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Research Progress on Rubidium Atomic Fountain Clock for Time-keeping

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Abstract

Even though the state-of-the art hydrogen masers exhibit high frequency stability, there are still long-term frequency drifts. To address this challenge, the National Institute of Metrology of China (NIM) has developed a rubidium fountain clock that shows a remarkable long-term stability and negligible frequency drift. By utilizing the rubidium atomic fountain clock to fast steer a hydrogen maser made by Beijing Institute of Radio Metrology and Measurement (BIRMM), a combined timekeeping system has been established. This system significantly mitigates the frequency drift of hydrogen masers, achieving improved long-term frequency stability over time intervals exceeding 4000 seconds, and improving the stability about 2.5 times in 1 day. Further research and optimization are still required to address the issue that the frequency stability of steered signal didn't fall as the $\tau^{-1/2}$ after 10,000 seconds.

1. Introduction

The rubidium fountain clock built by NIM with a VCH-1003M hydrogen maser as the local oscillator, achieved a stability of 4.1×10^{-16} in a day[1]. To facilitate a direct output of a standard frequency, an Oven Controlled Crystal Oscillator (OCXO) is locked directly to the rubidium atomic fountain clock, which also exhibits a stability of 6.5×10^{-16} in a day[2]. Even with a high operation rate, it is still difficult for a fountain clock to operate continously in a long time, thus it is cannot be used as a time keeping clock. An alternative method for the fountain clock to output standard frequency involves the implementation of a high-resolution offset generator (HROG) to rapidly steer the hydrogen maser [3, 4]. Currently, the long-term stability of hydrogen masers made by BIRMM is difficult to achieve lower than 1×10^{-15}. To improve its stability, a rubidium fountain clock has been employed to rapidly steer a hydrogen maser utilizing a domestic HROG, to enhance the stability of the output standard frequency.

2. Physical Design

The design of the NIM rubidium fountains has been introduced in detail in prior papers [1-2]. With the rubidium as the quantum reference, the clock exhibits a significantly smaller cold-collision shift in comparison to a cesium fountain clock. The rubidium atoms are captured directly from the ambient vapor by a magneto-optical trap. A notable feature of the NIM rubidium atomic fountain clock is that the Ramsey cavity also functions as a vacuum chamber, resulting in a more compact vacuum system. The NIM rubidium fountain's microwave synthesizers originally use 100 MHz from the high-quality hydrogen maser VCH-1003M as its reference, and the detail introduction is in the reference[2]. For this work, the BIRMM maser used offers only 5 MHz and 10 MHz frequency outputs. A module was designed for crystal oscillator phase-locked to the 5 MHz signal from the hydrogen maser. This module employs a two-stage phase-locking mechanism to generate both 100 MHz and 5 MHz outputs. The design is shown in Figure 1. The OCXO is phase-locked to a 5 MHz input, which comes from the BIRMM hydrogen maser, outputting a 5 MHz standard frequency. This 5 MHz standard frequency, labeled as signal ①, serves as the reference signal for the HROG. It is also multiplied up to 100 MHz, and used as the reference for the second phase phase-locked loop (PLL) for a low noise 100 MHz crystal oscillator.

As shown in figure 2, the second phase-locked loop of OCXO PLL module outputs a 100 MHz signal, label as signal ②, fed to a microwave synthesizer to generate the clock signal about 6.834682 GHz (abbreviated in the figure as 6.8 GHz) for Ramsey interrogation. The rubidium atomic fountain clock operates by measuring the frequency deviation of the 6.8 GHz signal and lock it to the clock transition. During the fountain clock operation, the frequency deviation data of 6.8 GHz that is continuously measured and recorded as data in the database. From these data, the relative frequency deviation of the 100 MHz (signal ②) can be obtained, which is essentially the relative frequency deviation of the 5 MHz output from the OCXO (signal ①). As this 5 MHz is the reference signal for the HROG, with the fast steer algorithm, the frequency adjustment amount for the HROG is calculated from the these data in the database. The frequency offset is sent to the HROG through Ethernet, and the output 5 MHz signal is obtained as steered frequency, labeled as signal ③, which is measured by the phase comparator at last.

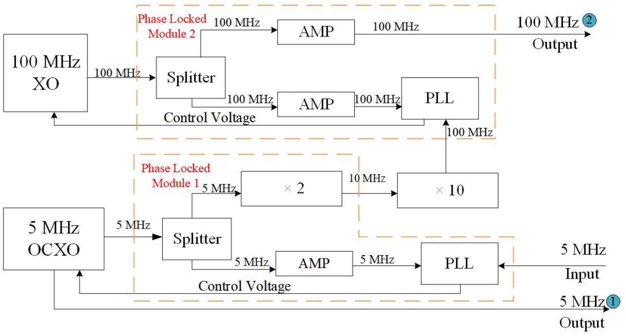


Figure 1. The scheme of crystal oscillator phase-locked to 5 MHz Module. AMP: Amplifier; PLL:Phase-Locked Loop. XO: Crystal Oscillator.

The current algorithm involves calculating the average frequency deviation of signal ① over the most recent 100 seconds of fountain clock data in database every 20 seconds, which is then used as the frequency offset for the HROG and generate the standard frequency signal ③ for time keeping. To measure its stability, a phase comparator is used with a VCH-1003M H-maser as the reference due to its exceptional stability. The other channel of the phase comparator measures the frequency stability of the signal ②.

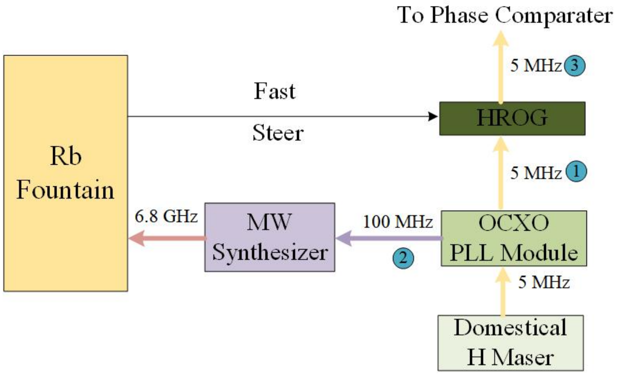


Figure 2. The scheme of rubidium fountain clock fast steering hydrogen maser

3. Results

Three different stabilities are measured: (1) the relative frequency differences of the signal ② (named as pre-steering 100 MHz) measured by the fountain clock (data in the database); (2) the signal ② measured by the phase comparator using the VCH-1003M hydrogen maser's 100 MHz as the reference signal; and (3) the signal ③ (named as steered 5 MHz) measured by the phase comparator using the VCH-1003M hydrogen maser's 100 MHz as the reference signal. The Allan variance for each of these three datasets were calculated, and the resulting stability curves are shown in Figure 3. In the figure, the stability of the first dataset is represented by blue circular dots, the second dataset by red square dots, and the third dataset by green diamond-shaped dots. From the figure, it can be observed that the signals measured in the first and second datasets are identical, but the stability differs significantly before 10,000 seconds due to the use of different reference sources, converging thereafter. This discrepancy arises because the frequency difference data measured by the fountain clock in the first dataset generally follows a $\tau^{-1/2}$ trend, thus not accurately reflecting the short-term stability of the 100 MHz signal under test. In contrast, the second dataset, obtained using a phase comparison measurement method with the highly stable VCH-1003M signal as the reference, accurately reflects the stability of the signal. This also indicates that the long-term stability of this BIRMM hydrogen maser is on the order of 2×10^{-15}. The stability of the steered 5 MHz signal surpasses that of the pre-steering signal after 4000 seconds. This indicates that the current fast steering method effectively improves frequency stability. However, the steered frequency stability does not follow the $\tau^{-1/2}$ trend after 10,000 seconds, which may be related to the frequency phase-locking module, the HROG, or the steering algorithm itself, necessitating further research and improvement.

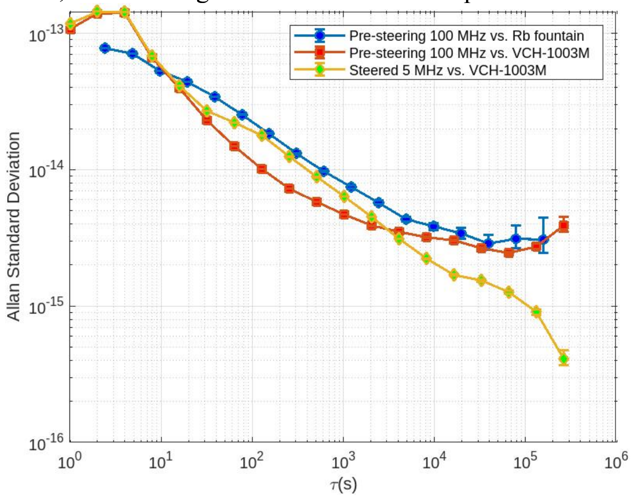
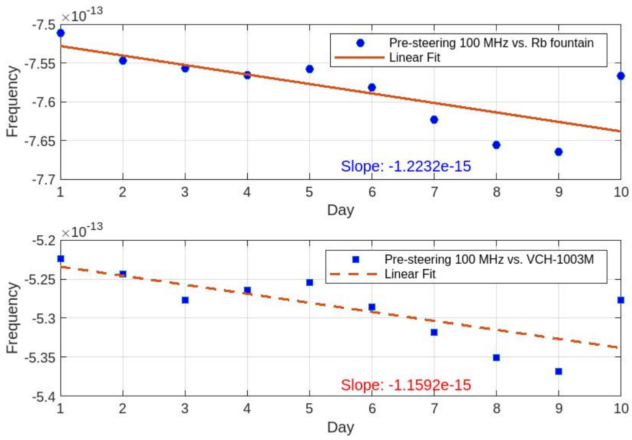


Figure 3. The stability of three frequency data sets

Additionally, we calculated the daily averages for these datasets and performed linear fitting on the results. The analysis reveals that the frequency drift rate of the pre-steering 100 MHz signal is approximately -1.2×10^{-15}, whereas the drift rate of the steered signal is reduced to below 1×10^{-16}. These results underscore the significant improvement in frequency stability achieved through the current fast steering methodology.



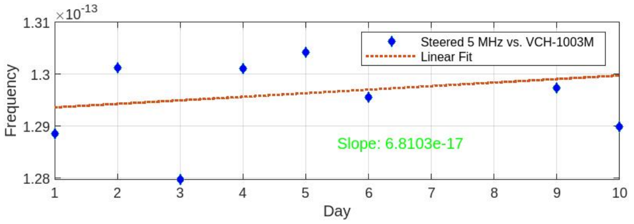


Figure 4. The daily average of frequency difference with linear fit line for three data sets

4. Conclusion

The rubidium fountain clock developed by the National Institute of Metrology of China (NIM) has been employed to fast steer hydrogen masers produced by BIRMM, significantly improving their long-term frequency stability. The experimental results demonstrate that the fast steering method effectively improves frequency stability, as evidenced by the steered 5 MHz signal surpassing the stability of the pre-steering signal after 4000 seconds. However, the steered frequency stability does not follow the expected $\tau^{-1/2}$ trend beyond 10,000 seconds, Further research and optimization are required to address these issues. Additionally, the analysis of daily frequency averages reveals a significant reduction in the frequency drift rate from approximately -1.2×10^{-15} for the pre-steering 100 MHz signal to below 1×10^{-16} for the steered signal. These findings highlight the potential of the rubidium fountain clock-based steering system to enhance the performance of BIRMM hydrogen masers. Future work will focus on refining the steering algorithm and other frequency noise suppression .

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