St. Petersburg Polytechnic University Journal. Physics and Mathematics. 2023. Vol. 16. No. 3.2
Научно-технические ведомости СПбГПУ. Физико-математические науки. 16 (3.2) 2023

Conference materials
UDC 53.06.
DOI: https://doi.org/10.18721/JPM.163.269

Improvement of the thermoregulator of the quantum frequency standard on rubidium-87 atoms

E.V. Isupova[1✉], S.Yu. Shvetsov[2], V.V. Davydov[1,3]

[1] Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia;

[2] Russian Institute of Radionavigation and Time, St. Petersburg, Russia;

[3] The Bonch-Bruevich St. Petersburg State University of Telecommunications, St. Petersburg, Russia

✉ isupova.e24@mail.ru

Abstract. The necessity of increasing the metrological characteristics of the quantum frequency standard on rubidium-87 atoms is substantiated. It is noted that the main destabilizing factor that reduces the accuracy of frequency determination is temperature. To control it, the quantum standard uses thermostating and thermoregulation. It is established that the systems currently used for laser and optical components cannot provide the necessary temperature stability, which is required to improve the metrological characteristics of the quantum standard. A new circuit of a quantum frequency standard temperature controller with a rubidium gas cell using a PID controller and an instrument amplifier has been developed, and its operation in the LTspice environment has been simulated. Transient processes in the circuit of the thermostat are analyzed. A decrease in the influence of temperature on the optical components and characteristics of the laser in the quantum frequency standard has been established (the signal—to-noise ratio in the recorded optical signal has increased), which, in turn, improves the short-term stability of the QFS frequency by 7-10%, synchronization of time scales in the satellite navigation system, increases the accuracy of determining the coordinates of the object.

Keywords: thermoregulation, thermostating, quantum frequency standard with rubidium gas cell, feedback, power amplifier, stability, differential amplifier, PID controller

Citation: Isupova E.V., Shvetsov S.Yu., Davydov V.V., Improvement of the thermoregulator of the quantum frequency standard on rubidium-87 atoms, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (3.2) (2023) 394—399. DOI: https://doi.org/10.18721/JPM.163.269

Материалы конференции
УДК 53.06.
DOI: https://doi.org/10.18721/JPM.163.269

Усовершенствование терморегулятора квантового стандарта частоты на атомах рубидия-87

Е.В. Исупова[1✉], С.Ю. Швецов[2], В.В. Давыдов[1,3]

[1] Санкт-Петербургский Политехнический университет Петра Великого, Санкт-Петербург, Россия;

[2] Российский институт навигации и времени, Санкт-Петербург, Россия;

[3] Санкт-Петербургский государственный университет телекоммуникаций
им. проф. М. А. Бонч-Бруевича, Санкт-Петербург, Россия

✉ isupova.e24@mail.ru

Аннотация. Представлена улучшенная схема терморегулятора квантового стандарта частоты с рубидиевой газовой ячейкой. Данный стандарт частоты является важной частью в спутниковых навигационных системах, так как обеспечивают точность и стабильность и определяют положение и скорость спутника. Для борьбы с основным дестабилизирующим фактором – температурой – в мерах частоты применяют термостатирование и терморегуляцию. Рассмотрена структурная схема терморегулятора, а также проведено моделирование принципиальной схемы в среде LTspice. Проанализированы переходные процессы в схеме и подобраны необходимые номинальные значения емкостей и сопротивлений.

Ключевые слова: терморегуляция, термостатирование, квантовый стандарт частоты с рубидиевой газовой ячейкой, обратная связь, усилитель мощности, стабильность, дифференциальный усилитель, ПИД-регулятор_

Ссылка при цитировании: Исупова Е.В., Швецов С.Ю., Давыдов В.В. Усовершенствование терморегулятора квантового стандарта частоты на атомах рубидия-87 // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 3.2. С. 394–399. DOI: https://doi.org/10.18721/JPM.163.269

Introduction

Space navigation systems largely depend on the generation of accurate time and frequency signals [1–3]. Global satellite navigation systems are the Russian Global Navigation Satellite System (GLONASS), the US Global Positioning System (GPS), the European System (Galileo) and the Chinese Navigation Satellite System (BeiDou). The widespread use of satellite navigation systems, which are used to determine the location of air, water and ground objects, would be difficult without the simultaneous development of frequency standards and synchronization methods [4, 5].

On board the satellites are atomic clocks that provide accuracy and stability and determine the position and speed of the satellite. The most widely used type of atomic clock is the quantum frequency standard with a rubidium gas cell [6].

One of the main factors impairing the frequency stability of the rubidium quantum frequency standard (QFS) is temperature. A change in temperature leads to a change in the values of the parameters of all elements. To combat the influence of temperature and its changes, QFS parts are made of heat-resistant materials with possibly small temperature coefficients [7–11]. In a wide range of ambient temperature determined by the operating conditions, this measure is not enough, so there is a need for the use of thermostating and thermoregulation.

The essence of thermostating is to provide for the entire circuit such a mode in which the average value and the change in temperature of the medium surrounding the thermostated object, as well as the change in heat flows in this medium are so small that they lead to changes in the generated frequency, significantly less than permissible [6].

These conditions are created with the help of special devices, thermostats, which ensure the constancy of temperature in a closed volume with a certain degree of accuracy of its maintenance.

Table 1 shows the main characteristics of the maximum deviations in temperature stability for different temperatures in the blocks of the quantum frequency standard.

Analysis of the developments has shown that it is quite difficult to solve the problem of thermal stabilization in various blocks of QFS on rubidium 87 atoms using these devices. This is due to the fact that quantum standards used on mobile objects have strict limitations both in mass and size. In addition, there are restrictions on the possible increase in electrical energy consumption during the modernization of the structure.

All these restrictions cannot be met when using the design of the thermoregulators presented in Table 1. Therefore, based on the analysis of modern developments, it is necessary to modernize the current design of the thermostat while maintaining the size of the unit in which it is installed, the characteristics of weight and energy consumption. One of the possible solutions to this problem is presented in the work.

Table 1

Comparative analysis of various developments of thermoregulators to compensate for temperature surges

Developers of thermoregulators	T_{max}, K	Obtained stability, uK	Scope of use
Bonetti	348	±500	communication base stations, guidance systems, precision measurements
Dratler	308	±10	radars, satellites
Esman	300	±100	precision measurements, radars, satellites, atomic clocks
Lee	296	±60	global positioning, telemetry, guidance systems
Sarid	333	±15	atomic clocks, communication base stations, telemetry
Grubic	320	±40	precision measurements, radars, satellites
Larsen	301	±25	global positioning, atomic clocks, telemetry
Harvey	301	±25	global positioning, atomic clocks, telemetry

Method of constructing and modeling the operation of the thermostat

In most cases, thermistor temperature sensors are used in the rubidium QFS thermostat in operation, since they are sensitive, small and have fairly good stability. To ensure good performance, the sensors must have good thermal contact with the thermostat, as well as avoid any mechanical influences.

The classical design of the thermoregulator used in the rubidium QFS is shown in Fig. 1.

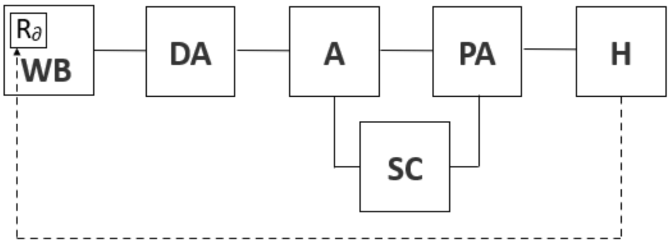

Fig. 1. Block diagram of the thermostat: temperature sensor R_∂, Wheatstone Bridge WB, differential amplifier DA, amplifier A, power amplifier PA, heater H, stabilizing circuit SC

One of the schemes suitable for temperature measurement is the Wheatstone Bridge with a temperature sensor used as one of the branches of the bridge. This sensor generates a signal proportional to the temperature value. Fig. 2 shows a diagram of the Wheatstone bridge, and the place where the sensor is switched on is marked.

Then the signal goes to the amplifiers, which are necessary to increase the sensitivity of the temperature control system and provide the power required for the operation of the executive bodies. In this case, the signal passes through the feedback – the stabilizing circuit. The output of the power amplifier is controlled by the currents that flow to the heater. It, in turn, is connected by temperature feedback to the sensor.

The main disadvantages of this scheme are the large error in reading temperature data, the slow reaction of the bridge to unbalance with fast flow effects, which often occur in outer space.

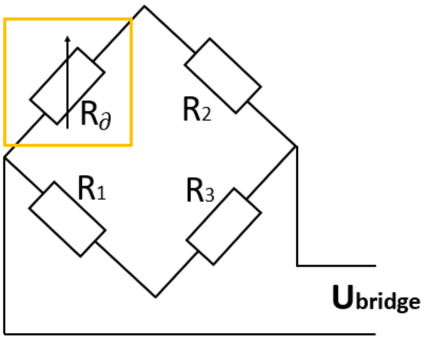

Fig. 2. Wheatstone bridge with temperature sensor

Therefore, we have developed a new design of the thermostat. In this scheme, instead of an amplifier block, a proportional-integral-differentiating (PID) regulator block will be used, which allows for a higher level of regulation. A control signal is generated in this device to obtain the necessary accuracy and quality of the transient process. The scheme of the developed PID controller is shown in Fig. 3.

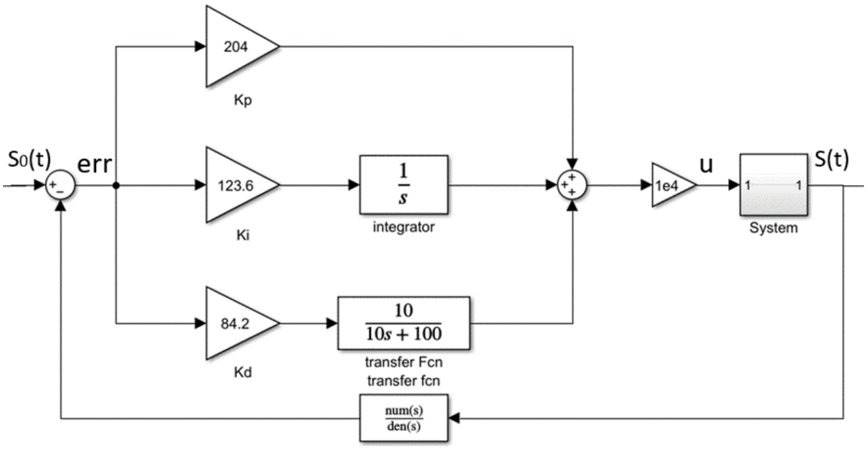

Fig. 3. Scheme of the developed PID controller

Also, an instrumental amplifier built on three operational amplifiers is introduced into the new circuit of the thermostat. The instrumental amplifier is a high-precision device for amplifying differential voltages, which is suitable for operation in conditions of high noise and strong temperature fluctuations. This device has a high input impedance, which allows to work with sensors with a large output impedance.

Results and Discussion

In the new design of the thermostat, in order to improve the stability of the entire QFS, the cascade of the power amplifier with a feedback chain was upgraded. In the LTspice environment, the schematic diagram of the new and old temperature controller is assembled. Transient processes at the output of the power amplifier are simulated. Fig. 4 shows its results.

Capacitances and resistances are selected in such a way that the output voltage located in the power amplifier unit instantly reacts to a single voltage surge at the input of the circuit, and the oscillatory processes after this surge are minimal.

Fig. 5,*a* shows the results of a study of changes in the resistance of a temperature sensor depending on the temperature of the air in the heat chamber for the old circuit of the thermostat in the discriminator. The temperature in the thermal chamber changed every 4 hours. The change in the resistance of the thermistor was about 3 ohms, which is unacceptable for a thermostat in the QFS. Fig. 5,*b* shows the simulated results of the same experiment for the new circuit of the thermostat.

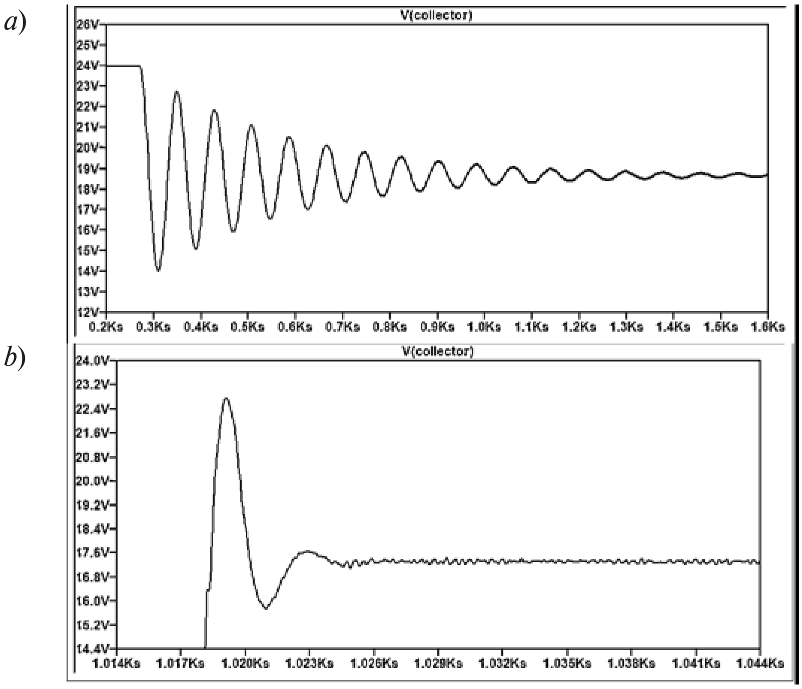

Fig. 4. Simulation results: transients in the old scheme (*a*); transients in the new scheme (*b*)

In the newly developed design, the sensitivity of the resistance to temperature changes is ≈ 1 ohm. The scheme works out the temperature change more quickly. The use of a PID controller in the design of the thermostat allows you to increase the speed in the thermal stabilization system by 65% compared to the previously used design.

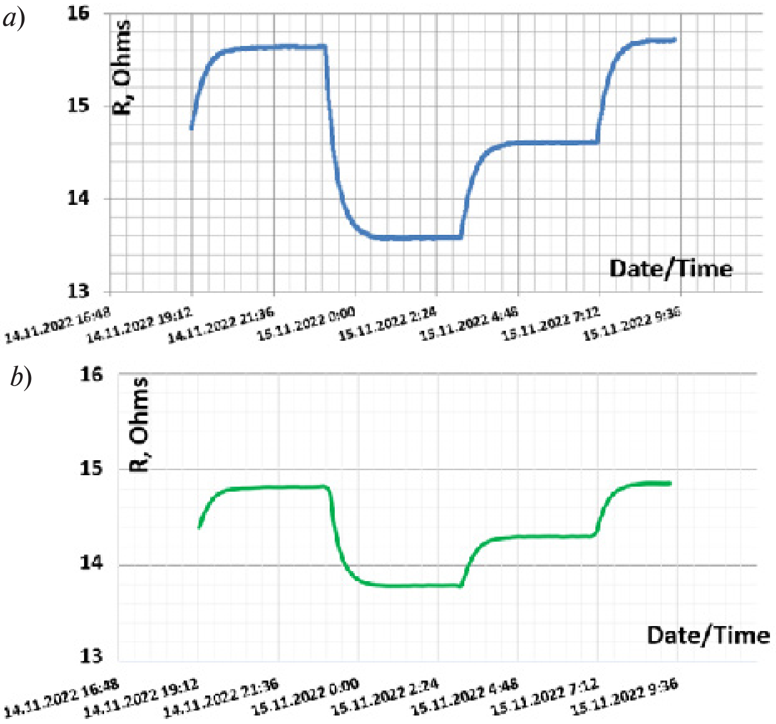

Fig. 5. Changing the resistance of the thermistor in the thermal chamber (*a*); simulation of changes in the resistance of the thermistor in the new circuit of the thermostat (*b*)

Conclusion

Analysis of data on the operation of temperature control systems in various models of QFS on rubidium–87 atoms with an optical gas cell and the results of modeling the thermostat circuit showed that the new implementation scheme works correctly, the introduction of a PID controller and an instrument amplifier instead of the previously used transistor power amplifier stage improves the operation of the thermostat. The threshold for changing the resistance of the thermistor in the Wheatstone bridge ≈ 1 Ohm allows to improve the signal-to-noise ratio of the recorded optical signal at least twice. This improves the short–term stability of the QFS frequency by 7–10%, synchronizes the time scales in the satellite navigation system and increases the accuracy of determining the coordinates of the object. The conducted experiments have shown the effectiveness of using a new circuit of the thermostat.

REFERENCES

1. **Petrov A., Davydov V. and Grebenikova N.,** Journal of Communications Technology and Electronics 63(11) (2018) 1159–1164.
2. **Lukashev N.A., Davydov R.V., Glinushkin A.P., Rud' V.Y.,** Improving characteristics of microwave frequency standard on Hg-199 ions for telecommunication systems Journal of Physics: Conference Series. 1326(1) (2019) 012046.
3. **Riehle F.,** Frequency standard. Basic and applications, WILEY-VCH Verlag CmbH Co. KGaA: New-York (2008).
4. **Riley W.J.,** Rubidium Frequency Standard Primer, W.J. Riley –Hamilton Technical Services Beaufort (2011) 149.
5. **Riley W.J.,** A Modern Militarized Rubidium Frequency Standard, Microwave Journal (2002).
6. **Daniel A. Steck.,** Rubidium-87 D Line Data, Los Alamos National Laboratory Technical report LA-UR-03-8638 (2001).
7. **Dupuis R.F., Lynch T.J., Vaccaro J.R.,** Rubidium Frequency Standard for the GPS IIF Program and Modifications for the RAFSMOD Program, Proceedings of the 2008 IEEE International Frequency Control Symposium, Honolulu, HI (2008) 655–660.
8. **Lutwak R., Emmons D., English T., Riley W., Duwel A., Varghese M., Serkland D. K., Peake G.M.,** The Chip-Scale Atomic Clock - Recent Development Progress, Proceedings of the 35th Annual Precise Time and Time Interval (PTTI) Applications and Planning Meeting, San Diego, CA (2003).
9. **Arinushkina K., Valov A., Isupova E.**, Improvement of the frequency standard on cesium atoms used in spacecraft for remote sensing of the Earth, in. Proceedings of 8th International Conference on Information Technology and Nanotechnology (ITNT), Samara, Russian Federation. (21992028) (2022) 20302.
10. **Huang X., Xia B., Zhong D., An S., Zhu X., Mei G.,** A Microwave Cavity with Low Temperature Coefficient for Passive Rubidium Frequency Standards, Proceedings of the 2001 IEEE International Frequency Control Symposium (2001) 105–107.
11. **Zhu H.B., Wu Z.B., Liu G.Q.,** Study of quartz temperature characteristics for precise oscillator applicationsr, Acta. Phys. SinCh Ed, (62 014205) (1) (2013).

THE AUTHORS

ISUPOVA Ekaterina V.
isupova.e24@mail.ru
ORCID: 0000-0002-0963-5497

SHVETSOV Sergey Yu.
shvetsov0000@gmail.com
ORCID: 0000-0001-6849-1481

DAVYDOV Vadim V.
davydov_vadim66@mail.ru
ORCID: 0000-0001-9530-4805

Received 10.07.2023. Approved after reviewing 09.08.2023. Accepted 11.08.2023.