About the microwave excitation signal formation in the quantum frequency standard on cesium atoms – 133

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Abstract. The features of microwave excitation signal formation in the quantum frequency standard on cesium atoms - 133 were determined. To improve the characteristics of microwave excitation signal, a new method for its formation has been proposed taking into account the features we have identified. Studies have shown that the use of this method allow to improving the spectral characteristics and reducing the step of tuning of microwave excitation signal. The obtained experimental results allowed establishing that the use of this method improves the stability of the output signal of the quantum frequency standard on 20%. The features we have identified allow us to expand the possibilities of research aimed at developing new methods and techniques for improving the characteristics of the microwave excitation signal and characteristics of quantum frequency standard output signal.

1. Introduction

At present, in conditions of rapid development of world science, technologies and data transmission devices time measurement with high accuracy is a vital to success in these fields [1-6]. Numerous devices that are used in navigation, telecommunication systems and other fields of science and technologies have different limits on accuracy, stability and data format [1, 2, 7-10], Therefore, mutual use of such devices can be difficult without synchronization systems.

High-precision reference generators are required to ensure synchronization of the transmitting and receiving devices. Quantum frequency standards (QFS) have the highest accuracy and reliability among the sources of reference oscillations used for time measurement [6, 7, 9-13]. With the development of scientific - technical progress and large amount of data transmitted over networks, new requirements for accuracy, reliability and frequency stability are produced to frequency standards [14-20]. This leads constantly upgrade existing and develop new models of quantum frequency standards.

Development of new models of QFS based on fundamental scientific research is a v1ery long and expensive process that requires the joint efforts of many scientific groups. There is usually no such reserve of time and means for the operative solution of the assigned tasks.

The process of quantum frequency standard modernization is associated with the development of new or expanding functionality of the blocks used in QFS, that allow to improving metrological characteristics of QFS.

One of the possible problem solutions of CSF modernization on cesium atoms is presented in our work. Features of microwave excitation signal formation were established and a method for improving its characteristics was proposed.
2. Quantum frequency standard on cesium atoms-133 and features of the microwave excitation signal formation

The work of QFS on cesium atoms – 133 or so called cesium atomic clock is based on the principle of adjustment a highly stable voltage-controlled quartz crystal oscillator (VCXO) to quantum frequency transition of atoms of cesium-133 [5-8]. Figure 1 shows a block diagram of a cesium atomic clock.

![Figure 1. Block diagram of a cesium atomic clock.](image)

The output signal of VCXO with the frequency of 5MHz is entered to the frequency synthesizer. Frequency synthesizer consists of frequency converter (FC), mixer signals (MS) and multiplier signals (MS). In FC input signal with the frequency of 5MHz is converted to the signal frequency 12.631772 MHz and entered to the input of MS. In MS input signal with the frequency of 5 MHz is multiplied to the frequency of 270 MHz and then to frequency of 9180 MHz. This signal frequency 9180 MHz is also entered to the input of MS. As a result, the output signal of the frequency synthesizer is the signal of ultrahigh frequency 9192.631772 MHz. This signal is entered to the Ramsey cavity.

In cesium atomic clock with the help of magnet polarizer the atoms are prepared such that they are either in $|F=4, m_F=0\rangle$ or in $|F=3, m_F=0\rangle$ state. Afterwards the atoms interact with an electromagnetic field that induces transitions into the former unoccupied state.

A magnetic field is used to separate energetically the otherwise degenerate magnetic sub-levels in order to allow the excitation of the clock transition $|F=3, m_F=0\rangle \rightarrow |F=4, m_F=0\rangle$ isolated from the other transitions. By convention such a field is referred to as the C-field as it is applied between the fields of the polarizer and the analyzer.

The magnitude of the C-field is chosen as a compromise between two conflicting requirements. First, it has to be large enough to separate the otherwise overlapping resonances. Second, the C-field shifts the resonance frequency quadratically which has to be corrected. However, in a larger field the frequency of the clock is influenced to a larger extent by fluctuations of the magnetic field. In the scheme of a commercial Cs clock the C-field is often generated by a coil with windings in the paper plane wound around the Ramsey resonator and hence, points perpendicularly to that plane. Owing to the dependence of the frequency of the clock transition from the magnetic field, efficient magnetic shielding has to be provided in order to attenuate the ambient magnetic field and the magnitude of the associated fluctuations.

The atoms in the former unoccupied state are detected and allow one to determine the frequency of the interrogating field where the transition probability has a maximum. In this case the signal-to-noise ratio (S/N) of the recorded resonance signal from the beam of cesium atom - 133 on the current detector will be maximal. The received signal is processed by the automatic frequency control system and is used to change the control voltage on quartz in proportion to the frequency shift from the nominal value. The observed resonance frequency is corrected for all known frequency offsets that would shift the transition frequency from the unperturbed transition. The main contribution to the frequency shift of the central resonance is made by magnetic field fluctuations, as well as the
parameters of the microwave excitation signal [5, 9, 11, 12]. The process of microwave signal formation has a number of features on which we have paid attention.

It is important that the microwave signal has a high accuracy of the output frequency, a high suppression of the lateral amplitude components in the spectrum, a low dependence of the frequency and amplitude changing on temperature, an ability to tune the frequency in a wide frequency band with a small frequency tuning step, high speed tuning output frequency, the ability to select different modulation frequencies.

The high accuracy of the microwave signal affects on the accuracy of the nominal value of the output frequency of the QFS. The higher accuracy of the microwave signal formation, the higher accuracy of resonant frequency of the atomic transition.

The lateral amplitude components in the spectrum of microwave signal, resulting from frequency transformations, cause additional shifts in the nominal value of the QFS. Thus, if one of the lateral side components coincides with the frequency of any Zeeman transition, it will lead to transitions of atoms at these levels and an error in nominal value of the output frequency of the QFS is appeared.

The shift of the top of the resonance line of the atomic transition $\Delta f$, which occurs due to the presence of side components in the spectrum of the microwave excitation signal can be calculated by the following expression:

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

(1)

where $A$ - is the amplitude of the side components, $I$ - is the amplitude of the carrier, $\delta f$ - is the width of the spectral line, $f$ - is quantum frequency transition of atoms of cesium-133, $(f-f_s)$ - is the tune of the side components relative to the carrier of the spectral line.

The low temperature dependence of the frequency and amplitude of microwave signal improves the temperature dependence of the QFS as a whole. Any changes in the frequency and amplitude of microwave signal, related with the temperature changes contribute to the deterioration of the temperature coefficient of frequency (TCF) of the QFS, defined as the ratio of the nominal value of the frequency to the temperature change by 1°C.

The ability to tune the frequency of microwave signal in a wide frequency band with a small frequency tuning will allow to implement an algorithm for adjusting magnetic field of QFS, which, as a result, should lead to an improvement in the long-term frequency stability of the QFS output signal.

The ability to select different modulation frequencies ($F_m$) of the output signal for automatic frequency control system of QFS allows to provide a compromise when two conditions are met. On the one hand, when choosing a low modulation frequency, the flicker noise of the discriminator increases in proportion to the $1/F_m$, on the other hand, the choice of a lower modulation frequency provides the best accuracy in measuring the error signal value. Also this ability will allow to apply a frequency synthesizer (a functional unit of QFS which forming microwave signal) in other QFS models, for which the optimal value of the modulation frequency may vary depending on the design.

With all these features, we developed a scheme for the formation of the microwave signal.

3. Results and discussion of experimental studies of the microwave signal formation scheme

As we noted earlier, sinusoidal signal with a frequency of 5 MHz from the quartz oscillator is enters to frequency converter and frequency multiplier, which are part of frequency synthesizer. The FS converts the input signal into a signal with a frequency of 12,6317727MHz. The FM converts the input signal into a signal with a frequency of 9180 MHz, and, like the signal from FC, enters to input of the MS. The work of MS can be described by the equation:

$$U_{out} = \cos\omega_1 t \ast \cos\omega_2 t = \frac{1}{2} \cos(\omega_1 - \omega_2) t + \frac{1}{2} \cos(\omega_1 + \omega_2) t.$$  

(2)
where \( \cos \omega_1 t \) – is a signal from FC, \( \cos \omega_2 t \) - is a signal from FM, \( \cos (\omega_1 - \omega_2) t \) - is a signal with a differential frequency of FC and FM, \( \cos (\omega_1 + \omega_2) t \) - is a signal with a total frequency of FC and FM.

As a result, the output signal of MS contains a multiple frequency combinations, including the frequency of 9,1926317727 GHz, which is used in the operation of the QFS.

Multiple frequency combinations which are result of the signal with a frequency of 5 MHz conversion lead to the appearance of lateral amplitude components in the spectrum of microwave signal. The lateral components appearing in FM are separated from the main signal by values that are multiples of the output frequency of quartz. This value (5 MHz) is quite large and exceeds the possible splitting of the Zeeman components of the spectrum, so the error in determining the nominal value of the frequency of the QFS generated by them can be neglected.

Special attention is paid to the suppression of lateral amplitude components in the spectrum of FC output signal. As a result of the fractional frequency conversion coefficient, where are many components with the frequency of Zeeman transition in the spectrum of FC output signal. These lateral amplitude components will make a significant contribution to the error in determining the nominal value of the output frequency of the QFS.

The design of the FC was developed based on the method of direct digital synthesis [8, 20]. On figure 2 as an example, a part of the spectrum of the microwave excitation signal is presented, for the formation of which the signal with frequency of 12631772,7 Hz is responsible.

![Figure 2](image_url)

**Figure 2.** Spectral characteristics of the FC output signal for the previously used (a) and developed (b) FC design. The maxima of the useful signal amplitudes and lateral components are marked as 1 and 2 consequently.

Experimental results show that the suppression of the lateral amplitude components in the signal spectrum with a frequency of 12631772,7 Hz was 88 dB in the 6 kHz registration band. With such suppression, the level of the lateral components does not has a significant effect on shift of the resonance frequency according to (1).

In addition, the use of a 40-bit accumulating adder and a clock frequency \( f_{\text{clk}} \) = 15 MHz in design of FC allow to obtain a tuning step of the output frequency \( \Delta f = 10^{-5} \) Hz. This makes it possible to fine-tune the frequency of the microwave excitation signal to the frequency of the central resonance \( f \).

Also, the new method made it possible to exclude the quartz filter (used in the previous design of FC), which has a high quality factor and a high temperature dependence of the output frequency. The results of the tests with a new FC scheme showed an improvement in the temperature coefficient of frequency by 2.9 times.

Another feature in the new FC design is the ability to select different modulation frequencies of the output signal (range from 15 Hz to 80 Hz). In this case, the design of the FC becomes universal and can be used in other models of QFS.

The new design of the FC allows to expand the frequency tuning range of the microwave excitation signal to 0.3 MHz. In previously used designs of FC this range was 3 kHz. This feature makes it
possible to implement an algorithm for adjusting the magnetic field inside the atomic beam tube by a neighboring resonance transition [1, 16]. This tuning compensates the frequency shift, which impairs the long-term stability of the output signal of QFS.

How experiment showed the use of the additional adjustment of the magnetic field allows maintaining the constant value of the field within the atomic beam tube, what leads to an improvement in the long-term stability of the output signal of the QFS by 20%.

4. Conclusion
Experimental results showed the validity of taking into account the established features of the microwave excitation signal formation. Application of new FC design in QFS has improved the TCF of QFS by 2.9 times, implemented an algorithm for adjusting the magnetic field, and also improved the Allan variance of the output signal of the QFS by 20% compared with the previously used designs.

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