Compact microwave frequency standard on Hg-199 ions for navigation systems

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Abstract. The design of a magnetic trap for low mass-dimensional microwave frequency standards is presented. The dependencies of the number of photons registered by PMT on magnetic field values are established. The new algorithm for optical processing has been developed. The comparison of experimental Allan deviation for different designs of microwave frequency standards on $^{199}$Hg$^+$ ions has been performed.

1. Introduction

The frequency standards are presently an integral element: for any high precision systems for object location determination, global time scales, signal transmission and processing, metrological systems [1-6]. Low overall-dimensional frequency standards which are capable of withstanding harsh G force while taking interstellar travels or landing on remote space objects (like the Moon etc.) stand a special place in this order [1, 4, 6-11]. Also it is required to note that mostly communication session between such station or space vehicle and an Earth satellite lasts for a short period of time. During that given period a large amount of information has to be sent to great distances with high speed. This fact lays certain conditions on the operating frequency value of a frequency standard, situated on the board of such object [2-4, 9-16]. Besides, the time scale of a space station or a vehicle must be precisely synchronized in time with corresponding scales of Earth satellites which receive navigational messages. It is a required condition for determining location of a space station or a vehicle on a remote planet [2, 3, 8, 9, 11].

In papers [17-19] the results of researching frequency ranges of various stations have been presented. According to them the frequency range from 40 to 75 GHz is occupied at the rate of only 5 % comparably to other ranges (S, X etc.). Operations in this range lower various interferences which may degrade Signal/Noise ratio while receiving information signal. Moreover, in most modules of frequency standards the laser and optical systems are used for various disturbances influences decreasing on measuring results. [7, 18, 20-25]

Microwave frequency standard on $^{199}$Hg$^+$ ions is for sure one of the most optimal solutions for space stations and vehicles because it possesses high precision characteristics and stable to large G forces [1, 19]. The only disadvantage of aforesaid cases of implementation of such a standard is its vast mass-dimensional parameters. That is why for its rational implementation it is necessary to
decrease its size and mass meanwhile saving precision characteristics, in other words – find a solution for construction modernization case.

The whole process of construction modernization while lowering mass-dimensional characteristics substantially leads to a search for new technical decisions targeted on decreasing mass and size of one of its main blocks as well as development of new algorithms for automatic control systems and systems for signal registration that is used for determining the resonant frequency [3, 4, 7-11, 18, 26, 27]. In the following paper one of possible solutions for modernization of \(^{199}\text{Hg}^+\) quantum frequency standard is presented.

In most cases there is no time and sufficient financial means for fundamental research performing and the development on basic then of new compact microwave frequency standards models.

2. Magnetic trap and a new algorithm for optical signal processing
The core block of the microwave frequency standard on \(^{199}\text{Hg}^+\) ions is a magnetic trap which is also implemented in a plenty of other devices [1, 18, 28-30]. The structure scheme of low-dimensional magnetic trap is presented on the figure 1. The magnetic trap is designed as \(n = 4\)-pole with radius \(r_0 = 0.7\) cm based on a design of Paul trap. [1, 28, 29]

![Figure 1. Structure scheme of low mass-dimensional magnetic trap for microwave frequency standard on \(^{199}\text{Hg}^+\) ions.](image)

The alternating electro-magnetic field holds a required number of \(^{199}\text{Hg}^+\) ions in the magnetic trap in order to make them interact with \(\lambda = 194.2\) nm radiation and emit a certain number of photons which then has to be registered by a Photomultiplier tube (PMT). Long-term and short-term stabilities are straight out connected a quality of ions’ trapping. Alongside with lowering mass and dimensions of the magnetic trap, electrode sizes for producing magnetic field are decreasing as well. That is why the requirements for parameter stabilization of the operating signal, used for forming magnetic field, are increasing vastly. In order to solve such a task we developed a new block for controlling electromagnetic field that provides a proper trapping of charged particles.

We handled preliminary calculations before the design of this block. Charged particles in the trap are held with an effective potential:

\[
V_{\text{eff}} = \frac{n^2 \psi^2}{4 \alpha^2} \frac{q^2}{m} r^{2n-2}
\]  

(1)
Trapping a particle with a single charge $q$ shall be limited by mass $m$: at the upper band – by a depth of effective potential and at the lower band – by a mean duration of an ion trapping. The requirements to voltage amplitude $V_0$ are performed when:

$$\Omega \geq \Omega_{\text{min}} = \frac{n-1}{3r} \sqrt[3]{\frac{E_m}{m_{\text{max}}} \frac{m_{\text{max}}}{m_{\text{min}}}}$$

where $E_m$ - kinetic energy of a single particle, $\Omega$ - frequency of the operating signal, $r'$ - normed radius value, $m_{\text{max}}$ and $m_{\text{min}}$ – maximum and minimum masses of trapped particles respectively.

According to calculation data from (1) and (2) alongside with held research we developed a new algorithm for processing registered optical signal. In this algorithm we considered one important mechanism that characterizes a connection between a number of photons registered by PMT and a voltage on the electrodes. It was counted while processing the signal in the created program for MCS-51 controller. The operation signal is formed based on results of calculations, it is employed in controlling power cascades from which voltages are fed through transformer coils onto the electrodes. In figure 2 a structure scheme for work regime control of magnetic trap is presented.

![Figure 2. Structure scheme for driving magnetic trap: 1 – Magnetic trap, 2 – Photomultiplier tube, 3 – Photon counter, 4 – automatic frequency control (AFC) system with signal maintenance, 5 – Externally controlled highly stable quartz generator, 6 – Driving system and power cascades, 7 – Output transformer.](image)

The photon counter determines during a time interval $\tau$, which may differ depending on exploitation conditions, from 1 to 110 seconds, the number of registered photons by PMT: from $10^4$ to $5 \times 10^5$. The control system on the grounds of the collected data gives out commands corresponding to our developed algorithm for controlling frequency of the quartz generator 5 and amplifying cascades 6, where through transformer 7 coils changed voltage values are fed on the magnetic trap electrodes and the electromagnetic field in order to assure a stable working regime of the microwave standard.

The received experimental data has shown that a low mass-dimensional magnetic trap with the implemented control system ensures a solid operation with a number of registered photons from $10^4$ to $5 \times 10^5$ and with the next parameters: frequency $\Omega$ shall be placed in the range: from 0.74 to 1.60 MHz, its amplitude $V_0$ from 120 to 200 V and kinetic energy of particles $E_m$ from 0.2 to 10 eV.

3. Experimental researches results and discussion

The executed researches of precision characteristics and parameters of various blocks of the microwave frequency standard has shown the following. The construction solutions proposed and the developed algorithm for processing optical signal allowed to make an influence of parasite disturbances insufficient (due to smallness of its amplitude). These disturbances are contained in spectrums of operating voltages, fed to the electrodes. Besides, this has allowed to improve short-term frequency stability. The experimental results are presented in figure 3.
Figure 3. The Allan deviation: graph 1 corresponds to the previous microwave standard construction, graph 2 – to the newly developed design.

Shown on the figure 3 value of Allan deviance has been calculated according to the given formula:

$$\sigma_y^2 = \frac{\sum_i^n \sigma_{0i}^2}{2(n-1)} \quad (3)$$

$$\sigma_{0i} = \frac{f_i + f_{i+1}}{f} \quad (4)$$

The analysis of the acquired data on the figure 3 shows that the implemented technical solutions and a newly developed algorithm for processing the optical signal alongside construction modernization have provided us the way to improve Allan deviance of 20%. Long-term stability in the new low mass-dimensional construction did not experience a decrease.

4. Conclusion
Implementing the new algorithm for processing the optical signal has allowed us to hold the required precision characteristics while decreasing its construction size in 3 times and mass by more than 60% in order to offer a reliable operation of navigation devices and communication systems in special space vehicles and stations.

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