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Development of automatic gain control for atomic frequency standard on rubidium-87 atoms

A. V. Shavshin [1]✉, V. V. Davydov [1, 2, 3]

[1] Peter the Great St. Petersburg Polytechnic University, St. Petersburg , Russia;
[2] Bonch-Bruevich Saint Petersburg State University of Telecommunications, St. Petersburg , Russia;
[3] All-Russian Research Institute of Phytopathology, Moscow Region, Russia
✉ shavshin2107@gmail.com

Abstract. The necessity of upgrading the optical path of the atomic frequency standard based on rubidium-87 atoms is substantiated. A new scheme for automatic gain control in the optical path of an atomic frequency standard based on rubidium-87 atoms is presented. The amplifier of the error signal formed on the photodetector for controlling the microwave signal is considered in detail. Experimental studies of the metrological characteristics of an atomic frequency standard based on rubidium-87 atoms with automatic gain control are presented. The validity of the developed automatic amplification scheme for the new frequency standard based on rubidium-87 atoms is confirmed.

Keywords: time scale, stabilization, automatic frequency control, rubidium frequency standard, gain control, operational amplifier, Allan dispersion

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Материалы конференции
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Разработка автоматической регулировки усиления для квантового стандарта частоты на атомах рубидия-87

А. В. Шавшин [1]✉, В. В. Давыдов [1, 2, 3]

[1] Санкт-Петербургский политехнический университет Петра Великого, Санкт-Петербург, Россия;
[2] Санкт-Петербургский государственный университет телекоммуникаций
им. проф. М. А. Бонч-Бруевича, Санкт-Петербург, Россия;
[3] Всероссийский научно-исследовательский институт фитопатологии, Московская область, Россия
✉ shavshin2107@gmail.com

Аннотация. Обоснована необходимость модернизации оптического тракта квантового стандарта частоты на атомах рубидия-87. Представлена новая схема автоматической регулировки усиления в оптическом тракте квантового стандарта частоты на атомах рубидия-87. Подробно рассмотрен усилитель сигнала ошибки, формируемого на фотоприемнике для управления СВЧ-сигналом. Представлены экспериментальные исследования метрологических характеристик квантового стандарта частоты на атомах рубидия-87 с автоматической регулировкой усиления. Подтверждена правомерность разработанной схемы автоматического усиления для нового стандарта частоты на атомах рубидия-87.

Ключевые слова: шкала времени, стабилизация, автоматическая подстройка частоты, рубидиевый стандарт частоты, регулировка усиления, операционный усилитель, дисперсия Аллана

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Introduction

At present, with the advent of new technologies, the need for accurate measurement of frequency and time is the most relevant topic in various areas of life [1–8]. In this case, it is necessary to divide the requirements for ensuring the accuracy of determining time and frequency into several areas [8–12]. The maximum accuracy of determining the frequency and time is extremely important when conducting scientific experiments and in spacecraft used in satellite navigation [13-20]. Atomic frequency standards are one of the main instruments that can provide the greatest accuracy in determining time and frequency [2, 3, 6, 11, 14–18, 20–25]. When used in navigation, they provide synchronization of satellites with each other or synchronization of a satellite with base stations on Earth [20–29]. At present, a large number of AFS models for space applications have been developed [20–35]. One of them is the atomic frequency standard on rubidium atoms-87 [21, 23, 24, 29, 31, 35, 36].

Similar frequency standards are used in GLONASS and GPS systems as synchronizing generators, as well as on moving objects in the earth's atmosphere. Performing accurate synchronization in satellite systems has a number of difficulties associated with both the features of the operating environment and the autonomy of the object itself. One of the main factors affecting the accuracy is the system errors introduced by the equipment of the space complex. This leads to errors in the formation of a signal from a highly sensitive photodetector after registration of optical radiation. These errors need to be compensated.

One of the elements of their elimination is automatic gain control (AGC) for the rubidium frequency standard. When the ambient temperature or other external influence changes, the output characteristic of the frequency standard without the AGC system changes. This change must be compensated to ensure stable operation of spacecraft systems. The paper considers the development of a new AGC system, which is necessary to modernize the design of AFS based on rubidium-87 atoms under the conditions of changing its operation in a spacecraft and new tasks when conducting sounding of the Earth's surface.

Atomic frequency standard based on rubidium-87 atoms and an automatic gain control system

The principle of operation of rubidium frequency standards lies in the resonant absorption of microwave electromagnetic waves in the beam of a rubidium atom; therefore, it is called a passive atomic standard [21, 31, 35]. A passive atomic frequency standard is a standard in which the frequency of absorption of electromagnetic waves of one of the energy transitions of atoms is used as a reference. The passive standard uses an atomic discriminator as a stabilizer. Atomic generators as part of frequency standards produce signals with a low output power, so they are first amplified using a microwave receiver. And only then stabilize the frequency of the quartz oscillator. Fig. 1 shows the automatic gain control circuit we developed to solve this problem.

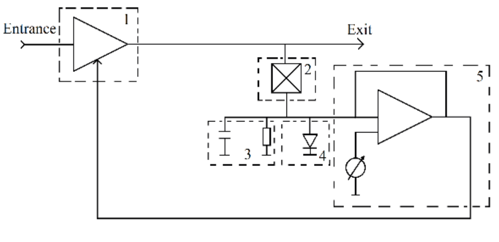

Fig. 1. Scheme of automatic gain control: voltage amplifier *1* of the microwave signal on a field-effect transistor; directional coupler *2*; low-pass filter *3*; detector diode *4*; 'error' signal amplifier *5* to control the power supply of the field effect transistor, the first amplifier

A voltage-attenuated signal is supplied to the input of the circuit, which must be amplified so that the total signal power at the system output is 20 μW. The signal is preliminarily amplified in *1* in a FET circuit. Further, to generate an 'error' signal, part of the signal passes through a directional coupler *2* to the power control circuit of the field-effect transistor of the first amplifier, and part of the signal goes to the system output. Then it is necessary to detect the future ‘error’ signal in order to obtain the DC component of the signal. For these purposes, a detector microwave diode *4* will be used. After detection, the signal will have a different amplitude in different cases, so it is necessary to be able to adjust its amplitude to the level we need. To do this, use the ‘error’ signal amplifier on the operational amplifier *5*.

Calculation of the elements of the automatic gain control system

In the simplest case, a directional coupler on coupled microstrip lines is an eight-terminal network consisting of two parallel microstrip lines, the electrical length of which is equal to a quarter of the excitation wavelength Fig. 2.

Such a coupler has two planes of symmetry, so the calculation of the bridge elements and the scattering matrix takes the following form:

$$1/Z_{\hat{A}2}^2 - 1/Z_{\hat{A}1}^2 = 1,\ s_{ii} = 0,\ s_{14} = s_{32} = 0,$$

$$s_{21} = -jZ_{B2},\ s_{31} = -Z_{B2} / Z_{B1},$$

$$|s_{21}| = |s_{31}| \Rightarrow Z_{B2} = \frac{Z_{B2}}{Z_{B1}} \Rightarrow Z_{B1} = 1 = Z_0 = 1 \text{ Ohm},$$

$$Z_{Bi} = \frac{Z_{Bi}}{Z_0};\ 1/Z_{B2}{}^2 - 1/Z_{B1}{}^2 = 1 \Rightarrow 1/Z_{B2}{}^2 = 2 \Rightarrow$$

$$\Rightarrow Z_{B2} = \frac{1}{\sqrt{2}} = \frac{Z_0}{\sqrt{2}} = 0.707 \text{ Ohm}.$$

Let us compose the scattering matrix for the directional coupler

$$S = \frac{1}{\sqrt{2}} * \begin{pmatrix} 0 & 1 & -\mathrm{j} & 0 \\ 1 & 0 & 0 & -\mathrm{j} \\ -\mathrm{j} & 0 & 0 & 1 \\ 0 & -\mathrm{j} & 1 & 0 \end{pmatrix}.$$

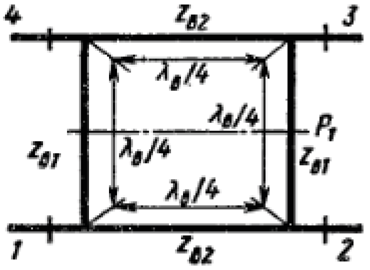

Fig. 2. Microstrip directional coupler

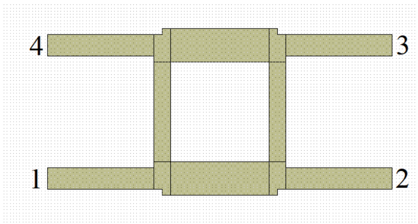

Fig. 3. Microstrip directional coupler topology

To synthesize the required directional coupler, you need to calculate its dimensions for a signal of a specific frequency. In our case, the directional coupler will be synthesized for a frequency of 6.834 GHz. Fig. 3 shows the topology of a microstrip directional coupler. To create a bridge, the following elements were used: MLIN to simulate microstrip lines, MTEE to implement separation into two channels.

Further, we obtain the final parameters of the microstrip directional coupler (Fig. 4).

As can be seen from the graphs, the directional coupler was successfully synthesized at -3 dB at 6.834 GHz. Fig. 5 shows a graph of the phase-frequency response of a directional coupler.

The obtained results of tuning the directional coupler and its phase-frequency characteristic completely satisfy the set requirements. On the phase-frequency characteristic graph, we can observe that the phase between outputs 3 and 2 differs by 90° (taking into account the allowable error), which indicates the correct setting of the directional coupler.

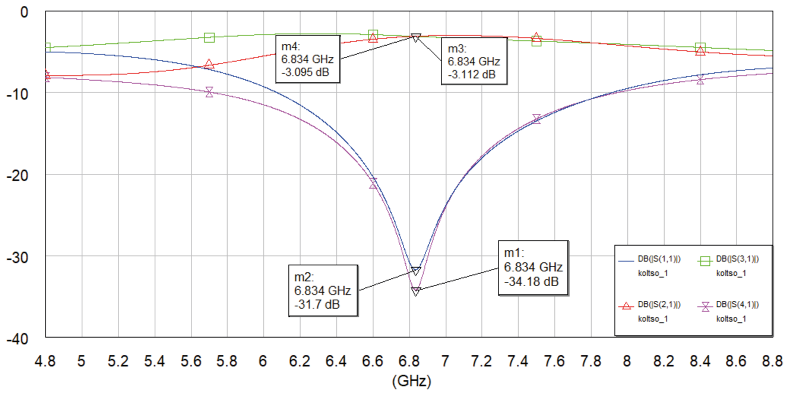

Fig. 4. Final parameters of the microstrip directional coupler

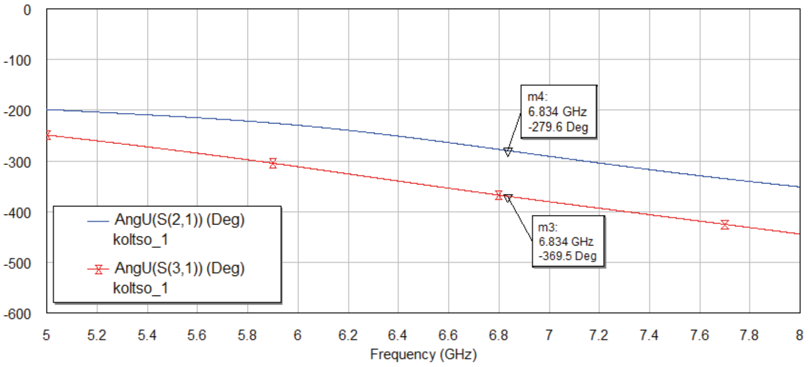

Fig. 5. Phase-frequency response of a directional coupler

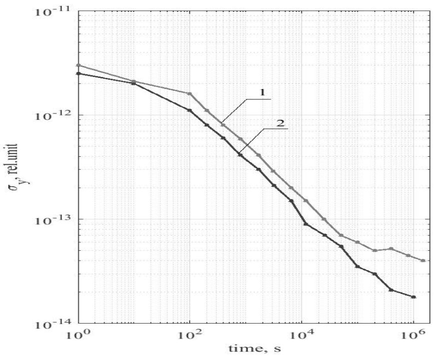

Fig. 6. Dependence of the change on the Allan variance

Graphs 1 and 2 correspond to QSC using the old system and the new AGC system

Results of experimental studies of the characteristics of the quantum frequency standard

As an example, the paper presents the results of a study of the characteristics of AFS in the temperature range from 253 to 308 K in accordance with the possible technical conditions for the operation of the device. The AGC prototype was included in the composition of the AFS, the output characteristics of which were measured. After processing the obtained data, plots of the dependence of the values of the Allan variance σ(τ) on time τ were plotted for the modernized and previous AFS designs (Fig. 6).

The results obtained show an improvement in the Allan variance σ(τ) by 12%. Studies of the work of AGC were carried out for 12 days in a heat chamber.

Conclusion

The results of the analysis of the operation of the prototype AFS with the new AGC system showed that there was no malfunction due to a low signal level at the input of the frequency converter. This confirms the adequacy of the AGC design scheme proposed by us.

In addition, it was found that the introduction of an automatic gain control system improves the output characteristics of the frequency converter, which affects both the Allan dispersion value and the long-term frequency value (LFC).

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THE AUTHORS

SHAVSHIN Artyom
shavshin2107@gmail.com
ORCID: 0000-0002-3597-8901

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

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