Frequency Stability Improvement of an Active Hydrogen Maser with a Single-State Selection System

Polyakov V., Timofeev Y., Demidov N.
Active hydrogen maser development and production department
Vremya-CH JSC
Nizhny Novgorod, Russia
email: polyakov@vremya-ch.com

***Abstract*—A single-state selection system based on the adiabatic rapid passage technique has been designed for active hydrogen masers to improve the frequency stability. This system eliminates more than 96% of undesirable atoms from the beam. State selection effectiveness was determined by measuring generation power as a function of atomic line quality and by the double resonance method for measurement of the population difference of hyperfine sublevels. Frequency stability caused by microwave cavity thermal noises has been improved by a factor of 1.5. Frequency stability of two active hydrogen masers with single-state selection systems was measured. Long-term frequency stability better than $1{\cdot}10^{-16}$ at averaging time 10^5 s has been achieved in the experiment.**

Keywords—hydrogen maser; state selection; adiabatic rapid passage

I. INTRODUCTION

The hydrogen maser utilises a transition between two ground state levels $F = 1$, $m_F = 0$ and $F = 0$, $m_F = 0$ of atomic hydrogen, with a frequency separation of 1.42 GHz [1]. Hydrogen atoms from the source after state selection are focused into a storage bulb, which is placed in a microwave cavity. In a conventional structure, selection is made by a magnet that focuses on the entrance of a storage bulb the atoms in two upper states, atoms in two lower states are removed from the beam [2]. This selection is not perfect, because atoms in F=1, m_F=1 state do not take part in the clock transition, but increase the atomic density in the storage bulb and decrease generation power by a spin exchange process [3].

A design enabling the elimination of atoms on undesirable state from the atomic beam has been proposed by authors [4-7]. The principle of single-state selection is as follows (figure 1). A first selecting magnet removes atoms in two lower states from the beam as well as in conventional selection. In inversion region atoms in F=1, m_F=1 state are changed to F=1, m_F= -1 state using adiabatic rapid passage technique. Atoms are then separated by a second selecting magnet and only atoms in the desired state penetrate into the storage bulb.

II. ADVANTAGES OF THE SINGLE-STATE SELECTION

Active hydrogen maser frequency stability is limited mainly by two terms depending on different averaging times (figure 2). Short-term frequency stability is limited by additional white phase noise added to the signal, represented by the first term and depend on the power that is received by the amplifier [8]:

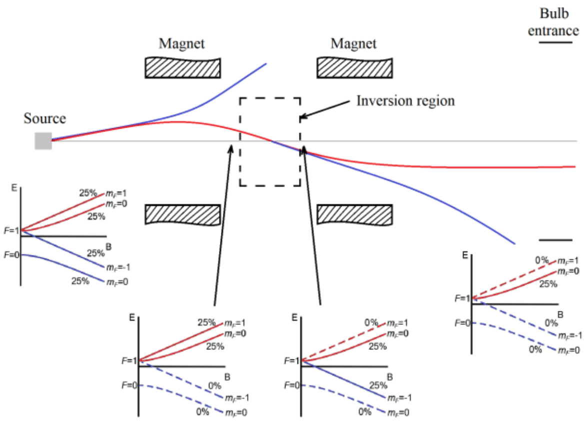

Fig. 1. Principle of the single-state selection

$$\sigma_y(\tau) = \frac{1}{2\pi\nu}\sqrt{\frac{k_B T_c F B}{P\tau^2}\frac{1+\beta}{\beta}} \tag{1}$$

where ν – transition frequency, k_B – Boltzmann constant, T_c – cavity temperature, F – amplifier noise factor, B – cut-off frequency defining the measurement equipment bandwidth, β – receiver's coupling factor, P – generation power, τ – averaging time, Q_{line} – atomic line quality.

Medium and long-term frequency stability is limited by white frequency noise, represented by the second term and depend on the power delivered by the atoms and the atomic quality factor [8]:

$$\sigma_y(\tau) = \frac{1}{Q_{line}\sqrt{P}}\sqrt{\frac{k_B T_c}{2\tau}} \tag{2}$$

Third plot shows typical Allan deviation of active hydrogen maser VCH-1003M Option L produced by our company.

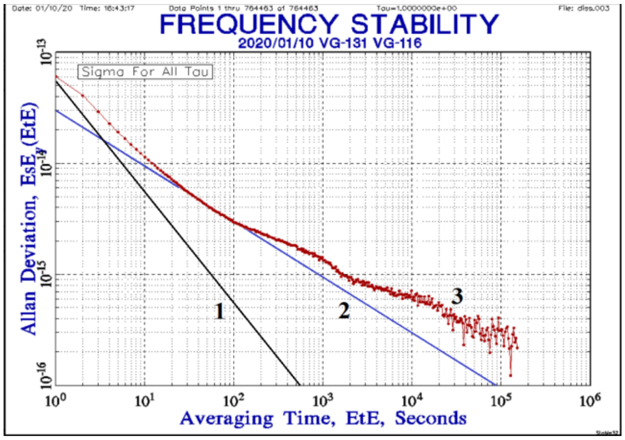

Fig. 2. Frequency stability: 1 – receiver white phase noise limit, 2 – cavity thermal noise limit, 3 – VCH-1003M Option L typical frequency stability

The first term dominates the stability for averaging intervals less than roughly 5 second, the second term is important between roughly 10 seconds and 1 day. As it shown (1-2) increasing $Q_{line}\sqrt{P}$ (let's call it parameter for simplicity) can greatly improve maser medium- and long-term frequency stability. To estimate the improvement of maser operation we calculated the enhancement of the product due to single-state selected beam. The relation between the power radiated and beam flux is the following []:

$$\frac{P}{P_c} = -2q^2\left(\frac{I}{I_{th}}\right)^2 + (1-3q)\left(\frac{I}{I_{th}}\right) - 1 \qquad (3)$$

where P_c – threshold power, I – beam flux, I_{thr} – threshold flux, q – quality parameter:

$$q \sim \alpha = \frac{I_{tot}}{I} \qquad (4)$$

where α – sorting parameter, I_{tot} – total flux of atoms in all states. The ratio between fluxes is typically more than two for the conventional selection and equals one for the perfect single-state selection. The ratio between parameters of single-state selected and conventionally selected beam depends on the quality parameter q:

$$\frac{\left(Q_{line}\sqrt{P}\right)_{\alpha=1}}{\left(Q_{line}\sqrt{P}\right)_{\alpha=2}} = \sqrt{1+\frac{1}{1-6q}} \qquad (5)$$

The typical value of q for our commercial active hydrogen masers is roughly 0.06. Therefore, theoretical enhancement of the parameter due to improved state selection is 1.6 times [9].

III. EXPERIMENTAL SETUP

We designed and built small-size state selection system suitable for our commercial active hydrogen masers (figure 3).

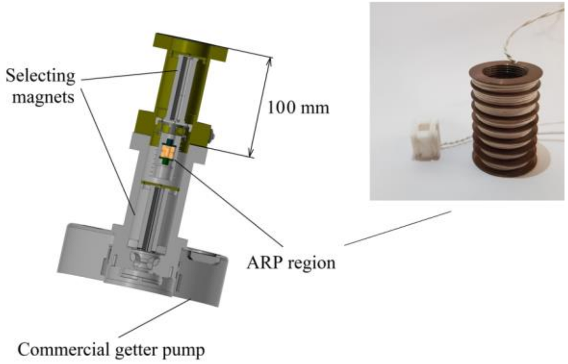

Fig. 3. Single-state selection schematic diagram

Mathematical modeling show that it is possible to have more than 96 % of atoms in the storage bulb in the desired state and that the fraction of hydrogen atoms in this state effused from the source that reach the storage bulb can be comparable to conventional design. The best design we discovered was to have first and second four-pole magnets due to higher magnetic field gradient compared with hexapole magnets. It is necessary to have the second magnet very long in order to eliminate atoms that have been transferred into the m_F = -1 state by the transition in adiabatic rapid passage region, and desirable to have the first magnet as short as possible to maximize the useful hydrogen atom flux. Other maser's parts were the same as our commercial instruments.

The main part of the single-state selection system is inversion region. The adiabatic rapid passage technique employs orthogonal RF and DC magnetic fields. DC field varies in strength along the beam path, producing in a reference frame rotating with the RF field a total effective field that reverses its direction, causing the precessing atoms to invert their spins (figure 4).

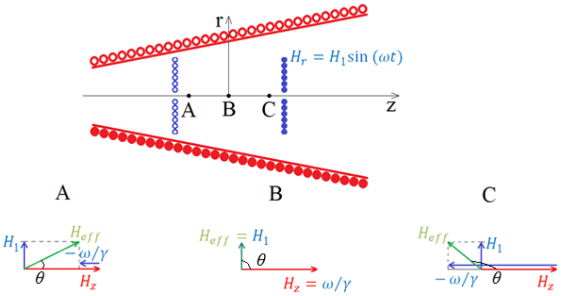

Fig. 4. Effective magnetic moment rotation in adiabatic rapid passage

The DC field is produced by the solenoid with a variable winding and a variable diameter along the beam path. The RF field, which is perpendicular to the beam, is produced by two coils. The solenoid is located within cylindrical magnetic shield to protect it from external magnetic fields. The calculations show that the highest transition probability for the following magnetic fields: DC field at solenoids center roughly 5 Gauss, RF field magnitude around 0.1 Gauss, RF frequency roughly 7 MHz.

IV. EXPERIMENTAL RESULTS

With no transition induced in adiabatic rapid passage region, the maser oscillated the same as commercial one. When transitions were induced, the power output typically increased about 1.3 times, and the hydrogen resonance linewidth decreased. To check the performance of single-state selected atomic beam we measured the power radiated by the atoms and the line quality for several values of beam flux. After combining this data one can calculate the dependence of maser power versus inverse line quality to estimate the maser's quality parameter according to authors of this article. We calculated roughly 2 times the quality parameter enhancement for all prototypes (figure 5).

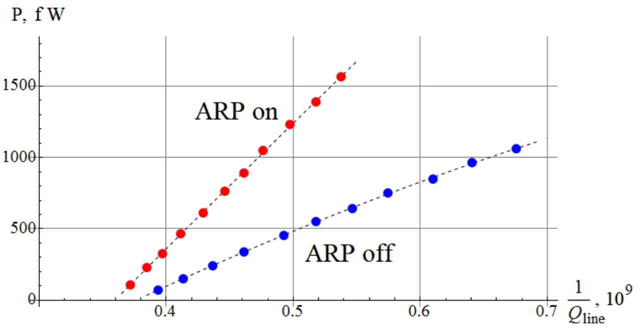

Fig. 5. The dependence of maser power versus inverse line quality

Also, we measured the max value of the parameter for all prototypes with no transition induced in adiabatic rapid passage region and compared results with the commercial instrument. As it's shown in table 1 values of parameter for prototypes and commercial maser are very similar. It means that the atoms in desired state were well focused to the storage bulb. Then we measured the max value of the parameter when transitions were induced and received very good results: the experimental enhancement of the parameter was roughly 1.5 times which is very close to the theoretical estimation (table 1).

TABLE I. Enhancement of $Q_{line}\sqrt{P}$ due to single-state selection

	$\left(Q_{line}\sqrt{P}\right)_{\max}, 10^3\sqrt{W}$		$\frac{\left(Q_{line}\sqrt{P}\right)_{\max} - ARP - on}{\left(Q_{line}\sqrt{P}\right)_{\max} - ARP - off}$
	ARP off	ARP on	
prototype AHM-1	1.528	2.31	1.51
prototype AHM-2	1.501	2.234	1.49
prototype AHM-3	1.439	2.206	1.53
Commercial VCH-1003M	1.446	-	-

To examine the frequency stability improvement, we used two prototypes and the frequency comparator placed in the environmental chamber to reduce temperature variations. 36 days long frequency stability measurement results for 1 of 2 unit scaling are shown in figure 6, linear frequency drift is removed. The theoretical limit represents the cavity thermal noise defining frequency stability at averaging time 100 seconds was measured at $1.85\times10^{-14}/\sqrt{\tau}$ level. The maser with single-state selected beam provides a theoretical limit that is 1.5 times lower than our commercial masers. We assume that medium-term frequency stability differs from the theoretical limit due cavity auto-tuning system noises. The best way to reduce this difference is increasing the signal-to-noise ratio of cavity tuning error signal. The frequency stability at averaging times one day is roughly 3 times better than our commercial maser VCH-1003M Option L. Such a big difference is probably caused by random variations of the external magnetic field. In case of the conventional state-selection frequency shifts may be observed due to magnetic fields gradients. Random variations may cause the flicker floor of the maser long-term stability. But these shifts are eliminated in the maser with single-state selected beam, therefore the frequency stability less than 10^{-16} can be achieved over intervals of 50 000 seconds.

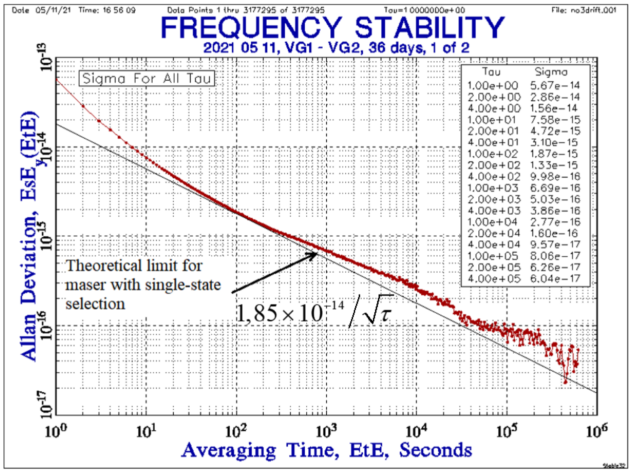

Fig. 6. Frequency stability of the hydrogen maser with a single-state selection

V. CONCLUSION

The designed single-state selection for hydrogen masers provides more than 96 % of atoms in the desired state in the storage bulb. The improvement in the operation of the maser using adiabatic rapid passage technique is proved. The experimental enhancement of the parameter $Q_{line}\sqrt{P}$ is roughly 1.5 times and very close to the expected value. Measured long-term frequency stability improvement is more than 3 times compared with the commercial maser VCH-1003M Option L, therefore the frequency stability less than 10^{-16} can be achieved over intervals of 50 000 seconds. The designed physics package of the hydrogen maser with single-state selection will be involved in a new model VCH-2021.

REFERENCES

[1] N. F. Ramser, D. Kleppner, H. C. Berg, S. B. Crampton, R. F. Vessot, H. Peters, and J. Vanier, Phys. Rev., vol. 138A, p. A972, 1965.

[2] D. Kleppner, H.C. Berg, S.B. Crampton, and N.F. Ramsey, “ Hydrogen-Maser Principles and Techniques ”, Physical Review, vol. 138, N. 4A, 1965.

[3] D. Kleppner, H.M. Goldenberg, and N.F. Ramsey, “Theory of the Hydrogen Maser ”, Physical Review, vol. 126, N. 2, 1962.

[4] C. Audoin, M. Desaintfuscien, P. Petit, and J.-P. Schermann, “Design of a Double Focalization in a Hydrogen Maser”, IEEE Trans. on Instrum. and Measur., vol. IM-17, N. 4, pp. 351-353, 1968.

[5] Urabe, K. Nakagiri, Y. Ohta, M. Kobayashi, and Y. Saburi, “ Majorana Effect on Atomic Frequency Standards ”, IEEE Trans. on Instrum. and Measur, vol. IM-29, N. 4, 1980.

[6] E.M. Mattison, Robert F.C. Vessot, and W. Shen, “ Single-State Selection System for Hydrogen Masers ”, IEEE Trans. on Ultrason., Ferroel., and Freq. Control, UFFC-34, N. 6, 1987.

[7] Aleynikov M. S., Boyko A. I. “On the single-state selection for H-maser and its signal application for fountain atomic standard”, in Proceedings EFTF, Neuchatel, 2014, pp. 169-172.

[8] F. Riehle, “Frequency standards: basics and applications”, pp. 133 – 146, PHYSMATLIT, transl., 2009.

[9] A. A. Belyaev, N. A. Demidov, V. A. Polyakov, and Yu. V. Timofeev, “Estimation of a possible decrease in the limiting frequency instability of a hydrogen generator with the use of a beam of atoms in a single quantum state,” *Izmer. Tekhn.*, No. 8, 28–31 (2018).