Improvement in medium-long term frequency stability of integrating sphere cold atom clock

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The medium-long term frequency stability of the integrating sphere cold atom clock was improved. During the clock operation, Rb atoms were cooled and manipulated using cooling light diffusely reflected by the inner surface of a microwave cavity in the clock. This light heated the cavity and caused a frequency drift from the resonant frequency of the cavity. Power fluctuations of the cooling light led to atomic density variations in the cavity’s central area, which increased the clock frequency instability through a cavity pulling effect. We overcame these limitations with appropriate solutions. A frequency stability of $3.5 \times 10^{-15}$ was achieved when the integrating time $\tau$ increased to $2 \times 10^4$ s.

I. INTRODUCTION

The atomic frequency standards have been rapidly developed in the past three decades for applications in space navigation, telecommunication, and timekeeping. In most cases, a portable and stable atom clock is required. Researchers have proposed several schemes for compact atom clocks and attempted to ensure the stability of the atomic clocks for a long operation time. A frequency instability of $3.2 \times 10^{-15}$ was determined using HORACE when the integration time was $2 \times 10^4$ s, which shows a good control of system noises [1]. The pulsed optically pumped (POP) clock developed at INRIM has an instability of $5 \times 10^{-15}$ at a $4000$ s integration time [2]. The clock based on the intracavity sample of cold Cs atoms proposed by Müller et al. achieved a frequency stability of $5.0 \times 10^{-13} r^{-1/2}$ and shows a good performance after $10^4$ s [3].

The integrating sphere cold atom clock (ISCAC) [4] is a kind of compact atomic clock that uses diffuse laser cooling [5,6] and the POP [8] operating scheme to achieve a good frequency stability with a small volume and weight. Compared with a vapor cell POP atomic clock, the ISCAC has less atomic collision frequency shifts and less sensitivity to the temperature fluctuations making it easier to achieve a better frequency stability for a long operation time. Unlike other compact cold atom clocks, ISCAC uses a microwave cavity to diffusely reflect cooling light and cools atoms without a quartz chamber in it [4]. This scheme can eliminate the influence of the quartz chamber on the microwave resonant frequency in the microwave cavity. In addition, the all-metal structure of the clock is more robust and convenient for space applications. However, the cooling-light heating effect on the microwave cavity is considerable and the resonant frequency shift of the microwave cavity should be compensated. The distribution of the cold atoms in the microwave cavity is determined by the injection scheme of the cooling lights and the corresponding intensities [9]. Therefore, in our system, stable cooling lights are necessary for decreasing the cavity pulling effect [10], which is the main limiting factor of the long-term frequency stability.

In this paper, we present the medium-long term frequency stability of ISCAC achieved recently and analyze factors that have a large impact on the frequency stability. The heating effect on the microwave cavity owing to the cooling lights and the necessity of stabilizing the power of the cooling lights are studied. Section II briefly introduces the experimental setup and the operating time sequence of the ISCAC. Section III presents the factors limiting of the clock frequency stability and the solutions to overcome these limitations. The results of the study of the clock frequency stabilities are presented in this section as well. The final section presents the conclusion and scope of improving the long-term frequency stability of the clock further on.

II. EXPERIMENTAL SETUP AND TIME SEQUENCE

The ISCAC is operated using the POP configuration, which involves a diffuse laser cooling process before the optical pumping [4]. In the cooling stage, $^{87}$Rb atoms were cooled to below $100 \mu K$ [11] in isotropic cooling light, which is diffusely reflected by the inner surface of the microwave cavity. Then, the atoms were pumped into the $^{5}S_{1/2},|F=1\rangle$ state of the $^{87}$Rb $D_2$ line with a short pumping light pulse in preparation for the Ramsey microwave interrogation process. Fig. 1 shows the atomic levels of the $^{87}$Rb $D_2$ line and the optical and microwave fields used during the operation. Finally, the atoms that experienced a clock transition

$^{5}S_{1/2},|F=2,m_F=0\rangle \rightarrow ^{5}S_{1/2},|F=2,m_F=0\rangle$ were detected using a standing wave probe light after the second Ramsey pulse. Acousto-optic modulators (AOM)
FIG. 1. Atomic levels of $^{87}$Rb $D_2$ line under biased magnetic field and transitions during the clock cycles. \( \omega_0 \) and \( \omega_L \) are the angular microwave and laser frequencies, respectively (colour online).

and mechanical shutters were both used to cut off the light to avoid optical frequency shifts of the clock transition. Fig. 2 shows the time sequence of the clock. We discarded the second pumping pulse, which was used for normalizing the probe light power fluctuation during the detection period [4], because the power lock of the probe light was used instead. In addition, the cycle time without the second pumping pulse was shortened to 88 ms, which reduces the effect of the microwave noise (Dick effect) and simplifies the time sequence. Fig. 3 shows the Ramsey fringes obtained with this time sequence.

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achieve better clock frequency stability, several physical factors such as temperature fluctuations of the microwave cavity and variation in the biased magnetic field, that limit on the medium-long term frequency stability. Therefore, to achieve better clock frequency stability, several physical and technical problems have to be solved.

Temperature stability is a very important factor that affects the stability of an atomic clock because many physical characteristics of the clock devices are temperature dependent. For the ISCAC, because the resonant frequency of the cylindrical microwave cavity is susceptible to temperature variations, we implemented a two stage temperature control loop to stabilize the microwave cavity temperature. However, this measure is not enough to ensure temperature stabilization, especially after a long period of operation. Owing to the special cooling scheme of the ISCAC, the cooling light, which has a total power about 200 mW was directly reflected by the microwave cavity with the inner diameter and height of 57 mm in each cycle. The laser heating effect on the microwave cavity is largely determined by the cooling light. Power fluctuations in the cooling lights will transfer to the instabilities of the cold atoms in the microwave cavity. The fluctuations in the number of cold atoms will further degrade the clock frequency stability according to the model for estimating the cavity frequency pulling effect of an atomic fountain:

\[
\Delta \nu_{\text{cp}} \propto \frac{\tau \mu_0 \mu_2^2 N_i Q}{2 \pi^2 h V_{\text{mode}}} \left[ \frac{2(\omega_2^2/Q)(\omega_2^2 - \omega_c^2)}{\omega_2^2 - \omega_c^2} \right],
\]

where \(Q\) and \(V_{\text{mode}}\) are the TE011 mode quality factor and mode volume, respectively, \(\omega_c/2\pi\) is the cavity eigen-mode resonance frequency and \(h\omega_c\) is the clock transition energy. \(N_i\) is the number of cold atoms that have experienced the microwave interrogation process. In our case, cavity pulling effect is a dominant factor to affect the medium-long term stability because the whole stage of Ramsey interrogation is carried on in the microwave cavity. Therefore, the intensity stability of cooling light has a larger impact on the clock frequency stability than other schemes of cold atom clocks. An active power stabilization loop was required to decrease the cooling light fluctuations. After this servo loop was implemented, the temperature stability of the microwave cavity was found to be not a restrictive factor affecting the clock frequency stability. The temperature stability of the microwave cavity during the experiment is shown in Fig. 6. The temperature sensitivity of the microwave cavity resonant frequency was 113.5 KHz/°C, which was calibrated in a vacuum environment before the installation. Then the relative resonant frequency variation \(\Delta \nu_c/\nu_c\) was less than \(2.0 \times 10^{-8}\) and the contribution to the clock frequency instability of the microwave cavity temperature fluctuations is at the level of \(2.6 \times 10^{-16}\). The microwave cavity is covered with five layers of magnetic shields which provide a well-shielded environment. The quantization magnetic field (C-field) is driven by two low noise current sources. Fig. 7 shows the measured stability of the current source. The second-order Zeeman shift of the clock frequency can be estimated using the equation shown below:

\[
\Delta \nu_z = K_0 |\mathbf{B} \cdot \hat{z}|^2,
\]
where $K_0 = 575.14 \times 10^9 H z/T^2$. $B$ is the biased magnetic field intensity and $\hat{z}$ is the unit factor of the quantization axis. To reduce the effect of the second-order Zeeman shift on the clock frequency stability, we reduced the the C-field intensity to 3.1 mG. In this situation, the second-order Zeeman shift was $5.5 \times 10^{-6} H z$ and the clock instability degraded to $3.2 \times 10^{-17}$ when the average time increased to $2 \times 10^4$ s, which can be ignored for the system.

Typically, the frequency stability of the ISCAC is measured by comparing it with an H-maser whose stability is $2.0 \times 10^{-13}$ at 1 s and $2.0 \times 10^{-15}$ after $10^4$ s. Fig. 8 shows two sets of frequency stability results of the clock with different experimental conditions. The Allan deviation (black triangles) result is measured without locking the cooling light power and the cycle time is 133 ms. The red dots curve is the clock frequency stability obtained after applying cooling light power stabilization and the clock cycle time is shortened to 88 ms. The white frequency region is extended to $2 \times 10^4$ s and a frequency stability of $3.5 \times 10^{-15}$ was achieved at $2 \times 10^4$ s after the improving the experimental conditions.

![FIG. 7. Stability of biased magnetic field current source.](image1)

![FIG. 8. Frequency stabilities of ISCAC under medium-term measurements (colour online).](image2)

IV. CONCLUSIONS

We reported the improvement on the medium-long term frequency stability of the ISCAC. The systematic factors that affect the clock medium-long term frequency stability are discussed and their limitations on the clock frequency stability were reduced by improving the experimental conditions. In addition, the laser heating effect on the microwave cavity and the effect of the cooling laser power fluctuations were studied and restrained by employing appropriate solutions. The clock frequency stability reached less than $10^{-15}$ when $\tau > 4000$ s and $3.5 \times 10^{-15}$ at $2 \times 10^4$ s. A new microwave synthesizer of low phase noise and small volume is in the development to decrease the noise and instability of the microwave interrogation pulses. Meanwhile, further investigation on improving the clock long-term frequency stability performance will be conducted to determine the requirements for practical applications.

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