COMPACT RUBIDIUM GAS CELL ATOMIC FREQUENCY STANDARDS

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Small-sized gas cells with 1 cm^3 volume for rubidium gas cell atomic frequency standards are developed, made and investigated. Digital rubidium frequency standard was designed and main features of this design are described. The results of specially designed rubidium frequency standard testing in conditions of the rarefied atmosphere are described.

rubidium frequency standard, small-sized gas cell, digital frequency lock loop, rarefied atmosphere

In RIRT there is a long-term experience of creation of onboard rubidium frequency standards (RFS). Since 1964 ALMAZ is produced in small batch, since 1972 - AMETIST, since 1986 - BERYLL is produced. AMETIST and BERYLL are producing at factory NAVIGATOR till now. Thus works on perfection of developed devices directed on reducing of their dimensions, increasing of precision characteristics (especially long-term characteristics), increasing of functionality are simultaneously carrying out.

In works [1,2] it was offered to use for stabilisation of frequency with the help of a radiooptical resonance small-sized cells. Carried out researches, have shown an opportunity of reception thus to high sensitivity of a radiooptical resonance. It has allowed to create two families of small-sized physics package which have lain in a basis of some small-sized frequency standards – RFS2001, RFS2002, etc., some from which are produced in sets, others are in a stage of development of manufacture. These devices provide high enough short-term stability and thus have small dimensions. However, long-term stability at set forth above devices rather low – instability per day achieves 5×10^{-12}, per month (in view of drift) 3×10^{-11}. One of principal causes of notice instability per day is dependence of frequency atomic transition from temperature owing to frequency fluctuates under action of fluctuations of an environmental temperature. Thus the frequency deviation of atomic transition in a cell placed in the physics package of the gas cell frequency standard a owing to a deviation of an environmental temperature, will be:

$$\sigma_f = k_{tc}\times\left(\partial f/\partial T_c\right)\times\sigma_t + k_{tfc}\times\left(\partial f/\partial T_{fc}\right)\times\sigma_t + k_{tl}\times\left(\partial f/\partial T_l\right)\times\sigma_l$$

where k_{tc}, k_{tfc}, k_{tl} – thermostatting factors of cells, filter-cell and a lamp, σt – fluctuation of temperature, $\partial f/\partial T_c$, $\partial f/\partial T_{fc}$, $\partial f/\partial T_l$ – change of frequency at change of temperature (TC) of a cell, the filter-cell and a lamp.

In a design of the which physics package is used now:

$$k_{tc}\approx 5\times10^{-2}, k_{tfc} = k_{tl}\approx 5\times10^{-3};$$

$$\partial f/\partial T_{fc}\approx 1{,}3\times10^{-10}, \text{ 1/°C}, \quad \partial f/\partial T_l = 5\times10^{-11}, \text{ 1/°C}$$

$$\sigma_t = (1...3)\times10^{-3}\times\tau^{0,5}, \text{ °C},$$

that is

$$\sigma_f(\tau) = (5...15)\times10^{-5}\times\tau^{0,5}\times\left(\partial f/\partial T_c\right) + (9...27)\times10^{-16}\times\tau^{0,5} \approx (5...15)\times10^{-5}\times\tau^{0,5}\times\left(\partial f/\partial T_c\right) + (1...2{,}7)\times10^{-15}\times\tau^{0,5}.$$

Hence, instability per day will be equal

$$\sigma_f(1day) = (1{,}5...4{,}5)\times10^{-2}\times\left(\partial f/\partial T_c\right) + (3...8{,}1)\times10^{-13}$$

Estimated deviations of frequency depending on value TC are shown in table 1:

Table 1.

$\partial f/\partial T_c, \times10^{-11}$	$\sigma_f, \times10^{-12}$
10	1,80…5,30
3	0,75…2,16
1	0,45…1,20
0,3	0,33…0,85

Thus, to get σ_f (1 day) – 1×10^{-12} it is need to reduce temperature dependence of frequency of a cell up to value less 3×10^{-11}1/°C. Difficulty of a problem consists in necessity to make compact rubidium gas cell frequency standards. The requirement on maintenance of a wide working range of temperatures for (-50…+70 °C). So the high operating temperature of a cell (+80…85 °C) is necessary.

There were carried out the researches of manufacturing gas cells. As a result gas cells fillings which allow to provide required operating temperature and to minimize value of its temperature factor of frequency in small-sized cells were developed. By the technique specified by us gas cells in volume of 1 cm^3 were made and investigated. In the table 2 the received results are presented: the frequency (f), the value of radiooptical resonance signal (U_s), temperature factors of frequency $\left(\partial f/\partial T\right)$ and radiooptical resonance sensitivity at temperature +80 °C for a series of gas cells (Mix Ne+Ar, alloy Rb^{87}+K).

Table 2.

№	f, Hz	U_s, mV (80 °C)	$\partial f/\partial T$, 1/°C	Sensitivity, $Hz^{-1}\tau^{0.5}$
1–0	6834685747,3	43	$5*10^{-11}$	11
2–0	6834685429,8	73	6×10^{-12}	19
3–0	6834685271,6	20	2×10^{-11}	5
4–0	6834685522,7	63	6.9×10^{-12}	16
5–0	6834685579,8	38	9×10^{-12}	10
6–0	6834685337,5	32	2.3×10^{-11}	8
7–0	6834685338,3	77	1×10^{-11}	20
8–0	6834685436,0	71	2.5×10^{-11}	18
9–0	6834685431,0	44	6.5×10^{-13}	11

From table 2 it is possible to see, that at small-sized gas cells the significant variance on frequency is observed. It is may be explained by low reproducibility at separating of cells from a vacuum post. But this defect is not important as in frequency standards the tunable synthesizers are used. Thus as it is possible to see in table 1 the temperature factor of frequency less 3×10^{-11} achieves, that will allow to reduce instability per day of small-sized atomic frequency standards up to values less1×10^{-12}. The operating temperature of cells is (81±1) °C, and sensitivity is in range from 10 up to 20 $Hz^{-1}\tau^{0,5}$, that provides short-term instability of frequency at time of measurement 100 s on a level $(2…1)\times10^{-12}$ (cells 3-0 and 6-0 are provided sensitivity less than 10 $Hz^{-1}\tau^{0,5}$and consequently they are discarded).

Test of small-sized gas cells in the accelerated regime of aging has shown, that the developed cells, due to use special alkali-resistant glass and the appropriating of manufacturing techniques have a resource more than 10 years during which they keep its characteristics.

Thus, as a result of the carried out work it is shown, that:

- in small-sized cells it is possible to provide TC less than 3×10^{-11} 1/°C at operating temperature (81±1) °C with sensitivity more than 10 $Hz^{-1}\tau^{0,5}$;
- the manufacturing techniques of gas cells in volume of 1 cm^3 with the mentioned above characteristics are developed.

Using small-sized gas cells, principal new digital rubidium frequency standard (RFS2002) was designed. The main goal of RFS2002 design was to establish probably more compact and technologic device based on Russian domestic elements suitable for manufacturing. Therefore, alongside with microcontroller usage, some new solutions are implemented. First of all, the 60 MHz TCXO was applied, that has enabled to reduce device dimensions and to simplify its manufacturing and tuning. The new frequency synthesizer was developed. Besides the DC-DC power converter with efficiency more than 80%, for input voltage in a range from 18 up to 80 volts was developed.

The basic feature of the RFS2002 is microcontroller usage which provides TCXO frequency adjustment by the rubidium reference and allows to control and monitoring the device by software.

It has enabled to carry out the following operations on inquiry through interface RS-232C:

- to supervise the frequency standard work by means of status/mode word reading;
- to supervise frequency capture;
- to supervise second harmonic presence and its level, as an integrated quality parameter of the device functioning;
- to read out the established frequency value;
- to correct frequency value concerning the current value with $2,74\times10^{-12}$ step;
- to write down the established frequency value into non-volatile memory.

Thus it is possible to carry out RFS2002 remote monitoring and functioning control in the equipment complexes both during development and tuning, and at work on objects. RFS2002 remote management and monitoring may be realized by the special software. It is possible to connect nothing to RS-232C socket of the standard when it no working with the digital data link.

In a fundamental of RFS2002 construction, as well as any passive quantum frequency reference, physics package usage lays. RFS electronic system with the synthesizer in the main loop (Fig. 1) provides frequency lock loop (FLL) of the quartz generator to the spectral line frequency of rubidium atoms transition.

The RFS2002 functional diagram (Fig. 1) shows the quantum discriminator containing both actually physics package, and the units necessary for its functioning: two oven controllers, voltage stabilizer and the light source exciter, C-field stabilizer and conditioning amplifier. RFS2002 electronic system parts shown on the functional diagram are implemented in a way combined with both linear, and digital circuit decisions usage. Some parts (Synchronous detector, Low frequency generator and Low pass filter) are implemented in microcontrollers' software.

RFS 2002 software consists of three pseudo-parallel tasks (in priority decreasing order): the task of equipment management (ADC, DACs and synthesizer), the task of RS232C data exchange and the task of data processing (Fig.2). As it was specified before, functions of the synchronous detector, the Low pass filter of frequency lock loop and the Low frequency generator are implemented in the microcontroller by algorithms of the appropriate devices functioning. That is the main part of data processing task.

TCXOs' and frequency synthesizers' controls are formed by the software also. Such RFS units realization (by software + digital hardware) should provide low sensitivity to various influences in comparison with classical (analog) RFS design. The drift of FLL parameters and components' parameters changing (aging, external influences) are completely excluded.

Parameters of non-recursive (FIR) third order low pass FLL filter (coefficients K1, K2, K3 and scaling coefficient Kx) are kept in non-volatile memory after calculation and adjustment (Fig. 2). ADCs' sampling frequency, time window position of SD, deviation value of frequency synthesizer are kept in non-volatile memory also. User can change only the value of synthesizer central frequency determining RFS actual frequency.

The structure of direct synthesis was implemented in the frequency synthesizer design. The frequency synthesizer provides forming of a 314,500 Hz frequency signal in the range ±2,500 Hz. Digital part of the synthesizer (28-bit accumulator with 28-bit phase register and 16-bit frequency code register) are designed with common IC usage. An additional digital mixer is used for full signal (with 5,314,500 Hz frequency) forming. The Band pass filter at the synthesizer output is tuned to 5,314,500 Hz frequency. The synthesizer frequency step is $2,74\times10^{-12}$ and it depends on the chosen word length of accumulator (28 bits). The signal for FLL detection (with approximately 120 Hz frequency) are forming by switching between two frequencies in the synthesizer. Such approach allows to have very low level of even harmonics in modulating signal (square-wave modulation).

One of RFS design features is rather compact 60 MHz TCXO usage, that allows to refuse a frequency multiplier. The output (5 MHz) frequency is forming by division of 60 MHz signal in 12 times by digital frequency divider.

Characteristics of the digital rubidium frequency standard (RFS2002) are given below:

The frequency stability, no more	
for τ_i=1 s,	3×10^{-11};
τ_i=100 s,	2×10^{-12};
τ_i=1000 s,	1×10^{-12};

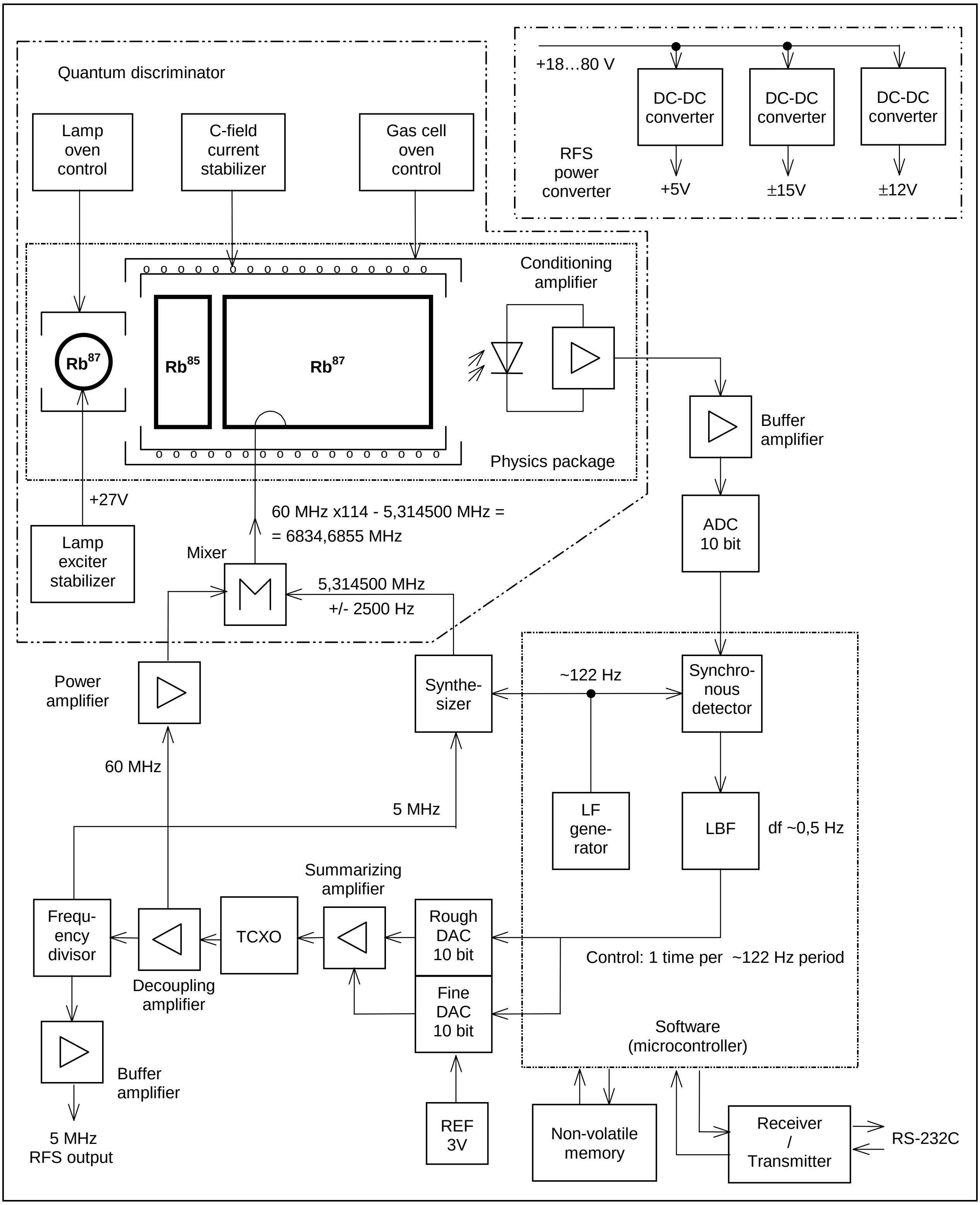

Fig.1 RFS 2002 functional diagram

The frequency drift, no more	
per day	1×10^{-12};
per month	5×10^{-12};
Power consumption, no more	
at 25°C, warm-up (about 2 min to lock)	50 W;
at 25°C, steady state	14 W;
The device volume	0.96 liter.

Hereinafter, it is supposed the software development to reduce temperature frequency shift of the device from 2×10^{-12} 1/°C to less then 3×10^{-13} 1/°C and to reduce frequency drift up to 3×10^{-12} per month.

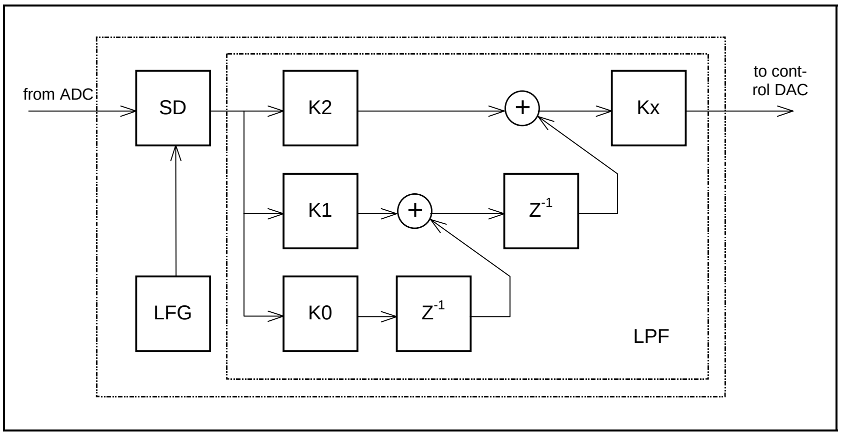

Fig 2. Block diagram of the RFS2002 FLL software

SD - Synchronous detector; LFG - Low frequency generator; LPF - Low pass filter; K1, K2, K3, Kx - digital filter coefficients; Z^{-1} - Integrator; (+) - Adder

Using small-sized gas cells rubidium frequency standard for special applications (RFS2001) was developed.

One of the reasons of frequency standard instability is transformations of pressure fluctuations to frequency fluctuations of atomic transition. The reason of it is deformation of an cell bulb. Typical values of sensitivity pressure of an environment lay within the limits of $1 \div 3 \times 10^{-13}$ 1/mm.Hg. Influence of this effect it is essentially reducing at work in conditions of low environment pressure. It is known, that frequency instability for more than 1 hour in gas cell frequency standards is caused by external influences to which radiooptical resonance in the physics package on a gas cell is more sensitive, than a signal in atomic beam tube. And the basic role in observably fluctuations is played transformation of temperature fluctuations in physics package.

For decrease of temperature fluctuations influence the best device thermostatting is necessary. In atomic gas cell frequency standards the external temperature fluctuations besides effect on electronics, act on the gas cell. As the thermostatting factor is always final the fluctuations of temperature influence on frequency of transition owing to change of gas cell filing depending on TC of cell. Except for that temperature fluctuations influence on intensity of light source radiation and owing to effect of light shifts define stability of frequency of atomic transition. In result typical TC atomic gas cell frequency standards appears in limits $(1 \div 4) \times 10^{-12}$ 1/°° , at the best samples this parameter is in limits $(1 \div 4) \times 10^{-13}$ 1/°° .

At work at low pressure conditions owing to exception of a heat transfer through an atmosphere the thermal mode of the device changes. In a result the organization of a heat-conducting path from the basic heat-producing element of the physics package becomes a problem. And in this case the heat-conducting path should be carried out on thermostatically controlled plate. In view of expected temperature factor of the atomic frequency standard 1×10^{-12} 1/°C and required instability less than 1×10^{-13} accuracy of temperature stabilization the Casis should Ce not worse than 0,1 °° .

For detailed research of the described phenomena in RIRT experiments with definition of frequency shifts of the physics package in frequency standard were carried out depending from a degree of environment rarefaction.

The important result of experiment was definition of pressure sensitivity for different areas of a rarefaction degree. So it was established, that at change of pressure in a range from normal atmospheric pressure up to 1 mm.Hg frequency shift of the physics package has made 1.5×10^{-10}, that corresponds to value of sensitivity 2×10^{-13} 1/mm.Hg. At the further environment pressure decrease up to 5×10^{-3} mm.Hg frequency shift has made 7×10^{-11}, that corresponds to integrated sensitivity of this range $1{,}4 \times 10^{-10}$ 1/mm.Hg. There were no appreciable frequency shifts at further pressure decrease. It is necessary to note, that on a area of high pressure sensitivity the frequency stability of standard decreased, and frequency shift occurred during the first day after an establishment necessary rarefaction. The analysis of the received results including thermal fields calculation inside the physics package at various values of environment pressure, has shown, that observably frequency shift is associated to change of temperature gradients in the area of a spectral lamp and the gas cell, caused, in turn the change of heat conductivity character.

As a result of the carried out analysis requirements to the design of the physics package providing the least contribution convectional of making environmental heat conductivity in the area of a gas cell and a spectral lamp were formulated. The account of these requirements will allow to minimize frequency shifts of the rubidium frequency standard at work in rarefaction environment conditions.

Expected characteristics of the gas cell atomic frequency standard developed for work in a wide range of environment pressure are given below:

Output frequency	5 MHz;
Relative frequency error at temperature (20±1) °C, and supply voltage 27(+0.8-1.8 B), no more	$\pm 10^{-11}$;
Long-term frequency stability in n.c.c. and supply voltage 27(+0.8-1.8 B) for first two days after switching on, no more	5×10^{-10};
for the subsequent three days, no more	5×10^{-11};
in 5 day after switching on for all service life, no more	5×10^{-12} 1/month;
TC of frequency in the range from 15 up to 30 °° , no more	1×10^{-12} 1/°° ;
Allan deviation drift removed, no more:	
for τ_i=1 c,	$\pm 1 \times 10^{-11}$;
τ_i=30 c,	$\pm 1 \times 10^{-12}$;
τ_i=1 h,	$\pm 1 \times 10^{-13}$;
τ_i=1 day,	$\pm (1 \ldots 4) \times 10^{-13}$.

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