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THERMAL PROPERTIES OF RUBIDIUM FREQUENCY STANDARD

The principle of rubidium standard operation is presented in the paper, with special attention to the influence of temperature on the components of the standard. Next, measurement results of the frequency of the output signal at different, variable temperatures in the environment of the standard itself are presented.

Keywords: Rubidium standards, Hold-Over, synchronization

1. INTRODUCTION

The Institute of Electronics and Telecommunications (IET) of Poznan University of Technology (PUT) has been for many years conducting design and construction work for the needs of the synchronization layer of the Polish telecommunication network [3]. A certain group of these activities is performed by generators of standard frequencies, synchronized from the GPS system. Rubidium standards, constructed in the IET laboratories, use the LPFRS generator manufactured by TEMEX [9]. The decision to choose this source was based upon its good frequency parameters, relatively low price, small dimensions, and power supply from a 12V voltage source. The application of constructed devices with this generator assumes two kinds of generator operation. Firstly, the generator works in synchronism forced by a digital phase loop controlled by the GPS system. In that case, the standard achieves a frequency instability not worse than 10^{-13} in a 24-hour observation time. The second type of generator operation consists in the switching of the standard into the “Hold-Over” mode, in which the generator is disconnected from its synchronization source. In such a state the rubidium standard works freely and its output signal is gradually detuned relative to the values of frequency established in the synchronous working mode. Closer examination of phenomena accompanying the detuning of the generator have revealed that the differences observed may be caused by different temperature in the room in which the standard is placed. This observation gave rise to carrying out research on thermal properties of the rubidium generator; the results of those experiments are presented in a following part of this paper. It is worth mentioning here that the same rubidium generators, manufactured by several companies in the world, among them also that by TEMEX, are thermostated. In the case of the LPFRS standard discussed here, the thermostat temperature was equal to 85°C and it is maintained with a tolerance of 0.3°C. Another reason for carrying out this research was the use of a double thermostat in the class of BVA generators, which made it possible to achieve a frequency instability by an order better than in classical OCXO generators.

2. OPERATION OF THE RUBIDIUM GENERATOR

2.1. General information about rubidium

Rubidium was discovered by Bunsen and Kirchoff in 1861. It is found in a few isotope forms; the basic form is Rb85. The form Rb87 was also applied in frequency standards; its half-period equals 45 milliard years [6].

2.2. Principles of operation of atomic standards

The operation of a standard makes use of the changes of energy levels of electrons. A change of energy level is accompanied by a frequency difference, expressed by the following equation [6]:

$$h\nu_0 = W_q - W_p, \tag{1}$$

where: $h = 6.63*10^{-34}$ *Js* Planck's constant; W_q, W_p - energy levels.

For rubidium the frequency resulting from Eq. (1) equals:

$$\nu_0 = 6\ 834\ 682\ 608 \text{ Hz}. \tag{2}$$

Owing to the so-called Zeeman effect, in the presence of an external magnetic field energy levels are split, which makes it possible to control the transitions of electrons between selected energy levels. In rubidium atoms, levels F_1 and F_2 are used as statistically most effective. An important feature of these transitions is a considerable difference in the population of levels N_i at levels F = 1.2. This enables easier capture of a signal with frequency ν_0, generated by transitions of electrons.

This relation is described by expression [7]:

$$\frac{N_2}{N_1} = \exp\frac{W_1 - W_2}{kT}, \tag{3}$$

where k – Boltzmann constant.

2.3. Simplified description of the rubidium operation

In modern rubidium generators two methods for obtaining effectively big population of transitions between levels F_1 and F_2 are applied simultaneously. The first one is the Zeeman effect [5, 7, 9] mentioned in section 2.2. The other method consists in using – apart from the rubidium radiation source – an additional absorption cell with a spectrum shifted relative to the rubidium source. Rubidium atoms are placed in gas cells with a temperature considerably higher than the ambient temperature. In this method a stream of rubidium lamp light is used, which contains the Rb87 rubidium isotope. A light pump excites the Rb87 atoms being at the lowest hyperfine level (F = 1) to a short-living excited state P, from which the atoms can fall onto two levels of state (F = 1.2). Thanks to filtration with vapours of rubidium Rb85 so many electrons can appear only at one level. Because the process of pumping is continuous, after some time almost all atoms are found at level F = 2, and the absorption process disappears. The emission of the microwave field takes the energy from level F = 2 and reduces it to level F = 1. The mechanism of maintaining equilibrium between these levels consists in emitting microwaves with a frequency of 6834 MHz [1, 7, 9].

The cell area is surrounded by the so-called C-coil fields, which generate small static magnetic fields to obtain the Zeeman sub-transitions of hyperfine lines; they also select a clock transition, i.e. a transition corresponding to the Zeeman excitation, for rubidium 6834 MHz. In order to reduce the influence of external magnetic fields, the whole device is placed in a magnetic shield. In Figure 1 the principle of optical pumping is illustrated for split energy levels [1, 9].

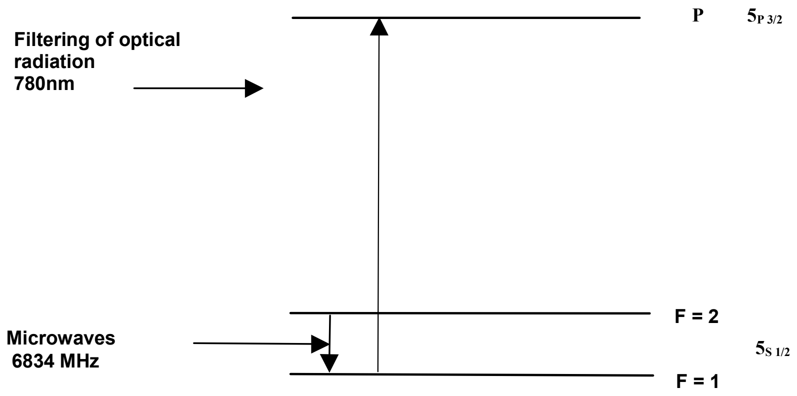


Fig. 1 Splitting of energy levels.

The radiation of a light wave with a length of 780 nm is detected by a photodiode. The current level of the photodiode is equivalent to the occurrence of an appropriate microwave field, corresponding to the frequency of 6834 MHz. The occurrence of the microwave level corresponds to the energy transition from level F = 2 to level F = 1. Through the maintenance of the photodiode signal in a system of automatic regulation it is possible to control the frequency of microwave resonance with an multiplied signal from the VCXO generator working in the PLL (Phase-Locked Loop) circuit with the microwave field. A simplified block diagram of a rubidium generator operating in that way is shown in Fig. 2.

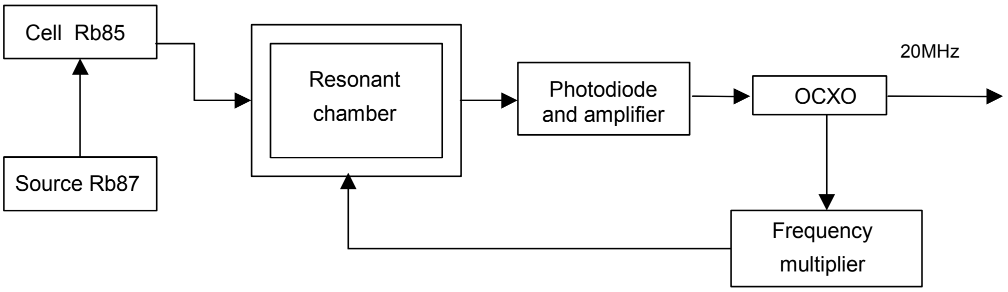


Fig. 2 Simplified block diagram of a rubidium standard.

3. INFLUENCE OF TEMPERATURE ON THE OPERATION OF A RUBIDIUM STANDARD

As mentioned in the introduction, the rubidium standard is a thermostated device. The necessity of maintaining a constant temperature is not the only reason for that. Physical phenomena forming the basis for the operation of the standard occur at much higher temperatures than the ambient temperature. Rubidium, as a metallic element, has its melting point at 38.9°C, and the boiling point at 688°C, so – although a temperature higher than 40°C is needed to obtain rubidium vapours to the filtering cell – other elements of the standard must also work at a temperature higher then the ambient temperature [9]. It concerns in particular the microwave resonant chamber in which the Zeeman effect occurs. The investigation of this effect in the function of temperature shows the maximum effectiveness at ca 130°C, and for temperatures 60°C and 160°C the effectiveness drops by several percent [5]. It is related with too-high atomic mobility of rubidium for higher temperatures, and too-low density of rubidium vapours for lower temperatures. In the LPFRS (Low Power Frequency Rubidium Source) standard the temperature of the resonant chamber itself is equal to 140°C [5]. Too-high temperature is also disadvantageous for the operation of electronic components packed in the standard, as well as due to energetic aspects related to the standard power supply. Therefore, there are areas of different temperature inside the standard, thermally isolated from one another. Another component of the rubidium standard which is particularly susceptible to the level of working temperature and temperature changes is the quartz generator.

Summarizing, we can state that the influence of temperature on the operation of rubidium standard concerns at least the following:

- light source Rb87,
- cell with rubidium Rb85,
- resonant chamber,
- Zeeman effect,
- OCXO generator.

It is beyond the research potential to define how the thermal response influences particular components of the whole active generator. Therefore, the tests will focus on measuring the frequency of the output signal of the rubidium standard, depending on the ambient temperature, controlled with an appropriate system of a thermostat with high thermal capacity. Thus three goals will be achieved:

- thermal isolation of the rubidium standard from variable ambient conditions;
- the maintenance of constant control of temperature in the environment of the standard;
- selection of an ambient temperature optimal for the operation of the standard.

4. TESTING OF THERMAL PROPERTIES OF THE RUBIDIUM STANDARD

4.1 Mesurement circuit

The rubidium generator under consideration operates at the temperature of 85°C, maintained with an accuracy of 0.3°C. The measuring system is shown in Fig. 3. It consists of the following devices:

- Heraeus thermostat, maintaining temperature with the accuracy of 0.1°C.
- rubidium frequency standard of Syn-Rb type, synchronized with GPS.
- measuring system SP 3000, enabling the evaluation of the output signal from the rubidium standard.
- rubidium frequency standard DATUM 2000, synchronized with GPS, giving the reference signal for measuring the frequency of the tested rubidium standard.

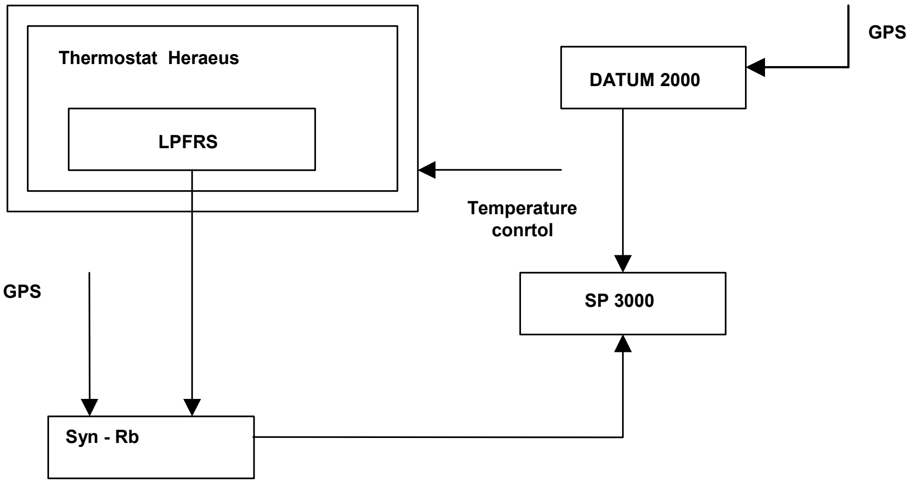


Fig. 3. Block diagram of a circuit for thermal research of the rubidium standard.

4.2. Measuring procedure

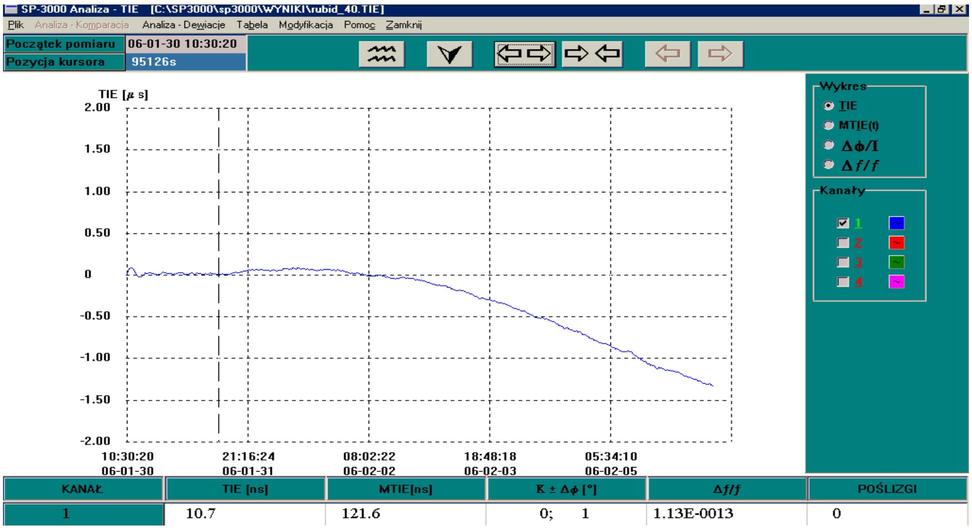
The Heraeus thermostat has a cube-size climatic chamber with 40cm-long edges. Within the area with stable temperature there is the LPFRS generator under investigation. Because the generator itself is stabilized and its temperature has a value of ca 80°C, and it therefore independently emits a lot of heat, the Heraeus thermostat can be set to a minimum temperature of 32.5°C. The temperature inside the thermostat is changed every 2.5°C, which allows a family of characteristics to be achieved for a set of data: {32.5°C, 35°C, 37.5°C, 40°C, 42.5°C}, and for a generator without thermostat. The rubidium generator tested is connected by cables to the Syn-Rb standard (the generator is part of the Syn-Rb standard), manufactured at the Institute of Electronics and Telecommunications, PUT, which ensures a stable power supply, control signals, synchronization with the GPS system and the processing of the output frequency of 20 MHz into the value of 2048 MHz [3]. This same output frequency characterizes the DATUM 2000 standard, which is the source of a reference signal for measuring the tested signal from the Syn-Rb standard.

The measuring system SP 3000 manufactured by the Institute of Electronics and Telecommunications is a device designed to test the timing signals in the synchronization layer of a digital telecommunication network [3]. The device measures the characteristic of the Time Error (TE) and converts this parameter into different forms, e.g. Time Interval Error (TIE), $\Delta f/f$. The system is equipped with software for analysing the obtained measuring data and calculating such parameters as Allan Deviance (ADEV), Maximal Time Interval Error (MTIE), Time Deviance (TDEV) [3]. This made it possible to fully assess the usefulness of the tested signal in telecommunication systems. The recorded characteristics may be compared with network standards, and on those grounds action can be taken to improve the operation of a network. According to telecommunication applications, the basic signal frequency generated by the DATUM 2000 standard is 2048 kHz. Therefore, this exact frequency value was adopted from the rubidium standard for the sake of comparison. To measure one thermal characteristic, the following actions were undertaken successively:

- the rubidium generator was placed in a thermostat,
- an appropriate temperature was set on the controller of the Heraeus thermostat,
- a synchronizing signal from the GPS system was connected for 24 hours (86400 s) to the Syn-Rb device,
- the synchronizing signal was disconnected from the Syn-Rb standard, which left the rubidium generator in the “Hold-Over” mode,
- after 4 to 5 days of recording the measurements were stopped, the results were registered and the thermostat temperature was changed into the next value.

5. MEASUREMENT RESULTS

The basic result of the measurement is the dependence between the recording time and the TIE characteristic; the dependence was indicated thanks to the measuring potential of SP 3000. An exemplary diagram of such a measurement is shown in Fig. 4.



SP-3000 Analiza - TIE [C:\SP3000\sp3000\WYNIKI\rubid_40.TIE]

Początek pomiaru: 06-01-30 10:30:20

Pozycja kursora: 95126s

Wykres: ● TIE ○ MTIE(t) ○ Δϕ/I ○ Δf/f

Kanały: ☑ 1 ☐ 2 ☐ 3 ☐ 4

KANAŁ	TIE [ns]	MTIE[ns]	K ± Δϕ [°]	Δf/f	POŚLIZGI
1	10.7	121.6	0; 1	1.13E-0013	0

Fig. 4. Exemplary diagram of the Time Interval Error TIE of the LPFRS generator for the ambient temperature of 40°C in non-synchronized mode.

The vertical dashed line in the diagram defines a time of ca 24 hours. This determines the moment of disconnecting the GPS synchronization of the rubidium generator. The quality of the output signal of the synchronized generator is very high and its frequency instability **Δ**f/f equals ca 10^{-13}. After that period the frequency changes in time, which is indicated by dropping of the curve. In order to compare the operation of the standard at different temperatures given in the thermostat, diagrams similar to that in Fig. 4. were set up from different measurements, starting the drawing of the function from the moment of disconnecting the satellite synchronization source, i.e. from the vertical line of the diagram. This comparison is presented in Fig. 5.

The characteristics in Fig. 5. themselves indicate a considerable effect of additional thermostating, positive for the generator. The rubidium generator working in a thermally unstable environment, despite its own internal thermostat, shows a considerably greater deviation from its working frequency in the state of synchronism - in relation to the generator's operation at a stable temperature of e.g. 40°C.

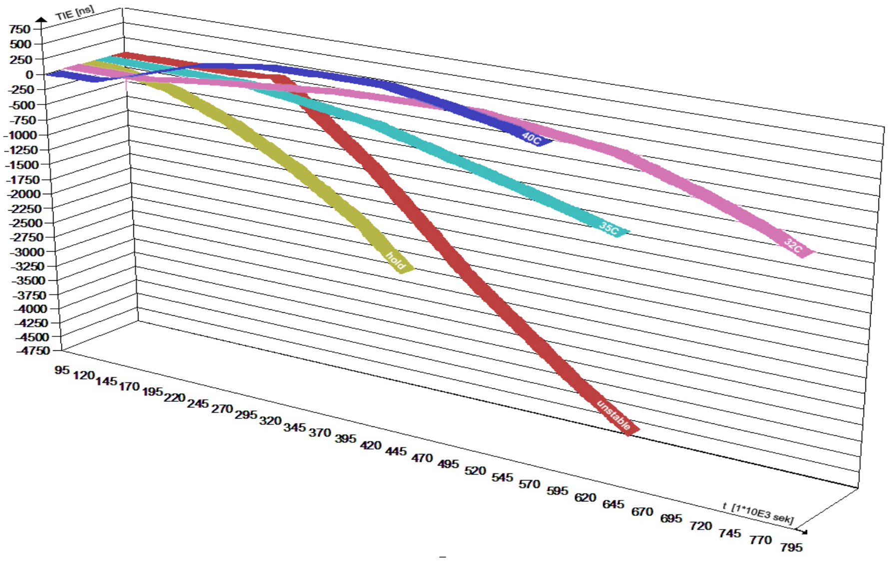


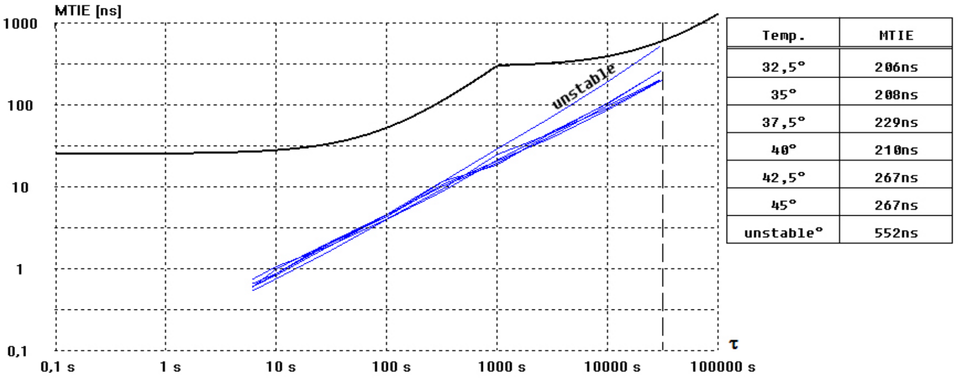
Fig. 5. Comparison of the TIE diagrams of the rubidium generator subjected to different temperatures.

Further comparison of the characteristics obtained in the measurements indicates a certain regularity. For lower temperatures of thermostating, after the synchronization signal was disconnected, TIE was initially increasing. It is especially evident in the diagrams for the temperature of 32.5 and 35°C. We can only regret here that it was impossible to achieve still lower temperatures in the thermostat so that we could study this phenomenon in a wider temperature range. To find an optimal ambient temperature – apart from the evaluation of TIE - it is worth while to analyse the MTIE for the recorded characteristics. Maximum Time Interval Error (MTIE) describes the behaviour of TIE for different values of the observation time. The smaller is the slope of the diagram of this characteristic, the better are the instability parameters of the tested characteristic.

5.1. Analysis of the measurement results

The SP3000 measuring system records measurement results as a characteristic of TIE in the function of time. Based on the diagrams obtained and compared in Fig. 5 we can estimate some trends resulting in a positive influence of additional thermostating on the Time Interval Error (TIE) of the output signal of the generator. A more interesting problem is what value of temperature of the additional thermostating is the best for the generator to maintain the previously synchronized frequency. Owing to applications of the Syn-Rb standard (in which the rubidium generator works) in telecommunications, the MTIE parameter was chosen for the assessment of this aspect. The parameter is normalised by ITU recommendations (International Telecommunication Union) [8]. In the case considered, in order to compare the calculated MTIE characteristics, the MTIE-PRC (Primary Reference Clock) standard was applied, which defines the required quality of timing signals for the synchronization from an atomic standard [7]. The Maximum Time Interval Error (MTIE) describes the behaviour of TIE for different values of the observation time. The smaller the slope in the diagram of this characteristic, the better the instability parameters of the tested characteristic [3].

In the diagram in Fig. 6. we find the MTIE characteristics for all measurements carried out at different temperatures. One of the measurements concerns the situation when the generator was taken out of the Syn_Rb device and placed in the thermostat which was not switched on. The measurements for that case are marked as “rubid_niestab”.



Temp.	MTIE
32,5°	206ns
35°	208ns
37,5°	229ns
40°	210ns
42,5°	267ns
45°	267ns
unstable°	552ns

Fig. 6. MTIE(t) for different ambient temperatures around the rubidium standard.

The characteristics in the diagrams of Fig. 6 indicate a different value of the MTIE parameter in the function of temperature. For precise assessment of the phenomena, particular attention was drawn to observation times of 31622 s, i.e. ca 8 working hours. For short observation times the characteristics for different temperatures do not differ significantly from one another. This is so until the observation time, equal to 10000 s, is exceeded; then the temperature characteristics are split. The most significant effect is steep rising of the characteristic in the case of a thermally unstable generator. Therefore the conclusion can be drawn that the rubidium generator placed outside the device and unprotected against temperature changes has a significantly worse thermal characteristic.

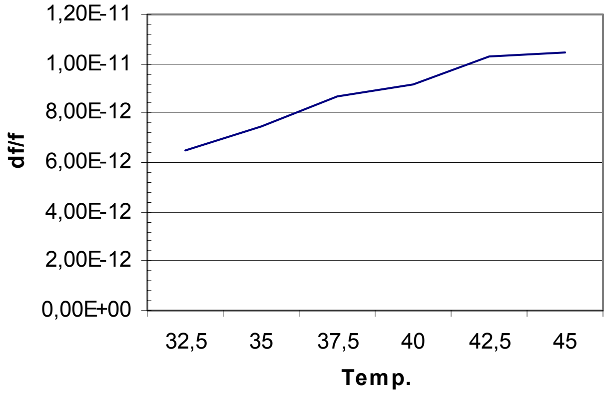


Fig. 7. Characteristic of the function of frequency instability for an observation time of 31622 s at different ambient temperatures of the rubidium standard.

The rest of the characteristics are also divergent, but the differences in slope between them are not great. In the diagram in Fig. 7 the values of frequency instability Df/f are compared, which were calculated from the MTIE parameter based on formula [2, 4]:

$$\frac{\Delta f}{f} = \frac{MTIE(t)}{t}. \tag{4}$$

In the characteristic in Fig. 7 the slope of the thermal characteristic of the LPFRS rubidium standard can be defined.

1. The working temperature of an additional thermostat is most favourable for the operation of the rubidium standard at lower temperatures.
2. The slope coefficient of the characteristic of frequency instability in the function of ambient temperature in the tested range of 32.5°C - 45°C, for an observation time of ca 8 hours, equals:

$$\frac{\frac{\Delta f}{f}}{°C} = \frac{2.4\times10^{-13}}{1°C}. \tag{5}$$

6. CONCLUSION

The measurement results presented in section 5 make it possible to estimate the influence of additional thermostating on the operation of the rubidium generator. It is worth remembering at the same time that the whole problem considered concerns the situation when the generator works in the “Hold-Over’ mode (here in accordance with the English naming). Based on the tests carried out, the slope coefficient of the characteristic of frequency instability in the function of temperature (5) was determined, which is a better result than that indicated in literature [2].

Typical are the measurement results for cases of unstable ambient temperature. The “rubid_unstable” characteristic is the worst of all other tested characteristics; the value of the MTIE parameter is then 3 times worse than for the optimal case. The best summary of the rest of the characteristics examined is given in Fig. 7. Unfortunately, because of the long duration of particular measurements, the influence of additional thermostating was not tested in the whole working range of the rubidium generator. From catalogue data [8] it results that the most favourable ambient temperature of the rubidium generator is 35°C, which coincides with the results of measurement carried out here. However, the tests carried out included only half of the thermal range of the operation of the generator; it is hard, then, to determine the characteristic of the function from Fig. 7 for temperatures of the interval 42.5°C - 55°C.

The tests carried out are suitable for the assessment of applying the LPFRS rubidium generator as a standard frequency source in the off-line working mode. The tests indicate that for such an application a variable ambient temperature of the rubidium standard reduces the working time with parameters required in telecommunication applications. The best working parameters are achieved for stable and lower ambient temperature. It can be noticed here that this conclusion is difficult to be realized in practice, because the internal thermostat of the rubidium generator emits a power of over 20W, so that in its close environment the temperature significantly exceeds 35°C. In order to satisfy this condition, it would be necessary to provide effective cooling in the device case or significantly increase the dimensions of the device.

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TERMICZNE WŁAŚCIWOŚCI RUBIDOWEGO WZORCA CZĘSTOTLIWOŚCI

Streszczenie

W artykule przedstawiono zasadę działania wzorca rubidowego ze szczególnym uwzględnieniem wpływu temperatury na jego podzespoły. Następnie przedstawiono wyniki pomiarów zachowania się częstotliwościowego sygnału wyjściowego w różnych, zmiennych temperaturach otoczenia samego wzorca.