A Compact Source of Ultracold Ytterbium for an Optical Lattice Clock

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Abstract— In this paper, we present the development of a compact source of ultracold Yb atoms for an optical lattice clock. All laser systems that are required for the operation of the compact source are based on diode lasers. We have already implemented the first cooling stage using laser diodes at 399 nm and could realize a magnetooptical trap of ^{174}Yb with 3×10^7 atoms.

I. INTRODUCTION

Neutral ytterbium (Yb) is an interesting candidate for the realization of an optical atomic clock at a wavelength of 578 nm [1]. Without application of external fields, the corresponding transition $^1S_0 \rightarrow {}^3P_0$ is strictly forbidden in the bosonic isotopes, while hyperfine interactions shorten the radiative lifetime of the $^3P_0$ state in the fermionic isotopes to $\approx 20\,$s leading to transition linewidths in the 10 mHz range, which are well-suited for the realization of an optical clock. The use of bosonic isotopes (e. g. ^{174}Yb) is also possible if well-controlled magnetic fields are used to enable direct optical excitation of the clock transition [2].

A promising scheme for the realization of an optical clock with Yb involves trapping of laser-cooled atoms in an optical lattice [3], where recoil shifts and Doppler shifts can be practically eliminated. The light shift on the clock transition can be minimized by tuning the lattice laser to the so-called "magic" wavelength at 759 nm as has recently been demonstrated by Barber et al. [4]. It is projected that perturbations to the transition frequency by the lattice light can be held below a level level of 10^{-17} [1]. This is supported by a recent experimental study of lattice-induced light shifts in an Yb optical lattice clock [5].

In this paper, we report on the development of a compact source of ultracold Yb atoms for an optical lattice clock which uses only diode-based laser systems for the two laser cooling stages as well as for the optical lattice. The development of this compact source for ultracold Yb is part of the ESA-funded project "'Space optical clocks" which aims at developing optical clocks towards their possible usage in space applications.

II. EXPERIMENTAL SETUP

The experimental setup of the compact source for an ultracold Yb optical lattice clock contains a vacuum system with a base pressure in the range of 10^{-9} mbar, a laser system with a wavelength of 399 nm for the Zeeman slower and the
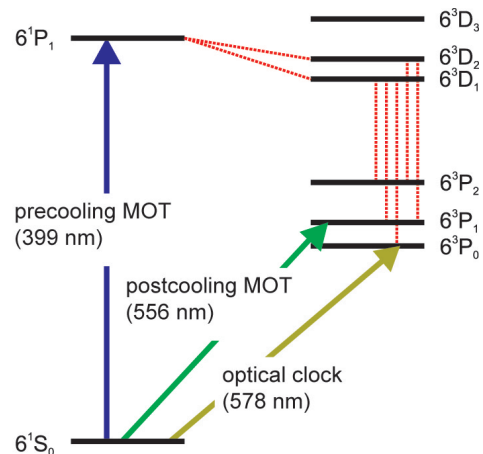

Fig. 1. Scheme of the relevant energy levels in Yb.

precooling MOT, a laser system with a wavelength of 556 nm for the postcooling mOT and a laser system at the magic wavelength of 759 nm for the optical lattice. The vacuum system and all the laser systems are contained on a $1 \times 2\,\text{m}^2$ optical table together with all optical components required for the operation of the MOTs and the optical lattice. For the realization of an Yb optical lattice clock, the system will be connected via an optical fiber to a diode-laser based clock laser with a wavelength of 578 nm [6], which is developed in the group of S. Schiller at the University of Düsseldorf.

A. Precooling MOT

The laser system for the precooling MOT operating on the $^1S_0 \rightarrow {}^1P_1$ transition at 399 nm is based on recently developed laser diodes which are used in novel data storage technology. Hereby, we rely on the availability of laser diodes with a wavelength at the edge of the production process, since the design wavelength of the laser diodes is 405 nm. Typically these laser diodes are spectrally broad (around 10 MHz in a grating-stabilized configuration) but due to the broad Yb resonance with a linewidth of 28 MHz they can still be used for efficient laser cooling and slowing.

Our laser system consists of two laser diodes in a master-slave configuration. We use a grating-stabilized laser diode (Nichia, NDHV310ACA, 30 mW) as a master laser which

756

generates $\approx$ 15 mW at the desired wavelength. The output of the master laser is split into three parts. After appropriate frequency shifting using acousto-optical modulators, the three beams are used for frequency stabilization of the laser to a fluorescence spectroscopy on an Yb atomic beam, for the Zeeman slower and as a seed for a slave laser (Nichia, NDV4313, 120 mW). The slave laser with a nominal wavelength of 401 nm (at room temperature) is operated at a temperature around 0°C and at a reduced output power of $\approx$ 50 mW, so that it can be injection-locked to the master laser. It is then used as a cooling laser for the precooling MOT. Due to the imperfect transverse mode structure of the laser diodes not all of the light can actually be used for atom slowing or cooling, so that the usable power in the experiment is about 5 mW for the slower and 15 mW for the MOT.

We have already succeeded in realizing a precooling MOT in the compact clock apparatus using the described diode laser system. The maximum number of atoms that could be captured from the Zeeman slower is 3×10^7 in the case of ^{174}Yb at a temperature of several mK. The atom number in the precooling MOT saturates after a few 100 ms of loading due to loss processes in the MOT involving light-assisted collisions and radiative decay into metastable states.

B. Postcooling MOT

In the second-stage or postcooling MOT the temperature is reduced to several 10 μK and the atomic density is increased to a level of 10^{11} cm^{-3}, which is required for efficient loading of the optical lattice. The typical approach to create the 556 nm radiation for the postcooling MOT in Yb operating on the $^1S_0 \rightarrow ^3P_1$ transition is a dye laser, as it was used in our previous experiments [7], [8]. For the compact source described here, we have developed an alternative approach consisting of a grating-stabilized laser diode with a wavelength of 1112 nm (Toptica) which is frequency doubled using a PPLN waveguide (HCPhotonics). The infrared light is coupled into the PPLN waveguide (2 cm length) using a standard laser diode collimating lens. The use of a PPLN waveguide structure allows for single-pass frequency doubling and thus significantly simplifies the generation of the 556 nm radiation as compared to the standard approach of frequency doubling in an enhancement resonator.

Out of 75 mW infrared radiation before the PPLN crystal, we were able to couple $\approx$ 30 mW into the waveguide. The relatively low coupling efficiency is probably due to the imperfect transverse mode of the diode laser. The maximum achieved output was 11 mW corresponding to a single-pass doubling efficiency of 37 %. In order to maintain a high doubling efficiency, the temperature of the PPLN waveguide has to be kept constant to better than 0.1 K (see Fig.2).

The radiation at 556 nm is split into two parts where one part is used for the stabilization of the laser frequency to a fluorescence spectroscopy on an Yb atomic beam. The other part will be superimposed on the laser beam for the precooling MOT using a dichroic mirror. Switching and control of the light power will be done using acousto-optical moodulators.
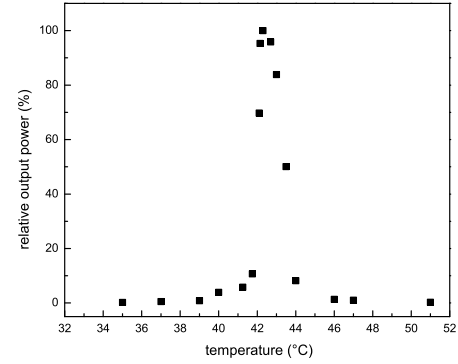

Fig. 2. Temperature dependence of the doubling efficiency of a PPLN waveguide with a length of 2 cm at a fundamental wavelength of 1112 nm.

Dichroic waveplates (for 398 nm and 556 nm) throughout the MOT setup ensure that the polarization for both the precooling and the postcooling MOT is suitable for MOT operation [9]. With the available power, it should be possible to transfer roughly 50% percent of the atoms from the precooling into the postcooling MOT and cool them down to temperatures below 40 μK.

C. Optical lattice

The first experimental investigations on the optical clock transition will be performed using bosonic ^{174}Yb or ^{176}Yb trapped in a three-dimensional optical lattice at the magic wavelength of 759 nm. The optical lattice which is located at the same position as the MOT will be loaded from the postcooling MOT by turning down the cooling light and switching off of the MOT magnetic field.

The laser system for the realization of the optical lattice is a self-injected tapered diode laser (Fig. 3). The gain region of the laser chip (M2K Laser, TA-L-765-1000) has a tapered shape with a short rectangular section at the narrow end. Both facets are antireflection coated and collimating lenses are used to collimate the laser output. At the back side, an optical grating is placed under an angle of $\approx$ 45° which provides an optical feedback of $\approx$ 65% in the first diffraction order. At the magic wavelength of $\lambda_m = 759.35$ nm, the self-injected tapered laser generates a power of up to 600 mW at a laser diode current of 2.5 A.

The optomechanical setup for the optical lattice in our apparatus consists of a single enhancement resonator which is mounted inside the vacuum chamber. If a single resonator is to be used for a 3D optical lattice, the light path inside the resonator has to be folded to create an intersection of three orthogonal standing waves. The feasibility of such a scheme was recently demonstrated by Akatsuka et al. [10] in an optical lattice clock with Sr. In our setup, the folded resonator is realized by placing five additional high-reflecting mirrors in between the coupling mirror and the backreflector
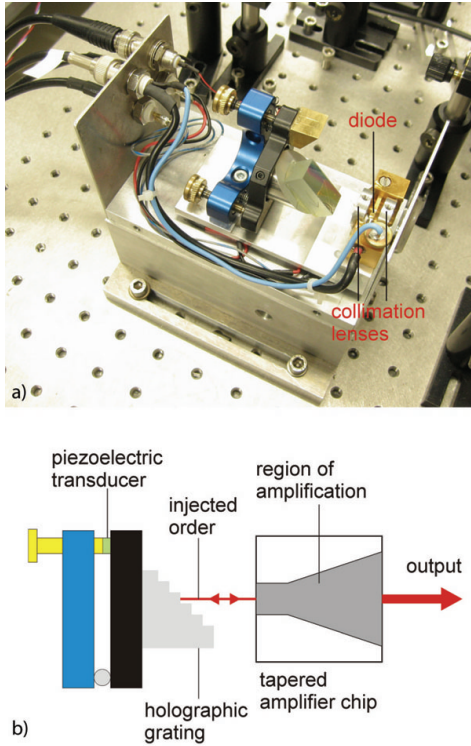
Fig. 3. a) Setup for the self-injected tapered diode laser at the magic wavelength of 759 nm. b) Operation principle of a self-injected tapered diode laser.

as is depicted in Fig. 4. Thus, the light field of the fundamental resonator mode creates an intersection of three orthogonal standing waves. As it is designed, the three standing waves are all linearly polarized, where two standing waves have parallel linear polarization and the polarization of the third standing wave is orthogonal. Care is taken in the placement of the mirrors, to ensure that all reflections at the mirrors preserve the linear polarization of the light field.
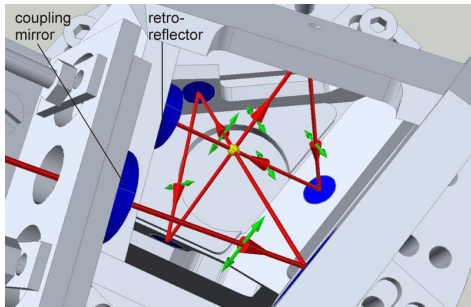

Fig. 4. Schematic drawing of the enhancement resonator. The red lines show the path and the green arrows the polarization of the circulating light field.

While the coupling mirror and the backreflector are both concave with focal length $f = 100$ mm, all other resonator mirrors are plain. The total length of the resonator is 200 mm in order to fulfill the condition of confocality and the resulting

size of the waist of the fundamental cavity mode is 155 μm. This results in sizes of the three standing waves at the intersection point of 160 μm, 170 μm and 210 μm, respectively. Due to interference effects, the maximum light intensity at the antinodes of the three-dimensional standing wave at the intersection is $I_{max} \approx 15\,I_{circ}$, where I_{circ} is the intensity of the running wave circulating inside the resonator at the focus position. The free spectral range of the enhancement cavity is 750 MHz and the experimentally determined finesse is close to $F_{exp} = 300$ resulting in a calculated power enhancement factor of $\eta_c = 90$. For perfect overlap at the intersection, this will result in a depth of the optical potential of 280 μK assuming that 200 mW are coupled into the enhancement resonator.. The large volume of the trapping region and the depth of the optical lattice inside the enhancement resonator should allow to transfer a significant percentage of atoms from the postcooling MOT into the optical lattice.

III. CONCLUSION

In this paper we have laid out our approach toward a compact source of ultracold Yb. We have demonstrated that the main laser sources can all be implemented using diode lasers. Currently we are working on the experimental realization of the postcooling MOT and subsequent loading of the optical lattice at the magic wavelength. Together with an ultrastable clock laser at 578 nm which is developed in the group of S. Schiller at the University of Düsseldorf, the compact source presented in this paper will be used for the realization of an Yb optical lattice clock.

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