Hyperfine Structure and Absolute Frequency Measurements of $^{127}I_2$ Transitions at 554 nm and Its Application for Yb^+ Ions Cooling

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***Abstract*—We have developed a system to stabilize the laser frequency by locking the laser to the hyperfine transitions of iodine molecules. The frequency stability of 5 × 10^{-12} is observed over a 1000 s integration time. This iodine frequency-stabilized laser system has simple structure, good portability, and high performance. It can also be applied to the development of ytterbium ion microwave frequency standards.**

Keywords*—*iodine molecules, ytterbium ions, quantum standards, hyperfine structures, frequency stability

I. Introduction

Quantum frequency standards are widely used in a broad range of applications, such as precision metrology, satellite navigation[1,2], wireless communications[3], and new physics investigations[4,5,6], etc. At Tsinghua University, our team has long been devoted to the development of laser-cooled quantum frequency standards, such as cadmium ion microwave clock[7-11], ytterbium ion microwave clock[12-15], and so on. Using proper laser frequency stabilization techniques to narrow laser output linewidth and improve laser frequency stability is very important for ion microwave frequency standard research. Previously, we used wavelength meter to stabilize the laser frequency[16,17]. This method is expensive and bulky. Due to the limitation of the response frequency of the feedback loop, the accuracy can only be realized to the order of megahertz. So it cannot be used to miniaturized transportable and high-precision quantum frequency standards. More seriously, the wavelength meter itself has a severe long drift, which is not conducive to the long-term work of microwave ion clocks. Based on this, we have developed an iodine frequency-stabilized laser system to stabilize the laser frequency by locking the laser frequency to the hyperfine transitions of iodine molecules[18]. The iodine frequency-stabilized laser system has simple structure, good portability, and high performance. In addition, we have built a high-precision laser wavelength measurement platform, which leads the laser to an optical comb through optical fiber link. The stabilized laser beats with the optical comb to achieve its absolute frequency with high precision. This iodine frequency-stabilized laser system can be well applied to the development of ytterbium ion microwave frequency standards.

II. Principles

A. Energy levels of $^{171}Yb^+$ ion

The electronic energy level structure of the trapped ions determines the specifics of the operation of the microwave ion clock. Here, Fig. 1 shows schematic diagram of the partial energy level structure of $^{171}Yb^+$ ion. In order to develop the ytterbium microwave frequency clocks, three lasers are essential. A 369 nm laser is used to cool $^{171}Yb^+$ ions and probe their states by cycling between the transitions states labeled $^2S_{1/2}$ $(F = 1)$ and $^2P_{1/2}$ $(F = 0)$. A 399 nm laser is used for isotope selection and ion ionization combined with the 369 nm laser. In addition, a 935 nm laser is used for repumping the ions which fall into the long-lived dark state $^2D_{3/2}$ $(F = 0)$[19].

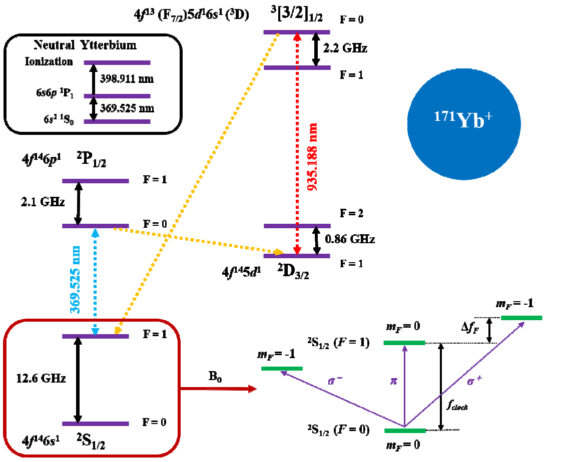

Fig. 1. Schematic diagram of the partial energy level of $^{171}Yb^+$ ion (not to scale).

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B. Laser frequency stabilization

The laser we used in the research of ytterbium microwave clock is a frequency-tripled laser (PreciLasers, Inc.), whose seed laser is a 1108 nm distributed feedback (DFB) fiber laser, and power boosted by a fiber-optic power amplifier. The 1108 nm seed laser is frequency-doubled by a periodically poled crystals (PPC) to generate the 554 nm laser. Then, the 1108 nm laser and the 554 nm laser is summed in another crystal to generate the 369 nm laser. Thus, we can obtain a frequency stabilized 369 nm laser by stabilizing the 554 nm laser via molecular iodine spectroscopy. Additionally, the 399 nm laser used for isotope selection and ion ionization can be frequency-stabilized by locking to the ytterbium atomic lines. The 935 nm laser used for repumping the ions could be frequency-stabilized by locking to the 1108 nm laser via transfer cavity. Fig. 2 shows the principle of the iodine frequency-stabilized laser system.

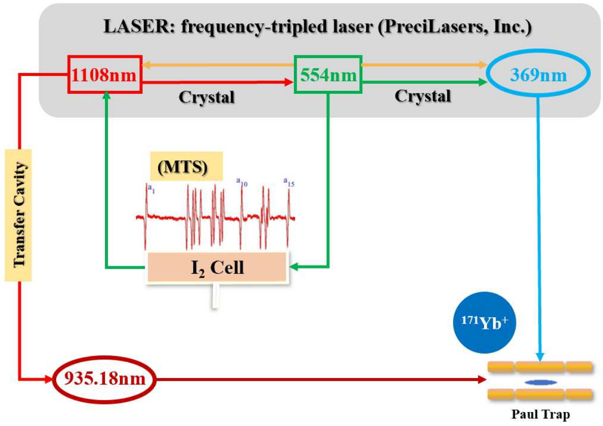
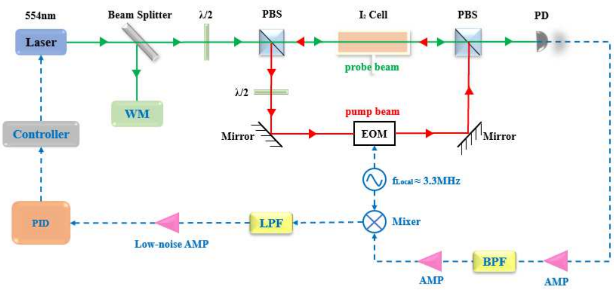


Fig. 2. Schematic diagram of the principle of the iodine frequency-stabilized laser system

III. EXPERIMENTAL SETUP

Fig. 3 shows both the schematic diagram and the physical device of the iodine frequency-stabilized system. The hyperfine structure of iodine molecule is obtained by modulated transfer spectroscopy and the absolute frequency of hyperfine transition is measured by an optical comb.



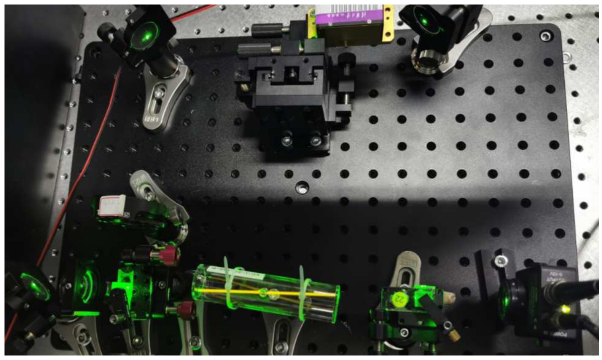


Fig. 3 The schematic diagram and the physical device of the iodine frequency-stabilized system.

The laser with a diameter of 1.5 mm was divided into two beams by a polarization beam splitter (PBS), which were the pump beam with higher power and the probe beam with lower power. After frequency modulated by an electro-optic modulator (EOM) and amplitude modulated by an optical chopper, the pump beam overlapped with the probe beam in a temperature-controlled iodine cell, and then converted into electrical signal by a photodetector (PD). The error signal was then demodulated, filtered and amplified. Thus, the modulation transfer spectroscopy (MTS) signal was obtained. The MTS signal was output to the laser through PID feedback control.

Meanwhile, as shown in Fig. 4, in order to obtain the absolute frequency of the laser, we also built a set of high-precision laser wavelength measurement platform. The 554 nm laser beam is combined with the optical comb referenced by the hydrogen maser through a polarization beam splitter (PBS), and the beam is diffracted through a grating and selected by an aperture, and then incident on the photodetector (PD). This beat note is measured by a frequency counter with a hydrogen clock referenced by the hydrogen maser after filtering and two-cascaded amplification. Thus, the absolute frequency of the 554 nm laser is obtained.

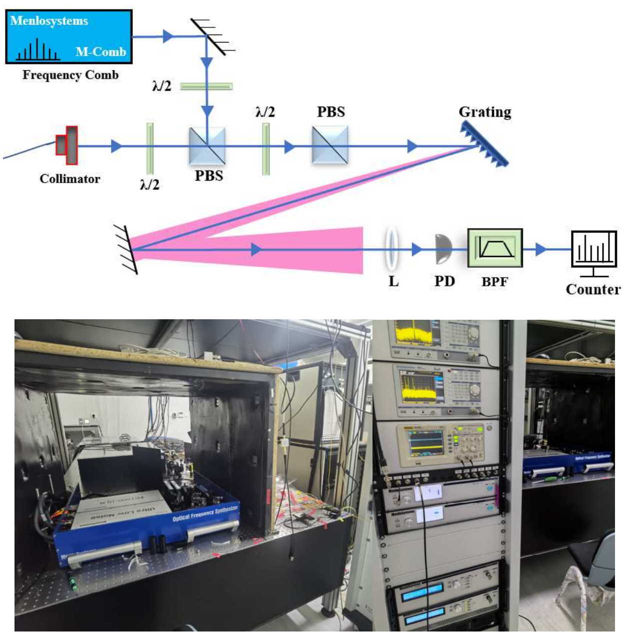


Fig. 3 The schematic diagram and the physical device of the absolute frequency measurement system.

IV. Results

A. Hyperfine structure

We observed the hyperfine structures of iodine molecules near 554 nm. Fig. 4 shows the modulation transfer spectroscopy signals of R146 (25-0) transitions.

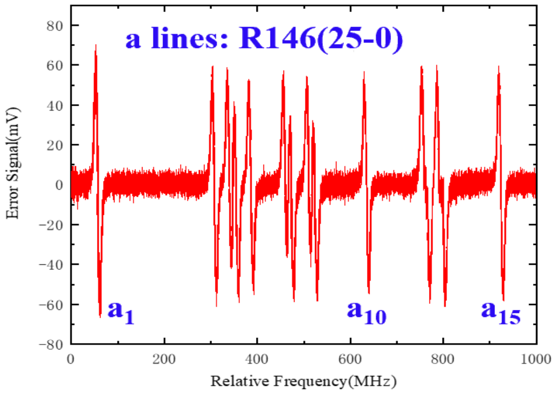


Fig. 4 Modulation transfer spectroscopy signals of $^{127}I_2$ hyperfime transitions around 554 nm.

B. Frequency stability

Since the frequency of R146 (25-0) a_{15} transition line of iodine molecules is very close to that of $^2S_{1/2} \rightarrow {}^2P_{1/2}$ cycling transitions of the ytterbium ions, so we locked the laser to this hyperfine transition for over 15000 s. The result shows that the frequency stability of the iodine frequency-stabilized laser reached a level of 5×10^{-12} over a 1000 s integration time with a 1 s gate time.

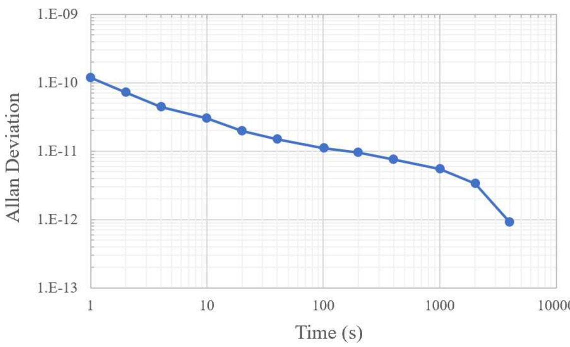


Fig. 5 Allan deviation of the measured beat frequency between the laser that is locked to the R146 (25-0) a_{15} line and the optical comb that is locked to the hydrogen maser. (gate time: 1s)

We also measured the absolute frequency of the R146 (25-0) a_{15} line and investigate its uncertainty. The result shows to be 540 859 322 747 (48)(31) kHz[18]. The first parentheses shows type-A (statistic) uncertainties (k = 2), and the second parentheses shows type-B (systematic) uncertainties.

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