Two Methods About C-field Evaluation in Beam Clock

Yuanhao Li, Chen Liu, Sifei Chen, Lifeng Fan, Yanhui Wang
State Key Laboratory of Advation, System and Network, School of Electronics, Peking University

***Summary*—Two new methods related to the evaluation of thermal beam clock's C-field are presented and experiments are shown. The first method measures the stability of C-field locking by using 1-1 line to lock the microwave frequency and 0-0 line to lock the C-field. As the 1-1 line is more sensitive to the magnetic field, such locking makes it easily to see the magnetic field fluctuations after locking. The second method uses a large modulation depth of the microwave frequency locking, so that the frequency points are in the left and right of the Rabi resonance curve instead of the Ramsey fringes. Using this method, we measure the deviation of the center of the Rabi and Ramsey resonance curve, which can evaluate the inhomogeneity of the C-field.**

Keywords—microwave; quantum frequency standard; C-field; C-field locking; C-field inhomogeneity

I. INTRODUCTION

Compared to laboratory clocks, compact clocks are used in more complex and variable environments with different temperature, air pressure, magnetic fields and so on. C-fields may deviate from the value at the time of assembly and may also vary over time. Although these problems can be partially solved with sophisticated simulations, efficient magnetic shielding, and high precision current control, sensitive atoms can still sense very weak C-field variations.

The atomic beam can be helpful if we want to measure the C-field. Such an idea has been applied to fountain clocks, where the maximum height of the atoms can be changed to scan the magnetic field in the whole space above, but this cannot be achieved in thermal beam clocks [1][2].

A common method to perform magnetic field locking is using the frequency difference between the π transitions of m_F = 1 (1-1 line) and m_F = 0 (0-0 line), since this frequency diff. is basically only related to the magnetic field. We can evaluate the locking of microwave frequency by frequency ratio measurement, but C-field locking is not. The effects of C-field locking often take a very long measurement time, and will also be mixed with other long-term effects. A new method is proposed to evaluate C-field locking loops. The 1-1 line is used for frequency output and the 0-0 line is used to detect the deviation of the C-field. This method can be called as "exchange locking". Since the 1-1 line is more sensitive to the magnetic field, the C-field fluctuation under locking can be measured by measuring the output frequency. This will help to determine the parameters of C-field locking (e.g. the gain of the error signal) and to evaluate it.

The second method proposed in this paper is a measurement method for C-field inhomogeneities. When the C-field is inhomogeneous, the center of the Rabi resonance curve and the center of the Ramsey resonance curve are misaligned, thus causing an extra frequency shift. Such inhomogeneity may arise from assembly errors, non-ideality performance of the magnetic shielding, changes of the environment and so on. The second method uses a large modulation depth of the microwave frequency locking, so that the frequency points are in the left and right of the Rabi resonance curve instead of the Ramsey fringes. The result of this locking is that the center frequency of the microwave will be aligned with the center of the Rabi resonance curve.

II. METHODS/RESULTS

A microwave module with six multiplication factors is used in the experiment. Digital signal locking often uses square wave modulation. The frequency jumps between the left and right side of the peak. The error signal can be expressed as $I_{err} = I(f_0 + f_m) - I(f_0 - f_m)$, where $I(f)$ is the spectrum related to the frequency, f_0 is the central frequency and f_m is the modulation depth. When $I_{err} = 0$, The center frequency will be aligned with the peak frequency. In the actual operation of the clock, the frequency can be switched between $f_0 + f_m$ and $f_0 - f_m$ by modifying the multiplication factors of the microwave module.

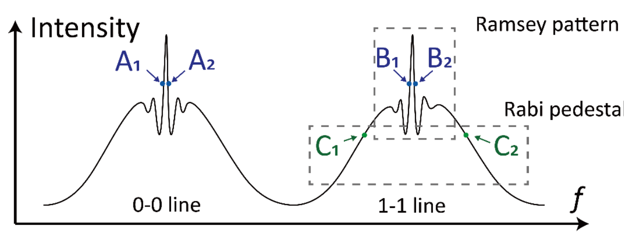

Fig. 1. The diagram of the Ramsey curve in the thermal beam clock. (0-0: mf=0→mf-0; 1-1: mf=1→mf=1) When using A_1A_2 for locking, the center frequency will be 0-0 Ramsey curve's peak; when using B_1B_2: 1-1 Ramsey curve's peak; when using C_1C_2: 1-1 Rabi pedestal's peak.

In normal locking, the frequency jumps between A_1A_2, and after locking the frequency is aligned to the center of the 0-0 line Ramsey fringes. If B_1B_2 is used, the error signal will represent the deviation of the microwave frequency and the center of 1-1 line Ramsey fringes. Using this error signal to adjust the C-field coil current, the C-field locking can be achieved. Fig. 2 shows the process of the locking loop. Since the multiplier factors of $A_1A_2B_1B_2$ are preset constant values, the frequency deviation between the Ramsey peak of 0-0 line and 1-1 line will be locked to a preset fixed value as a result of C-field locking.

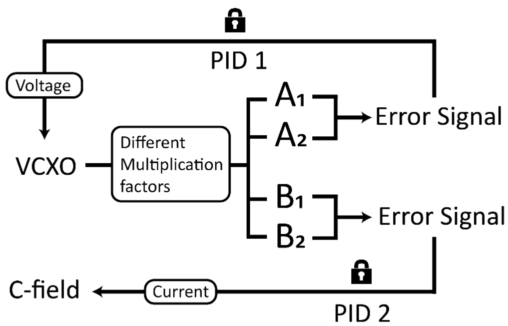

Fig. 2. The locking loop of the microwave frequency and C-field in normal locking (VCXO: Voltage Control Crystal Oscillator).

A. Exchange Locking

When using exchange locking, we need to exchange A_1A_2 and B_1B_2. Then 1-1 line is used to lock the microwave frequency, while 0-0 line is used to lock the C-field. The 1-1 line is very sensitive to the magnetic field because of the first-order Zeeman effect. This means that fluctuations in microwave frequency now will reflect fluctuations in the magnetic field. Since the C-field locking relies on the frequency deviation between the two Ramsey patterns' peaks, it is not affected by the exchange.

One difference in exchange locking is that each time the C-field current is adjusted, we cannot see the central frequency of the 0-0 line approaching the Ramsey peak, because C-field has little effect on 0-0 line. However, at the same time 1-1 line will be shifted, which means that the frequency deviation between the two Ramsey patterns' peaks is still changed. When 1-1 line is used to lock the microwave frequency afterwards, the 0-0 line and 1-1 line will move at the same time, so that the deviation of the C-field will still be reflected in the 0-0 line and the error signal for the next C-field lock phase will not be affected.

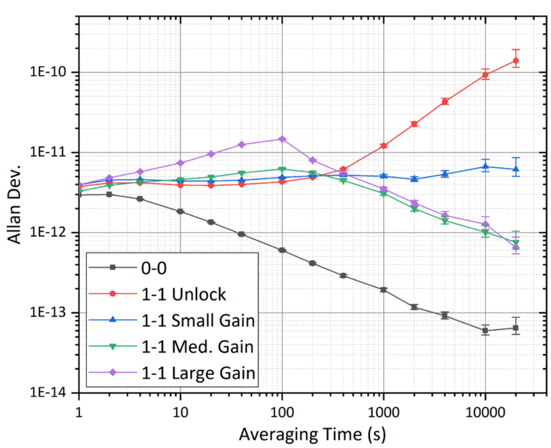

Fig. 3. The results of exchange locking and normal locking. 1-1 means exchange locking; 0-0 means normal locking. From the Allan deviation we can clearly see that a proper gain will make the C-field locking better

By measuring the Allan deviation for exchange locking, we can get the suitable locking gain and predict the C-field fluctuations in normal locking (divide the Allan deviation by the ratio of the magnetic field sensitivity of 1-1 line and 0-0 line). Fig. 3 shows the results in our experimental systems. An optical detected magnetic-state-selected cesium beam clock [3] is used for demonstrating these two methods.

B. Large-Modulation-Depth Locking

Since the atoms of the thermal beam clock have velocity distribution, the Ramsey pattern appears only in the near-resonant region. This means that the curve away from the peak frequency will be very close to the Rabi resonance curve. When large-modulation-depth locking is used, A_1A_2 will be instead by C_1C_2, and the average value of the output frequency becomes the central frequency of the Rabi resonance curve. The deviation of the central frequency of the Rabi resonance curve and of Ramsey resonance curve corresponds to the deviation of the average C-field in the drift region and it in the microwave region.

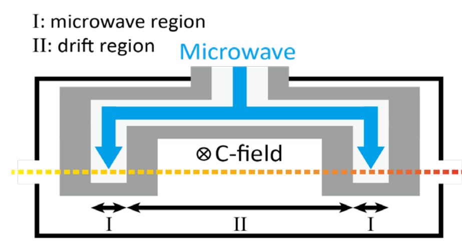

Fig. 4. The structure of Ramsey cavity.

Not only C-field coils contribute C-field, the environmental magnetic field after shielded also contributes part of it. Both may introduce inhomogeneity. The former can be optimized by simulation and experiment, but the latter is difficult to optimize in advance because the environmental magnetic field of the compact atomic clock is complex and variable.

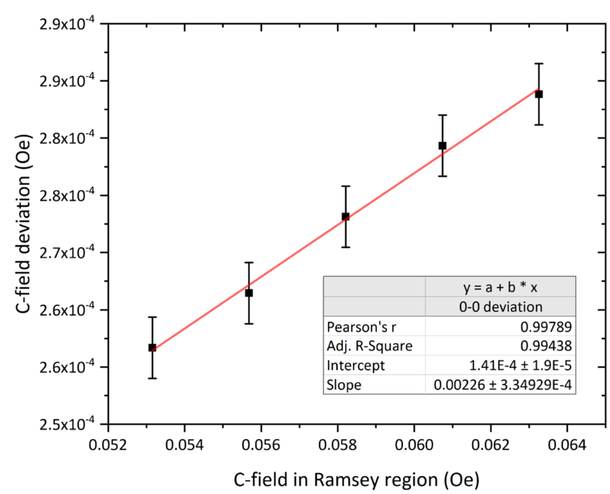

Fig. 5. C-field deviations at different C-field values in Ramsey region. A positive slope indicates the inhomogeneity generated by the C-field coil. The non-zero intercept indicates that the shielded external magnetic field also contributes to the inhomogeneity

The best way to study the contribution of the C-field coil and the environmental magnetic field to the inhomogeneity is to separate these two parts. This requires zero-magnetic-field environment over a large area. We offer a simpler way. By varying the current in the C-field coil, we plot the variation of the C-field deviation with the value of C-field using large-modulation-depth locking. From the result we can analyze the source of C-field inhomogeneity. Fig. 5 shows the results of our measurements. If the C-field coil introduces inhomogeneity, then the inhomogeneity increases when increasing the C-field current. If there is a nonzero intercept of the fitting curve, it means that the remaining environmental magnetic field after μ-metal shielding also contributes to the inhomogeneity. Our results basically illustrate that our C-field coil provides part of the inhomogeneity, while the external magnetic field after shielded also contributes a large amount of inhomogeneity. This method can be performed dynamically and therefore can be used to dynamically adjust C-field inhomogeneities.

III. Conclusions

Two new methods, exchange locking and large modulation depth locking, are proposed for thermal beam clocks. The exchange locking can evaluate the C-field locking and helps to choose locking parameters. The large-modulation-depth locking can measure the C-field inhomogeneities and demonstrate the sources of the in homogeneities.

Acknowledgment

We are grateful to engineer Chaojie Li and engineer Shaoyi Wang, for their assistance in engineering and equipment.

References

[1] W. Zhao, W. Qian, D. Lv and R. Wei, "Improvement of average magnetic field measurement based on magnetic-field-sensitive Ramsey fringes," Opt. Lett., 47(8):2073-2076, 2022.

[2] L. Devenoges, G. Di Domenico, A. Stefanov, et al., "Measurement of the magnetic field profile in the atomic fountain clock FoCS-2 using Zeeman spectroscopy," Metrologia 54:239-246, 2017.

[3] C. Liu, S. Wang, Z. Chen, Y. Wang, et al., "A caesium atomic beam microwave clock detected by distributed feedback laser diodes," 282-284. 10.1109/FCS.2017.8088868, 2017.