4] C. Y. Park, D.-H. Yu, W.-K. Lee, S. E. Park, E. B. Kim, S. K. Lee, J. W. Cho, T. H. Yoon, J. Mun, S. J. Park, T. Y. Kwon, and S.-B. Lee, "Absolute frequency measurement of $^{1}S_0$ ($f = 1/2$) - $^{3}P_0$ ($f = 1/2$) transition of ^{171}Yb atoms in a one-dimensional optical lattice at KRISS," *Metrologia*, vol. 50, no. 2, p. 119, 2013.

[5] M. Pizzocaro, D. Calonico, P. C. Pastor, J. Catani, G. A. Costanzo, F. Levi, and L. Lorini, "Efficient frequency doubling at 399 nm," *Appl. Opt.*, vol. 53, no. 16, pp. 3388–3392, Jun 2014.

[6] M. Pizzocaro, G. A. Costanzo, A. Godone, F. Levi, A. Mura, M. Zoppi, and D. Calonico, "Realization of an ultrastable 578-nm laser for an Yb lattice clock," *IEEE Trans. Ultrason., Ferroelect., Freq. Cont.*, vol. 59, no. 3, pp. 426–431, march 2012.

[7] M. Pizzocaro, D. Calonico, C. Calosso, C. Clivati, G. A. Costanzo, F. Levi, and A. Mura, "Active disturbance rejection control of temperature for ultrastable optical cavities," *IEEE Trans. Ultrason., Ferroelect., Freq. Cont.*, vol. 60, no. 2, pp. 273–280, february 2013.

[8] G. Bolognesi, D. Parisi, D. Calonico, G. A. Costanzo, F. Levi, P. W. Metz, C. Kränkel, G. Huber, and M. Tonelli, "Yellow laser performance of Dy_3^+ in co-doped $DyTb:LiLuF_4$," *Opt. Lett.*, vol. 39, no. 23, pp. 6628–6631, Dec 2014.

[9] F. Levi, D. Calonico, C. E. Calosso, A. Godone, S. Micalizio, and G. A. Costanzo, "Accuracy evaluation of itcsf2: a nitrogen cooled caesium fountain," *Metrologia*, vol. 51, no. 3, p. 270, 2014.

[10] H. Margolis, R. Godun, P. Gill, L. Johnson, S. Shemar, P. Whibberley, D. Calonico, F. Levi, L. Lorini, M. Pizzocaro, P. Delva, S. Bize, J. Achkar, H. Denker, L. Timmen, C. Voigt, S. Falke, D. Piester, C. Lisdat, U. Sterr, S. Vogt, S. Weyers, J. Gersl, T. Lindvall, and M. Merimaa, "International timescales with optical clocks (ITOC)," in *European Frequency and Time Forum International Frequency Control Symposium (EFTF/IFC), 2013 Joint*, July 2013, pp. 908–911.

[11] G. Cappellini, M. Mancini, G. Pagano, P. Lombardi, L. Livi, M. Siciliani de Cumis, P. Cancio, M. Pizzocaro, D. Calonico, F. Levi, C. Sias, J. Catani, M. Inguscio, and L. Fallani, "Direct observation of coherent interorbital spin-exchange dynamics," *Phys. Rev. Lett.*, vol. 113, p. 120402, Sep 2014.

[12] D. Calonico, E. Bertacco, C. Calosso, C. Clivati, G. Costanzo, M. Frittelli, A. Godone, A. Mura, N. Poli, D. Sutyrin, G. Tino, M. Zucco, and F. Levi, "High-accuracy coherent optical frequency transfer over a doubled 642-km fiber link," *Applied Physics B*, vol. 117, no. 3, pp. 979–986, 2014.