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Improving microwave output in rubidium-87 atomic frequency standard with new automatic gain control

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Abstract. It's necessary to upgrade the existing scheme automatic control of the optical signal. The presented design was created to maintain the output power of an atomic frequency standard (AFS) based on rubidium-87 atoms at a given level, correcting changes in its operation introduced by external conditions. An improved circuit for automatic gain control with an additional link in the form of a proportional-integral-derivative (PID) controller and an improved circuit for extracting the 'error' signal are presented. A separate contribution of the subtractor and PID controller to the final gain control is considered, and mathematical modeling of microwave devices included in the microwave path is carried out.

Keywords: optical signal, atomic frequency standard, automatic gain control, optical pumping, stimulated emission, error signal, PID controller, Allan deviation

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Материалы конференции
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Улучшение выходной мощности квантового стандарта частоты на атомах рубидия-87 с помощью новой автоматической регулировки усиления

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Аннотация. Обоснована необходимость модернизации существующей схемы автоматической регулировки оптического сигнала. Представленная конструкция создана для поддержания выходной мощности квантового стандарта частоты (КСЧ) на атомах рубидия87- на заранее заданном уровне, корректируя изменения в его работе, вносимые внешними условиями. Представлены усовершенствованные схемы автоматической регулировки усиления (АРУ) с дополнительным звеном в видео пропорционально-интегрального-дифференциального (ПИД) регулятора, и схема выделения «сигнала ошибки». Рассмотрен отдельный вклад системы выделения «сигнала ошибки» и ПИД-регулятора на конечную регулировку усиления, а также выполнен математических расчет СВЧ-компонент, входящих в СВЧ-тракт.

Ключевые слова: оптический сигнал, квантовый стандарт частоты, автоматическая регулировка усиления, оптическая накачка, вынужденная эмиссия, сигнал ошибки, ПИД-регулятор, девиация Аллана

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Introduction

In the modern world, quantum frequency standards are indispensable sources of highly stable, spectrally pure electrical signals to consider more in-depth topics in the scientific and technical fields [1–6]. There are areas in which they cannot be dispensed with [7–11]. Special requirements are imposed on atomic frequency standards (AFS), which are used in navigation systems, and common time systems [2, 8, 10, 12–14]. One of such AFSs are standards based on rubidium-87 atoms [1, 2, 8]. Considering more stringent conditions for accuracy and stability of the output optical signal formation, it becomes necessary to modernize the AFS or develop new types of AFS based on other physical principles of operation. To carry out work to improve the accuracy characteristics of the AFS, in some cases it is sufficient to upgrade the functional units that directly affect total output values of the AFS. Thus, this paper presents the modernization of the path for the formation of the microwave signal of the excitation of rubidium-87 atoms, aimed at the formation of both the microwave signal itself and the parameters of the AFS output signal. Similar situations arise for other types of standards.

Updated atomic frequency standard circuit and system of automatic gain control with additional adjustment elements

During the analysis of the block diagram of the quantum frequency standard based on rubidium-87 atoms, it was decided to make a number of adjustments to its general form. The modified scheme of the atomic frequency standard is shown on Fig. 1.

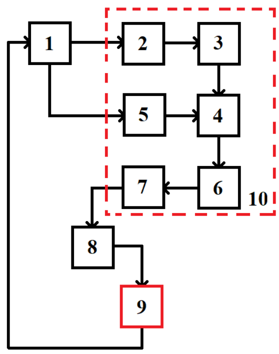

Fig. 1. Updated block diagram for the rubidium frequency standard: quartz oscillator *1*; phase locked loop (PLL) rings *2* and *3*; mixer *4*; frequency synthesizer *5*; automatic gain control *6*; attenuator *7*; quantum discriminator *8*; automatic frequency control system (AFC) *9*; frequency converter *10*

The block diagram shows the operation of AFS, based on the principle of stabilization of the frequency of a quartz oscillator by the transition frequency of rubidium-87 atoms. CFS on rubidium atoms is a passive type frequency standard. The output signal of a 5 MHz quartz oscillator is used in the microwave frequency generation path as follows [1, 2, 8]. Frequency of 5 MHz to signal is fed from a crystal oscillator to a phase locked loop (PLL), which consists of two subsystems. From the output of the first subsystem, a wave with a frequency of 100 MHz is generated, which is a reference for the second PLL subsystem. The output signal of the second system is a signal with a frequency of 6.8 GHz. At the same time, another signal comes from the quartz oscillator to the frequency synthesizer. The output signal of the frequency synthesizer is a frequency modulated signal with a frequency of 34.5 MHz. After that, both signals enter the mixer, at the output of which the exact frequency of the transition of the rubidium atom from one sublevel to another, equal to 6.834 GHz, is already formed. Next, the signal enters the automatic gain control (AGC) scheme, created to equalization the power level of the microwave signal with the same values. After the signal has stabilized thanks to the AGC system, it goes further to the attenuator. In our scheme, the final attenuator needed for the ending correction of the output microwave signal, which is then fed to the quantum discriminator.

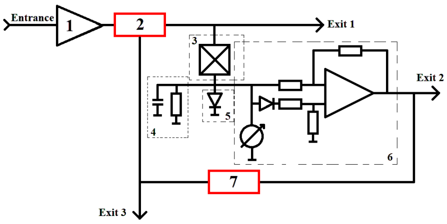

Fig. 2. Upgraded automatic gain control circuit, with the addition of a PID controller section; attenuator *2*; directional coupler *3*; low-pass filter *4*; detector diode *5*, 'error' signal amplifier *6* connected as a subtractor; PID controller *7*

As can be seen from the presented description of the operation of the AFS, the AGC system is one of the most important functional units of the microwave generation path and the entire structure of the AFS. Fig. 2 shows a modernized circuit diagram of the AGC system.

Since the input of the system receives a signal of insufficient power. The initial task is to strengthen it so that its power is captured for the work of combating discrimination. To fulfill this condition, an amplifier was integrated (1). Then attenuator (2) will be used as a controlled element, due to the adjustment of which the output power of the signal will be adjusted. To create an 'error' control signal, a portion of the original signal is applied to the AGC circuit using a directional coupler set to -3dB. (3) and the rest of the signal passes at the output of the system. Next, the 'error' control signal must be straightened for the AGC system to work. Therefore, the signal passed through the directional coupler will then pass through the detector diode. (4). After detection, the signal, depending on the external operating conditions of the AFS, can have a different amplitude, based on which there is a need to be able to set the level yourself. For this, an 'error' signal enhancer is used on the operational amplifier (5), connected according to the subtractor circuit. Further, the generated 'error' signal is fed to the input of the PID controller (7). Depending on the values coming to the proportional-integral-derivative (PID) controller, the necessary corrective gain is analyzed, which will be applied to the attenuator.

Modeling and calculation of individual parts of automatic gain control

Initially, a directional coupler can be described as two pairs of parallel microstrip lines, representing an eight-terminal network. It is important to note that the electrical length of such microstrip lines must be equal to 1/4 of the wavelength to which the coupler must be tuned, Fig. 3. In the diagram, the numbers 1—4 indicate the inputs and outputs of the microstrip directional coupler.

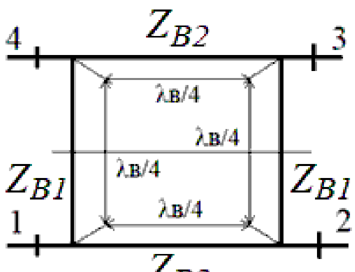

Fig. 3. Microstrip stub bridge

The calculation of such a microstrip directional coupler will look like this:

$$1/Z_{\hat{A}2}^2 - 1/Z_{\hat{A}1}^2 = 1,\ s_{ii} = 0,\ s_{14} = s_{32} = 0,$$
$$s_{21} = -jZ_{B2},\ s_{31} = -Z_{B2}/Z_{B1}.$$

Using the following well-known formulas [15], where in the calculations the unit wave impedance of a microstrip line Z_0 is taken as 1 Ohm, in our case we will take it as 50 Ohm. Next, we find the unknown parameters of the stub bridge.

The modular values of S_{21} and S_{31} will only be equal if Z_{B1} is equal to unit impedance. In our case, let us take it equal to 50 Ohms.

$$Z_{B1} = 50 \text{ Ohm},$$

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

In our case, the resistance Z_{B2} will take a value equal to 35.5 Ohms. Having completed all the calculated for a directional coupler, we obtain its final scattering matrix.

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

To model a directional coupler for a specific frequency, it is necessary to calculate it in Microwave Office with the given substrate parameters. In our case, the calculation will be performed for the Rogers RO4003C substrate at a frequency of 6.834 GHz. In the program to draw the model, using the MLIN element, a microstrip line was simulated, and the element MTEE was simulated the implementation of the separation of microstrip lines in two directions. Figs. 4 and 5 show calculated parameters and circuit of a new microstrip directional coupler.

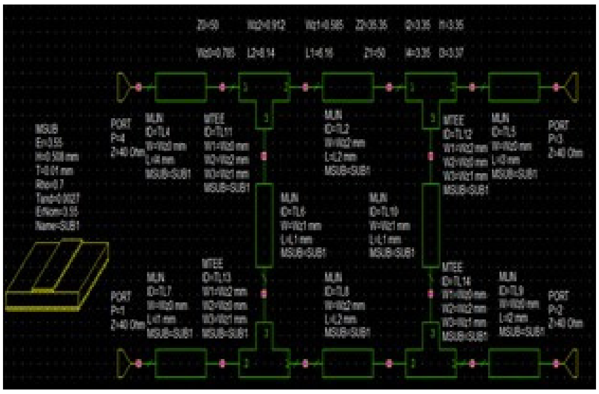

Fig. 4. Schematic view of a directional coupler in Microwave Office

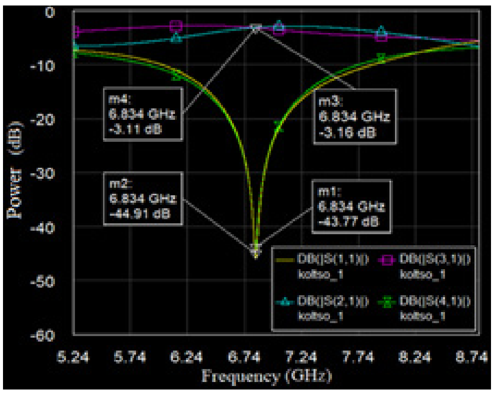

Fig. 5. Spectral power distribution in a new microstrip directional coupler design.
Decibels are plotted on the vertical axis

On the final characteristics of the spectral power distribution in the directional coupler, one can observe an improvement in performance by 10 dB, which is due to the correct choice of substrate and more precise tuning.

Analysis of experimental data

For illustration, in the work of this study, the results of the values of the QFS in the temperature range from −20 °C to 35 °C are given. Allan variance measurements $\sigma^2(\tau)$ are presented for three different AFS configurations: the first characteristic was taken without AGC, the second characteristic was taken using the old version of AGC, the third characteristic was taken using the new AGC configuration using a PID controller Fig. 6.

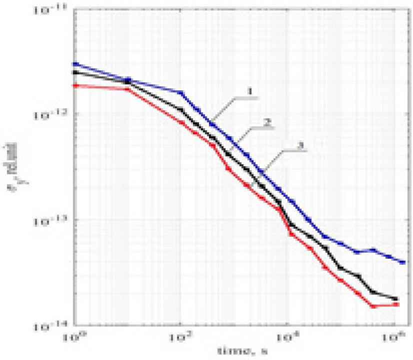

Fig. 6. Diagram of Allan variance versus time with an upgraded AGC system (graph 3), previously used (graph 2) and without the AGC system (graph 1) in AFS

Thanks to dispersion, it is possible to estimate the level of stability of the frequency of atomic clocks and generators. Analyzing the obtained results, we can make sure that the addition of the AGC system in the first case improved the Allan variance values $\sigma^2(\tau)$ by 12%, and with an additional link in the form of a PID controller, it showed an improvement by 16%.

Conclusion

Through a series of improvements, a new AGC system was implemented for the microwave path of the ASC based on rubidium-87 atoms using a PID controller. An improved directional coupler for a frequency of 6.834 GHz was configured on a new substrate, removed its characteristics, which turned out to be better than the previous model necessary for use in AFS.

After analyzing all the obtained results of the prototype AGC system, it can be seen that the output characteristics of the frequency converter have been improved. Thanks to the new AGC system, it was possible to achieve a decrease in the values of the Allan variance by 16%.

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