Improving characteristics of microwave frequency standard on Hg-199 ions for telecommunication systems

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Abstract. The article presents the development of a new low mass-dimensional microwave frequency standard on Hg-199 ions. The optimal ion trap parameters are calculated. The new control algorithm is developed. The compact driver for trap field is constructed. The experimental data received show the decrease in size and mass while saving precision characteristics.

1. Introduction

Any complex high precision system nowadays uses a frequency standard for precise time synchronization or object location [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 electro-magnetic field holds a required number of 199Hg+ ions in the magnetic trap in order to make them interact with λ = 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.

The task of finding the optimal operation signal parameters is backboned with solving deferential Mathiu equations and empirical formulas of tracking a charged particle in a harmonic electromagnetic field.

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

\[
V_{\text{eff}} = \frac{n^2 \cdot \nu^2}{4} \cdot \frac{q^2}{r_0^2} \cdot \frac{1}{m} \cdot r^{2n-2}
\]  

And the low edge of the operational frequency Ω is determined as:

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

where \(n\) – number of electrodes, \(r'\) - normed trap radius, \(E_m\) – kinetic energy of particles, \(r_0\) – trap radius, \(m_{\text{min}}\) and \(m_{\text{max}}\) – minimum and maximum particle mass, \(q\) – particle charge

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:

![Circuit schematic diagram of the supplied trap](image)

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 track 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.

The operation parameters for the trap are calibrated by the photon emission criteria. The Rubi line which represents the photon emission against frequency offset at figure 3 is set to the maximum efficiency – highest line quality in order to rise up the photon counter resolution and precision characteristics. The data has proven to us that the new standard with automatic field control 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.

**Figure 3.** Hg-199 resonance near 40.507 GHz transition
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 primary experiments show the short-term stability improvement. On the figure 4 the measurement results are presented.

![Figure 4](image)

**Figure 4.** Standard relative deviation: graph 1 represents exploited Rb-87 standard, graph 2 – the newly developed design

Shown on the figure 4 values of the deviance have been calculated according to the given formula:

\[
\sigma = \frac{\sum \epsilon_i^2}{(n-1)} \quad (3)
\]

\[
\epsilon_i = \frac{f_i - \bar{f}}{f} \quad (4)
\]

where \( \epsilon_i \) – relative frequency deviance

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.

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