Optical frequency standard with ytterbium single ion

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Abstract. We report on the progress in development of a highly accurate optical frequency standard based on the single ion of ytterbium-171 at the Institute of Laser Physics, Novosibirsk.

1. Introduction
Frequency standards play very important role in both fundamental research and various applications. This is primarily related to the fact that the accuracy of modern frequency standards, which implement a reference for one of the basic units of measure of the SI system (second) is several orders of magnitude higher than the accuracy of references for other physical values. Development of a new generation of highly accurate optical frequency standards is a fundamental problem of laser spectroscopy. Currently, the standards based on atoms or ions localized in space are considered to be the most stable ones.

A promising candidate for the use in these optical frequency standards is the $^{171}$Yb ion. The specific features of the energy level diagram of ytterbium ion make it possible to develop optical frequency standards based on two transitions (figure 1): (i) the $^2S_{1/2}$ ($F = 0$) - $^2D_{5/2}$ ($F = 2$) quadrupole transition with a wavelength of 436 nm and a natural linewidth of 3.1 Hz and (ii) the $^2S_{1/2}$ ($F = 0$) - $^2F_{7/2}$ ($F = 3$) octupole transition at 467 nm with a natural lifetime of several years.

Figure 1. Energy level diagram of the $^{171}$Yb ion.
The largest frequency shift that contributes to the systematic uncertainty of many atomic frequency standards is the interaction of the thermal blackbody radiation with the atomic eigenstates. Presence of two ultra narrow optical transitions in the same thermodynamic environment makes possible implementation of so called “synthetic” frequency standard with suppressed blackbody radiation (BBR) frequency shift [1]. In $^{171}$Yb ion at room temperature the residual BBR shift is estimated to be on the order of $10^{-18}$ for the “synthetic” frequency which is a combination of the octupole (467 nm) and the quadrupole (436 nm) optical transition frequencies. Thus, the “synthetic” frequency standard based on $^{171}$Yb can be practically immune to the blackbody radiation shift.

Miniature endcap trap is used for capturing and retaining the single ion by means of a quadrupole radio frequency potential (figure 2).

![Radiofrequency ion trap](image)

**Figure 2.** Radiofrequency ion trap.

Open design allows laser beams conveniently access the trapped ion. Outer trap electrodes, ytterbium oven, electron source and two additional electrodes are used to apply constant voltages for stray field compensation.

![Laser system](image)

**Figure 3.** Laser system for Doppler cooling of the ion. ECDL - external cavity diode laser, ISO - optical isolator, AOM - acousto-optical modulator, EOM - electro-optical modulator, PZT - piezo-electric transducer, PLL - phase-locked loop, PD - photodetector, PMT - photo-multiplier tube, CCD - charge-coupled device camera.
The quasicycling $^2\text{S}_{1/2} (F = 1) - ^2\text{P}_{1/2} (F = 0)$ electric dipole transition with natural linewidth of 23 MHz at 370 nm is used for Doppler cooling and detection of the ion (figure 1). Doppler cooling of the ion is performed with the help of a frequency modulated radiation of the diode laser resonantly frequency doubled in a nonlinear crystal [2] (figure 3).

Up to 100 µW of the UV light is available for the ion cooling. A commercial external cavity diode laser with 10 mW at 739 nm is frequency-modulated in a high speed EOM at 14.75 GHz to generate a sideband that excites the $^2\text{S}_{1/2} (F = 0) - ^2\text{P}_{1/2} (F = 1)$ hyperfine component of the cooling transition. ECDL frequency is resonantly doubled in a cavity-enhanced SHG BIBO crystal. The enhancement ring cavity has a finesse of 400 and FSR of ~740 MHz chosen to be resonant with the sidebands of the modulated light. The laser is frequency locked to the cavity for short-term stability.

![Figure 4. Trapped $^{171}$Yb single ion (left) and resonance fluorescence signal (right) from the cooled single ion.](image)

Using the developed laser system ytterbium ions can be captured and cooled in the ion trap. Figure 4 shows a CCD camera image of the trapped $^{171}$Yb single ion and a spectral profile of the resonance fluorescence signal on the cooling transition. The signal has a HWHM of ~10 MHz which indicates the absence of the Doppler broadening.

Narrow line probe laser is constructed to excite the ion clock transition. The radiation from a frequency doubled extended-cavity diode laser at a wavelength of 871 or 934 nm is used (figure 5).

![Figure 5. Laser system for excitation of the $^{171}$Yb ion clock transition.](image)
The linewidth of the free-running laser is decreased to ~1 Hz by the Pound-Drever-Hall frequency stabilization to a high-finesse Fabry-Perot etalon made of ultralow expansion (ULE) glass (figure 6). To suppress fluctuations of the cavity length caused by low-frequency mechanical (acoustic) perturbations a suspension mount design is employed [3]. The geometry of suspension allows to reduce sensitivity of the cavity to horizontal and vertical vibrations by one order of magnitude. In addition a vacuum chamber is mounted on a passive vibration isolation platform.

![Vibration-insensitive design of the reference cavity.](image)

**Figure 6.** Vibration-insensitive design of the reference cavity.

Cavity length is 102.5 mm, diameter is 50 mm. Suspension point coordinates are $Y_P = -0.9$ mm, $Z_P = 35$ mm, blind bore depth and diameter are 10 mm and 8 mm correspondingly.

The ULE cavity finesse was measured to be $\sim 3 \times 10^5$. The coefficient of cavity thermal expansion (CTE) is nearly zero at the temperature of 26° C, the corresponding thermal frequency drift of the cavity is ~0.25 Hz/s (figure 7).

![Thermal frequency drift of the reference cavity.](image)

**Figure 7.** Thermal frequency drift of the reference cavity.

To obtain an excitation spectrum of the ion clock transition a specially tailored laser pulse sequence was employed (figure 8). The cooling and repumping laser pulses were alternating with the clock laser. The ion is laser cooled for typically ~20 ms and the induced fluorescence light is detected by a photomultiplier. For the cooling power of about 5 μW typical fluorescence count rate at the half-maximum of the cooling resonance is 10 kHz, with a background count rate of 500 Hz. Then the HFS sideband of the cooling laser is switched off and within a time of 20 ms the ion is being transferred
with high probability to the $^2S_{1/2}(F = 0)$ ground state via non-resonant excitation to the $^2P_{1/2}(F = 1)$ state and the fluorescence signal will disappear. The cooling and repumper lasers are then blocked by mechanical shutters and the magnetic field is switched from the high value of 400 μT needed for cooling to 1 μT for the clock transition spectroscopy. Within about 10 ms when the magnetic field has settled to its new value, a 4-20 ms pulse from the probe laser is applied. As long as probe pulse spectral width is larger than the natural linewidth of the atomic transition, it determines the frequency resolution of the resonance signal via the Fourier transformation, while the laser intensity and the detuning from resonance determine the effective Rabi frequency for the excitation.

![Figure 8](image_url)

**Figure 8.** Time sequence for the interrogation of the $^{171}\text{Yb}^+$ clock transition.

The cooling and repumper lasers are unblocked in a few milliseconds after the end of the probe pulse to avoid disturbing by stray light. The ion state is detected on the cooling transition by so-called electron shelving method introduced by H. Dehmelt [4]: when the cooling laser is on, the fluorescence signal appears immediately if the ion is in the ground state, while no signal is detected during detection time of 4 ms when the ion was excited to the $^2D_{3/2}(F = 2)$ state. The excitation attempt is valid if the following requirements are met: (1) the fluorescence rate during cooling step exceeds a threshold of 5 kHz which ensures that the ion is in the F = 1 ground state during the cooling step and is cooled to low temperatures, (2) the fluorescence rate during the ground state preparation step (after turning off the cooling sideband) is below the threshold of 5 kHz, this means that the ion is in the F = 0 ground state when the probe laser pulse is applied. The sequence of interrogation cycles is repeated several times at a certain frequency of the probe laser. The excitation spectrum of the ion clock transition is obtained by repeating the procedure described above for different probe laser frequencies.

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