Progress toward a microwave frequency standard based on laser-cooled large scale $^{171}$Yb$^+$ ion crystal

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We report on progress towards a microwave frequency standard based on a laser-cooled $^{171}$Yb$^+$ ion trap system. The electronics, lasers, and magnetic shields are integrated into a single physical package. With over $10^5$ ions are stably trapped, the system offers a high signal-to-noise ratio Ramsey line-shape. In comparison with previous work, the frequency instability of a $^{171}$Yb$^+$ microwave clock was further improved to $c$ for averaging times between 10 and 1000 s.

In recent years, numerous atomic clocks have been developed that offer precise and stable time frequency signals. Such signals are crucial for both basic physics and practical applications. In particular, with the excellent performance, atomic clocks operating with a cloud of trapped ions are showing extremely strong promise in the quest for high precision. For instance, optical clocks based on Al$^+$ exhibit a systematic uncertainty of $9.4 \times 10^{-19}$. Whereas Hg$^+$ microwave clocks demonstrate a frequency instability of $1.5 \times 10^{-13}/\sqrt{\tau}$. In targeting the microwave spectral region, Hg$^+$, Cd$^{109}$, Yb$^{171}$, and Ba$^{139}$ trap systems have been investigated meticulously during the past few decades. The investigations show that while ensuring a decent performance, an atomic microwave frequency standard based on trapped ions has great potential in high transportability because their interaction time are long and the structure of the system is relatively simple. For these reasons, microwave ion clocks are being touted as promising candidates for the next generation of practical atomic clocks.

Much progress on microwave clocks based on ytterbium ions ($^{171}$Yb$^+$) has been achieved. For the buffer gas cooled Yb$^+$ microwave clock, an instability of $10^{-11}/\sqrt{\tau}$ has been demonstrated, which was limited by collision and pressure related shifts. The instability of the laser-cooled Yb$^+$ microwave clock was measured to be $2.09 \times 10^{-12}/\sqrt{\tau}$ and was limited by second-order Zeeman effect. In absolute terms, the frequency instability potential of a laser-cooled Yb$^+$ microwave clock is the same as for the microwave clocks based on Hg$^+$ and Cd$^{109}$. Lately, researchers at the National Physical Laboratory (NPL) have built a prototype of a laser-cooled $^{171}$Yb$^+$ microwave clock that is both compact and portable. The entire system fits into a 6U 19-inch rack unit ($51 \times 49 \times 28$) cm$^3$, verifying the feasibility of such miniaturized Ytterbium-based clocks.

In this study, we report the design and prototyping of a laser-cooled $^{171}$Yb$^+$ microwave clock, based on the ground-state hyperfine transition of $^{171}$Yb$^+$ at 12.6 GHz. The clock system is well integrated into a single physical package and operates successfully in the laboratory environment. More than $10^5$ ytterbium ions are stably trapped in the system enabling it to offer a high signal-to-noise ratio (SNR) Ramsey signal of the ground-state transition. The short-term stability of the $^{171}$Yb$^+$ microwave clock has been improved to $8.5 \times 10^{-13}/\sqrt{\tau}$, a current record level, and its performance in practice demonstrates that the laser-cooled $^{171}$Yb$^+$ clock has promising potential that is as good as other types of ion trap systems. Our research is helpful for developing a compact microwave clock device that can used in ground-based time-keeping, navigation station networking, and terrestrial network synchronizing.

![Schematic energy levels of single $^{171}$Yb$^+$ ion (not to scale).](http://faculty.dpi.tsinghua.edu.cn/team/zhangjw)

FIG. 1. (Color online) Schematic energy levels of single $^{171}$Yb$^+$ ion (not to scale).

The specifics of the operation of an microwave clock are determined by the electronic energy-level structure of the trapped ions. The simple energy-level structure of single $^{171}$Yb$^+$ is shown in Fig.1. To cool the ions and probe their states, a 369 nm laser is used to cycle between the transition states labeled $^2S_{1/2}(F = 1)$ and $^2P_{1/2}(F = 0)$. The neutral Yb atoms are ionized using a combination of two laser beams of wavelengths 369 nm and 399 nm. An extra 935 nm laser is
used to drive ions out of the long-lived state $^2D_{3/2}(F = 0)$
Moreover, to drive ions out of the state $^2S_{1/2}(F = 1)$ during
cooling, microwave radiation of 12.6 GHz is also applied. The
ground state hyperfine splitting, $(^2S_{1/2}(F = 1) \rightarrow ^2S_{1/2}(F = 0))$ of 12.6 GHz, is used as the clock transition.

In regard to the clock system (Fig. 2), an $^{171}$Yb$^+$ cloud is
trapped in a well-designed linear Paul trap. Details of the ion
trap are given elsewhere$^{22}$ and hence only a brief description
is presented here. The trap is made up of four trisected cylin-
deral electrodes made of copper. The radius of each electrode
is $r = 6.2$ mm. The ratio of $r_c/r_o$ is optimized and set at 1.15, to reduce RF heating effects and
to increase the number of trapped ions.$^{23}$ The lengths of the electrode sections are 20, 40, and 20 mm. Direct current (DC)
voltage is applied across adjacent sections, whereas a radio
frequency (RF) voltage, with frequency fixed at 1.144 MHz,
I. EXPERIMENT RESULT

To load the ions, the 369 nm laser is detuned by approximately 50 MHz to the low-frequency side of the corresponding transition. Because the natural Yb solid metal used is a mixture of various stable isotopes, the 399 nm laser is tuned to the peak-frequency of the $^1S_0 \rightarrow ^1P_1$ transition of $^{171}$Yb atom to achieve isotope selection. Confined by both the RF and DC voltages, a long narrow $^{171}$Yb$^+$ cloud is obtained and captured by the CCD camera (Fig. 3).

![EMCCD image of a trapped $^{171}$Yb$^+$ ion cloud. The semi-major and semi-minor axes of the ellipsoid are $L_1 = 6.07$ mm and $D_2 = 0.48$ mm. The amplitude of the RF voltage is approximately 200 V; the DC voltage is set to 4 V. The image has been rotated 90° for convenience; the long axis of the ion cloud is actually oriented vertically.](image)

FIG. 3. EMCCD image of a trapped $^{171}$Yb$^+$ ion cloud. The semi-major and semi-minor axes of the ellipsoid are $L_1 = 6.07$ mm and $D_2 = 0.48$ mm. The amplitude of the RF voltage is approximately 200 V; the DC voltage is set to 4 V. The image has been rotated 90° for convenience; the long axis of the ion cloud is actually oriented vertically.

To estimate the number of ions of a cloud, the number densities of ions are estimated by using low-temperature ion-density theory, from which we have

$$n = \frac{\varepsilon_0 V_{RF}^2}{M \Omega^2 r_o^2}$$

(1)

where $\varepsilon_0$ denotes the vacuum permittivity, $M$ is the mass of $^{171}$Yb$^+$, $V_{RF} = 200$ V, $\Omega = 2\pi \times 1.144$ MHz, and $r_o = 6.2$ mm. The number density of $^{171}$Yb$^+$ ions is estimated to be approximately $n_{Yb^+} = 1.634 \times 10^{13}$ m$^{-3}$, the number of trapped ions being $N_{Yb^+} = 1.1(0.3) \times 10^6$.

To obtain an unambiguous Ramsey signal of the microwave clock transition at 12.6 GHz, all lasers, microwave radiation, and magnetic fields of the coils must be precisely controlled. A field-programmable gate-array circuit board is used to generate control signals to within millisecond order. During measurements, all laser frequencies are first stabilized to within 2 MHz by locking to the wavelength-meter. The ions are then trapped and cooled using the 369 nm and 935 nm laser beams directed downward into the system. A strong external magnetic field and high-power microwave radiation is applied to suppress the dark states. To pump the ions into the $(S_{1/2}(F = 0))$ state via the decay from the off-resonance excited $(^{2}P_{1/2}(F = 1))$, the high-power microwave radiation is turned off. During the interaction with the $\pi/2$ pulse, only the steerable magnetic field is applied to compensate the residual magnetic field and splitting of the Zeeman sublevels. Finally, the upward-directed low-power 369 nm laser beam is used to detect the number of ions in the $(^{2}S_{1/2}(F = 1))$ states. An interval of approximately 20 ms is set to wait for closure and establishment of the strong magnetic field, the control of which is based on a transistor. From the Ramsey fringes (Fig. 4) recorded by the PMT, peak-to-peak values are calculated along with their amplitudes at half-waist, from which estimates of the SNR, typically 35, for the clock resonance are obtained. The high SNR of the Ramsey signal ensures a decent stability performance for the designed $^{171}$Yb$^+$ microwave frequency standard.

![Typical Ramsey lineshape of the clock transition (12.6 GHz) with a microwave pulse time of 60 ms, free time of 500 ms, microwave power of -29.8 dBm, and a fluorescence signal integration time of 150 ms. Each data point is the average of five results. The fitted curve has a central frequency of 12642812121.47 Hz](image)

FIG. 4. Typical Ramsey lineshape of the clock transition (12.6 GHz) with a microwave pulse time of 60 ms, free time of 500 ms, microwave power of -29.8 dBm, and a fluorescence signal integration time of 150 ms. Each data point is the average of five results. The fitted curve has a central frequency of 12642812121.47 Hz.

The short-term frequency instability limitation can be estimated after acquiring the Ramsey signal. Here, we have mainly considered quantum projection noise, pump noise, and shot noise, which are typical limitations to the frequency stability of a passive frequency standard.

To estimate the quantum projection noise $\sigma_{proj}$, pump noise $\sigma_{pump}$ and shot noise $\sigma_{shot}$, the maximum photon counts of the Ramsey signal $S_{max}$, the minimum photon counts of the Ramsey signal $S_{min}$, the photons counts arising from background scattered light $S_{back}$, and the number of ions $n$ need to be confirmed first. Typically, for our system, $S_{max} = 10500$, $S_{min} = 2500$, $S_{back} = 1500$, $n = 100000$. Then the noise is calculated from

$$\sigma_{proj} = \sqrt{\eta n K}$$

(2)

$$\sigma_{pump} = \sqrt{n \eta (1 - \eta) K}$$

(3)

$$\sigma_{shot} = \sqrt{S_{max} + S_{min}}$$

(4)

where $K = (S_{max} - S_{back}) / n$, $\eta = 1 - S_{min} / S_{max} - S_{back}$. Therefore, the overall calculated noise is:

$$\sigma_{cal} = \sqrt{\sigma_{proj}^2 + \sigma_{pump}^2 + \sigma_{shot}^2}$$

(5)

With $\sigma_{cal} = 81$, the corresponding SNR is around 48.8, which indicates that the frequency instability limitation is around $5.9 \times 10^{-13}$ at 1 s.
We conducted a preliminary closed-loop run to verify the potential of the system. A detailed description of the measurement setup has been fully discussed. We set the free time at 1 s and the cooling time at 1.2 s for measurements during the closed-loop run to reduce the linewidth and increase the theoretical instability limitation. After comparing our 10 MHz output signal with an active hydrogen maser, the Allan deviations of the frequency standard are presented (Fig. 5). Moreover, the frequency stability of our free-running OCXO, together with the performance of recent microwave clocks of other research groups, are also presented for direct comparison. The measured frequency stability of our clock is $8.5 \times 10^{-13}/\sqrt{\tau}$ for averaging times between 10 and 1000 s.

Overall, as the number of trapped ions increases to around $10^5$, the SNR of our system is vastly enhanced, which explains the reason for the improved performance of our system. However, our system has not reached the performance limit that we expected from the calculation results. Fluctuations in the laser power, laser frequency, magnetic field, and working temperature are suspected to increase noise and degrade system performance. The slight bump in our measured Allan deviation at around 500 s (Fig. 5) is considered to be related to fluctuations in room temperature and laser power, the fluctuation period of which lasts thousands of seconds. To further enhance the short-term instability of our system and provide long-term system accuracy and stability, active feedback must be used to suppress these fluctuations, which is our objective for the next round of measurements.

We reported on progress towards a highly stable and high performance $^{171}$Yb$^+$ microwave frequency standard. In attaining this microwave frequency standard, cooling, pumping and detecting of $^{171}$Yb$^+$ are achieved. In our experiment, $10^5$ Yb ions are stably trapped. A high SNR Ramsey fringe line-shape is obtained and the microwave frequency standard shows a short-term stability of $8.5 \times 10^{-13}/\sqrt{\tau}$.

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**DATA AVAILABILITY STATEMENT**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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