Features of direct digital synthesis applications for microwave excitation signal formation in quantum frequency standard on the atoms of cesium

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Abstract. Features of direct digital synthesis applications in quantum frequency standard on the atoms of cesium are considered. A new design of a frequency synthesizer based on direct digital synthesis method and magnetic field stabilization system are presented. Experimental research of frequency synthesizer showed improvement parameters of a microwave excitation signal, such as step frequency tuning, time frequency tuning, range of generating frequencies and spectral characteristics. Magnetic field stabilization system eliminates one of the most important perturbing factors affecting on long-term frequency stability. Experimental research of metrological characteristic of quantum frequency standard showed improvement long-term frequency stability by 15%.

1. Introduction

The accurate measurement of time and frequency is vital to the success of many fields of science and technology [1-8]. For examples success in atomic physics (atom-photon interactions, atomic collisions, and atomic interactions with static and dynamic electromagnetic fields), geodesy, radio-astronomy (very long baseline interferometry) and pulsar astronomy depends on very high stable output signal of frequency standards and uniform timescales [5-12]. The same is valid for the operation of satellite-based navigation systems, metrological services and telecommunication systems. [1, 2, 4, 5, 12-14]

Quantum frequency standards on the atoms of cesium (also named cesium atomic clock) also 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 [12-14]. Also these standards perform a role of the reference signals with high precision and stability in radio equipment. [1, 14-17]

Considering the high importance of precision atomic clocks in science and technology and a vast area of their application, modernization of existing and development new quantum frequency standards are the urgent tasks [1, 14-17].

The process of frequency standards modernization includes various directions: reducing energy consumption, reducing weight and dimensions, improving metrological characteristics. And in present
work some directions related to direct digital synthesis applications of cesium atomic clock modernization for improvement its metrological characteristics are considered.

2. **Principles of cesium atomic clock operation**

Work of a 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 caesium-133 \[1, 5, 12, 16\]. Figure 1 shows a block diagram of a cesium atomic clock.

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

Output signal frequency 5 MHz of the VCXO is supplied to the frequency synthesizer. Frequency synthesizer consists of frequency converter, mixer signals and multiplier signals. In the frequency converter input signal frequency 5 MHz is converted to the signal frequency 12,631772 MHz and supplied to the input of mixer signals. In the multiplier signals input signal frequency 5 MHz is multiplied to the frequency 270 MHz and then to frequency 9180 MHz. This signal frequency 9180 MHz is also supplied to the input of mixer signals. As a result, the output signal of the frequency synthesizer is the signal of ultrahigh frequency 9192,631772 MHz. This signal is supplied in the Ramsey cavity.

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

A uniform magnetic field is used to separate energetically the otherwise degenerate magnetic sub-levels in order to allow the excitation of the clock transition \( |F = 3, mF = 0> \rightarrow |F = 4, mF = 0> \) 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. In the scheme of a commercial Cs clock the C-field is often generated by a coil with windings around the Ramsey resonator. 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. 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 [1, 5, 12, 16].

Scanning the frequency ν 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.

The central resonance with the frequency transition ν₀ is used to stabilize the frequency of the crystal oscillator to the atomic transition frequency. To this end, the output synthesizer’s frequency is modulated. The signal from the detector is detected, integrated and used for changing the voltage of the VCXO proportional to the frequency. From this suitable output frequencies are derived, such as 5MHz or a 1 PPS signal.

3. New design of frequency synthesizer

Frequency synthesizer is one of the main blocks of quantum frequency standard. Frequency synthesizer takes a part of generating the microwave signal at ~9.2 GHz (used to interrogate the ¹³³Cs atoms hyperfine resonance transition) from the 5 MHz quartz oscillator frequency [1, 16, 17].

The main characteristic of the frequency synthesizer is ability to impact on the characteristic of frequency stability of the quantum frequency standard output signal. 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.

In order to provide the best possible frequency stability, it is crucial that the microwave signal which interrogates the ¹³³Cs atoms be as “clean” as possible; that is, free of unwanted sidebands and spurious signals which can cause Bloch-Siegert frequency shifts.

Experimental study showed that the present method of generating the frequency synthesizer output signal needs to increase the accuracy. The large resolution of step frequency is necessary. New scheme of the frequency synthesizer is designed by using method of direct digital synthesis (DDS - Direct Digital Synthesis). This method allows to generate the output signal of the synthesizer with accuracy about $10^{-5}$ Hz. Step frequency tuning $\Delta F_{\text{out}}$ calculated by the formula below:

$$\Delta F_{\text{out}} = \frac{F_{\text{clk}}}{2^N},$$

where $F_{\text{clk}}$ is the clock frequency, $N$ is the capacity of accumulator.

In our scheme the clock frequency is equal $F_{\text{clk}}=15$ MHz, the capacity of accumulator is equal $N=40$. Step frequency tuning is equal $\Delta F_{\text{out}} = 1.36 \times 10^{-5}$ Hz.

When we calculate step frequency tuning relatively resonant frequency of the microwave transitions of cesium atoms, using parity (1), we get relative step frequency tuning $\Delta F_{\text{out,rel}}$.
The application of direct digital synthesis gave the possibility of obtaining the generated frequencies in a wide range (~1 MHz), in contrast to previous schemes, where this feature was absent. This feature gets a possible to develop a magnetic field stabilization system. Range of generated output frequencies may be calculated by the formula below:

$$F_{out} = \frac{M \times F_{clk}}{2^N}$$

where $M$ is the frequency code in decimal, $F_{clk}$ is the clock frequency, $N$ is the capacity of accumulator.

To meet the requirements for spectral purity of output signal 10 bit DAC was used. It is possible to obtain the suppression of lateral amplitude components in the spectrum of the output signal is not worse than -90 dB.

In figure 3, as an example, oscillograms measured in the band of 6 kHz of the output signal of a previously used design (a) and a new (b) of the frequency synthesizer are presented.

![Figure 3](image)

Figure 3 Suppression of the lateral components in the band of 6 kHz.

The experimental results show that the suppression of lateral components in the spectrum of microwave-excitation signal in the band of 6 kHz is improved on 24 dB.

With decrease of lateral components 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.

One of the differences between the design of the frequency synthesizer developed by using DDS from the previously used is the absence of a quartz filter in it. Quartz filter with good frequency selectivity has a high temperature dependence of the output frequency. In the new design of frequency synthesizer quartz filter is absence. At the same time, the level of suppression of combinational components due to the use of the new method remained at the same level, and the temperature-dependent elements became less. This allows to improve the temperature coefficient of frequency (TCF) of the quantum frequency standard.

An experimental study of quantum frequency standard with new design of frequency synthesizer based on DDS showed an improvement in the TCF by to 2.4 times compared to the previously used designs of frequency synthesizer.

In addition new design of the frequency synthesizer allows eliminating one of the most important perturbing factors affecting on long-term frequency stability.
4. Magnetic field stabilization system

The stable isotope Cs-133 has a two hyperfine states F = 4 and F = 3 which are split in the magnetic field into 16 components. In accordance with the selection rules seven transitions between the components of hyperfine sublevels are possible [1, 16, 17]. These are represented in figure 4.

![Figure 4 Microwave resonances in the Ramsey cavity.](image)

The central resonance $|F = 3, m_F = 0\rangle \rightarrow |F = 4, m_F = 0\rangle$ (marked on the figure 4 as a «1») due to the Zeeman effect expose a quadratic frequency shift. With the help of formula (1) we can calculate a frequency shift.

$$\Delta f_B \approx 4.2745 \times 10^{-2} \text{ Hz} \times (6 \times 10^{-6} T)^2 = 1.5388 \text{ Hz}$$

(4)

For a typical value of the C field near 8 μT the frequency shift is 2.7 Hz corresponding to a relative frequency shift of $3 \times 10^{-10}$.

The accuracy of the output signal quantum frequency standard is dependent on the shift of the central resonance. It should be noted that not only the central resonance is exposed the frequency shift, but also all six transitions $(3, m_F) \leftrightarrow (4, m_F)$, which $\Delta m_F = 0$. To express these changes as a function of magnetic induction B and atomic constants use the equation Bright Rabi:

$$E(F, m_F) = -\frac{h \nu}{2(I+1)} - g_I \mu_B B m_F + \frac{\nu}{2} (1 + \frac{4 m_F}{2I+1} x + x^2)^{\frac{1}{2}},$$

(5)

where $E(F, m_F)$ is the change energy of atoms in the ground state; I is the quantum number of nuclear spin; $g_I$ is the factor Lande for electron; $\mu_B$ is the Bohr magneton; $m_F$ is the magnetic quantum number; $x = \frac{(g_e + g_I) \mu_B B}{h \nu}$.

This formula can be used for calculation the frequency shift of any transition between two hyperfine sublevels, depending on the magnetic field. Revealing this expression, we find that the first order member is proportional to the magnetic field B. For cesium beam primary frequency standards we must consider the quadratic order member of this expression.

In theory, the frequency shifts can be taken into account in the calculation of the functional dependence on magnetic field values and the atomic constants using equation Bright-Rabi. But in
practically, any changes of the magnetic field shift the resonance frequency. And values of these frequency shifts cannot be accounted for in advance.

Thanks to the development of a new frequency synthesizer the range of generated output frequencies has been expanded. It allowed detuning output synthesizer’s frequency to the neighboring resonance frequency of spectral line that makes it possible to adjust the C-field in quantum frequency standard.

Now in cesium atomic clock the magnetic field is maintained by the active stabilization system. For this purpose the neighboring transition $|F =3, m_F=1> \leftrightarrow |F =4, m_F=1>$ (marked on the figure 4 as a «2») is used. The method of C-field adjustment is similar to the method of frequency adjustment to the main maximum. For this purpose, the average value of the sampling frequency $v_i$ is changed from the value of the $v_{Cs}$ to $v_{Cs} + \Delta v$, where $v_{Cs}$ is the frequency of the main transition of the cesium atom, $\Delta v$ - difference between the transitions for a preset value of the magnetic field. Then the value of magnetic field is adjusted in such way that the frequency of transition $|F =3, m_F=1> \leftrightarrow |F =4, m_F=1>$ match the preset frequency. This adjustment set up automatically several times per minute. The value of the field is automatically maintained at a predetermined level.

Alternately closing the ring-locked loop at the central and the neighboring transition we adjust the frequency of the VCXO to the frequency of the central atomic transition, and support the constant value of the magnetic field inside the Ramsey cavity.

In this case effects associated with any changes in the magnetic field (for example, long-term drift of the current source, temperature dependence, effect of external magnetic field, etc.) are excluded.

5. Conclusions

Application the DDS in quantum frequency standard on the atoms of cesium allowed to improve the output characteristics of frequency synthesizer and also to develop magnetic field stabilization system. The use of new design of the frequency synthesizer and system for stabilizing magnetic field in quantum frequency standards construction allow to improve frequency stability of quantum frequency standard.

Experimental research of the metrological characteristics of the modernizing quantum frequency standard on the atoms of cesium - 133 showed improvement in the TCF by to 2.4 times and long-term frequency stability on 15 %.

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