Dependence of microwave-excitation signal parameters on frequency stability of caesium atomic clock

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Abstract. New scheme of the microwave – excitation signal for the caesium atomic clock is based on method of direct digital synthesis. The theoretical calculations and experimental research showed decrease step frequency tuning by several orders and improvement the spectral characteristics of the output signal of frequency synthesizer. A range of generated output frequencies is expanded, and the possibility of detuning the frequency of the neighboring resonance of spectral line that makes it possible to adjust the C-field in quantum frequency standard is implemented. Experimental research of the metrological characteristics of the quantum frequency standard on the atoms of caesium - 133 with new design scheme of the microwave – excitation signal showed improvement in daily frequency stability on $1.2 \times 10^{-14}$.

1. Introduction
Most of modern technologies based on the use of precision measuring instruments. The most accurate measurements are frequency measurements. Therefore, modernization of existing and development of new frequency generation devices are some of the most relevant physical and technical problems of modern science [1-3]. High-precision atomic clocks have a high importance in science and technology and a vast area of their application. So these devices are requirements for high accuracy and reliability of measurements.

A quantum frequency standards on the atoms of caesium $^{133}$Cs have a special place among the atomic clocks. These standards are used as a clock generators in the communications equipment and in a data transmission devices, applied in the satellite navigation systems GLONASS and GPS as a clock generators and in the various metrological services. Also these standards perform a role of the reference signals with high precision and stability in radio equipment [3 - 5]. Due to the high accuracy and reliability quantum frequency standards on atoms of caesium $^{133}$Cs are applied in the positioning systems of underwater devices.

With the development of scientific - technical progress operating conditions of caesium atomic clocks are constantly changing. Therefore new requirements for measurement accuracy, reliability and weight - dimensional characteristics are produced to frequency standard. This leads constantly upgrade existing and develop new models of caesium atomic clocks. For this aims it is reasonable to carry out research, develop new methods and find a new design solutions based on the latest appearing electronic components and discovered physical phenomena.

Development and commissioning of new atomic clock are very long and costly process, which in most cases is not enough funds and time. Therefore, in most cases, for specific tasks related to the operating conditions of frequency standards modernization is occur. The process of modernization of frequency standards includes various directions: change the weight and dimensions, reduced energy consumption, improved metrological characteristics. And for frequency standards characterized by the
fact that modernization may not be for the whole construction and may be for individual units or blocks.
In present work one of the directions of modernization of the cesium atomic clock is considered. A new implementation of a digital frequency synthesizer for atomic clocks is presented. Improved microwave – excitation signal parameters leads to improvement of characteristics of quantum frequency standard in particular the frequency stability.

2. Frequency synthesizer of the cesium atomic clock

The work of a caesium atomic clock is based on the principle of adjustment of the frequency of a highly stable crystal oscillator to quantum transition frequency of atoms of cesium-133 [3]. Figure 1 shows a block diagram of a caesium atomic clock

![Block diagram of a caesium atomic clock](image)

Figure 1. Block diagram of a caesium atomic clock. 1 - a source of caesium atoms, 2 - magnet polarizer 3 - magnetic field 4 - magnetic shield 5 - Ramsey resonator 6 - the waveguide 7 - frequency converter 8 - crystal oscillator 9 - automatic frequency control system 10 - magnet analyzer, 11 – detector

The output signal frequency of 5MHz of the crystal oscillator 8 is supplied to the frequency converter 7. Frequency converter consists of the frequency synthesizer, the mixer signals and the multiplier signals. In the frequency synthesizer input signal frequency of 5MHz is converted to the signal frequency of 12,631772 MHz and supplied to the input of mixer signals. In the multiplier signals input signal frequency of 5 MHz is multiplied to the frequency of 270 MHz and then to frequency of 9180 MHz. This signal frequency of 9180 MHz is also supplied to the input of mixer signals. As a result, the output signal of the frequency converter is the signal of ultrahigh frequency of 9192,631772 MHz. This signal is supplied in the waveguide 6 and then on the input of atomic beam tube.

In caesium atomic clock with the help of magnet polarizer 2 the atoms are prepared such that they are either in the F=4, m_F=0 or in F=3, m_F=0 state. Afterwards the atoms interact with an electromagnetic field that induces transitions into the former unoccupied state. The atoms in this state are detected and allow one to determine the frequency of the interrogating field where the transition probability has a maximum. The observed transition frequency is corrected for all known frequency offsets that would shift the transition frequency from the unperturbed transition and is used to produce a standard frequency or pulse per second every 9192631772 cycles [3].
Scanning the frequency \( \nu \) of the atomic resonance leads to a detector current like the one shown on the figure 2. The signal shows the Ramsey resonance structure on a broader, so-called, Rabi pedestal.

![Figure 2. Ramsey resonance structure on the Rabi pedestal](image)

The central feature with the maximum at the transition frequency \( \nu_0 \) is used to stabilize the frequency of the crystal oscillator to the atomic transition frequency. To this end, the frequency from the synthesizer is modulated across the central peak. The signal from the detector is phase-sensitively detected in the automatic frequency control system, integrated and this signal is used for stabilising the frequency of the crystal oscillator.

Improvement the accuracy of the signal frequency of 12,631770 MHz results in better accuracy of the resonant frequency of the atomic transition [3-5].

The main characteristic of the frequency synthesizer is its ability to impact the characteristic of frequency stability of the output signal of quantum frequency standard. Frequency instability introduced by the synthesizer is determined by the lateral discrete spectrum components of the signal that occurs in dividing, multiplying, mixing frequency signals, the accuracy of the generated frequency, and the impact on the signal of natural and technical noise.

Experimental study showed up that the present method of generating the output signal of the frequency synthesizer needs to increase the accuracy. New scheme of the frequency synthesizer is designed using direct digital synthesis (DDS - Direct Digital Synthesis) [6]. This method allows to generate the output signal of the synthesizer with accuracy more than \( 10^{-6} \) Hz.

The implementation of our proposed method enables us to control the frequency of the output signal frequency synthesizer in real time. This ensures a high rate of frequency tuning, which makes it possible to more efficiently adjust the crystal oscillator frequency in contrast the previously used scheme.

The application of direct digital synthesis gave the possibility of obtaining the generated frequencies in a wide range (0-3MHz), in contrast to previous schemes, where this feature was absent [7, 8].
In figure 3 a new design of the frequency synthesizer is presented.

3. Experimental results and discussion
Experimental study of the output signal parameters of a new scheme frequency synthesizer, confirmed the simulation results and showed great advantages in comparison with previously used scheme. In figure 4, as an example, oscillograms measured in the band of 1 kHz of the output signal of a new scheme (a) and a previously used (b) of the frequency synthesizer are presented.

![Figure 4 Suppression of the amplitude of the lateral components in the band of 1 kHz.](image)

The experimental results show that the suppression of lateral discrete components in the spectrum of microwave-excitation signal in the band of 1 kHz is improved by 75%.

The shift of the peak of the line resonance atomic transition $\Delta f$ is arising due there are lateral discrete components in the microwave-excitation signal spectrum. The shift is defined by the following expression [3]:

$$\Delta f = \frac{A}{I} \frac{(\delta f)^2}{(f - f_0)},$$

where $A$ is the amplitude of the lateral components, $I$ is the amplitude of the carrier, $\delta f$ is the width of the spectral line, $(f - f_0)$ is the detuning of the lateral components relative to peaks of the spectral line.
In the developed scheme of the frequency synthesizer the suppression of lateral components is not less than -72 dB, spectral line width is equal 500 Hz and the band of the lateral components is equal 1 kHz. Then relative frequency shift of the atomic transition is equal $\Delta f / f = 2.2 \times 10^{-14}$. Previously obtained result is equal $\Delta f / f = 1.62 \times 10^{-13}$ Hz. By reducing the frequency shift of the atomic transition $\Delta f$ the more fine-tuning on the center of the resonance line is occur. This leads to a more accurate determination of the value of the nominal output frequency of frequency standard and, consequently, improves the long-term frequency stability of a cesium atomic clock.

4. Conclusion
Experimental study of frequency synthesizer showed improvement parameters of the microwave-excitation signal, such as the step of frequency tuning, time of the frequency tuning, range of generated frequencies, phase stability and spectral characteristics. Experimental research of the metrological characteristics of the quantum frequency standard on the atoms of caesium - 133 with new scheme of the microwave – excitation signal showed improvement in daily frequency stability on $1.2 \times 10^{-14}$.

Reference
[1] Davydov V V, Dudkin V I and Karseev A U 2013 Optical Memory & Neural Networks (Information Optics). 112–117 237
[2] Davydov V V and Semenov V V 1999 Radiotechnika i Elektronika. 1528–1531 1965
[3] Riehle F 2004 Frequency standards. Basics and applications. 496
[4] Oduan K and Gino B 2002 Chronometry and basics of GPS. 400
[5] Dudkin V I and Pachomov L N 2012 Quantum electronics. Devices and their applications. 422
[6] Ridiko L I 2005 Components and Technology. 27-39 83
[7] Petrov A A and Davydov V V 2014 J. Proc of the International youth scientific forum "LOMONOSOV-2014". 187–188 232
[8] Petrov A A and Davydov V V 2014 Proc of the 52nd international scientific student conference "ISSC - 2014" 15 101