Microwave low mass-dimensional frequency standard on Hg-199 ions

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Abstract. In the paper the design of a magnetic trap for low mass-dimensional microwave frequency standards is presented. The dependencies between the number of registered photons by PMT and magnetic field values are established. The new algorithm for optical processing is developed. The results comparison of experimental Allan deviation researches for different designs of microwave standard on ¹⁹⁹Hg+ ions are performed.

1. Introduction

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 [1-9]. Low mass-dimensional frequency standards stand a special place in this order [8-14]. These devices are applied in various technical cases (for example, ecological Earth monitoring) on land as well as in airborne applications [13-18]. During frequency standard exploitation in mobile flying vehicles some important issues may appear. They are bounded with mass-dimensional restrictions of the standard and power consumption [8-10, 16, 17, 19-24].

Besides, frequency standards, especially used for objects’ location in space or on Earth, have got to posses high precision characteristics [8-15, 21-24]. The best solution for aforesaid cases is quantum frequency standards (QFS) [20-25]. These devices allow to produce frequency with high precision.

In case of lowering construction size of a QFS for solving hard tasks connected with determining coordinates of moving objects the unavoidable outcome is decreasing short-term and long-term frequency stability. That is because QFS require a high thermostabilization order of the most operational blocks. Especially in cases of implementation laser or photodetection devices [26-29].

Besides that, QFS use magnetic fields in order to split energy levels of atoms into sublevels. While applying magnetic fields thermostabilization must be achieved [30-33]. It is necessary to note that most QFS models (for instance, those based on cesium-133 or rubidium-87) are not stable to high G-force overloads. These overloads appear due to obtaining fast speed in short periods of time.

The held research by us has shown the microwave frequency standard on Hg-199 ions is the best solution in this situation. This standard has one major disadvantage to the other QFS models – big mass-dimensional parameters of magnetic system, operation and signal processing blocks. That is why
for successful implementation of such a standard in moving objects it is necessary to decrease its size and mass, not affecting the precision characteristics sufficiently.

It is not a trivial task to solve, because all the blocks are interlinked with one another in a certain way. That is why the issue of standard modernization must be solved as a whole. Lower mass and size of the major blocks, develop new algorithms for automatic frequency control, magnetic field maintenance and photon registration systems. One of the solutions of this task is presented in the present work.

2. Microwave low mass-dimensional frequency standard on 199Hg+ ions

The main block of the microwave standard is a magnetic trap. That is why the directions of modernizations which lead to lowering its mass-dimensional parameters are primarily connected with reducing the size of the trap itself.

The alternating electromagnetic field holds a required number of 199Hg+ 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 PMT (Photomultiplier tube). 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 have developed a new magnetic trap construction for the low mass-dimensional microwave frequency standard. A new automatic frequency control system has been developed for guiding the trap through managing the frequency of the quartz generator and the supply voltage of the power cascades.

Charged particles in the trap are held with an effective potential:

$$V_{eff} = \frac{n^2 \cdot V_0^2}{4 \cdot \frac{m}{q} \cdot n^2 - 2}$$

(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 low edge of the operational frequency $\Omega$ is determined as:

$$\Omega \geq \Omega_{min} = \frac{n-1}{3r'} \frac{\sqrt{E_m}}{r_0} \frac{m_{max}}{m_{min}}$$

(2)

where n – number of electrodes, $r'$ - normed trap radius, $E_m$ – kinetic energy of particles, $r_0$ – trap radius, $m_{min}$ and $m_{max}$ – minimum and maximum particle mass.

This has allowed to fulfill an effective parameter control of the magnetic trap, judging by the analysis of the photon counter data, even in relatively rough conditions (for instance overpressure etc.). The circuit diagram for supplying the trap is show at the Figure 1:
Figure 1. Circuit schematic diagram of the supplied trap

Oscillator signal is fed and amplified through the compact driver and transformation coupling to the trap electrodes. Highly stable DC voltage is applied as well in order to compensate the axial component and hold the ion assembly in the trap region.

Figure 2. Structure scheme for driving magnetic trap: 1 – Magnetic trap, 2 – Photomultiplier tube, 3 – Photon counter, 4 – Controller, 5 – Externally controlled highly stable quartz generator, 6 – Driving system and power cascades, 7 – Output transformer.

The generator 5 supplies the trap through the driver 6 and the transformer 7. Leaked photons from the trap are registered by the PMT that sends amplified signal to the Photon counter 3, programmed with VHDL language and set to precisely tract the number of leaked photons through different periods of time. The whole control loop is managed by the MCS-51 controller unit that receives signals from the Photon counter and produces control codes for the synthesizer, Automatic frequency control (AFC) generator, and the highly stable DC unit in order to operate values in real time. In other words, the negative feedback system is implemented.

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 $5 \cdot 10^5$ 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. The results of the experimental research
The held research has shown that spectrums of the driving voltages in the new magnetic trap construction have no sufficient perturbations which may affect the stability of operation. The
experiments show the short-term stability improvement by Allan deviation. On the fig. 3 the measurement results are presented.

![Graph showing Allan deviation](image)

**Figure 3.** The Allan deviation: graph 1 corresponds to the previous microwave standard construction, graph 2 – the newly developed design by us.

Shown on the fig. 3 value of Allan deviation has been calculated according to the given formula:

\[
\sigma_y^2 = \frac{\sum_i \sigma_0^2_i}{2(n-1)} \tag{3}
\]

\[
\sigma_0_i = \frac{f_{i+1} - f_i}{f} \tag{4}
\]

The analysis of the acquired data on the fig. 1 shows that the implemented technical solutions have provided us the way to improve Allan deviation of 20 %. Long-term stability in the new low mass-dimensional construction did not experience a decrease.

4. **Conclusion**

The received experimental data has shown that while decreasing construction size of the standard in 3 times and mass by more than 60 % the suggested technical solutions allow us to save and improve the required precision characteristics in order to offer a solid operation of navigational devices and communication systems in mobile flying vehicles.

**Acknowledgments**

This work partly supported by Grant of RFBR No 18-29-25071.

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