Improvement of the atomic hydrogen maser for Chinese Compass System

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***Abstract*—Four hydrogen masers have being put into operation at the earth station of Chinese positioning system for more than six years. We have made many physical and electronics improvements on these hydrogen masers for improving the long-term performance. The hydrogen maser's size is 110cm(high)*54cm(width)*73cm(depth). It weighs 180kg. By performance comparing with each other, we may choose the best one as a frequency reference for this system. A kind of cavity auto-tuning system was applied for improving of the long-term performance. Now another 13 H masers were prepared for the Compass-2 system. Performance evaluation showed the frequency stability is in the order of E-15 for time interval from 100s to 1day and the phase noise (SSB) is -150 dBc/100Hz. The environmental sensitivities are also given in this paper.**

1. INTRODUCTION

In 1969, Shanghai Observatory began to make research on atomic hydrogen frequency standard. During these 40 years. We have made many great developments on the design and the performance of hydrogen maser. [1] Not only it's technical and performance improvement, but also great decreasing of its size and weight. Now a rugged transportable hydrogen maser was available for many scientific search purposes. Such as Chinese VLBI network, establishment of local atomic time scale, time and frequency metrology, frequency standard for military bases etc. for the purpose of establishment of frequency standards of Chinese positioning system. Three hydrogen masers was consist of a clock group .We can choose the best one as the frequency standard of this positioning system. Fig.1 is the photograph of the standard.

Fig.1 Photograph of the Transportable H Maser

2. Improved design features

A Physical improvement

The hydrogen oscillator is shown in Fig.2. It consists of a microwave resonant cavity and storage bulb, a discharge that creates a hydrogen atoms beam that are selected and focused into the storage bulb by

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a six-pole magnetic state selector. The 240l/s pumping speed ion-pump absorbed atomic hydrogen and other background gas. These are all housed in a titanium vacuum envelope.

A hydrogen bottle is used to supply the molecular hydrogen, which is purified and regulated by passing through a heated palladium leak. The discharge bulb of the atomic hydrogen source, with 40mm in diameter and 30 mm long, is made of quartz glass. Molecular hydrogen is dissociated by a nearly 100MHz radio-frequency discharger. Its power consumption is 5 watt or less. The six-pole magnetic state selector is the best suited to accomplish the state selection of hydrogen atoms while allowing the realization of the desired value of the population difference at the bulb entrance. Hydrogen atoms in the upper hyperfine quantum states ($F=1, m_F=\pm 1, 0$) are focused into the storage bulb .

The microwave cavity resonates at about 1420MHz on the TE_{011} mode, for which the microwave field has an axial component of a given phase on a large volume around the cavity center. It is made of relatively inexpensive material and has a low thermal expansion coefficient ceramic of about of 10^{-7}/℃. The inner surface is coated with silver. The storage bulb has the light weight of 180 grams, thus minimizes the temperature dependence of the resonance frequency of the cavity-bulb assembly to approximately 800Hz/℃ or less. In the presence of the bulb, the loaded cavity quality factor Q is approximately equal to 4×10^4. Two two-turn Zeeman coils, placed on opposite sides of the outside wall of the bell-jar, are used to produce a RF magnetic field perpendicular to the cavity axis for fine measuring C-field by means of transitions between two Zeeman levels of the F=1 state and decide the magnetic frequency shift.

Barometrically induced stresses on the vacuum tank are isolated from the cavity resonator by a double-base structure. Longitudinal stress which was produced by the thermal expansion coefficient of the resonator hold-down can be absorbed by the belleville spring washer. Thermally induced radial stress in the resonator base is relieved by a six-roller quasi kinematic mount. Thus the microwave cavity’s resonance frequency is approximately independent of the thermal expansion of the hold-down can.

The region where the hyperfine transition occurs is shielded against the ambient magnetic field and its variations. The magnetic shield comprises four concentric layers of 1J85 permalloy and 0.8 to 1mm in thickness. The new maser shields have torrisperical end caps. The overall longitudinal shield factor is about 2×10^4. Care is taken to eliminate any magnetic material and to prevent spurious magnetic fields caused by the thermoelectric currents in the shielded region. The internal magnetic field is provided by a two-layer flexible printed circuit solenoid, which is a simple, lightweight and rugged structure just inside the innermost magnetic shield. It is useful to have a few turns at each end to diminish the end effect and trim the magnetic field between the state selector and the shield and can be used to compensate the inhomogeneity due to the hole on the center of magnetic shield end top. So it is useful for providing a small uniform axial C-field within the microwave cavity.

The pumping speed of the ion pump is 240L/s. It holds eight 30L/s titanium pump elements that are used to absorb the hydrogen gas and to provide a clean vacuum, avoiding pollution of the bulb's inner surface. Their pumping capacity enables more than 4 to 5 years of continuous operation. In order to minimizing the gas load on the ion pump. The atomic hydrogen beam is form by a multi-pole crystal collimator.

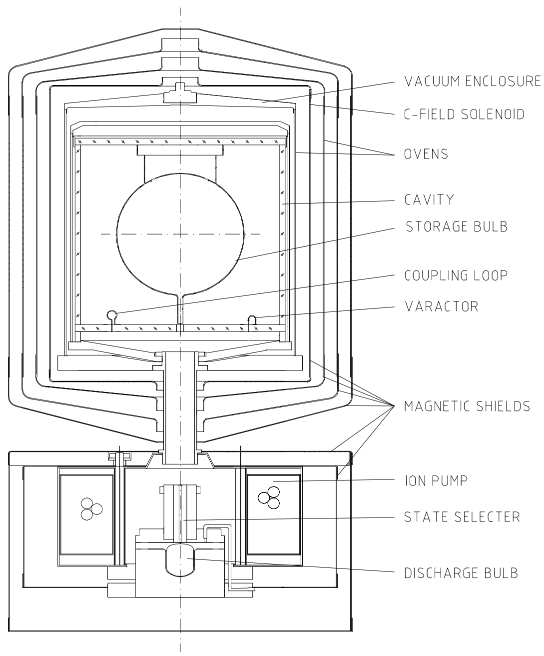

Fig.2 Physical unit structure

B Auto-tuning system

As we know the long-term frequency stability performance of hydrogen maser is mainly deteriorated by the resonant microwave cavity frequency pulling due to the changes in microwave cavity dimension. In order to minimize this effect, a kind of cavity frequency auto-tuning system was applied .It keeps the resonant cavity to be maintained automatically at the correct frequency. A square wave frequency modulated microwave signal is transmitted through the TE011 mode microwave cavity. We choice f_m=10 kHz. By up-conversion switched frequencies of 1420.395MHz and 1420.415MHz were applied to the diode coupling-loop of the maser resonant cavity. The amplitude of the transmitted signal is modulated at 1 Hz on the maser output. When the mean value of the microwave cavity center frequency is different from the reference frequency. A synchronous detector provides an error signal. Then an error voltage is applied to the diode to set the microwave cavity to the correct frequency. The experimental results show that the CAT system does not degrade the short and medium term frequency stability very much, and allows the long-term frequency stability in the order of E-15.

C Phase-lock receiver

The microwave receiver combines the techniques of heterodyne mixing and frequency synthesis. The maser signal is picked up by a coupling loop at a level of –100 dBm and sent through a ferrite isolator which is used to match the maser output and a very low noise 1420MHz preamplifier having a low noise factor (1.5db) necessary to minimize the white phase noise added by the receiver. The resultant 1400MHz signal and 1420MHz output from the maser are mixed to give a beat output of 20.405MHz, which is amplified by the intermediate-frequency amplifiers having a limited bandwidth and compared with a synthesized signal of 405.751xxxxkHz. The output of the hydrogen maser is accurately related to a quartz oscillator with a nominal frequency of 10MHz by means of phase-locked loop is generally of second order and its transfer function is adapted to the frequency noise characteristics of the quartz crystal oscillator to be phase controlled. The electronics is shown in fig.3.

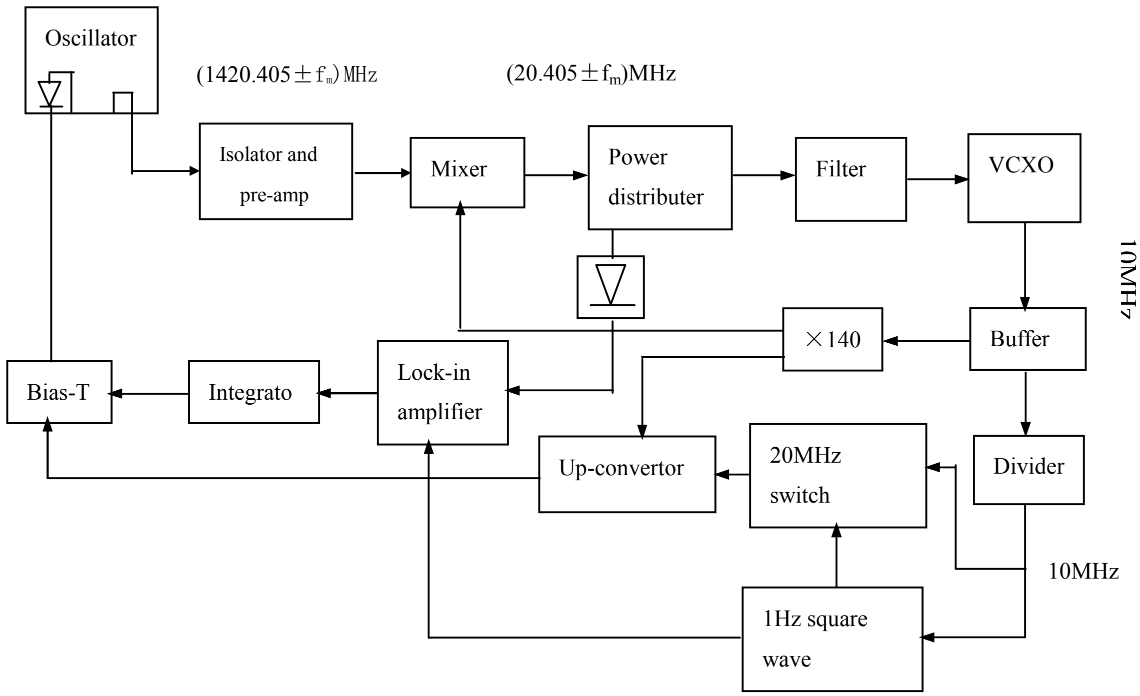

Fig.3 show the block diagram of this device.

D Supporting electronics

The hydrogen maser has a multizone two-stage oven. The tank (oven) surface is divided into 2 or 3 independent sensed and controlled zones. It has been shown a powerful technique for minimizing temperature gradient. The vacuum tank is divided into three zones (dome, cylinder, and base) having their own sensing thermistor, amplifier and heater. Each zone can respond independently to external thermal loads without affecting the other zones. To minimize the thermal stress on vacuum tank controller, the outer oven is divided into a dome-cylinder zone and a base zone. They are electrically isolated from their support to ensure that the current intensity is the same in the feeding and the return conductors and therefore that no spurious magnetic field id created over the storage bulb volume.

We have developed a microprocessor for the transportable hydrogen maser. The hydrogen maser can be switched on or off automatically. Remote control and monitoring of the hydrogen maser operating conditions is via a RS-232 serial port. It provides for either local or remote observation and recording of 30 channels of the hydrogen maser working data as well as control of the receiver-synthesizer which gives an output frequency resolution of 7*E-14. The data includes all main power supply voltages, all heater voltages, vacuum pump voltage and current, the phase-locked receiver I.F. level, VCXO tuning voltage and diode voltage.

3. Performance evaluation

The hydrogen maser frequency stability is limited by thermal noise within the atomic line-width and by additive noise in the receiver. These two noise processes can be combined as uncorrelated processes which was given by Vessot-Cutler-Seale formula. [2]

$$\frac{\Delta f}{f}=\left[\frac{kT}{2}\left(\frac{FB}{2\pi^2 f_0 P_0 \tau^2}+\frac{1}{Q_l^{\,2} P_b \tau}\right)\right]^{1/2}$$

here f is the maser oscillating frequency. τ is sampling interval. K is Boltzman constant. T is absolute temperature. P_b is power released by atoms. Q_l is quality factor of atomic line. P_0 is signal power received by receiver. B is effective bandwidth of receive system. F is noise efficient of receiver.

The influence degree to the frequency stability by these two noises is determined by the sampling time. When these two noises is the same. We may get:

$$\tau=\frac{FBQ_l^{\,2}}{2\pi^2 f_0^{\,2}}\cdot\frac{1+\beta}{\beta}$$

β is coupling coefficient. In our lab, F=6,B=6Hz, β +1/ β =5,we can get τ =100S. The frequency stability is limited by the cavity thermal noise and the externally added noise. The frequency stability is measured for τ <1 s ,in this region it is typical of that of high-quality quartz crystal oscillator. When τ >100S, thermal noise within the atomic line-width is dominate. If we neglect systematic effects, this intrinsic stability of hydrogen maser is limited by thermal noise within atomic line-width and is given by $1\sim 2\times 10^{-15}/\sqrt{\tau}$.

Some factors may influence the long-term stability of hydrogen maser. [3] The asymmetry of magnetic field and the pulling of microwave cavity's frequency are the most important factors.

Table 1 show the average frequency stability $\sigma_y(\tau)$ of these hydrogen masers as a function of averaging time interval τ . Here, by couple comparing between these 3 hydrogen masers, we may get the frequency stabilities of the individual oscillators. In our hydrogen masers we observe that the Allan deviation turns up for long averaging time intervals, going through a level of about 5 to 6*E-15. The typical results of the environmental sensitivities of the hydrogen masers are summarized in table 1. In the environmental sensitivities tests [3], The output frequency was carefully monitored while one maser's environmental conditions were varied.

Phase noise spectrum (SSB) of the maser's output signal of 5MHz and 10MHz is shown in table 2. We select a 5MHz or 10MHZ reference quartz oscillator whose signal noise spectrum below –150dB/Hz for frequency offsets is more than 1kHz.

4. Conclusion

Since 1988,we have developed more than 70 transportable hydrogen masers for Chinese VLBI network, time keeping and military purposes. During these years we made technical development too. [3] [4] The hydrogen maser group for Chinese positioning system has been designed and built at Shanghai Observatory and set up at the earth station of the Chinese positioning system in April 2000. The hydrogen maser frequency stability, as represented by Allan variance, had been measured for averaging time interval from 10ms to 1day. The variance is in the order of 10^{-15} for averaging intervals between 100s and 1 day. The data indicates the environmentally induced frequency perturbation for the hydrogen maser is better than the other hydrogen masers we made before. Now 13 hydrogen maser are finished and preparing for transportation to the earth stations of Chinese positioning system.

Items	Performance								
Frequency Stability	10ms	100ms	1s	10s	100s	1000s	3600s	10000s	1 day
	4.6E-11	5.6E-12	4.8E-13	6.4E-14	8.4E-15	5.6E-15	4.0E-15	4.2E-15	3.7E-15
Accuracy	$<5\times10^{-13}$								
Reproducibility	$\pm1.4\times10^{-13}$ (after 24 hours switching off)								
Temperature sensitivity	8.74×10^{-14}/℃ (15℃-35℃)								
Magnetic sensitivity	1.3×10^{-14}/G (-0.5G<H<0.5G)								
Voltage ce	$<4\times10^{-14}$ (220V±10%)								
Drift	$<2\times10^{-15}$/day								

Table1 Performance of the hydrogen maser

Frequency Offset	Phase noise	
	5MHz(dBc)	10MHz(dBc)
10Hz	-129.1	-132.2
100Hz	-143.0	-145.3
1KHz	-151.5	-156.2
10KHz	-154.6	-159.7
100KHz	-160.0	-161.0

Table2 Phase noise of the maser

5. Reference

[1] Z.C. Zhai H.X.Huang. C.F.Lin et.al. The new generation of hydrogen maser at Shanghai Observatory.[J] Proc. of 41st Annual symposium on Frequency Control 1987. p82

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