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An optical frequency standard based on ultracold magnesium atoms

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Abstract. This paper presents the recent experimental results on development of an optical frequency standard based on ultra cold magnesium atoms with relative frequency uncertainty and long term stability at the level of $\Delta\nu/\nu < 10^{-16}$. We stabilized the frequency of our clock laser system at 655 THz to narrow Ramsey fringes in a time separated laser fields interacting with cooled Mg atoms localized in a magneto-optical trap (MOT). The intercombination line $^1S_0 \rightarrow {}^3P_1$ was used as the reference for frequency stabilization. The results of stabilization were studied with femtosecond comb based on Ti:Sa laser.

Optical frequency standards based on cooled and localized atoms play an important role in both fundamental research and various metrological and navigational applications. Alkaline-earth and alkaline-earth-like atoms such as Yb [1], Ca [2], Sr [3–5], Hg [6] and Mg [7, 8] are the main candidates to create frequency standards of a new generation. Today, Yb and Sr optical-lattices frequency standards demonstrate a relative instability and uncertainty of extremely low levels $10^{-17} \div 10^{-18}$ [1, 4]. Mg frequency standard at the moment much less developed compare to Sr and Yb optical standards. At the same time, magnesium atoms have some advantages compared to the other candidates in terms of the frequency standard. Thus, the blackbody radiation (BBR) shift of the clock transition for magnesium is much smaller than for Yb, Ca, Sr. The simplified level scheme of Mg atoms is shown at figure 1.

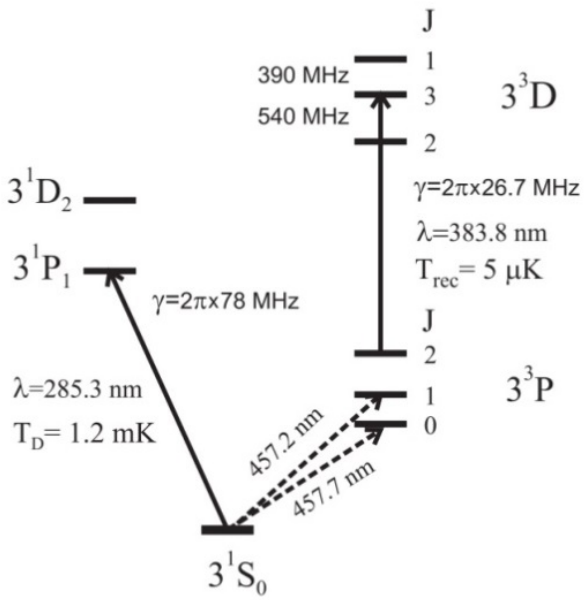

Figure 1. Simplified term diagram of ^{24}Mg atoms. Solid lines denote the cooling transitions with corresponding temperature limits, while dashed lines denote possible "clock" transitions, which can be used for laser frequency stabilization.

The resonant strong transition $^1S_0 \rightarrow {}^1P_1$ is a very suitable for an effective laser cooling and trapping of Mg atoms in a magneto-optical trap (MOT) directly from a thermal atomic beam. The ^{24}Mg $^1S_0 \rightarrow {}^3P_1$ transition natural width is only 31 Hz and it could be used to develop an optical frequency standard with high long term frequency stability. Strongly forbidden $^1S_0 \rightarrow {}^3P_0$ transition is of particular interest to develop an "optical lattice" standard with relative frequency uncertainty of $10^{-17} \div 10^{-18}$. To observe $^1S_0 \rightarrow {}^3P_0$ transition the magnetic-field-induced spectroscopy method could be used [9].

Despite a number of difficulties for deep cooling of Mg atoms down to a temperature less than 100 μK due to a large value of recoil energy, studies aimed at creating an optical frequency standard based on Mg atoms are carried out at the Institut für Quantenoptik, Hannover, Germany [7] and the Institute of Laser Physics, Novosibirsk, Russia [8]

In our previous studies we localized a cloud of cooled Mg atoms in MOT and have observed narrow Ramsey resonances in time separated laser fields at the intercombination transition $^1S_0 \rightarrow {}^3P_1$ [8]. This paper presents preliminary results on a clock laser frequency stabilization using Ramsey resonances and a frequency stability measurements with a frequency comb generator based on a femtosecond Ti:Sa laser. A schematic diagram of Mg optical frequency standard is shown at figure 2.

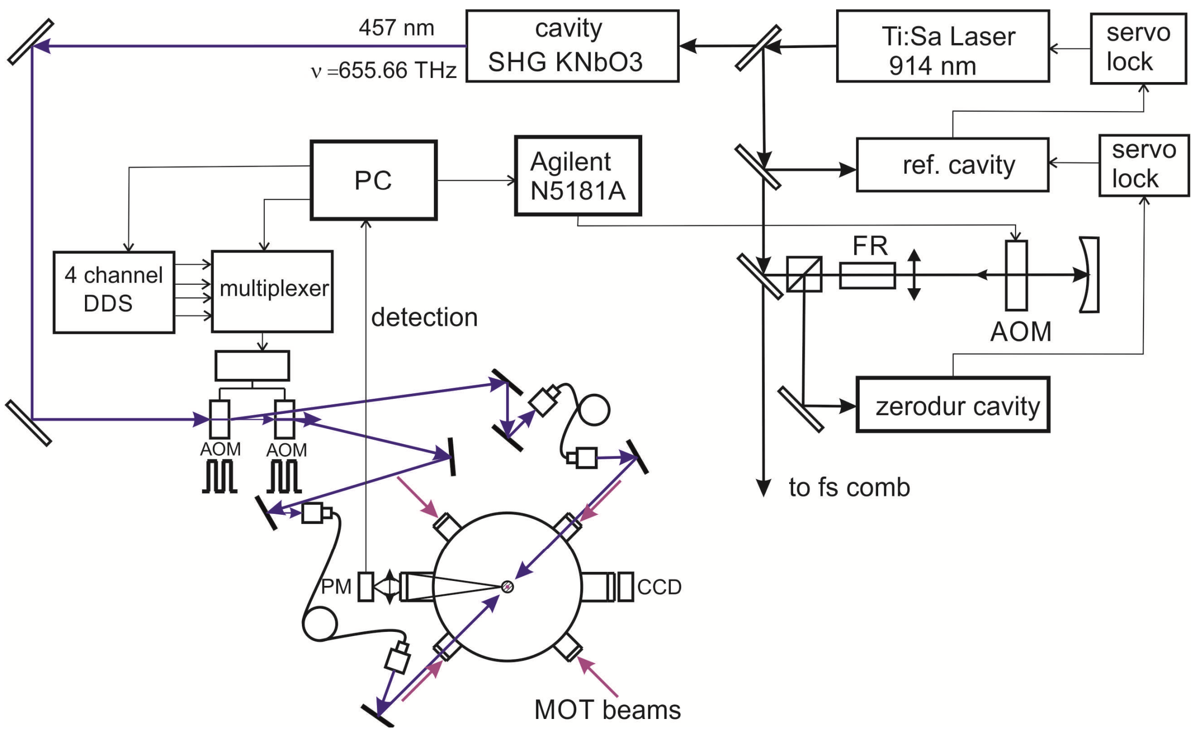

Figure 2. Simplified schematic of the experimental setup, showing the 914 nm Ti:Sa laser, the cavity with $KNbO_3$ crystal for frequency doubling to the "clock" wavelength of 457 nm, the reference cavity for Ti:Sa laser linewidth preliminary narrowing, the zerodur cavity with a two pass acousto-optical modulator (AOM) for frequency stabilization and fine tuning of the clock laser frequency, the MOT with a detection system.

The frequency of clock laser system was stabilized using a highly stable zerodur cavity and was tuned with the generator Agilent N5181A controlled AOM. A digital version of the third harmonic detection method is used to generate an error signal for frequency stabilization of the clock laser system to a central Ramsey fringe [10]. The four radio frequencies were generated with four channel DDS generator. These frequency were $\Delta_1 = f_0 + \Delta/4$, $\Delta_{-1} = f_0 - \Delta/4$, $\Delta_3 = f_0 + 3\Delta/4$, $\Delta_{-3} = f_0 - 3\Delta/4$, were Δ is a value of the Ramsey fringes period, f_0 = 80 MHz is a central frequency of AOM, that formed time separated pulses for cooled Mg atoms excitation. A calculated error signal $dS = (S_{\Delta\text{-}3} - 3S_{\Delta\text{-}1} + 3S_{\Delta 1} - S_{\Delta 3})$

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was used for frequency stabilization. Figure 3 shows detected signal dS with a time separation of excitation pulses equal to 58 μs and with the pulses duration of 4 μs.

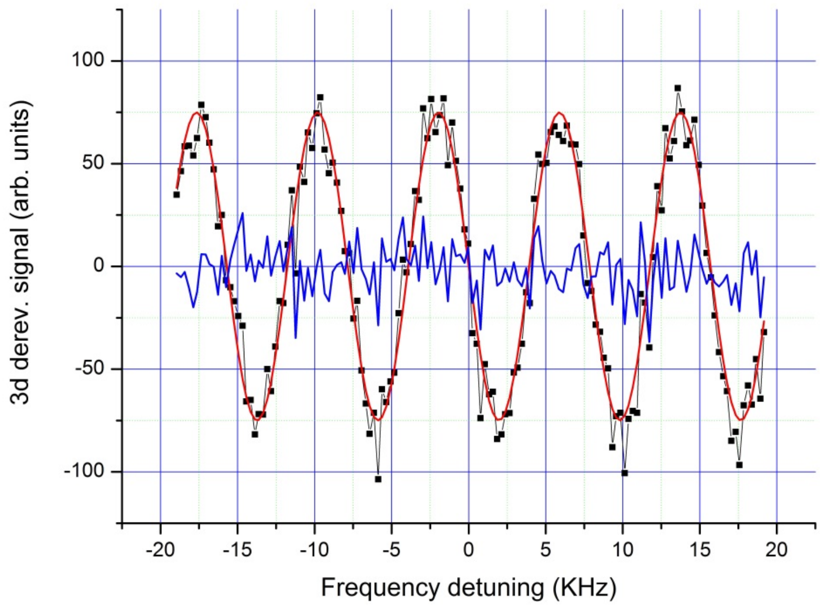

Figure 3. The error signal (a third harmonic of Ramsey fringes) that used for frequency stabilization (black line and symbols), red line is a sinusoidal fit of the error signal, blue line is a difference between the error signal and the fit. Blue line characterizes a signal/noise ratio S/N= 6, an averaging time is τ = 0.2 s for a point (total curve comprises 144 points).

Femtosecond frequency comb based on Ti:Sa laser [11] and referenced to Yb:YAG/I_2 optical frequency standard [12] was used to measure frequency stability of clock laser system stabilized to central Ramsey fringe. The scheme of the setup is shown at the figure 4.

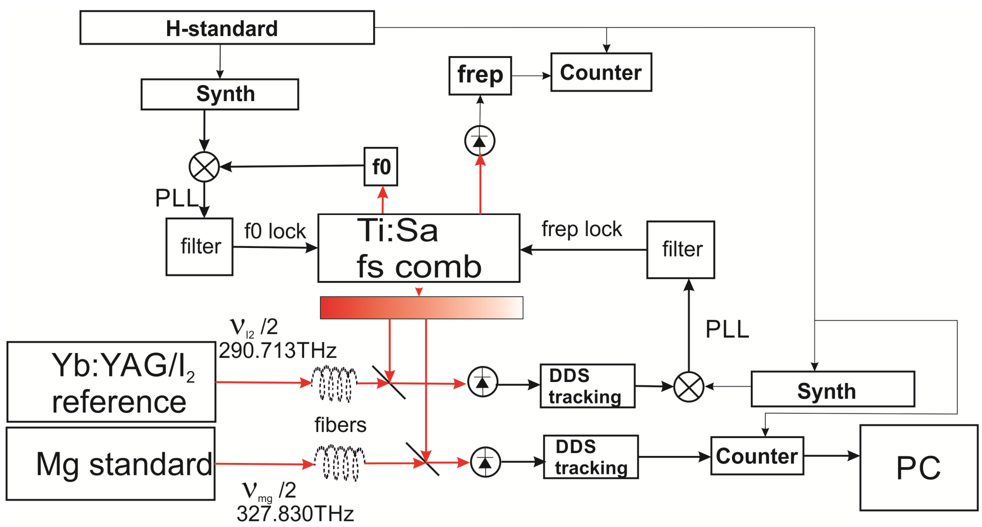

Figure 4. Scheme of the experimental setup for a frequency stability measurement of the clock laser system.

The precision of a frequency stability measurements was limited by the stability of the reference Yb:YAG\I_2 frequency standard. Figure 5 shows Allan deviation of our Mg optical frequency standard measured with femtosecond comb generator.

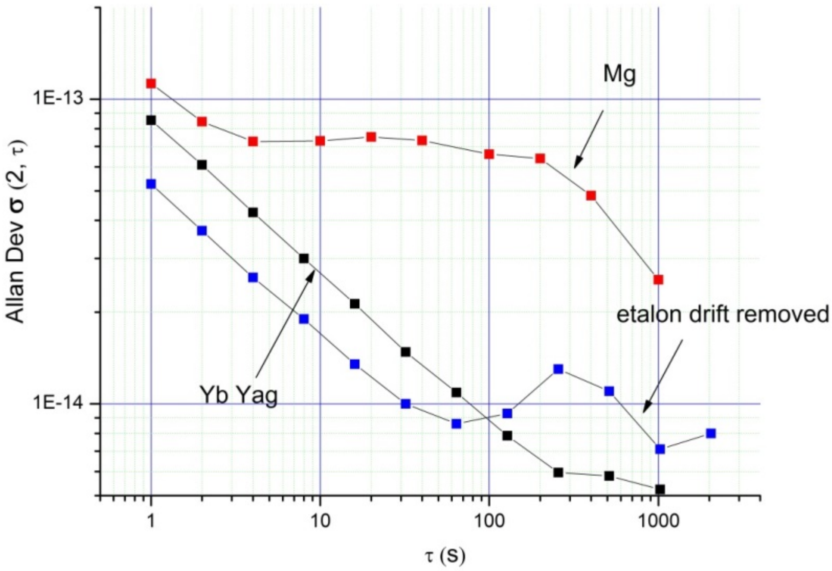

Figure 5. Allan deviation for the Mg frequency standard: locked to Ramsey fringes – red square, blue square –laser frequency lock to reference cavity only with a frequency drift removed from the measured data. Black square – Allan deviation for the Yb:YAG/I_2 reference laser measured with a beat signal of two Yb:YAG/I_2 lasers. The pick at the curve with blue square at 200 ÷ 400 s is due to frequency perturbations of the reference cavity that differ from a polynomial low and can't be removed from the data.

Preliminary experiments on frequency stability measurement demonstrate that at the moment the main limitation factors are large frequency drift of our zerodur reference cavity due to it temperature variation and relatively small value of S/N. The frequency stability of Mg standard will be improved substantially in future with an improvement of reference cavity thermal stabilization system and an optimization of Ramsey fringes detection.

In a future we plan to realize sub-Doppler laser cooling of magnesium atoms using $^3P_2 \rightarrow ^3D_3$ transition [13, 14] and localize atoms in an optical lattice for Mg optical frequency standard with relative frequency uncertainty of $10^{-17} \div 10^{-18}$.

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