Compact transportable $^{171}\text{Yb}^+$ single-ion optical fully automated clock with $4.9 \cdot 10^{-16}$ relative instability

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Abstract: The paper describes the results achieved in the development of the compact transportable fully automated optical clock based on a single $^{171}\text{Yb}^+$ ion in a radiofrequency (RF) quadrupole trap. The resulted measurements demonstrated the $4.9\cdot10^{-16}$ output RF signal relative instability on 1000 s integration time with 298.1 kg weight, 0.921 volume, and 2.766 kW input power consumption of the device. A transformation of the ultrastable optical signal into the RF range was performed via the optical frequency comb with a supercontinuum fiber laser generator. The transformation was conducted without loss of initial stability and accuracy characteristics of the signal.

Keywords: optical clock; ytterbium; transportable clock; fully automated; Paul trap; optical molasses; frequency comb; single-ion clock; frequency standard; satellite navigation; space applications

1. Introduction

Nowadays the frequency standards, also known as ultrastable clocks, became a significant part of our being: they are implemented in the space, air, water and terrestrial transport systems, agriculture, fossils industry, fundamental science and so on. The clocks based on the radio frequency (RF) oscillators referenced to the atomic transition in cesium define the Systeme International (SI) second and hertz, and play a central role in the network synchronization, the global positioning systems, the tests of the fundamental physics along with a variety of the other significant practical applications.

Such applications of the ultrastable clocks as a global navigation (i.e. an unmanned automobile transport and a precise agriculture), tests of the fundamental physical constants (such as a fine structure constant and a Rydberg number) [1], local Lorentz invariance tests [2], search for the dark matter [1], and so on, make demands to the level of relative uncertainty of the reference system. The perspective way to increase the stability of the frequency standards is shifting of their operating frequency from the RF ($10^{10} \ldots 10^{11}$ Hz) to the optical ($10^{14} \ldots 10^{15}$ Hz) range increasing the Q-factor of the oscillator ($f / \delta f$) [1]. The best operating optical clocks already developed or preparing by different countries and institutes demonstrate the possibility of reaching the level of $10^{-16}$ relative long-time instability and the same accuracy [3-5].

Besides the increasing of the characteristics of the uncertainty, a development of the compact transportable ultrastable clocks is also the primary task for the worldwide engineering and science [6-10]. Transportable compact ultrastable clocks and their components such as frequency combs [11] can be applied on the boards of the global navigation systems spacecrafts and can be used for purposes of precise gravimetry and gradiometry: mineral exploration, seismology, geophysics, and...
so on. The ion clocks are more appropriate for the space applications than standards based on the neutral atoms in the optical lattices because of a higher depth of the potential well (lifetime of the single ion in the optical ion clock can reach a duration of several months), higher coherence time, a lower rate of the initial substance, and a smaller size of the trap [1].

2. Materials and Methods

2.1. Principle and laser systems

The single $^{171}$Yb$^+$ ion is a well investigated candidate for an ultrastable and accurate optical clock [8] because of its narrow quadrupole transition $^2S_{1/2}$ ($F = 0$) → $^2D_{3/2}$ ($F = 2$) with the wavelength $\lambda \approx 435.5$ nm and the natural linewidth $\Gamma \approx 3.1$ Hz, and the octupole transition $^2S_{1/2}$ ($F = 0$) → $^2F_{7/2}$ ($F = 3$) with the wavelength $\lambda \approx 467$ nm and the natural linewidth $\Gamma \approx 1$ nHz (Fig. 1). Our research was devoted to the quadrupole transition investigation; the optical clock based on the octupole transition is described in [8, 12, 13].

We used the $^2S_{1/2}$ ($F = 1$) → $^2P_{1/2}$ ($F = 0$) transition with the wavelength $\lambda = 369.5$ nm and the natural linewidth $\Gamma \approx 23$ MHz for the Doppler cooling of the ion in the optical molasses [1]. About 0.5% of the decays lead to the metastable $^2D_{3/2}$ state, so we used the repump transition $^2D_{3/2}$ ($F = 1$) → $^3[3/2]_{1/2}$ ($F = 0$) with the wavelength $\lambda \approx 935.2$ nm and the natural linewidth $\Gamma \approx 4.2$ MHz to clean the $^2D_{3/2}$ level.

![Figure 1. The reduced $^{171}$Yb$^+$ energy levels scheme [14-22].](image)

To excite the clock transition we used the second harmonic of the 871.0 nm probe laser, which was locked to the ultrastable cavity. Also due to the collisions in the vacuum chamber an ion could decay in long living F-state so the repump laser at 760.0 nm is used. As the laser sources there were three Littrow scheme diode lasers (369.5 nm, 398.9 nm, and 871.0 nm) and two distributed feedback (DFB) lasers (760.0 nm and 935.2 nm) locked to the wavelength meter within 2 MHz. The external view of the laser system assembly is demonstrated in the Fig. 2. To excite the hyperfine structure, we used the high-frequency EOMs at 2.1 GHz, 3.1 GHz, 5.4 GHz and 14.7 GHz.
The laser system: Doppler cooling, photoionization (the left picture) and repump lasers (the right picture).

The full process of locking of the probe laser frequency to the quadrupole transition consisted of the several steps (Fig. 3). Firstly, the ion was loaded in the trap, then it was cooled down and prepared in the \( ^2S_{1/2} (F' = 0) \) state. Then we tried to excite the clock transition and performed the electron shelving technique [8, 23-25] to detect the final state. The excitation of the metastable level was detected in this technique by the absence of fluorescence while probing on the cooling transition [8]. A laser frequency of the probe laser was being calibrated by the difference of the signal on the left and right slopes of the transition.

To achieve a high speed of the laser radiation switching we used the acoustooptical modulators (AOM) for the cooling, repump and probe lasers. Also the radiation of the cooling and repump lasers was additionally being terminated with the mechanical shutters during the clock transition excitation. As our frequency comb spectrum couldn’t reach the 435.5 nm wavelength we used the diode probe laser at 871 nm and the second-harmonic generation (SHG) in the butterfly scheme with a lithium triborate LiB\textsubscript{3}O\textsubscript{5} (LBO) non-linear crystal.

2.2. Ion trap

In our work we used a 3-dimensional Paul trap with the end-cap design (Fig. 4) which was described in several articles and books [1, 26-29]. The RF electrodes were driven through the amplifier and the helical resonator. To compensate the external DC fields and reduce the DC-Stark effect there is a possibility of usage of the ground electrodes. The atomic ovens (shown in the right picture in the Fig. 4) located in the center plane of the trap on the different sides may be also used as electrodes.
Figure 4. The principle scheme of the Paul trap (the left picture) [29] and the crafted specimen (the right picture).

The voltage on the RF electrodes was set as: $U_{dc} = 0; V_{ac} = 600$ V on a frequency $\omega = 14$ MHz. In such realization the trap depth was equal to 18 eV and secular frequencies were equal to: $\nu_z = 2$ MHz; $\nu_r = 1.2$ MHz. The stability parameters were equal to: $q_z = 2 q_r = 0.26; a_{z,r} = 0$.

2.3. Ultrastable cavities

As the clock transition has the width of about 3 Hz and the laser line width is about 100 kHz, we had to stabilize the probe laser radiation on the short times. We applied a cavity made of the ultra-low expansion (ULE) glass with the quartz mirrors (Fig. 5). A thermal noise floor for this cavity configuration reaches $10^{-15}$. The cavity was placed into the vacuum chamber with 3 thermal shields, and the temperature was locked at the point where linear thermal expansion coefficient was equal to zero. For the laser locking we used the Pound-Drever-Hall technique [1] with the PID signal sent to the current modulation input of the laser. The second ultrastable cavity had the same configuration and stabilized the 1550 nm compact fiber laser, which provided a short-time stability for the frequency comb. The PID signal in this case was sent to the high frequency fiber AOM which modulated 1550 nm laser radiation. The advanced version of our optical clock will have only one cavity and no 1550 nm laser; frequency comb will reach its short-time (~1…85 s) stability directly from the short-time stabilized probe laser.

Figure 5. Two ultrastable cavities (871 and 1550 nm) external view with the probe laser system.
2.4. Frequency comb

For the practical applications, inter alia aerospace, a frequency standard is useful only in the RF range. An optical frequency comb allows to achieve an accurate RF signal from the accurate optical signal. The frequency comb in the ytterbium optical clock was based on a femtosecond multichannel fiber laser generator of supercontinuum with a passive mode synchronization based on a Kerr lens in a Sagnac interferometer. The spectrum of this laser had a number of equidistant laser modes: \( f = f_{CEO} + n \cdot f_{REP} \), where \( f_{CEO} \) was a frequency shift of the wave package in comparison with the main line, \( f_{REP} \) was a frequency of the laser pulse repetition, and \( n \) was a number of a mode. We used in our device a frequency comb created by the Avesta company working in the offset-free scheme \( (f_{CEO} = 0) \). This scheme made stabilization and shift to the RF range significantly easier. As it was mentioned before, the frequency comb stabilization at the short times was achieved in our device via the ultrastable compact 1550 nm fiber laser locked to his external optical cavity. At the long times the frequency comb was stabilized by locking to the ion clock transition with the clock transition excitation system. The frequency comb provided an ultrastable output RF signal at 1 GHz.

3. Results and discussion

The ultrastable \(^{171}\text{Yb}^+\) clock was finally assembled as a stand-alone, autonomous and automatic device. Its structural design included a carrying metalware of the aluminum-magnesium alloy, a 19” rack of the electrical components, a rack of the optical components, and non-metallic light-weight decorative shell (Fig. 6, 7).

![Figure 6](image_url). The \(^{171}\text{Yb}^+\) transportable optical ultrastable fully-automated clock.
The optical components rack contained the most precision and fragile part of the clock. It was mounted on the active vibration isolation platform with piezoelectrical force engines. The platform protected the device from the stochastic and systematic vibrations, shocks, acoustic oscillations. The air temperature, humidity and purity were strongly stabilized inside the optical rack via the automatic climate control system based on the thermoelectrical Peltier air-conditioner. The rack had five mounting levels for the optical components and laser devices. The lowest level was adjusted for placement of the vacuum optical spectroscope with an ion Paul trap. A spectroscope section of the rack was additionally protected by a magnetic fields reflecting system (not demonstrated in the figures). Two ultrastable cavities and the laser system were mounted in the second and third tiers. The last level contained an optical frequency comb with several electronic devices.

The relative instability of the ytterbium optical clock was measured by the comparison with the optical reference that had better relative instability on the considered measurement interval. We used for this purpose the laboratory thulium reference developed in the Lebedev Physical Institute of the Russian Academy of Sciences [30]. The scheme of the signal conversion and its measurement is demonstrated in the Fig. 8. The measurement of the relative instability was performed via phase counter working in $\pi$ and $\lambda$ modes without a dead time. The counter registered a phase of the beat signal between the optical signal of the ytterbium clock and the optical reference. The data was handled by grouping of the measurement intervals in the packages with resultant duration $T$ and calculating of the integrated beat signal.
Figure 8. The schematic picture of the relative instability comparison between the ytterbium optical clock and the thulium optical reference.

The phase in the beginning of the first interval of the package was taken from the phase of the last interval of the package and divided by T. Then we took away a relative value of the beat signal:

$$\xi_i = \frac{\nu_i}{f_L},$$

(1)

where $$\nu_i$$ is the average frequency for the $$i$$-th integrating intervals package, $$f_L$$ is the average radiation frequency of the optical reference. Then the relative mean square two-sample deviation $$\xi$$ was calculated:

$$\sigma_b^2 = \frac{\sum_{i=1}^{n-1} \delta_{0i}^2}{2 \cdot (n - 1)},$$

(2)

$$\delta_{0i} = \xi_{i+1} - \xi_i.$$

(3)

Here n is the total quantity of packages. The relative instability of the output RF signal of the frequency comb was calculated for the measurement time T using the equation:

$$\sigma(T) = \sqrt{\sigma_b^2(T) - \sigma_{ref}^2(T) + \sigma_{conv}^2(T)},$$

(4)

where $$\sigma_{ref}$$ is the relative instability of the referent frequency, $$\sigma_{conv}$$ is the relative instability of the output signal conditioner. The resulted values of the relative instability and Allan deviation are presented in the Table 1.

| T, s  | The relative instability of the beat signal frequency | The relative instability of the output RF signal of the ytterbium clock |
|-------|-----------------------------------------------------|---------------------------------------------------------------------|
| 1     | $$3.7 \cdot 10^{-15}$$                               | $$8.9 \cdot 10^{-15}$$                                              |
| 100   | $$1.1 \cdot 10^{-15}$$                               | $$9.4 \cdot 10^{-16}$$                                              |
| 1000  | $$5.0 \cdot 10^{-16}$$                               | $$4.9 \cdot 10^{-16}$$                                              |

The results of the weight, volume and power consume measurements of the device are shown in the Table 2.
Table 2. The weight, volume and input power parameters of the ytterbium optical clock.

| Parameter       | Value  |
|-----------------|--------|
| Input power, kW | 2.766  |
| Mass, kg        | 298.1  |
| Volume, m³      | 0.921  |

4. Conclusions

The great changes in the ultrastable frequency standards development for the last decade made the quantum optical technologies very important and promising for the next decade in the ground-based and space-born applications. Nowadays the inaccuracy and instability of the optical clocks exceed the Cs fountains values. The optical clocks are incessantly developing in the compactness, weight, power consume and reliability.

The development and manufacturing of the compact optical clocks for the space applications is the task full of difficulties. Besides the science component, this problem requires the developing of the various related photonic technologies (short-line lasers, fiber optical components, electrooptic components, photonic integrated circuits, etc.).

We demonstrated the successful development of a single-ion optical transportable $^{171}$Yb$^+$-based optical fully-automated clock with the $4.9\cdot10^{-16}$ relative instability on the 1000 s integration time with the 298.1 kg weight, 0.921 m$^3$ volume, and 2.766 kW input power. The present status of this work shows that the functionality of some components (power supply, central computer, laser supply, etc.) of the device is redundant. There is a possibility of the significant weight and dimensions reduction of the whole system by the way of developing and usage of the new components with the specific functions. Changeover to the fiber optics and getting rid from one of the ultrastable cavities will also help in further weight and size reduction.

5. Patents

The performed research resulted in the several patents, registered in the Russian patent department. Among them:

- The atomic evaporator (the patent № 191175)
- The RF resonance transformer for the Paul trap electrodes supply (the patent № 192509)
- The ultrastable frequency reference signals generator management and control device (the patent №192267)
- The diode laser with an external cavity (the patent № 268387)
- The optical and laser equipment rack (the patent № 192519)

Supplementary Materials: Figure S1: The reduced $^{171}$Yb$^+$ energy levels scheme, Figure S2: A laser control sequence, Figure S3: The principle scheme of the Paul trap (left picture) and the crafted specimen (right picture), Figure S4: Two ultrastable cavities (871 and 1550 nm) external view with a part of the laser system, Figure S5: The supercontinuum spectrum of the multichannel fiber laser, Figure S6: The $^{171}$Yb$^+$ transportable optical ultrastable clock, Figure S7: The $^{171}$Yb$^+$ transportable optical ultrastable clock without a decorative shell, Figure S8: The resulted RF signal shape, Figure 9: The relative instability (Allan deviation) of the different frequency standards, Table S1: The relative frequency instabilities of the output signal, Table S2: The weight, volume and input power parameters of the ytterbium optical clock.

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