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Investigation of Frequency Stability and Advancement of Active Hydrogen Clock

Rongjing Sun[1], Bing Han[2], Zhendong Peng[3]
1School of Economics, Anhui University of Finance and Economics, Bengbu, 233000, China;
2School of Aeronautics and Astronautics, University of Electronic Science and Technology, Chengdu, 611731, China;
3School of Glasgow, University of Electronic Science and Technology. Chengdu, 611731, China

Abstract: The active hydrogen atomic clock (hydrogen clock) based on a hydrogen atom maser (hydrogen maser) has an excellent short-to-medium-term frequency stability, and the atomic storage bubble is a key technology of the hydrogen maser. In this paper, the interaction between the electromagnetic field and the hydrogen atom ensemble in an atom storage bubble in a microwave resonator is discussed. The influence of system noise on the stability of self-excited oscillation frequency is analyzed from the perspective of phase noise. Considering different atomic storage time, the effect of different atomic storage time on frequency stability is analyzed. Finally, the development prospect of hydrogen bell is discussed.

Keywords: Atomic clocks; Hydrogen maser; Atomic storage bubble relaxation; Frequency stability

1. Introduction

Both the maser and the laser can realize the excited radiation amplification of electromagnetic field, and the similar principle is the important content of quantum electronics. The laser is mainly used as a coherent monochromatic source, and the maser is mainly used as the frequency source. The hydrogen maser (hydrogen maser) was designed by Kleppner et al in 1961, Its function is realized by the use of atomic storage bubble technology. Ideally, the hydrogen maser of self-excited oscillation frequency is stable, but in fact the atomic beam of fluctuations, the temperature of the cavity, the change of the frequency, magnetic field changes in the environment and other environmental factors will affect the state of self-excited oscillation and frequency stability. The actual hydrogen maser needs to design the physical components of stable beam, stable temperature and stable cavity frequency and corresponding electronics. In order to obtain long-term stability, a variety of automatic tuning methods can be used to stabilize the cavity frequency. According to the frequency domain analysis, the phase noise of the phase-locked loop and the electronic part of the high-pass crystal oscillator are discussed. The stability of hydrogen clock should be slightly lower than the physical limit stability determined by the thermodynamic noise of hydrogen maser. To keep the hydrogen clock stable for a long time, stable ionization source system, beam optical system, thermostat system, vacuum system, magnetic shield system and receiver system are required. The physical structure of hydrogen maser was shown in figure 1 respectively.

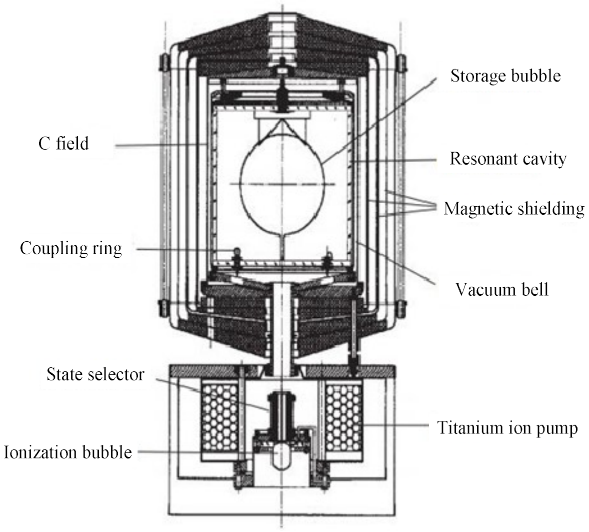

Figure 1. A diagram of the hydrogen sear structure

To the 1990 s, the basic theory of hydrogen clock has been relatively mature, nearly 20 years of main work focused on the improvement of the technology, including the new automatic tuning method, double cavity frequency selected state of cladding pump instead of ion beam optical systems, pump, etc., in order to stability can be close to its physical limits. Currently, hydrogen clocks in Russia, Switzerland and the United States are stable at 2(3) x 10-16/d. There are also some work on the miniaturization of cavity bubble structure and hydrogen clock machine with medium load resonator. Hydrogen clock or to participate in the clock of a group as a steady time and frequency measuring device is widely used in punctuality, navigation, very long baseline interferometry and other engineering projects and scientific experiments, and because of the hydrogen maser of self-excited oscillation frequency is influenced by the physical environment and can be used for the validation of basic physics theory.

2. Analysis of Frequency Stability of Active hydrogen Atoms

2.1. Analysis of stability of frequency

The influence of system noise on the frequency stability of self-excited oscillation can be analyzed from the angle of phase noise. The self oscillation of hydrogen maser has phase and amplitude fluctuations. Phase noise will affect the frequency stability of hydrogen maser, and amplitude noise will affect the sensitivity of automatic tuning. The amplitude and phase equations can be established by classical method and simplified, and the simplified phase equation and amplitude equation can be obtained.

In the active hydrogen atom clock, hydrogen maser controls a servo crystal oscillator through a phase-locked loop, and outputs 5MHz, 10MHz, or second signals through a servo crystal oscillator; the hydrogen maser in a passive hydrogen atom clock controls the servo crystal oscillator through a locking ring and outputs the corresponding signal. The phase-locked loop is composed of a mixer, a phase detector, a filter and a controlled crystal oscillator. It is divided into a first loop and a two order loop. The time constant of the phase locked loop is determined by the parameters of each device in the loop, and its value is in the order of seconds. In frequency domain, phase jitter of low hydrogen maser and high pass filter, for example, for the two order loop, the phase jitter of the controlled crystal oscillator is:

$$\triangle\Omega_C(s)=\frac{\Gamma\tau_1 s^2}{1+\tau_2 s+\Gamma\tau_1 s^2}\triangle\Omega_f(s)+\frac{1+\tau_2 s}{1+\tau_2 s+\Gamma\tau_1 s^2}\frac{\triangle\Omega_r(s)}{n} \quad (1)$$

The theoretical thermodynamic phase noise of hydrogen maser and the distribution of the actual noise of hydrogen clocks in the frequency domain are shown in Figure 2. The position of point A is related to the time constant of the phase-locked loop. The left side of point A can be mainly understood as the thermodynamic noise of the hydrogen pulse maser, and the right side of point A is mainly understood as electronic noise. The measured phase noise has several larger burrs, which reflect the abnormal noise of the hydrogen clock. For the hydrogen clock of Russian VCH-1003M, point A is more left to the left, that is, the time constant of the phase locked loop is smaller, and the phase noise spectrum is smoother. The thermodynamic noise is the white frequency noise, and the actual hydrogen clock has other order noise, such as flicker noise and the white phase noise.

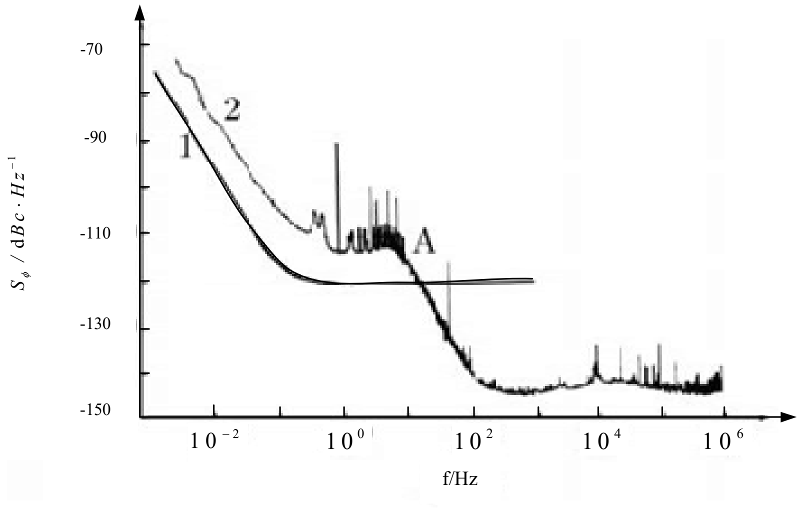

Figure 2. Distribution diagram of theoretical thermodynamic phase noise and actual noise in frequency domain

2.2. The effect of atomic storage time on frequency stability

The atomic storage time, the size of the atom storage bubble and the atomic beam flow determine the density of the atom in the storage bubble, thus affecting the relaxation of the spin exchange collision and the bubble wall collision relaxation. When the ratio of atomic storage time to other relaxation time is 0.5, it is more appropriate. Considering the different atomic storage time, the corresponding spin exchange collision relaxation and bubble wall collision relaxation are calculated, and the effect of different atomic storage time on the frequency stability is analyzed, as shown in Figure 3. It can be seen that the storage time of atoms should be shortened properly when the storage foam is miniaturized. The adjustment of atomic storage time should be achieved according to the volume of the storage vesicles, by adjusting the bubble area and the length of the tube connected to the bubble mouth.

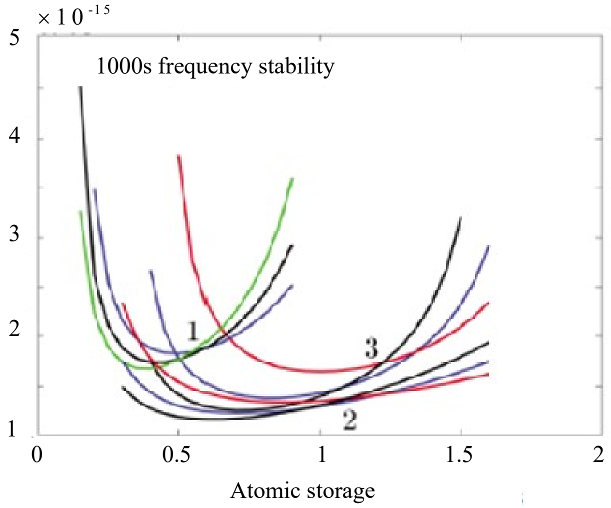

Figure 3. Relationship between frequency stability of 1000s and storage time

Note: Curve 1 represents a small storage bubble (7.1×10-4 m3) with a dielectric loaded resonator. Curve 2 indicates the adoption of dual selective state system and conventional atomic storage bubbles; Curve 3 indicates the use of conventional atomic storage bubbles (2.1 x 10-3 m3).

3. Recent Advances in Research on Active Hydrogen Atoms

3.1. Development of miniaturized hydrogen maser in dielectric loaded resonators

By using dielectric loading resonator, the volume of resonator cavity and storage bubble can be reduced effectively. So as to reduce the magnetic shielding, vacuum, constant temperature and other peripheral structures of hydrogen maser and realize the miniaturization of active hydrogen maser. The active hydrogen clock for space application and its associated space atomic clock group are being developed. The dielectric loading resonant cavity provides a possibility for the space application of the active hydrogen clock. The sapphire dielectric loading resonator is the only dielectric loading resonator that has been successfully applied to the active type of hydrogen maser at present because of the low loss of sapphire medium and the high Q value. The application of the resonant cavity of TE111 mode to hydrogen maser has also been studied, but due to the low Q value of TE111 mode cavity, it is difficult to meet the conditions of self-excited oscillation of the active type hydrogen maser. Since the 1990s, there have been some domestic and foreign studies on hydrogen masers loading resonant cavity with sapphire media. The volume of the sapphire loaded resonator and the storage bubble can be reduced to one third and one quarter of the traditional volume respectively. Since the number of atoms in the storage bubble is the atomic beam times the storage time Tb, when the storage bubble changes, if the storage time remains the same, the atomic density in the bubble will increase. Spin exchange collision relaxation becomes very large and affects self - excited oscillation. According to the calculation of spin exchange collision relaxation, bubble wall collision relaxation and magnetic relaxation, the relationship between maser output power and stability with atomic storage time can be calculated. Thus, the appropriate atomic storage time is selected. As shown in figure 4, the sapphire loading medium is a hollow cylinder with a end cover, and the inner wall of the medium is coated with teflon film as an atomic storage bubble. The internal cavity volume is about 7.1×10-4 m3. Due to the change of cavity structure, ideal sapphire cavity (sapphire medium for the rule of the hollow cylindrical) of eigen mode is not strictly TE011 mode, but the similar TE0n1 model no definite meaning (n), eigen mode electromagnetic field of the axial component radial distribution curve 1 as shown in figure 5. The filling factor of sapphire media loading cavity is higher, which can reach 0.5, while the traditional cavity is only about 0.4. The ultimate stability of hydrogen maser using dielectric loading resonator is slightly lower than that of traditional hydrogen maser.

Figure 4. Sapphire (α-Al2O3 crystal) storage bubbles

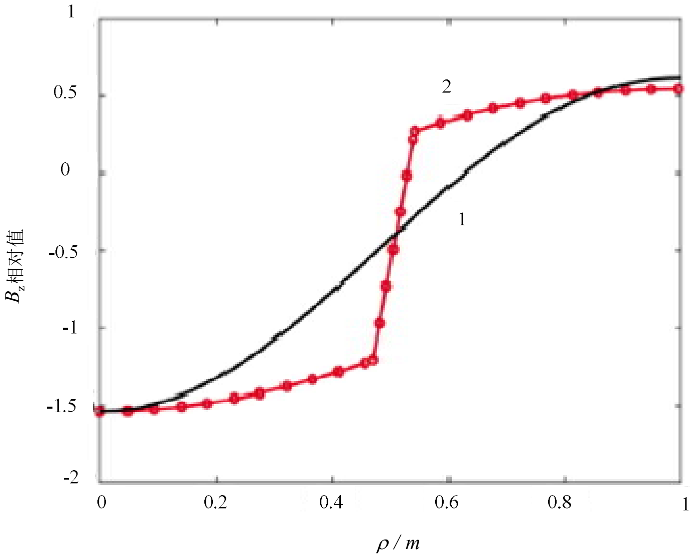

Figure 5. Radial distribution of resonant cavity TE011 mode Bz(ρ)

3.2. Development of automatic tuning system

In order to eliminate the influence of cavity frequency change on the frequency of hydrogen maser, an automatic tuning system of cavity frequency is needed to stabilize the cavity frequency. Four methods can be used: spin exchange tuning, phase tuning, cavity frequency switching tuning, and unloaded cavity searching for tuning. Different modulation and detection methods are used for each tuning method, and different noises are introduced. The time constant (the time it takes to offset from the cavity frequency to the non-offset) and the frequency stability of the modulation loop (equivalent to the modulation resolution) are the two most important parameters.

The automatic tuning system is a feedback loop, and the power spectral density of the frequency fluctuation of the whole loop is:

$$S_{y,c}(f) = \frac{(2\pi f\tau)^2}{1+(2\pi f\tau)^2} S_{y,f}(f) + \frac{1}{1+(2\pi f\tau)^2} S_{y,\gamma}(f) \qquad (2)$$

Where, T is the time constant of the loop; Sy, c(f), Sy, f (f), Sy, r(f) are the power spectral densities of the entire loop, the free state of maser, and the fluctuation of the reference frequency modulation respectively.

The following is a description of the spin exchange tuning method. Spin exchange tuning method: the atomic density in the storage bubble changes with the atomic beam flow by modulating the atomic beam. Different atomic beams have different collision relaxation and different atom line width Ql. When the cavity frequency and transition frequency are not offset, the maser oscillation frequencies of the two beams are the same. When the cavity frequency and transition frequency are offset, the maser oscillation frequency in the two beam states is different, and error signal can be generated by detecting the difference in the frequency of the maser oscillation. With each beam modulation, the self-excited oscillation takes several seconds to reach stability, and the time constant of the tuned loop is large enough to reach the order of 1 d. In the process of detection, an independent reference source needs to be mixed with the maser signal to make the lower frequency conversion of the maser signal. Independent frequency reference sources introduce noise, limiting the resolution of tuning and limiting the long-term stability of maser.

3.3 Microwave problem

The energy of the microwave field maintained by the self-excited oscillation of hydrogen maser in the resonant cavity is small, approximately -90dbm. The microwave signal with stable frequency is output from the resonant cavity to the electronic system through the microwave coupling ring. The coupling between the coupling ring and the microwave cavity is a weak coupling, and the coupling coefficient is about 0.1. A coupling ring with a capacitor diode is also placed to adjust the cavity frequency by changing the voltage applied to the diode. For the cavity frequency switching tuning method, a coupling ring with a variable-capacitance diode is needed to modulate the cavity frequency. The resonant cavity can be equivalent to a series resonant circuit, and the connection between the resonant cavity and the coupling ring can be equivalent to the ideal transformer model. The critical point method can be used to measure the coupling coefficient. The critical point method is a simple and fast method to measure the coupling coefficient. The principle is shown in figure 12. The shape of the impedance of the resonant cavity near the resonant frequency on the Smith circle is shown in figure 12. The frequencies corresponding to the maximum and minimum of impedance f1 and f2 and the frequencies corresponding to the intersection of impedance f3 and f4 can be found. The unloaded Q value of the resonant cavity is approximately (f1 +f2)/2(f1-f2). Because the resonator and the coupling ring are weakly coupled, the traveling wave state cannot be reached from the point of view of the coupling ring. In other words, impedance matching cannot be realized, and there will be reflection at the coupling ring. An isolator is inserted at the end of the maser output line to avoid the effect of external noise on the cavity self-excited oscillation. When the cavity frequency is regulated by the variable-capacitance diode, the voltage of the diode is generally increased and the cavity frequency is increased. But the opposite is true for sapphire loaded resonators. When the diode voltage is increased, the cavity frequency decreases. There is no good explanation for this.

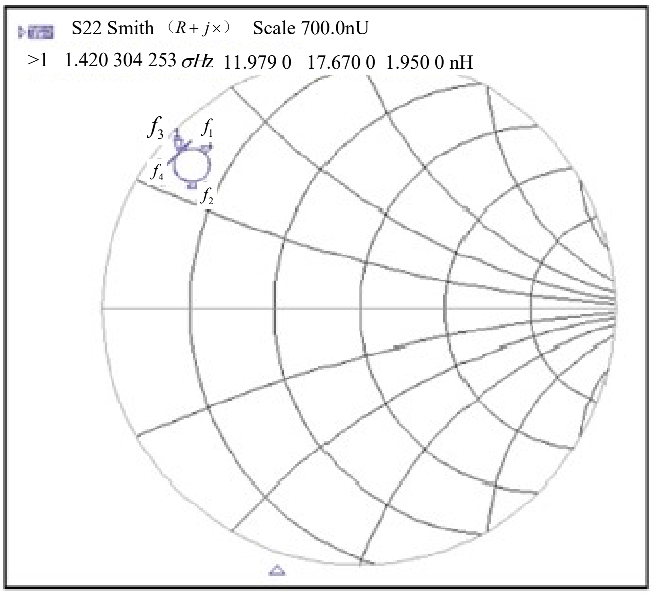

Figure 6. Schematic diagram of coupling coefficient measurement by critical point method

4. Conclusion

The research on hydrogen microwave laser and active hydrogen clock has been carried out for half a century. In the last 20 years, much has been focused on improving technology to reach its physical limit in terms of frequency stability. Although much research has been done on optical clocks in the last decade, and most of them are two orders of magnitude or more theoretically stable than hydrogen clocks, they are still in the laboratory stage. It is difficult to run stably for a long time, and hydrogen clock is still the atomic clock with the best stability in the short and medium term. At present, the stability index of SOHM hydrogen clock of Shanghai observatory is significantly lower than that of vch-1003m hydrogen clock of Russia, nhm-2010 hydrogen clock of America and iMaser2000 hydrogen clock of Switzerland, as shown in figure 7. As mentioned above, there is still room for further development in vacuum system, automatic tuning method, dual state selector, mechanical structure and miniaturization, which need to be further improved in theory and technology. In the future, the day stability of the hydrogen clock should reach or approach the magnitude of 10-17.

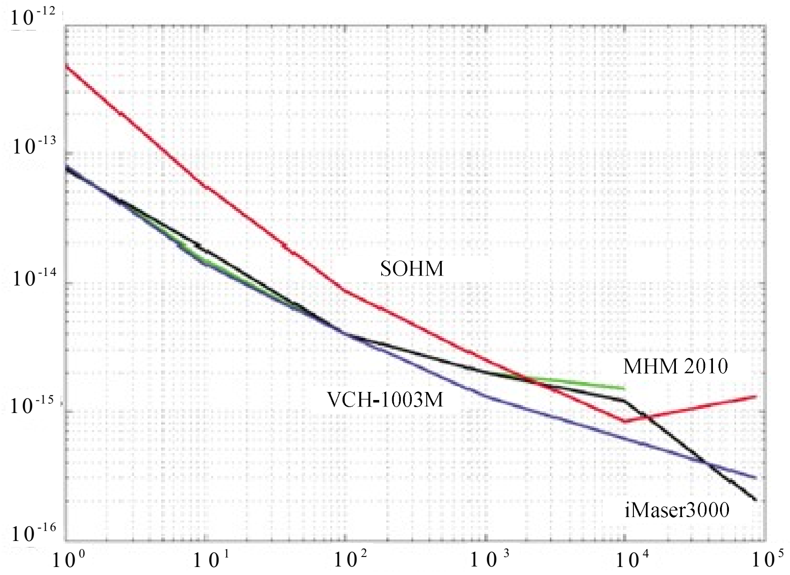

Figure 7. Dynamic hydrogen clock stability comparison

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