Hydrogen Maser Modulation Techniques and Postprints

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Abstract

For hydrogen atomic clocks, the cavity pulling effect of the microwave resonator and variations in external ambient temperature influence the resonator' s oscillation frequency, leading to degradation in long-term frequency stability. To address this issue, cavity auto-tuning methods are utilized to stabilize the resonator frequency at the operating frequency. Currently, three primary cavity auto-tuning techniques are employed both domestically and internationally: the external probe signal tuning method, the microwave cavity frequency switching tuning method, and the modulation method. This study analyzes the external probe signal tuning method and the microwave cavity frequency switching tuning method, and further investigates the latter based on the external probe signal tuning method implemented in the SOHM-4 system at the Shanghai Astronomical Observatory. Circuit design and program development are conducted using digital signal processors, ultimately achieving cavity auto-tuning on the SOHM-4 hydrogen atomic clock.

Full Text

Abstract

For hydrogen atomic clocks, the oscillation frequency of the microwave resonator is affected by cavity pulling effects and external temperature variations, which degrades the long-term frequency stability. To correct this, cavity auto-tuning methods are employed to stabilize the resonator frequency at the operating frequency. Currently, three main cavity auto-tuning techniques are used internationally: external detection signal tuning, microwave cavity frequency switch tuning, and modulation mode. This paper analyzes the external detection signal tuning and microwave cavity frequency switch tuning methods, and further explores the microwave cavity frequency switch tuning approach based on the SOHM-4 external detection signal tuning system developed at the Shanghai Astronomical Observatory. Through circuit design and program development on a digital signal processor, cavity auto-tuning has been successfully implemented on the SOHM-4 hydrogen maser.

Keywords: Cavity auto-tuning; Hydrogen atomic clock; External detection signal tuning; Microwave cavity frequency switch tuning

1. Cavity Pulling Effect

When the resonant frequency of the microwave cavity does not match the atomic transition frequency, the atomic transition frequency shifts with changes in the cavity oscillation frequency, producing the cavity pulling effect. The cavity pulling formula is given by:

$$\Delta f = \frac{Q_c}{Q_l} \cdot \Delta f_0 \quad (1)$$

where Δf is the output frequency variation of the hydrogen maser, Δf_0 is the cavity frequency change, Q_c is the loaded quality factor of the resonator, and Q_l is the atomic line quality factor. For active hydrogen masers, the typical Q_c is approximately 40,000 and Q_l is about 1.1×10^9. According to the formula:

$$\frac{\Delta f}{f_0} = \frac{Q_c}{Q_l} \cdot \frac{\Delta f_c}{f_0} \quad (2)$$

where f_0 is 1.4 GHz. From equation (2), to maintain the long-term frequency stability of the hydrogen maser at the 10^{-15} level, the cavity frequency variation must be controlled within 1 Hz, imposing stringent requirements on cavity tuning precision. Although the cavity pulling effect is relatively small, it degrades the long-term frequency stability of hydrogen masers, preventing them from meeting practical engineering requirements. Therefore, an efficient and practical cavity auto-tuning system is essential.

2. Long-Term Frequency Stability

The frequency stability of active hydrogen masers is expressed as:

$$\sigma_y(\tau) = \frac{1}{Q_l}\sqrt{\frac{kT}{P_m \tau}} \quad (3)$$

where Q_l is the atomic line quality factor, τ is the measurement time, k is the Boltzmann constant (1.38×10^{-23} J/K), T is the absolute temperature of the hydrogen maser, and P_m is the power supplied by hydrogen atoms to the resonator. Equation (3) shows that hydrogen maser frequency stability is related to measurement time, improving with τ. However, due to physical factors such as static magnetic fields and cavity pulling effects, the long-term frequency stability degrades, causing this formula to not always hold. The significant influencing factors are summarized in Table 1 . For static magnetic field issues, a multi-layer magnetic shielding system ensures field stability. For cavity pulling effects, temperature control systems and cavity auto-tuning systems address frequency shift problems.

3. External Detection Signal Tuning

External detection signal tuning, proposed by French scientist C. Audoin in 1981, utilizes an external signal injected into the resonator. This signal is tuned and then demodulated after passing through the cavity. This technology is primarily applied in hydrogen masers at the Shanghai Astronomical Observatory, exemplified by the SOHM-4 active hydrogen maser.

The SOHM-4 maser uses a square wave as the external detection signal. Its auto-tuning principle diagram is shown in Figure 1 [Figure 1: see original paper], and the auto-tuning system block diagram is shown in Figure 2 [Figure 2: see original paper]. A 20.405 MHz signal is mixed with a 1.4 GHz microwave signal to generate a modulated signal, where f_m is the square wave detection signal. When the average of the resonator frequency and detection signal frequency is not equal to the atomic transition frequency, the output signal from the cavity coupling loop becomes amplitude-modulated. This modulated signal is synchronously detected to extract an error signal, which passes through an integrating circuit to generate a voltage that tunes the varactor diode in the resonator, pulling the cavity response curve from the dashed line back to the solid line in Figure 1 [Figure 1: see original paper], thereby stabilizing the cavity frequency and achieving automatic tuning.

This square wave detection method achieves good signal-to-noise ratio. However, the carrier signal may interfere with the maser signal, affecting its inherent short-term frequency stability, which represents a challenge for this method. Additionally, RF signals generated by circuit boards may be susceptible to environmental interference, which can affect hydrogen maser frequency stability to some extent. Frequency stability tests show that while the square wave detection signal injected into the cavity impacts the short-term frequency stability of the hydrogen maser, it improves the long-term frequency stability.

4.1 Principle Analysis of Microwave Cavity Frequency Switch Tuning

Microwave cavity frequency switch tuning operates by switching between two cavity frequencies equally spaced from the transition frequency. This tuning technique is primarily used in active hydrogen masers in the United States and Russia, with typical representatives including the VCH-1003M and MHM-2010. The VCH-1003M cavity frequency adaptation principle diagram is shown in Figure 3 [Figure 3: see original paper], and the cavity tuning block diagram is shown in Figure 4 [Figure 4: see original paper].

This cavity tuning system installs three coupling loops in the resonator: one for coupling the hydrogen maser signal and two others with varactor diodes for tuning. A modulation signal generator produces an 87.2 Hz square wave signal applied to DAC 2, which generates two different voltages U_m to continuously switch the cavity frequency between two resonant frequencies, with the frequency difference shown as Δf in Figure 2. If the average cavity frequency f_c deviates from the hydrogen maser frequency f_0, the maser output signal becomes modulated, generating a modulation voltage V_m.

The 87.2 Hz square wave signal, after passing through operational amplifier and low-pass circuits, serves as a detuning signal applied to the synchronous detector. Another 87.2 Hz square wave signal passes through phase-shifting circuits to eliminate propagation delay before reaching the synchronous detector. The synchronous detector generates "+" and "-" pulses to control DAC 1, adjusting the output voltage U_c applied to the varactor diode to achieve automatic tuning. The cavity frequency switching is relatively fast, with each cavity frequency maintained for approximately 0.01 s. This modulation time is longer than the cavity response time to electromagnetic signals (about 10^{-5} s) but shorter than the atomic relaxation time (about 1 s), ensuring the cavity frequency switching process does not affect the oscillation state of the hydrogen maser signal—that is, it does not affect the inherent frequency stability of the hydrogen maser signal —representing a major advantage of this method.

Frequency stability tests show that the VCH-1003M' s long-term frequency stability has improved to the 10^{-15} level without affecting the short-term frequency stability or phase noise of the hydrogen maser output signal.

4.2 Experimental Results

After injecting an 87 Hz square wave signal into the resonator via a signal generator, the 1.4 GHz RF signal is extracted from the coupling loop and, after passing through an isolation amplifier, mixer, IF amplifier, and integrator, acts on the varactor diode to achieve tuning, with the varactor diode adjustment range being 0–9 V. Experiments show that when manually adjusting the voltage applied to the varactor diode, the frequency differences from the reference atomic clock at 1 V, 5 V, and 9 V are shown in Figure 5 [Figure 5: see original paper]. According to equation (4), the cavity pulling formula and varactor diode sensitivity formula, frequency differences can be converted to voltage signals. It can be concluded that within the 0–9 V range, there exists a voltage value that achieves tuning when applied to the varactor diode.

$$\Delta f = K \cdot \Delta U \quad (4)$$

The implementation block diagram of the microwave cavity frequency switch tuning method is shown in Figure 6 [Figure 6: see original paper]. Since the maser output signal is an RF signal, a mixer is required to convert it to an IF signal, which is then amplified by an IF amplifier. The amplified IF signal is sent to an amplitude detector, and the resulting half-wave signal is sampled by an ADC. The DSP processes the digitized signal from the ADC and sends the processed digital signal to a DAC to convert it into a voltage signal that acts on the varactor diode, ultimately achieving automatic cavity tuning.

5. Conclusion

Research on active hydrogen maser technology has been ongoing for over half a century, with increasingly mature theoretical foundations. Recent research has focused on technology optimization to achieve higher frequency stability. One optimization direction is investigating new tuning methods to efficiently achieve automatic tuning. The frequency stability indicators of active hydrogen masers using microwave cavity frequency switch tuning or external detection signal tuning are shown in Table 2 .

As shown in Table 2, the long-term frequency stability of hydrogen masers using microwave cavity frequency switch tuning (such as VCH-1003M) is superior to that of the SOHM-4 using external detection signal tuning. This result may be partially attributed to the simpler auxiliary electronic system design of the microwave cavity frequency switch tuning method, which introduces less electronic noise and improves electronic system performance, thereby enhancing long-term frequency stability.

In future research, we will further implement cavity auto-tuning using the microwave cavity frequency switch tuning method based on the SOHM-4 active hydrogen maser auto-tuning system at the Shanghai Astronomical Observatory, aiming to improve the long-term frequency stability of hydrogen masers.

References

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Note: Figure translations are in progress. See original paper for figures.