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RESEARCH ARTICLE

Study of the reliability of quartz resonators in miniature ceramic packages

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Abstract

Objectives. In the development of radio electronics and communications, it is important that the requirements for the reliability, stability of the generated frequencies, and selectivity of the receiving equipment are fulfilled. The use of quartz resonators, widely used in radio circuits today, has partially allowed for the reliability of communication devices and guaranteed high frequency stability to be enhanced without complicating the circuit. Modern global trends in the development of electrical equipment are associated with miniaturization. The dimensions of quartz resonators are decreasing every year, while the requirements for reliability remain high. The study aimed to evaluate the possibility of using quartz resonators packaged in a miniature ceramic case $2.5 \times 2.0 \times 0.6$ mm, under conditions of elevated ambient temperature. It has also allowed for the development of optimal requirements for the thermal training regime as the basic technological operation for stabilizing the oscillation frequency.

Methods. Reliability testing of quartz resonators and methods of statistical modeling in radio engineering.

Results. The results established the requirements for the reliability of *RK588* quartz resonators in miniature ceramic cases $2.5 \times 2.0 \times 0.6$ mm in size under the influence of elevated ambient temperatures of $+85^\circ\text{C}$ and $+125^\circ\text{C}$. The requirements for frequency drift when exposed to elevated ambient temperature on the crystalline plate type based on RF patent No. 27122426 “Method of manufacturing thin crystalline plates and thin crystalline elements” were also specified. The method of thermal training was optimized and the ageing coefficients were established.

Conclusions. The coefficients of ageing calculated for the resonators during the reliability tests was as follows: Batch No. 1 at a temperature of $+85^\circ\text{C}$ was 0.75; and for Batch No. 2 at a temperature of $+125^\circ\text{C}$ was 0.18. For this type of piezoelectric element with a size of 1.5×1.0 mm at an operating temperature of $+125^\circ\text{C}$ the ageing coefficient is 4 times lower than at a temperature of $+85^\circ\text{C}$. This indicates the possibility of using the *RK588* resonator at elevated ambient temperatures.

Keywords: quartz resonator, reliability, ceramic case, oscillation frequency, temperature

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НАУЧНАЯ СТАТЬЯ

Исследование надежности характеристик кварцевых резонаторов в миниатюрных керамических корпусах

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Резюме

Цели. При разработке современных приборов радиоэлектроники и связи большое значение имеет выполнение требований, предъявляемых к ее надежности, стабильности генерируемых частот, избирательности приемной аппаратуры. Применение кварцевых резонаторов, широко используемых в радиосхемах сегодня, частично позволило повысить надежность средств связи и гарантировало высокую стабильность частоты без усложнения схемы. Современные мировые тренды разработки электротехнической аппаратуры связаны с ее миниатюризацией. Габариты кварцевых резонаторов с каждым годом уменьшаются, при этом требования к надежности характеристик остаются высокими. Цель работы – оценка возможности применения кварцевых резонаторов, представленных в миниатюрном керамическом корпусе размером $2.5 \times 2.0 \times 0.6$ мм, в условиях повышенной температуры окружающей среды, а также выработка оптимальных требований к режиму термотренировки, который является базовой технологической операцией для стабилизации частоты колебаний.

Методы. Испытание кварцевых резонаторов на безотказность и методы статистического моделирования в радиотехнике.

Результаты. Установлены требования к надежности характеристик кварцевых резонаторов РК588 в миниатюрных керамических корпусах размером $2.5 \times 2.0 \times 0.6$ мм при воздействии повышенной температуры окружающей среды $+85^\circ\text{C}$ и $+125^\circ\text{C}$. Установлены требования по уходу частоты при воздействии повышенной температуры окружающей среды на тип кристаллической пластины, созданной на основе патента РФ № 27122426 «Способ изготовления тонких кристаллических пластин и тонких кристаллических элементов». Оптимизирован способ термотренировки и установлены коэффициенты старения.

Выводы. Расчетный коэффициент старения резонаторов в процессе испытаний на безотказность для партии № 1 при температуре $+85^\circ\text{C}$ составил 0.75, а для партии № 2 при температуре $+125^\circ\text{C}$ составил 0.18. Для данного типа пьезоэлемента размером 1.5×1.0 мм при рабочей температуре $+125^\circ\text{C}$ коэффициент старения ниже в 4 раза, чем при температуре $+85^\circ\text{C}$, что говорит о возможности применения резонатора РК588 в условиях повышенной температуры окружающей среды.

Ключевые слова: кварцевый резонатор, надежность, керамический корпус, частота колебаний, температура

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INTRODUCTION

In the development of devices for radio electronics and communications, it is important that the high requirements for its reliability, stability of the generated frequencies, and selectivity of the receiving equipment are fulfilled. The problem of increasing the reliability of communications has been partially resolved through the use of quartz resonators as widely used in radio circuits today. The use of quartz resonators in power generators has allowed for high frequency stability to be guaranteed without complicating the circuit. Electronic filters with quartz resonators have a higher performance than similar filters with inductors and capacitors¹.

At the present time, the production of quartz resonators is considered economically profitable, despite the appearance of materials whose stability of some parameters is higher than that of quartz.

One way in which the competitiveness of production can be enhanced is to reduce the price of products. This can be achieved by changing the technology of their manufacture. For example, by changing the thermal training regime, it is possible to reduce the production time without compromising the quality of the product. However, not all technological processes can be changed.

Heat treatment, i.e., maintaining at a high temperature for a certain time, is one of the important steps in manufacturing quartz resonators. This process takes place at the final stage of production [1]. This aim of this technological operation is to create artificial conditions for the ageing of a quartz resonator.

The quartz resonator ageing process is a combination of different physical processes which over time lead to a change in the resonant frequency of the product. Since most of these processes tend to return to the state of thermodynamic equilibrium after their completion, the resonator goes into a stable state, while frequency drifts become insignificant and acceptable for most devices [2].

The ageing process is complex and multi-stage. Thus, the thermal training regime is selected experimentally, based on the operating conditions of the given type of quartz resonator.

Thermal training most often requires more time than the manufacture of the resonator itself. The complexity and diversity of the quartz resonator ageing processes do not allow for an evaluation of the behavior of each specific product, or calculation of the most suitable regimes [3].

The aim of this study is to evaluate the possibility of using quartz resonators packaged in a miniature ceramic case $2.5 \times 2.0 \times 0.6$ mm, under conditions of elevated ambient temperature. An additional objective is to develop optimal requirements for the thermal training regime as the basic technological operation for stabilizing the oscillation frequency.

STUDY OF THE RELIABILITY CHARACTERISTICS OF RK588

Change in the frequency of a quartz resonator over time occurs under stable operating conditions. This is due to irreversible changes in the properties of crystals, fasteners, and associated devices. In this case, several particular features are observed:

- in most cases, the ageing process is described by the exponential law of resonator frequency drift over time. The smooth course of the ageing curve is disturbed. Its magnitude and nature depend on the type of resonator;
- the rate of ageing increases with increasing temperature;
- the relative frequency drift during ageing and its characteristics depend on the properties of the inert gas in the case where the quartz resonator is located [4].

Quartz Oscillators and Resonators, a research and production facility of the joint-stock company *LIT-FONON*, possesses equipment which allows for experiments at temperatures of +85°C and +125°C to be conducted. For the experiment, 42 resonators of the RK588 type in a ceramic case with overall dimensions of $2.5 \times 2.0 \times 0.6$ mm and a nominal frequency of 40 MHz (Fig. 1) were selected at random. These resonators were created based on the RF patent No. 27111426 “A method of manufacturing thin crystalline plates and thin crystalline elements.” The size of a quartz piezoelectric element with a sputtered silver-containing electrode was 1.5×1.0 mm.

¹ Boychuk M.I. *Digital temperature-compensated crystal oscillator in a ceramic case for surface mounting*. Cand. Sci. Thesis. Moscow: MIREA; 2019. 163 p. (in Russ.).

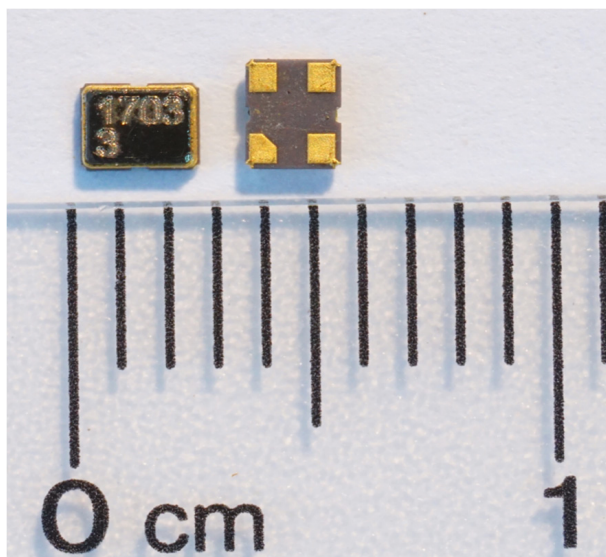


Fig. 1. General view of quartz resonator *RK588*

Of 42 resonators, 3 batches of 14 resonators were formed (hereinafter—Batch No. 1, Batch No. 2, and Batch No. 3). Batch No. 1 consisted of resonators which underwent thermal training at a temperature of +85°C for 1000 h. Batch No. 2 consisted of resonators which were studied at a temperature of +125°C for 1000 h. Batch No. 3 was also studied at 125°C, but over a period of 100 h. The frequency of the resonators in batches No. 1 and No. 2 was measured in the following order of thermal training time: 125, 250, 500, and 1000 h. For Batch No. 3, measurements were performed daily every 24 h. Before starting the experiment, the frequencies of all resonators were measured using the Dinar technological equipment (Fig. 2). After measuring Batch No. 1, the resonators were placed in a heat chamber at a temperature of +85°C. For batches Nos. 2 and 3 a temperature regime of +125°C was set. After each pre-set period of time, the thermal chamber entered a slow cooling regime. This prevented a high temperature in the crystal piezoelectric element of the quartz resonator which could lead to a high load on the crystal, electrode and affect its frequency [5].

The resonators reached thermodynamic equilibrium with the environment at room temperature 12 h after the thermal chamber had completed the process of slow cooling. Under such conditions, the frequency measurements described below were performed.

All tests and measurements of the frequencies in this experiment were conducted using the Dinar frequency measuring setup. The setup allows for measurements of resonator frequencies in the range from 1 Hz to 100 MHz. Measurement accuracy decreases with increasing resonator frequency. In order to avoid errors in the calculation of the frequency deviation from the norm, the measurement error for each type of a resonator needs to be determined.



Fig. 2. Dinar temperature-controlled setup for frequency measurements

Most often, frequency measurements are carried out in relative units [6]:

$$\frac{\Delta f}{f_{\text{DAC}}} = \frac{f - f_{\text{DAC}}}{f_{\text{DAC}}}, \quad (1)$$

where f_{DAC} is the nominal resonance frequency of the resonator, Hz; f is the actual resonator frequency, Hz.

For resonators in a sealed case, the dimensionless relative frequency, expressed in relative units, is applicable. In order to reduce the probability of an accidental error, measurements of the resonators frequencies were conducted in the same pads (sockets) of the Dinar setup.

Fourteen resonators with a frequency of 40 MHz were selected. They underwent thermal training for 1000 h at a temperature of +85°C. If we assume completion of the ageing processes in these resonators, then the frequency distribution of the resonators over a short time interval can be used to determine the error of the Dinar frequency-measuring setup.

The measurements were performed at a temperature of +25°C, low air humidity, and normal pressure. First, the frequency of each resonator of a given batch was determined. Then, the resonators were removed from the Dinar setup and remained under unchanged conditions for 4 h.² Subsequently repeated frequency measurements were carried out under the same conditions. As a result, relative frequency offsets were obtained. Their distribution is shown in Fig. 3. During repeated measurements, the frequency offsets changed, but their interval did not become larger and was in the range from $-0.5 \cdot 10^{-5}$ to $+0.4 \cdot 10^{-6}$. Based on the

² Determination of the parameters of quartz resonators. URL: http://www.cqham.ru/ua1oj_2.htm. Accessed November 17, 2021 (in Russ.).

results of the experiment, we can conclude that the error in measuring the frequency using the Dinar setup does not exceed $\pm 0.5 \cdot 10^{-6}$, i.e., the absolute error in measuring the frequency of resonators with a nominal frequency of 40 MHz obtained by the Dinar setup is no more than 11 Hz.³

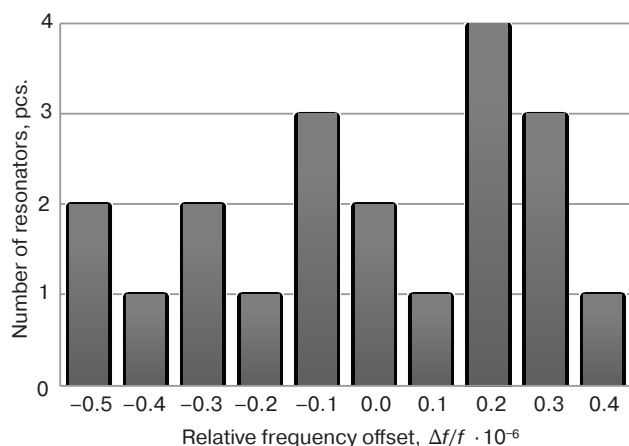


Fig. 3. Frequency distribution of resonators

In accordance with the reliability requirements for resonators of the RK588 type, the relative frequency drift during and after testing should not exceed $\pm 15 \cdot 10^{-6}$. Graphs of the frequency drift of Batch No. 1 of quartz resonators after thermal training operation are shown in Fig. 4. All resonators passed the reliability test, while the frequency deviations did not exceed $\pm 15 \cdot 10^{-6}$. This indicates the high quality of the products [7].

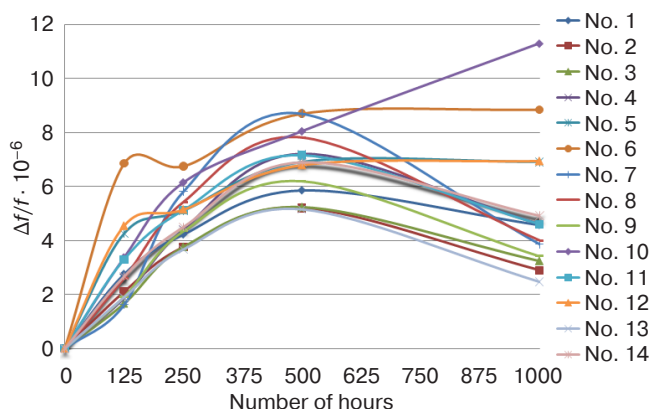


Fig. 4. Relative frequency drift over time of each resonator of Batch No. 1 at a temperature of +85°C and total testing time of 1000 h

From the graphs presented, we can conclude that after 500-h measuring, the frequency drift decreased for all resonators, with the exception of resonator No. 10. On the contrary, its frequency drift increased, but did

not exceed the norm of $\pm 15 \cdot 10^{-6}$. The frequency drift of resonators No. 5, 6, and 12 decreased; the resonators stabilized [8].

Based on the data presented in Fig. 4, the coefficient of ageing of the resonators k was calculated. The average value of the sum of the relative frequency deviations of the resonators at two key points was found:

$$s = \frac{\frac{\Delta f_1}{f_1} + \frac{\Delta f_2}{f_2} + \dots + \frac{\Delta f_n}{f_n}}{n}, \quad (2)$$

where, n is the number of units; $\frac{\Delta f_i}{f_i}$, $i = \overline{1, n}$ is the frequency offset of each resonator [9].

It is considered by most researchers and developers of quartz resonators involved in reliability prediction that long-term change in frequency over time is exponential. At the first stage, the frequency change is nonlinear. At the second stage, an almost linear section in the graph is observed with a slight change in frequency which stabilizes and smoothly decreases. It is worth noting that most products stabilize within 500 h and reach their upper frequency value, after which frequency begins to gradually decrease. Therefore, the 500-h maximum point was chosen as the base for calculating the ageing coefficient. Furthermore, in order to obtain the ageing coefficient, the resulting average value of the sum of relative frequency offsets at the 1000-h end point is divided by the average value of the sum of relative frequency offsets at the 500-h point:

$$k_1 = \frac{5.18}{6.87} = 0.75.$$

Graphs of the frequency drift of quartz resonators of Batch No. 2 after performing the thermal training operation at a temperature of +125°C are shown in Fig. 5.

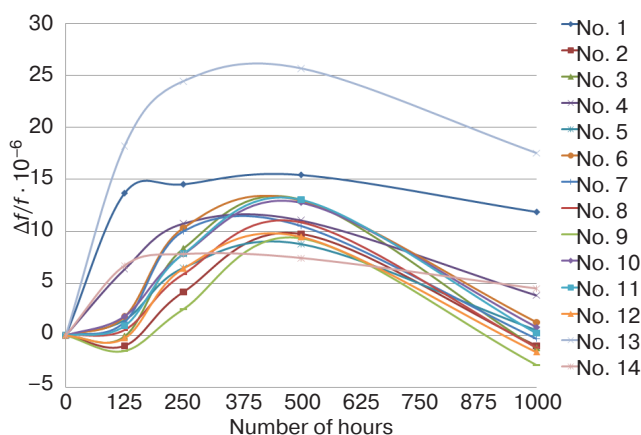


Fig. 5. Relative frequency drift over time of each resonator of Batch No. 2 at a temperature of 125°C and total testing time of 1000 h

³ Designation of a quartz resonator in the diagram: principle of operation and design. URL: <https://math-nttt.ru/teoriya/kvarcevyj-rezonator-dlya-chego-nuzhen.html>. Accessed November 15, 2021 (in Russ.).

The graphs in Fig. 5 show that the frequency drifts of resonators No. 2, 3, 5–12 at the 125-h point are minimal. The frequency drifts of resonators No. 4 and 14 at the 125-h point slightly exceed $+5 \cdot 10^{-6}$. After completion of the measurement at the 500-h point, the frequency drift of the resonators gradually decreases. However, the frequency drifts of the two resonators No. 1 and 13 go beyond the limits of $\pm 15 \cdot 10^{-6}$ established in this test. Therefore, these products will not pass the reliability test at such a high temperature⁴. The data presented in Fig. 5 was used to calculate the ageing factor:

$$k_2 = \frac{2.3}{12.14} = 0.18.$$

In order to assess the possibility of reducing the time of thermal training by increasing the temperature more precisely, the frequency drift of quartz resonators at a temperature of $+125^\circ\text{C}$ over 100 h with more frequent measurements of parameters needs to be defined. Taking the results obtained earlier into account, we planned a same frequency drift of quartz resonators as at a temperature of $+85^\circ\text{C}$ for 250 h.⁵

Figure 6 shows the relative frequency drifts of the resonators of Batch No. 3 after thermal training at a temperature of $+125^\circ\text{C}$ with daily frequency measurements every 24 h over 100 h.

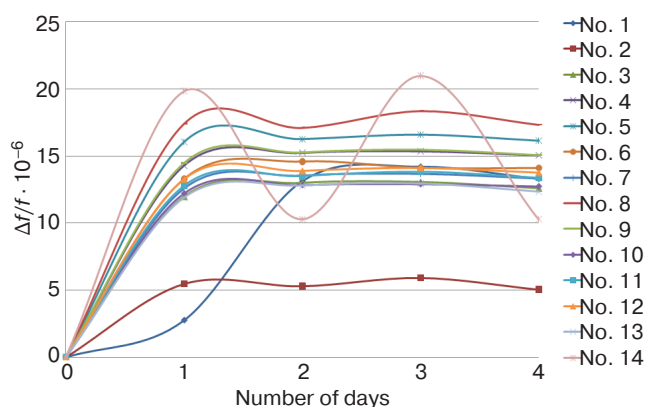


Fig. 6. Relative frequency drift over time of each resonator of Batch No. 3 at a temperature of 125°C and total testing time of 100 h

The relative frequency drift of almost all resonators of Batch No. 3 for the first day is significantly higher than for the rest of the period. After that the frequency drift stabilizes. The frequency drift of the resonators Nos. 5, 8, and 14 slightly exceeds the norm $\pm 15 \cdot 10^{-6}$.

⁴ Generators with quartz resonators. URL: <https://inventori-steam.ru/elektroteoriya/kvarcevyj-generator-princip-raboty.html>. Accessed November 20, 2021 (in Russ.).

⁵ Quartz resonators. Types and application. Device and work. URL: <https://34rozetki.ru/svet/chto-takoe-kvarcevyj-rezonnator.html>. Accessed November 20, 2021 (in Russ.).

Thus, in order to stabilize the frequency of quartz resonators in miniature ceramic cases, a minimum of 24 h is required at a temperature of $+125^\circ\text{C}$.

CONCLUSIONS

As a result of the research, requirements were formulated to define the reliability characteristics of *RK588* quartz resonators in miniature ceramic packages measuring $2.5 \times 2.0 \times 0.6$ mm when exposed to elevated ambient temperatures of $+85$ and $+125^\circ\text{C}$. Furthermore, requirements were developed for a frequency drift at elevated ambient temperature for this type of quartz resonator. These were created pursuant to RF patent No. 27122426 “Method of manufacturing thin crystalline plates and thin crystalline elements.” The method of thermal training was optimized and the ageing coefficients established.

It is worth noting that the products of Batch No. 1 and Batch No. 2, when exposed to high temperatures, reach their upper frequency value within 500 h, after which the frequency of the resonators begins to gradually decrease. Therefore, the maximum point was chosen as the base for calculating the ageing coefficient [10].

Thus, based on the results of tests of quartz resonators for failure-free operation for Batch No. 1 at a temperature of $+85^\circ\text{C}$, the calculated ageing coefficient was $k_1 = 0.75$. For Batch No. 2 at a temperature of $+125^\circ\text{C}$ it was $k_2 = 0.18$. The ratio of the coefficients during the ageing processes was:

$$d = \frac{k_1}{k_2} = \frac{0.75}{0.18} = 4.1. \quad (3)$$

For this type of piezoelectric element with a size of 1.5×1.0 mm at an operating temperature of $+125^\circ\text{C}$, the ageing coefficient is 4 times lower than that at a temperature of $+85^\circ\text{C}$. This indicates the possibility of using the *PK588* resonator at elevated ambient temperatures.

Authors' contribution

M.I. Boychuk—organizing experimental tests based on the LIT-FONON equipment, forming a schedule for tests, selecting the test methods, preparing the necessary equipment and tools, system analysis of the obtained results, and preparation of a technical report.

V.E. Krivonogov—carrying out initial and intermediate measurements of quartz resonators during and after tests and monitoring compliance with test deadlines.

S.A. Mikaeva—analysis of the technical report and test results, systematization of the data obtained, writing and editing the text of the article, and consultations on the selection and analysis of the literature used.

L.A. Vasilieva—selection of quartz resonators for tests, statistical analysis of the test results, and entering the data obtained on the frequency drift of the resonators at elevated ambient temperatures in the technical report.

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