Features of the formation of the frequency of the microwave excitation signal in the quantum frequency standard on rubidium atoms - 87

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Abstract. The article discusses the main disadvantages of the current design of a quantum frequency standard based on rubidium-87 atoms. The main disadvantages of the current design of the quantum frequency standard on rubidium-87 atoms are considered. It is noted that the processes associated with light shifts in the optical part contribute to the greatest instability in the long-term operation of the quantum frequency standard. A solution is proposed to improve the design of the rubidium standard. A forecast for improving its metrological characteristics is presented. The results of experimental investigations are presented.

1. Introduction

In modern navigation systems, without determining the exact time and frequency, it is impossible to achieve the required accuracy in determining the coordinates [1-10]. Data on the coordinates of the object is necessary for solving problems of environmental monitoring, carrying out various works, etc. [10-19]. The operating satellite navigation constellations (Russian GLONASS, European GALILLEO, American (USA) GPS and Chinese BSD) actively use quantum frequency standards (QFS) to determine the exact time [1, 2, 8, 20-24]. Among quantum standards in satellite communication systems, rubidium QFSs are most widely used due to their small size and low cost in comparison with other types of standards [25-32].

At present, with the development of electronic equipment, the requirements for the accuracy of satellite navigation systems are constantly increasing, which makes the task of their modernization especially urgent [1, 2, 6, 7, 20-22, 31, 33]. Especially interesting are the areas of modernization using laser radiation, new models of photodetectors and additional feedback systems [34-39]. The modernization of frequency standards is no exception, this process includes changes in the dimensions and weight of the structure, as well as the improvement of metrological characteristics. It should be noted that for the QFS, modernization can be carried out not for its entire structure, but only for individual units [4, 8, 17, 25-29]. This paper discusses one of the possible solutions for modernizing the design of a quantum frequency standard based on rubidium-87 atoms.
2. Features of the formation of the microwave excitation signal in the design of the rubidium frequency standard

To date, domestic and foreign manufacturers successfully represent different models of QFS based on rubidium-87 atoms, however, the basic principles of operation remain unchanged [25-31]. Figure 1 shows a diagram of the current rubidium frequency standard (RFC).

The principle of the QFS operation is based on automatic tuning of the crystal oscillator (CO) frequency to the value of the quantum transition frequency in optically oriented Rb-87 atoms. For the optical orientation of rubidium - 87 atoms in satellite systems, a special pump lamp with a filter cell is used [25-31].

To implement the tuning of the CO frequency, the working cell of the atomic discriminator (DA) is irradiated with a microwave signal, the frequency of which corresponds to the frequency of the quantum transition of excited rubidium-87 atoms. In the case of a deviation of the frequency of the microwave signal from the value of the frequency of the resonant transition, an error signal (ES) is generated, according to which the CO is adjusted. Therefore, one of the important points in the functioning of the RFC is the formation of a microwave signal.

The formation of a microwave signal begins in a frequency converter (FC), which consists of a frequency multiplier (FM), a frequency synthesizer (FS), as well as amplifiers and a matching device (MD). The signal from the CO goes to the FM, converting it into a signal with a frequency of 60 MHz, and then fed to the FS, which generates signals of 5 and 5.313 MHz. Then the mixture of 60 and 5.313 MHz signals enters the MD to match the signals with the DA microwave multiplier diode. Inside the DA, a microwave diode multiplies the 60 MHz signal and separates the difference harmonic $f_{\text{diff}}$, determined by formula (1), the frequency of which coincides with the transition frequency of Rb-87 atoms.

$$f_{\text{diff}} = 60 \cdot 114 - 5,313 = 6834,7 \text{ MHz}$$

(1)

The method of forming a microwave signal, discussed in detail above, has the following disadvantages. The spectrum of the output signal with a frequency of 5.313 MHz contains side amplitude components. The presence of lateral components can lead to an error in establishing the value of the frequency of the output signal of the rubidium standard. Another disadvantage is that the final formation of the microwave signal occurs inside the atomic discriminator. The coincidence of the
frequencies of the optical quantum transition and the microwave signal can be judged only by indirect signs, namely, by the magnitude of the error signal, which is formed by the difference in the intensities of the recorded optical signals on the photodetector. Moreover, for different designs of photodetectors [34-36], there may be a small variation in values. For this reason, it was decided to modernize one of the RFS units.

3. Modernization a optical part to design of the rubidium frequency standard

In the new design of the RFC, the microwave signal with a frequency of 6834.7 MHz is proposed to be synthesized using a system of two ring phase-locked loop (PLL). The synthesis scheme is shown in Figure 2. The main elements of the PLL system are a phase detector (PD), one of the inputs of which is fed with a signal from a voltage-controlled oscillator (VCO). Another PD input is connected to a reference signal source with a frequency \( f_{\text{ref}} \). A phase detector compares the signals at both inputs and generates an error signal, which, after filtering and amplifying (if necessary), adjusts the VCO frequency. As part of the PLL system, a low-pass filter (LPF) is also used, which is connected between the output of the PD and the input of the VCO and determines its frequency properties.

![Figure 2](image.png)

The microwave signal is synthesized in two stages. The first loop of the PLL adjusts the VCO with an output frequency of 100 MHz. The main element of the first ring is a synthesizer microcircuit, which contains the following units: a prescaler, a main divider, a reference frequency divider, an input frequency amplifier, and also the main element - a phase-frequency detector. The principle of PD operation is shown in Figure (3). If the slave generator lags behind the reference, then the Down signal is generated in accordance with Figure (3.a), if the slave generator is ahead of the reference, then the Up signal is generated, in accordance with Figure (3.b), if the signals of the slave and reference oscillators coincide in frequency and phase, the Up Down signals are generated as shown in Figure (3.c).
Figure 3. Time diagrams of signals. a) The signals of the slave generator are lagging behind the signals of the reference generator, b) The signals of the slave generator are ahead of the signals of the reference generator, c) The signals of the slave and the reference generator are the same.

To obtain the required output frequency according to formula (2), the division factors of the reference and input frequencies are selected.

\[ f_{\text{in}} = \frac{f_{\text{ref}} \times K}{K_{\text{ref}}} \]  \hspace{1cm} (2)

where \( f_{\text{ref}} = 5 \text{ MHz} \) – is the frequency of the reference signal, \( K \) is the division factor of the input frequency, \( K_{\text{ref}} \) – is the division factor of the reference frequency, \( f_{\text{out}} \) – is the output frequency of the VCO.

After the formation of the required frequency of 100 MHz at the output of the first ring, the signal enters the second PLL ring, where it is used as a reference. In the second PLL, the VCO with an output frequency of 6.8 GHz is adjusted in a similar manner. At the same time, the implementation of the VCO with a PLL in the form of one compact module was chosen, which will reduce the weight and size characteristics.

To create an accurate value for the frequency of the quantum transition at the final stage, it is necessary to add a fractional component equal to 34.7 MHz to the output signal. Fractional part of 34.7 MHz is created using a special synthesizer. Further, the required signal of 6.8347 GHz is immediately fed to the atomic discriminator input, the microwave diode is excluded from the circuit.

The developed design of the RFS has several significant advantages. First, the use of an indirect synthesis method, namely a phase-locked loop system, allows a cleaner spectrum of the output signal to be obtained. Secondly, the formation of the microwave signal at all stages of the new circuit is controlled; it is possible to precisely adjust the signal frequency to the frequency of the quantum transition of rubidium-87 atoms. In the previous scheme, this was not realized, since the final formation of the microwave signal took place inside the atomic discriminator and the presence of resonance was judged by indirect signs.

4. Conclusion

The developed design of the QFS unit has a number of main advantages: first, a cleaner spectrum of the output optical signal arriving at the photodetector. Second, the possibility of direct control of the
microwave signal, and, consequently, its precise tuning to the resonant frequency of rubidium atoms. This makes it possible to reduce the error in establishing the actual value of the frequency of the output signal of the rubidium QFS, which improves the stability of the device.

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