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Modernization of quantum frequency standard with optical pumping

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Abstract. The development of information transmission systems, satellite navigation systems, metrological service systems lead to the need for constant modernization of the currently used quantum frequency standards (QFS). In radar systems, frequency standards determine the synchronism of work on moving objects. A small frequency deviation from the nominal value leads to large errors, especially when transmitting large data streams. The article presents a method for upgrading QFS in order to improve short-term stability. Experimental studies of the metrological characteristics of QFS with laser optical pumping have shown the effectiveness of the new development. The practical significance of the work lies in the development of an assembly device and the substantiation of new methods for improving the metrological characteristics of QFS. The proposed method for improving the frequency standard can be used for further research in the field of frequency standards. It also found an improvement in metrological characteristics, such as daily frequency stability of the output signal of the frequency standard, by 25%.

Keywords: time scale, stabilization, automatic frequency control, frequency stabilizer, cesium frequency standard, operational amplifier, remote sensing spacecraft, atomic beam tube

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Модернизация квантового стандарта частоты с оптической накачкой

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Аннотация. Развитие систем передачи информации, систем спутниковой навигации, систем метрологического обслуживания приводит к необходимости постоянной модернизации используемых в настоящее время квантовых стандартов частоты (КСЧ). В радиолокационных системах стандарты частоты определяют синхронность работы по движущимся объектам. Небольшое отклонение частоты от номинального значения приводит к большим ошибкам, особенно при передаче больших потоков данных. В статье представлен метод модернизации КСЧ с целью повышения кратковременной стабильности. Экспериментальные исследования метрологических характеристик КСЧ лазерной оптической накачкой показали эффективность новой разработки. Практическая значимость работы заключается в разработке нового устройства и обосновании методов улучшения метрологических характеристик КСЧ. Предлагаемый метод усовершенствования стандарта частоты может быть использован для дальнейших исследований в области стандартов частоты. Также установлено улучшение метрологических характеристик, таких как суточная стабильность частоты выходного сигнала стандарта частоты на 25%.

Ключевые слова: шкала времени, стабилизация, автоматическая подстройка частоты, стабилизатор частоты, цезиевый эталон частоты, операционный усилитель, космический аппарат дистанционного зондирования Земли, атомно-лучевая трубка

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Introduction

Various academic studies of the last decades have made it possible to make quantum frequencies standard the basis of highly stable, precise, spectrally purest electrical signals [1–7]. The obtained accuracy, as well as frequency stability, made it possible to effectively use QFS as synchronizing generators in communication technology, as well as data transmission devices, and, in addition, to use them as signal sources in radio measuring equipment [6–11].

At present, the world does not stop improving the use of satellite navigation systems (SNS) in various fields of human activity [1–3, 6, 10–13].

Over the past 10 years, the GLONASS SNS has been rapidly developing in the Russian Federation, and as practice shows, it has a high location accuracy and is highly competitive compared to American, European and Chinese systems [1–3, 10–17]. The continuous expansion of the range of tasks, the solution of which should be provided by the SNS, requires both the development of new systems and the modification of existing ones. Also, with the development of technology, the composition of the radio-electronic means used is changing. All this requires constant modernization of the QFS [3, 6, 10, 11, 13–20].

Solving the problem of precision synchronization of reboarded time scales required the installation of highly stable synchronization devices on satellites. To improve the accuracy characteristics of the navigation system, in particular, when determining the position on a real scale, time, with an error of no more than 1 m, in addition to increasing the degree of reliability of its operation, it significantly depends on increasing the accuracy of the metrological characteristics of the QFS.

In order to solve this problem, the work of atomic clocks is being improved. The procedure for studying the newest type of QFS based on basic academic studies and putting them into practice is a rather lengthy process [13–17, 19–22]. Research and implementation require large financial resources, for this reason, in a number of cases, studies are being carried out to solve specific navigation problems in order to modernize single structures and blocks. This paper considers the modernization of the block of the automatic frequency control system using the input of a thermal compensation device.

Materials and Methods

In laser frequency standards, a suitable atomic, ionic or molecular transition is selected, in which a laser with a tunable wavelength is used to excite it. This helps to achieve the highest possible accuracy of the standard. The frequency standard with laser pumping on cesium-133 atoms works on the principle of adjusting the frequency of a quartz oscillator to the frequency of the cesium-133 atomic transition. To implement the noted frequency adjustment of the quartz oscillator, a microwave signal is applied to an atomic beam tube (ABT) filled with cesium-133 atoms [2, 3, 11, 17, 22].

The output signal of an atomic ray tube contains a stable part, as well as an unstable part, which characterizes the discrepancy between the signal and the average value of the error signal component. The frequency auto-tuning system creates a control voltage of magnitude, as well as polarity, which make it possible to compensate for the deviation of the actual (real) value of the frequency of the quartz oscillator relative to the value that corresponds to the frequency of the atomic transition of the ABT (5 MHz). Fig. 1 shows a QFS device with laser pumping.

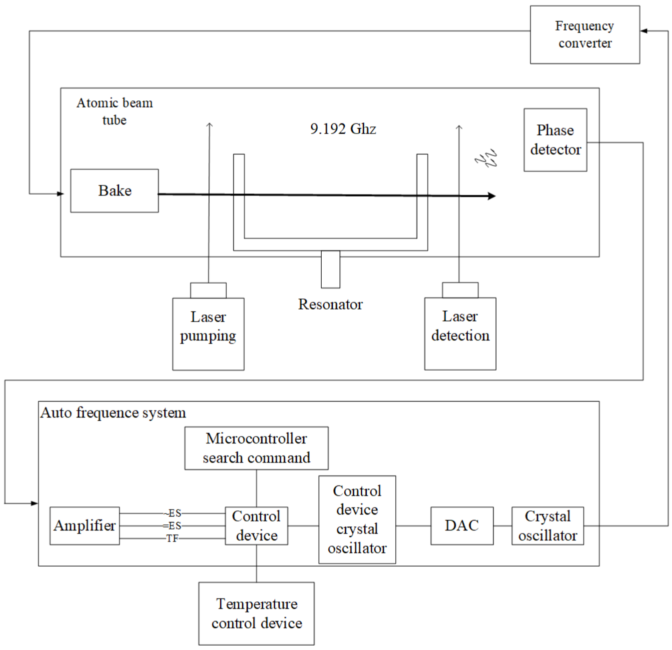

Fig. 1. QFS with laser pumping

After receiving the "Search" command, the (control device) CD begins to change from 0 to 255 the upper eight bits of the code transmitted via the serial interface to the CD crystal oscillator (CDXO). The output voltage of the CDXO is supplied to the varicap of the crystal oscillator (XO) frequency adjustment. Changing the voltage on the XO leads to a change in the frequency of the XO and, consequently, to a change in the frequency of the microwave signal at the input of the ABT, which in turn leads to a change in the voltage at the output of the ABT in accordance with the resonance curve. The voltage from the ABT output goes to the amplifier, where it is filtered and fed into the output circuit. The signal from the output of the amplifier goes to the input of the CD. In the process of rebuilding the code between the extreme values in the CD, the code value at which the signal voltage has the highest value is stored, and at the end of the code rebuilding cycle between the extreme values, the integrator automatically sets the stored code value.

After that, the CD switches to the auto frequency system ("AFS" mode), which is the main mode of operation of the product. The output voltage of the CD by a quartz oscillator is supplied to the varactor of the frequency adjustment of the crystal oscillator (XO). Changing the voltage on the varactor XO leads to a change in the frequency of the XO and also to a change in the frequency of the microwave signal at the ABT input. Further, this leads to a change in the voltage at the output of the ABT in accordance with the resonant curve.

The voltage supplied to the control unit in the automatic frequency control circuit, as well as the voltage supplied to the crystal oscillator, depends on the ambient temperature. These dependences lead to a mismatch in the frequencies of the microwave signal and the atomic transition, which leads to miscalculations in the matching of satellite time scales. Moreover, this process occurs regardless of whether the QFS uses highly stable laser radiation or a magnetic field to create a population inversion in ABT [2, 3, 11, 17, 22].

The modernization of this device allows improving the metrological characteristics of the entire QFS system, since the signal from this block is used in other functional devices, including frequency converters and frequency synthesizers that form microwave signals for the quantum discriminator. The properties of these signals directly affect the metrological properties of the QFS system.

The ambient temperature determines the voltage supplied to the control device in the automatic frequency control circuit, and, consequently, the voltage supplied to the crystal oscillator. This leads to a mismatch between the frequencies of the microwave signal and the atomic transition, which leads to errors in the matching of satellite time scales. Moreover, this process occurs regardless of whether the QFS uses highly stable laser radiation or a magnetic field to create a population inversion in ABT.

The following principle is implemented in the system developed by us. The ambient temperature directly affects the resistance of the thermistor and the output signal of the operational amplifier (op-amp), which is located in the automatic frequency control system. Depending on the design of the resistor, there is a different change in voltage with temperature.

The temperature control device is designed to generate a voltage range from 0.01 to 5.00 V at the output, proportional to the ambient temperature range from 0 °C to +50 °C. Due to the change in the resistance of the thermistor as part of the temperature control device due to temperature changes, the output voltage will depend on the ambient temperature.

The output voltage of the amplifier at a temperature of 0 °C is from 0.01 to 1.00 V, and at a temperature of +50 °C from 4 to 5 V.

Results and Discussion

According to the data obtained, the graph of the dependence of RMSD on time was recalculated. After ten days of testing, the value of the daily instability of the QFS decreased by $0.8 \cdot 10^{-14}$, that is, it improved by 25%. One of the main characteristics of the QFS is the Allan deviation.

Graphs 1 and 2 in Fig. 2 correspond to the AFS system previously used in QFS and developed by us. The results obtained show an improvement in the Allan deviation at a measurement time of 1-day $\sigma_y(t)$ by 25%. Studies of the work of the laboratory model of the QFS were carried out for 10 days in a temperature chamber. The experiments performed have shown the efficiency of using automatic frequency control systems with a thermal compensation device.

As a result, it can be seen that if the U(T) dependence goes into a non-linear form, auxiliary errors arise. In the new studied concept of auto-tuning of frequency, this error is eliminated.

The modernization of this device allows improving the metrological characteristics of the entire QFS system, since the signal from this block is used in other functional devices, including frequency converters and frequency synthesizers that form microwave signals for the quantum discriminator. The properties of these signals directly affect the metrological properties of the QFS system.

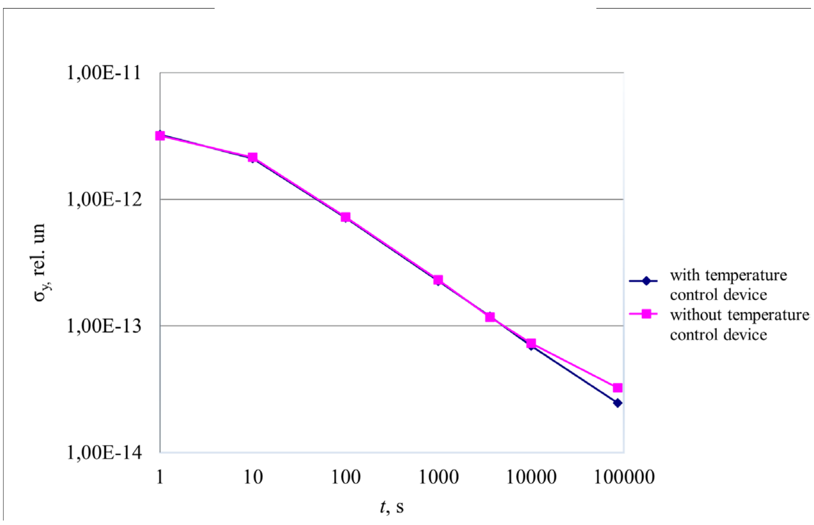

Fig. 2. Plot of Allan deviation σ_y versus time t

Conclusion

As a result of the development of a device for compensating the temperature coefficient of frequency, the temperature sensitivity has decreased by 6 times, which can improve the synchronization of the satellite time scale of the navigation system, while reducing the time scale matching error, which can reduce the geolocation error to meet new requirements.

The results obtained indicate an enhancement in the Allan deviation $\sigma_y(t)$ by 25%. The conducted experiments have shown the efficiency of using automatic frequency control systems with the thermal compensation device developed by us.

In addition, an improvement in metrological properties was determined in the role of daily frequency stability of the output signal of the frequency standard by 25%. The conducted studies demonstrate the effectiveness of the application of an automatic frequency control system with a thermal compensation device.

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