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The Development of the NIM-Yb1 Ion Optical Clock

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Abstract

Optical clocks serve as the benchmark devices for the next-generation definition of the second and have significant applications in testing the theories beyong the standard models, dark matter research, and related fields. The ytterbium ion optical clock, featuring two clock transition lines, is among the most precise optical clocks with the lowest uncertainties. The National Institute of Metrology, China (NIM), initiated research on ytterbium ion optical clocks in 2021. Based on an end-cap ion trap, a vacuum system has been established. A 370 nm third-harmonic fiber laser, along with 760 nm and 935 nm DFB lasers, ensures a stable operation of the optical system. To date, both the electric quadrupole and electric octupole clock transitions have been observed. A 2.8 Hz linewidth of the electric octupole transition has been achieved, with a stability of 1.7E-15 $\tau^{-1/2}$ after closed-loop locking. The uncertainties due to AC Starks shift from clock laser and second-order Doppler shifts are being evaluated, with an expected total uncertainty below 5E-18.

1. Introduction

Optical clocks will be the primary frequency standards for the next-generation definition of the SI unit second, offering exceptionally low uncertainties. They also play a crucial role in the fundamental physics research [1], such as dark matter detection [2], and general relativity testing[3]. Tens of laboratories worldwide are engaged in optical clock research. Multiple types optical clocks (^{87}Sr [4-6], ^{171}Yb [7], ^{171}Yb^{+} [8-9], ^{27}Al^{+} [10-11], ^{40}Ca^{+} [12], ^{176}Lu^{+} [13]) have demonstrated uncertainties in the low 10-18 range or even lower.

Due to the two clock transition frequencies and the insensitivity of the electric octupole (E3) transition frequencies to thee electric and magnetic fields, the ^{171}Yb^{+} optical clock can obtain lower uncertainty more easily, and has a congenital advantage in optical clock comparison. In 2016, PTB in Germany reported an analysis of systematic frequency shifts of the E3 transition yielding a total systematic relative uncertainty of 3.2×10^{-18} [14]. In 2019, the corresponding uncertainty of two ^{171}Yb^{+} optical clocks was measured to be 3.6×10^{-18} [8]. In recent years, NPL in England has also begun the ^{171}Yb^{+} optical clock research and reported the systematic relative uncertainty of 2.2×10^{-18} in 2024[9]. In addition, Institute of Laser Physics in Russia [15], Innovation Academy of Precision Measurement Science and Technology in China [16] and Beijing Institute of Radio Metrology and Measurements in China [17] are also developing ^{171}Yb^{+} optical clocks.

The National Institute of Metrology(NIM), China, has been conducted in optical clock research for two decades. The Sr optical lattice clock has achieved an uncertainty of 7.2×10^{-18}[18]. To address the redefinition of the second and meet the roadmap requirement for comparisons between different types of optical clocks, NIM initiated the development of a Yb^{+} optical clock. The system has been established, with both the electric quadrupole and octupole clock transitions being locked. Uncertainty evaluation is currently in progress.

2. Ytterbium Ion Optical Clock System Setup

The Yb^{+} optical clock consists of three units: the physical system, the optical system, and the ultra-stable laser system.

The physical system employs an end-cap ion trap provided by PTB, as shown in Figure 1. Its high thermal conductivity design ensures efficient dissipation of heat generated by the RF electrodes. Additionally, gold plating on the electrode surfaces minimizes the influence of stray electric fields on the trapped ion[19]. The vacuum system operates at an ultra-high vacuum of approximately 10^{-9} Pa, ensuring the collisional frequency shift due to background gas below 1E-18[20].

Based on the energy level structure of ytterbium ions (Figure 1), the cooling laser for ytterbium ions operates at 369.5 nm, while the repumping lasers are at 935 nm and 760 nm for the $D_{3/2}$ and $F_{7/2}$ respectively. The electric quadrupole clock transition is driven by a 435.5 nm laser, and the electric octupole clock transition is driven by a 467 nm laser.

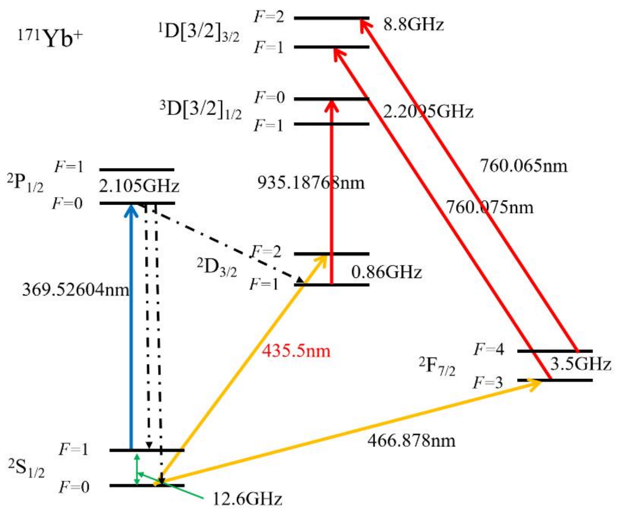

Figure 1. Energy level structure of $^{171}Yb^{+}$.

To enhance the reliability of the optical system, the 369.5 nm cooling laser is generated using a third-harmonic fiber laser, with its 1108 nm fundamental frequency locked to a fiber-based femtosecond optical frequency comb, ensuring frequency accuracy and long-term stability. The 935 nm and 760 nm repumping lasers are distributed feedback (DFB) lasers, locked to a wavelength meter (HighFinesse WS8). The detailed optical system design is illustrated in Figure 2.

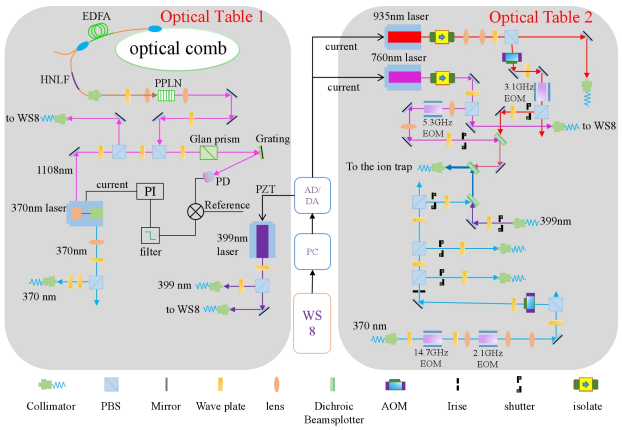

Figure 2. Optical system design. EDFA, Erbium doped optical fiber amplifier; HNLF, Highly-nonlinear fiber; PPLN, Periodically polarized lithium niobate; WS8, Wavelength meter (HighFinesse WS8); PD, Photo diode; PI, Proportional-Integral; PZT, Piezoe-lectric Transducer; PBS, Polarization beam splitting prism; EOM, Electro-optical modulator; AOM, Acoustic optical modulator.

The E3 transition clock laser is a 467 nm ultra-stable laser with its 934 nm fundamental frequency being locked to a 200 mm ultra-stable cavity with the Pound-Drever-Hall (PDH) lock technique. The stabilized 934 nm laser is then beat with a fiber-based femtosecond optical frequency comb for frequency measurements. The beat signal is shown in Figure 3, revealing a laser frequency drift of 51.3 mHz/s due to cavity aging effects.

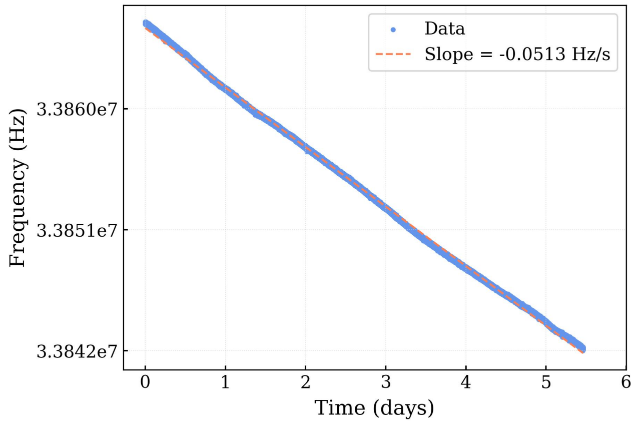

Figure 3. Beat signal between the 934 nm ultra-stable laser and the optical frequency comb.

The 467 nm laser interacts with a trapped ion, enabling the detection of the ytterbium ion's electric octupole clock transition. When the clock laser pulse duration is set to 300 ms, the measured linewidth of the clock transition is 2.8(2) Hz as shown in figure 4.

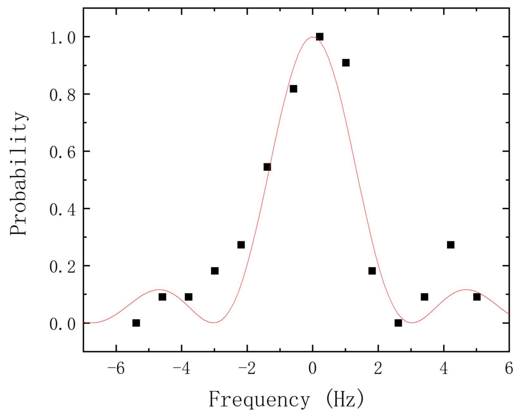

Figure 4. The Rabi spectra of the $^{171}Yb^{+}$ $^{2}S_{1/2}$ (F=0) -$^{2}F_{7/2}$ (F=3) clock transition, showing a linewidth of ν_{FWHM} =2.8(2) Hz for a Rabi probe of τ =300 ms.

After implementing closed-loop locking, the in-loop stability of the optical clock reaches 1.7E-15 $\tau^{-1/2}$ as shown in Figure 5.

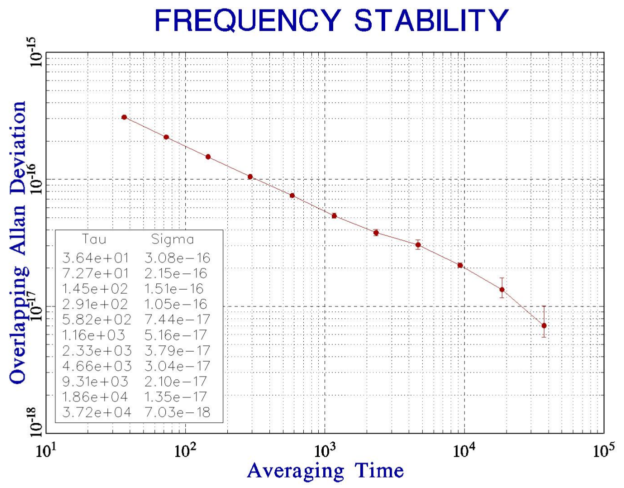

Figure 5. The closed-loop stability of the electric octupole clock transition of NIM-Yb1 Ion

3. Conclusion

The ytterbium ion optical clock system has been successfully established, with the electric octupole clock transition frequency locked in a closed-loop configuration. After locking, the in-loop stability reaches 1.7E-15$\tau^{-1/2}$.

The preliminary evaluations of blackbody radiation shift and collisional shift have been completed, with uncertainties of 1.6E-18 [21] and 0.6E-18 [20], respectively. Due to an extremely long lifetime of the $2F_{7/2}$ state of an ytterbium ion, a 0.1 mW of the 467 nm clock laser is applied to excite a clock transition, which induces an AC Starks shift of about 10 Hz. To minimize the uncertianty due to this effect, precise stabilization of the 467 nm laser power is required.

Further evaluations of the other uncertainties, including second-order Doppler shift and second-order Zeeman shift, will be evaluated soon shooting for a total uncertainty below 5E-18.

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