Применение водородного генератора повышенной мощности в стандартах частоты фонтанного типа

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Application of H-maser with increased power in fountain atomic clocks

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Современное состояние науки и техники в области метрологии времени и частоты является определяющим во многих отраслях человеческой деятельности, особенное внимание сегодня в России уделяется развитию глобальной навигационной спутниковой системы ГЛОНАСС и ее функциональным дополнениям. В рамках реализации федеральной целевой программы (ФЦП) «Поддержание, развитие и использование системы ГЛОНАСС на 2012 – 2020 годы» в 2016 году предусмотрено создание опытного образца наземного рубидиевого стандарта частоты фонтанного типа с предельно достигаемой девиацией Аллана не более $2\cdot10^{-16}$*. Одной из главных проблем стандартов частоты фонтанного типа является фазовый шум сигнала, зондирующего часовой атомный переход. В настоящей работе показано решение этой проблемы за счет применения водородного генератора повышенной мощности в качестве опоры в схеме формирования зондирующего сигнала. Данное решение отличается сравнительной простотой, поскольку не требует применения ни криогенных микроволновых осцилляторов, ни сложных оптических систем.*

The state of the art in time and frequency metrology defines many fields of human activity. At present in Russia a special attention is devoted to development of the global navigation satellite system GLONASS and its functional supplements. According to the federal program "Maintenance, advancement and usage of the system GLONASS in 2012-2020 years" a creation of terrestrial rubidium fountain atomic clock with limit achievable Allan deviation no more than $2\cdot10^{-16}$ *is envisaged in 2016 year. A main problem of the fountain atomic clock is a phase noise of interrogation signal probing the atomic clock transition. In the present work a solution of the problem via application of the hydrogen maser with increased power as a reference in synthesis scheme of the interrogation signal is described. This solution caused by simplicity because it does not require cryogenic microwave oscillators or complicated optical systems application.*

I INTRODUCTION

Increase of accuracy and stability of the time and frequency unit performance is associated with creation and further improvement of new standards. Time and frequency standards based on a quantum transition of atomic ensemble have allowed to increase the frequency stability to several orders as compared with quartz clocks and have been rapidly developing. Today the definition of the second based on microwave transition of the ^{133}Cs [1], according to BIPM's recommendation one of the possible candidates for redefinition of the second is microwave transition of the ^{87}Rb [2]. Thus the increase of frequency stability and accuracy of the standards in microwave field is extremely important and relevant issue.

In the key world metrology laboratories the rubidium or cesium fountain atomic clocks have replaced atomic standards based on heat atoms and operates as a reference standards. In the FGUP "VNIIFTRI" according to implementation of the federal program the rubidium and cesium fountain atomic clock prototypes also are being developed. It is important to note that the created cesium fountain atomic clock is exploiting as the state reference time and frequency standard, and has the record accuracy of $5 \cdot 10^{-16}$ currently in Russia [3].

The Allan deviation of fountain atomic clock is the basic metrology feature and has the following form [4]:

$$\sigma_y(\tau) = \frac{1}{\pi Q_{at}} \sqrt{\frac{T_c}{\tau}} \sqrt{\left(\frac{1}{N_{at}} + \frac{1}{N_{at} n_{ph}} + \frac{2\sigma_{\delta N}^2}{N_{at}^2} + \gamma \right)} \quad (1)$$

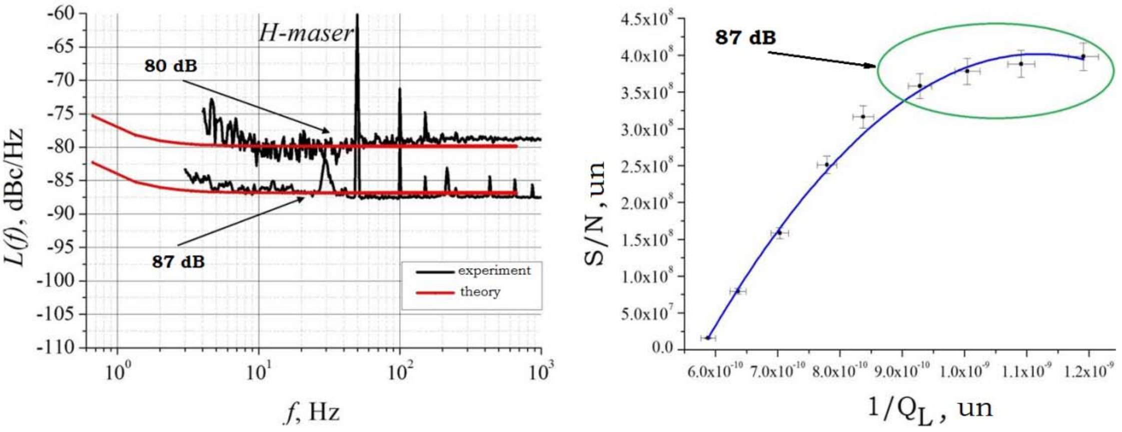
here Q_{at} – quality factor of the clock transition line, N_{at} – number of detected atoms, T_c – duration of one operation period (about 1.5 s). The first term in (1) describes the noise caused by measurement of quantum atomic state. The second term describes the Poisson noise of the average number of the detected photons n_{ph}. The value $\sigma_{\delta N}$ represents independent mean-square fluctuations of the atom number in each measurement. The last term γ describes a contribution due to phase noise of the microwave interrogation signal. This contribution known as Dick effect is usually dominant term and limits the device's stability [5-8].

Decrease of the noise contribution γ is associated with the phase noise suppression of a synthesizer (local oscillator) or a reference signal delivered to the synthesizer. In the first case ultra low noise cryogenic microwave oscillators [9] or ultra stable optical oscillators with laser femtosecond comb [10] are applied. The second case is significantly easier when applying H-maser with improved stability which reached due to multiple increase of power radiated by operating atoms in the H-maser's storage bulb. The main results of research and application analysis of the developed "special" H-maser are described further.

II MAIN RESULTS

There are several well-known methods to increase a power radiated by atoms in H-maser's storage bulb [11]. In the paper a few main results of complete series of works dedicated to creation and research of a special hydrogen maser with increased output power based on the methods are represented.

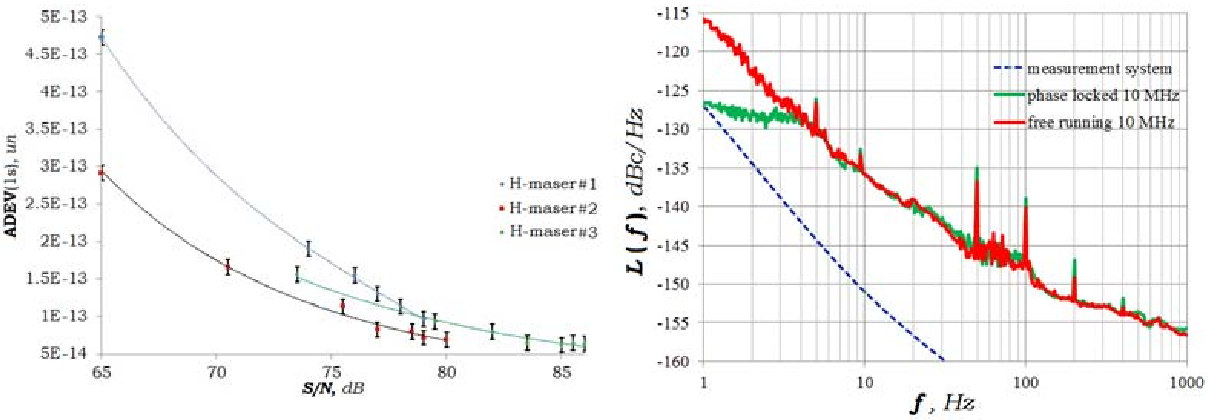
Firstly, experimental results, which are represented in figure 1, show that actual achievement of a signal to noise ratio (*S*/*N*) in bandwidth 1 Hz at the special H-maser's output is close to 87 dB level, what is greater about 15 dB than typical value of *S/N* for industrial masers. This special hydrogen maser, according to theory prediction and the experimental results, has an extreme low phase noise level near carrier due to large signal to noise ratio. This parameter is highly important in microwave frequency standards operated in pulse mode when a period of one cycle is equal to T_c. So, in fountain atomic frequency standards a usage of the special H-maser as a reference source for a microwave synthesizer can significantly suppress the phase noise of the interrogation signal at the offsets n/T_c from clock transition frequency (where T_c = 1.5 s, n = 1…10), i. e. decrease the Dick effect because these harmonics cause a dominant contribution in a value of the effect [12].



(*a*) (*b*)

Figure 1. Experimental data of H-maser's signal-to-noise ratio from phase noise (*a*) and signal analyzer (*b*) measurements

Secondly, the large level of the signal to noise ratio also allows to get a high short and medium term stability of the hydrogen frequency standard. In figure 2*a* the frequency Allan deviation (ADEV) of 5 MHz at 1 second average versus signal to noise ratio of the special H-maser is represented, the measurements were performed at precision frequency comparator *VCH*-314 (“Vremya-Ch” JSC, Russia) in bandwidth 3 Hz. As it is shown from the figure the ADEV is decreasing with *S/N* being increased and achieves $6.5 \cdot 10^{-14}$ at 1 s. The results of the phase noise measurements near carrier of low noise quartz oscillator 10 MHz phase locked to the special H-maser and being in free running mode are shown in figure 2*b*. The free running quartz oscillator 10 MHz has the stability near $1.0 \cdot 10^{-13}$ at 1 s.



(*a*) (*b*)

Figure 2. (*a*) The measured Allan deviation at 1 s of three special hydrogen standards versus signal to noise value at maser’s output. The used inner quartz oscillator 5 MHz has the stability about $6.5 \cdot 10^{-13}$ at 1 s in free running mode. (*b*) The measured phase noise of the 10 MHz quartz oscillator near carrier

At last the interrogation signal’s principal scheme based on the special H-maser with metrology features, which represented in figure 2, as the reference for the commercial synthesizer SpectraDynamics Rb-1, which is the optimal device among its category, is being discussing. According to the results of the Dick effect calculation adduced in the table 1 the application of the H-maser with increased power in such scheme provides the contribution, which is less than $1.0 \cdot 10^{-13}/\sqrt{\tau}$. This value with a margin ensures requirements dedicated to the interrogation signal: to achieve the fountain Allan deviation of $2 \cdot 10^{-16}$ the value γ is estimated to be less $1.5 \cdot 10^{-13}/\sqrt{\tau}$.

Thus, the key benefit of such hydrogen maser application in microwave atomic frequency standards is the significant reduction of metrological requirements, such as phase noise and limit frequency stability, of the local oscillator – quartz oscillator or dielectric resonator oscillator (DRO).

Table 1. The calculated Dick effect for SpectraDynamics Rb-1 synthesizer with different reference H-masers.

Synthesizer	Reference	Dick effect γ
SDI Rb-1	“usual” H-maser with S/N = 70 dB	$2.1 \cdot 10^{-13}/\sqrt{\tau}$
	“special” H-maser with S/N = 80 dB	$1.2 \cdot 10^{-13}/\sqrt{\tau}$
	“special” H-maser with S/N = 87 dB	$6.7 \cdot 10^{-14}/\sqrt{\tau}$

III SUMMARY

The metrology performance of the developed H-maser with increased power, due to usage of several original methods, has been researched. The analysis of the application of such maser as the reference in interrogation signal's scheme of the fountain atomic clock has been performed. This analysis demonstrates that the proposed approach in the work resolves the issue of the fountain atomic clock's stability limit due to the phase noise of the interrogation signal. Further decrease of the noise impact on the stability is possible due to improvement of synthesizer's performance.

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