# A transportable optical lattice clock using $^{171}$Yb

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***Abstract*—We present first results on the spectroscopy of the $^1\mathrm{S}_0 \rightarrow {}^3\mathrm{P}_0$ transition at $578\,\mathrm{nm}$ in a transportable $^{171}$Yb optical lattice clock. With the Yb atoms confined in a one-dimensional optical lattice, we have observed linewidths below 200 Hz, limited by saturation broadening. Currently the system is being upgraded towards full clock operation and use of more compact and robust subsystems.**

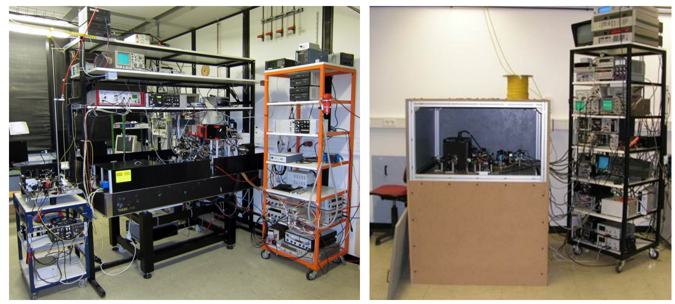
## I. Introduction

Optical lattice clocks based on elements with two valence electrons are strong competitors in the quest for next generation time and frequency standards. Promising results have already been obtained in several stationary setups using Sr [1]–[4], Hg [5], Mg [6] and Yb [7], [8]. In particular, a record instability in the $10^{-18}$ range has recently been demonstrated for Yb lattice clocks [9]. However, in addition to stationary setups, transportable clocks are desirable for a variety of reasons. The ability to transport them and compare them with other frequency standards allows for a performance evaluation beyond what is possible with standards at a single institute. Furthermore, many applications, e.g. geodesy and ground stations for space missions, will benefit from transportable optical clocks. Last but not least, sending optical clocks into space will allow greatly improved tests of fundamental physics [10].

In the framework of the ESA candidate mission "Space Optical Clock", an optical lattice clock is foreseen to be operated on the ISS around the year 2018. As part of technology development towards that goal, breadboard and transportable lattice optical clock demonstrators using Sr and Yb are being developed in a EU FP7 project [11].

Our transportable Yb clock system is based on compact diode lasers ($399\,\mathrm{nm}$, $1156\,\mathrm{nm}$ frequency doubled in a PPLN waveguide, $759\,\mathrm{nm}$) and a fiber laser ($1111\,\mathrm{nm}$ frequency doubled in a PPLN waveguide), and features an intra-vacuum enhancement resonator to allow the formation of a large-volume one-dimensional optical lattice using moderate laser power. Our current experimental setup for the atom source is shown in figure 1a and comprises an optical table of $2\,\mathrm{m} \times 1\,\mathrm{m}$ for the optical and vacuum setup and approximately two standard 19" rack shelves of non-optimized electronics.

This does not include the clock laser setup shown in figure 1b, which takes up another $90\,\mathrm{cm} \times 120\,\mathrm{cm}$ breadboard and is currently located in another laboratory. Here a commercial ECDL is frequency doubled and stabilized to sub-Hertz linewidths using a highly stable ULE cavity [12]. A phase-stabilized $300\,\mathrm{m}$ intra-building fiber link connects this setup to the atom apparatus, where after frequency doubling $1.5\,\mathrm{mW}$ are available for spectroscopy.



(a) Atom apparatus (b) Clock laser

Fig. 1: Photographs of the experimental setup, showing (a) the atom source including the lattice and cooling lasers and (b) the clock laser setup.

### A. Atom source

The ytterbium atoms are loaded into the first-stage MOT on the $^1S_0 \rightarrow {}^1P_1$ transition at $399\,\mathrm{nm}$ with a typical time constant of $500\,\mathrm{ms}$, resulting in $10^7$ atoms after $2\,\mathrm{s}$ loading time. The second-stage MOT operating on the $^1S_0 \rightarrow {}^3P_1$ transition at $556\,\mathrm{nm}$, optimized for temperature, contains several times $10^5$ atoms at a temperature of around $25\,\mu\mathrm{K}$.

From this second-stage MOT the atoms can be efficiently transferred to the optical lattice. By using an intra-vacuum enhancement resonator, we achieve a circulating laser power of $10\,\mathrm{W}$, corresponding to a trap depth of $40\,\mu\mathrm{K}$ in a large volume trap ($155\,\mu\mathrm{m}$ trap radius) using a moderate laser power of a few hundred mW. Due to good matching of the lattice to the volume of the postcooling MOT, we routinely achieve transfer efficiencies in excess of $20\,\%$ for atom temperatures of $\sim 25\,\mu\mathrm{K}$. The addition of optical pumping on the $^1S_0 \rightarrow {}^3P_1$ transition will allow us to spin polarize the atoms. After the clock probe pulse is applied, the atoms remaining in the ground state are detected by fluorescence on the $^1S_0 \rightarrow {}^1P_1$ transition.

When operating at an appropriate oven temperature, the

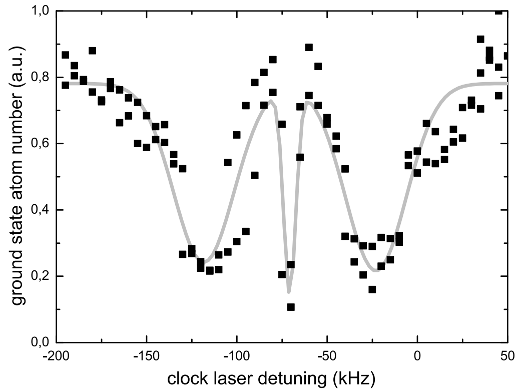



Fig. 2: Spectrum of the clock transition using the chopped lattice technique. The number of atoms remaining in the ground state after the chopped lattice sequence is plotted as function of the detuning of the clock laser.

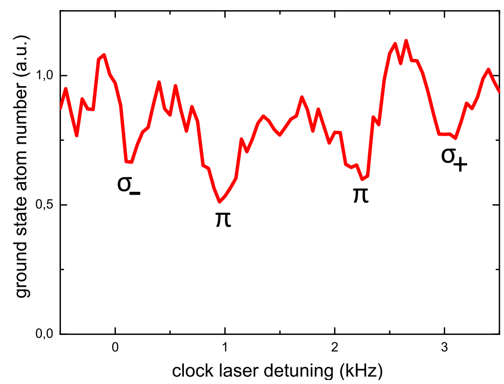



Fig. 3: Spectrum of the clock transition with the atoms held in a one-dimensional optical lattice in the presence of a magnetic bias field. The number of atoms remaining in the ground state after the clock pulse is plotted as function of the detuning of the clock laser. The four Zeeman components of the transition can be resolved.

total cycle time can be reduced to below 1 s while retaining sufficient signal from the atoms captured in the lattice.

### *B. Spectroscopy on the clock transition*

In order to rapidly locate the clock transition, we use a *chopped lattice* technique, similar to that applied during the first frequency measurement of this transition [13]. Alternating short pulses of 578 nm light to excite the clock transition and of 556 nm light to retrap and cool the atoms allows us to achieve high contrast signals, with observed linewidths adjustable between a few kHz and hundreds of kHz. The retrapping pulses allow us to interrogate the atoms for several trap lifetimes, thus yielding a high contrast even for incoherent excitation due to loss of excited atoms. Figure 2 shows a spectrum obtained in this manner. The sharp carrier transition is clearly visible, surrounded by sidebands corresponding to motional excitations in the lattice. The sideband spacing corresponds to a trap depth of 40 µK.

Probing the transition on atoms trapped in the lattice we have successfully resolved the Zeeman components and achieved linewidths of less than 200 Hz, consistent with saturation broadening. A typical spectrum is shown in figure 3. The observed Zeeman splitting is due to a magnetic background field of $\sim 2.5\,\mathrm{G}$, which for clock operation will be partially compensated using the magnetic coils.

### *C. Next generation laser systems*

Having demonstrated the capabilities required to operate our experimental apparatus as an optical clock, we are currently improving several aspects of the experimental setup, with a focus on more compact and robust subsystems. In particular, we are replacing most laser systems by more compact modules promising better performance. While several hours of hands off operation have been achieved with the previous setup, we are striving for improved reliability as well as a more compact and modular overall system.

For the first-stage cooling and detection at 399 nm we have developed a new laser system shown in figure 4, comprising two injection-locked diode lasers. For the generation of

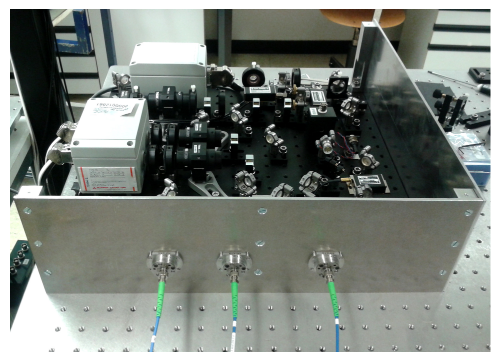


Fig. 4: New 399 nm laser system module during testing. The grey boxes contain the master ECDL and two slaves respectively. The whole system fits into a 19” rack shelf and all outputs are fiber coupled.

seed light, we are investigating several setups, among them AR coated laser diodes in an interference-filter-based ECDL design [14], developed in collaboration with the University of Hannover (LUH). The master as well as the two slave lasers and all frequency generation steps for frequency stabilization, slower and precooling MOT are contained on a $45\,\mathrm{cm} \times 45\,\mathrm{cm}$ breadboard with fiber outputs.

An interference filter based design from LUH is also currently being evaluated for the generation of the lattice light at 759 nm. Together with a new enhancement resonator providing higher finesse and tighter focusing, this self-injecting tapered amplifier will present a considerable simplification with respect to the current MOPA system consisting of a commercial ECDL and a tapered amplifier.

Our home-built 556 nm laser has already been replaced with an integrated module by Menlo Systems, which directly provides output at 556 nm employing frequency-doubling of a fiber laser, with the actual laser system requiring a volume of only 3 l. Using this system, we have successfully operated the experiment and demonstrated improved atom numbers and stability in the postcooling MOT.

Additionally, we are currently integrating a DFB laser at $1388\,\mathrm{nm}$ into the experiment, which will be used as a repumper for the upper clock state and allow direct detection of the excited atoms. Together with further efforts to improve detection, this will lead to improved signal quality.

## II. Conclusion

We have demonstrated spectroscopy of the clock transition in $^{171}$Yb in a one-dimensional optical lattice. We have already observed linewidths of below $200\,\mathrm{Hz}$ and estimate an uncertainty of less than $10^{-14}$ to be readily achievable with minor modifications to our setup.

The current setup provides a solid foundation for a transportable $^{171}$Yb lattice clock. Several ongoing modifications of the experimental apparatus will improve transportability, reliability and performance of the system and will allow rapid characterization of the system for competitive clock operation.

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