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CESIUM ATOMIC CLOCK FOR GLONASS SATELLITE NAVIGATIONAL SYSTEM

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Abstract: One of the essential elements of satellite navigation system is an atomic clock. The proper operation of any navigation system depends on the performance of atomic clock. Several directions of modernization of the cesium atomic clocks are considered. New design of the frequency synthesis circuitry is presented. The theoretical calculations and experimental researches showed the decrease of step frequency tuning by several orders and improvement of spectral characteristics of the frequency synthesizer output signal. New magnetic field control unit eliminates one of the most important perturbing factors affecting on long-term frequency stability. Experimental research of the cesium atomic clock metrological characteristics showed the improvement of Allan variance by 10%.

Keywords: cesium atomic clock, quantum frequency standard, frequency synthesizer, direct digital synthesis, magnetic field control unit, Allan variance.

Introduction

Global navigation satellite constellations such as European Galileo, Russian GLONASS, and the USA Global Positioning Systems (GPS) use atomic frequency standards for precision time-keeping and stable frequency generation [1].

One of the central problems of satellite systems is the problem of mutual synchronization of the satellite time scale up to nanoseconds and less. The error of the navigation signals emitted by the different satellites at 10 ns causes an additional error in determining the location of the consumer to 10–15 meters.

The solution of the high-precision synchronization problem of the on-board time scales requires the implementation of highly stable on-board cesium and rubidium frequency standards on satellites, as well as the creation of ground-based devices for comparing time scales.

The concept of development of the space navigation systems and development of the metrological services makes it necessary to modernize the currently used quantum frequency standards or to develop new ones.

Development and commissioning of new atomic clock is very long and costly process, and in most cases there is not enough funds and time. Therefore, in most cases, modernization is needed for specific tasks related to the operating conditions of the frequency standards.

The process of quantum frequency standards modernization includes various directions: changing the weight and dimensions, reducing energy consumption, improvement of metrological characteristics. For frequency standards, modernization may not be necessary for the whole construction but only for individual units or blocks. In present work several directions of metrological characteristics improvement are considered.

Several directions of improvement of cesium atomic clock metrological characteristics

Frequency synthesizer is one of the main blocks of quantum frequency standard. Frequency synthesizer generates the microwave signal at ~9.2 GHz (used to interrogate the ^{133}Cs atoms hyperfine resonance transition) from the 5 MHz quartz oscillator frequency [1–3].

The main characteristic of the frequency synthesizer is an ability to impact on the characteristic of frequency stability of the quantum frequency standard output signal. Frequency instability introduced by the synthesizer is determined by the lateral discrete spectrum components of the signal that occurs in dividing, multiplying, mixing frequency signals, the accuracy of generated frequency, and the impact of natural and technical noise [5–7].

In order to provide the best possible frequency stability, it is crucial that the microwave signal which interrogates the ^{133}Cs atoms is as “clean” as possible; that is, free of unwanted sidebands and spurious signals which can cause Bloch-Siegert frequency shifts [1–2].

To meet the requirements for spectral purity of output signal 10 bit DAC was used. It is possible to obtain the suppression of lateral amplitude components in the spectrum of the output signal not worse than -70 dB.

Experimental study showed that the accuracy of present method of generating the frequency synthesizer output signal needs to be increased. The large resolution of step frequency is necessary. New scheme of the frequency synthesizer has been designed by using a method of direct digital synthesis (DDS) [4]. This method allows us to generate the synthesizer output signal within the accuracy about 10^{-5} Hz.

In Fig. 1 new design of the frequency synthesizer is presented.

Fig.1. New design of the frequency synthesizer.

In addition, a new design of the frequency synthesizer also allows eliminating one of the most important perturbing factors affecting on long-term frequency stability.

The stable isotope ^{133}Cs has two hyperfine states F = 4 and F = 3 which are split in the magnetic field into 16 components. In accordance with the selection rules, seven transitions between the components of hyperfine sublevels are possible. The central resonance $|F=3, m_F=0> \leftrightarrow |F=4, m_F=0>$ due to the Zeeman effect exposes a quadratic frequency shift. For a typical value of magnetic field or so-called C-field near 8 uT the frequency shift is 2.7 Hz corresponding to a relative frequency shift of $3 \cdot 10^{-10}$.

The accuracy of the output signal quantum frequency standard is dependent on the shift of the central resonance. It should be noted that not only the central resonance is exposed the frequency shift, but also all six transitions $(3, m_F) \leftrightarrow (4, m_F)$ with $\Delta m_F = 0$. To express these changes as a function of B and atomic constants we used the Bright Rabi equation [1–3].

In order to control any changes of magnetic field a new magnetic field control unit was developed. In modern quantum frequency standards the magnetic field is maintained by the active stabilization system. For this purpose the neighboring transition $|F=3, m_F=1> \leftrightarrow |F=4, m_F=1>$ is used. The method of C-field adjustment is similar to the method of frequency adjustment to the main maximum [1–2].

In this case, the effects, associated with magnetic field changes, such as long-term drift of the current source, temperature dependence, effect of external magnetic field, etc., are excluded.

Experimental research of quantum frequency standards with two new functional blocks includes measuring of the output signal frequency and calculation of Allan variance, which allows to evaluate the frequency instability.

Time dependencies of Allan variance for previously used cesium atomic clock (1) and cesium atomic clock with new frequency synthesizer and new magnetic field control unit (2) are presented in fig.2.

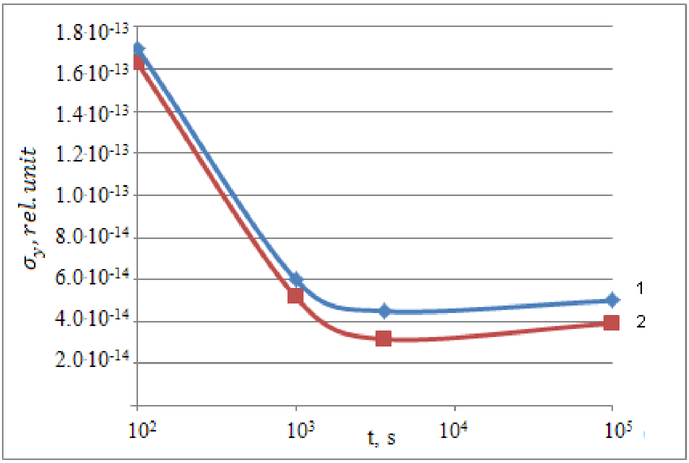

Fig.2. A plot of Allan variance vs time for cesium atomic clock (1) and cesium atomic clock with new frequency synthesizer and new magnetic field control unit (2).

From these results it is clear that the use of new design of the frequency synthesizer and system for stabilizing magnetic field makes it possible to obtain better frequency stability of quantum frequency standard. A pure spectrum of the frequency synthesizer output signal and best resolution of frequency step improved short-term frequency stability. System for stabilizing magnetic field eliminated one of the most important perturbing factors affecting on main metrological characteristic of cesium atomic clock.

Conclusion

Experimental research of the cesium atomic clock with new design of frequency synthesizer and system for stabilizing magnetic field showed the improvement in main metrological characteristic, being the long-term frequency stability, by about 10%.

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