Experimental set-up for loading Sr atoms into a hollow-core fiber for continuous operation of optical clocks

Sławomir Bilicki
Institute of Physics, Faculty of Physics, Astronomy and Informatics,
Nicolaus Copernicus University
Grudziadzka 5, PL-87-100 Torun, Poland
slawko@fizyka.umk.pl

Marcin Bober
Institute of Physics, Faculty of Physics, Astronomy and Informatics,
Nicolaus Copernicus University
Grudziadzka 5, PL-87-100 Torun, Poland
bober@fizyka.umk.pl

Maciej Chomski
Time and Length Department, New Technologies of Time and Length Laboratory
Central Office of Measures
ul. Elektoralna 2, 00-139 Warszawa
maciej.chomski@gum.gov.pl

Piotr Morzyński
Institute of Physics, Faculty of Physics, Astronomy and Informatics,
Nicolaus Copernicus University
Grudziadzka 5, PL-87-100 Torun, Poland
pmorzynski@fizyka.umk.pl

Marcin Witkowski
Institute of Physics, Faculty of Physics, Astronomy and Informatics,
Nicolaus Copernicus University
Grudziadzka 5, PL-87-100 Torun, Poland
marcin_w@fizyka.umk.pl

Michał Zawada
Institute of Physics, Faculty of Physics, Astronomy and Informatics,
Nicolaus Copernicus University
Grudziadzka 5, PL-87-100 Torun, Poland
zawada@fizyka.umk.pl

***Abstract*— We present a recent progress regarding an experimental system for loading Sr atoms into hollow-core fiber (HCF) for continuous operation of optical clocks.**

Keywords—hollow core fiber, ultra-cold atom source, atomic transfer

I. Introduction

Optical clocks (OC) are based on the highly precise interrogation of an optical transition, where instabilities and inaccuracies in the 10^{-18} range can now be reached [1] . Most OC realizations include an oven at over 500 K and strong dynamic magnetic fields which operates at elevated temperatures and under much higher pressures, leading to increased background gas load and unavoidable contamination of surfaces in the vicinity of the source.. Spatially separation between the production region and the measurement region would be a great improvement. In the present generation of OC a laser locked to an ultra-stable optical cavity preserves the frequency stability while a new sample of ultracold atoms is prepared and loaded into the atomic standard. At the same time, the linewidth provided even by the best reference lasers is much broader than the atomic clock transition. One of the proposed solution is the system with continuous superradiant lasing of an ensemble of atoms on the clock transition [2], producing light directly at the clock frequency. Our way to continuously load ultra-cold atoms to the reservoir is the development of a fibre-based delivery system for atoms based on laser guiding through a HCF. Almost all this type of experiments to date are based on the alkali element rubidium [3], [4]. However the advanced computation and sensing machines like optical lattice clocks, trapped-ion based quantum computers and quantum simulators are built on the class of alkaline-earth-metal atoms (e.g., calcium, strontium, ytterbium, or mercury).

II. Experimental Setup

In our project we develop an experimental setup to trap ^{88}Sr atoms in double stage magneto-optical traps and transfer them spatially with assist of optical dipole potential inside a HCF. Strontium atoms have a level structure with narrow intercombination lines, which allow for second-stage laser cooling to temperatures in the range of a few µK. This lower temperature promises to reduce the required trap depth inside the fiber, which is a great advantage. We focus on the delivery of atoms from a preparation area that consists double stage cooling by $^1S_0$-$^1P_1$ and $^1S_0$-$^3P_1$ transitions into the measurement area on the other side of the fibre. Assuming a transport velocity of order 1 m/s and loss rates well below 1 s^{-1} , which can be achieved in free-space optical traps, atom guiding over a distance of many meters is feasible. The dominant source for heating in the fibre has been identified as a modulated potential caused by back reflections from the fiber end [5]. The associated heating rate of 300 µK/s can be compensated by continuous laser cooling. Heating due to an elliptic polarization of the guiding light is relevant only for atoms with a Zeeman substructure in the ground state, which does not apply to the Sr atoms.

We want to experimentally determine the optimal cooling and loading strategy for Sr. Given the observations in previous experiments, we do not expect the atom flux to be a major concern for this project. Prior demonstrations achieved atom flux rates on the order of 10^5 per second in Rb [6], and we expect this number to grow substantially for alkaline-earth-metal elements due to the much higher phase-space density of the pre-cooled atoms before the fiber. During guiding we aim to increase atom lifetime to the range of 1 s by reducing the residual heating by employing targeted cooling schemes, and a moving optical lattice to control the atoms' forward velocity. We will extend length of the fibre to 5 meters.

We use the hollow core anti-resonant fibre with 38 µm core diameter (iXblue Photonics, IXF-ARF-40-240) with low dispersion in the transmission band and high demage threshold. Currently around 7 cm length of the vertically oriented HCF is put inside the vacuum chamber with vacuum level at low 10-8 mbarr. The atomic fluorescence signal from magneto-optical trap at 461 nm transition above a few milimeters above the HCF is observed.

ACKNOWLEDGMENT

This project has received funding from the European Union's Horizon Europe research and innovation programme under grant agreement No 101080166 (AQuRA project) and has been supported by the QuantERA grant QuantumGuide, by National Centre for Research and Development the grant number QUANTERAII/1/92/ QuantumGuide/2022.

REFERENCES

[1] The OC18 collaboration, Guidelines for developing optical clocks with 10 -18 fractional frequency uncertainty

[2] M. A. Norcia and J. K. Thompson, Cold-strontium laser in the superradiant crossover regime, Phys. Rev. X 6, 011025 (2016)

[3] M. Bajcsy et al., Phys. Rev. A 83 063830 (2011)

[4] T. Peters, L. P. Yatsenko, and T. Halfmann, Phys. Rev. A 103 063302 (2021).

[5] S. Okaba et al., Lamb-Dicke spectroscopy of atoms in a hollow-core photonic crystal fibre, Nature Commun. 5, 4096 (2014)

[6] A. P. Hilton et al., High-efficiency cold-atom transport into a waveguide trap, Phys. Rev. Appl. 10, 044034 (2018)