11

Chaotic instability of oscillations in microwave power amplifiers when amplifying a biharmonic signal

© L.A. Morozova, S.V. Savel'ev

Fryazino Branch, Kotel'nikov Institute of Radio Engineering and Electronics, Russian Academy of Sciences,
141190 Fryazino, Moscow oblast, Russia
e-mail: mila-morozova.ludmila@yandex.ru

Received April 20, 2024
Revised October 1, 2024
Accepted October 29, 2024

The occurrence of chaotic instability of oscillations at the output of a single-stage amplifier on a powerful bipolar microwave transistor when a biharmonic signal is amplified is considered. It has been established that at a high level of the input signal at the output of the amplifier, the signal contains a significant chaotic component. Cases were experimentally studied when the frequency distance between the partial frequency components of a biharmonic signal is close to the gain band and when it is much smaller than this band. It has been established that in the first case, the chaos in oscillations is associated with the emergence of a sequence of trains of a forced oscillatory process with arbitrary initial phases and durations. In the second case, the appearance of a chaotic pedestal is associated with the chaos in the passive underexcited mode of the nonlinear circuit formed by the capacitance of the $p-n$ junction and the input matching circuits of the amplifier stage.

Keywords: chaos, power amplifier, biharmonic signal, sequence of oscillation trains, chaotic modulation.

DOI: 10.61011/TP.2025.01.60520.137-24

Introduction

The issues of amplifier stability have been extensively studied within the framework of the general theory of stability of circuits containing active elements [1,2]. However, the stability of amplifiers is a much more serious problem in the microwave range than at low frequencies. This is especially true in case of usage of semiconductor active elements, when, the impact of parasitic parameters associated with the final dimensions of the terminals and housing elements of such active elements simultaneously increases with an increase of the absolute frequency range in which the stability of the amplifier should be ensured [3]. At the same time, a powerful microwave amplifier easily loses stability when the bias voltage exceeds a certain value and can switch to the mode of generation of both deterministic and chaotic oscillations [4].

Unusual phenomena associated with stability changes are also observed in a number of cases in multimode active systems [5,6], as well as when they are exposed to complex, for example, biharmonic signals [7,8] with both very different frequencies and similar frequencies. The output signal becomes chaotic at certain parameter values in case of interaction with the system's eigen modes.

Amplification cascades of transistor microwave devices are known to operate in a significantly nonlinear range of modes in case of a high input signal level. The properties of $p-n$-junction under these conditions depend on the input signal level, and the output signals depend non-linearly on the input effects. The experimental results presented in this paper show that a violation of the linearity of the amplifier in the case of several input signals leads to chaotic oscillations at the output in addition to the known distortions.

Intermodulation distortions may occur in case of amplification of complex signals in microwave amplifiers. They constitute additional components in the output signal spectrum that appear in the nonlinear elements of amplifiers (transistors) when several signals with different frequencies interact (for example, [9]). An important role is also played by the phase distortion of signals that occur on large signals in case of designing of power amplifiers for cellular base stations [10]. The forced generation of chaotic oscillations in case of amplification of complex signals has not been considered in the scientific literature.

The purpose of this paper is to study the conditions for the occurrence of the phenomenon of chaotic oscillations at the output of high-power microwave amplifiers on bipolar transistors.

1. Setting up the experiment

This paper experimentally studied the complex operating modes of powerful amplifiers in the centimeter wavelength range that occur when a biharmonic signal is amplified with comparable amplitudes of its components. The block diagram of the measuring unit is shown in Fig. 1.

Amplification cascades comprised single-stage microwave amplifiers, which included: one active element — a bipolar microwave transistor and matching circuits based on microstrip lines. Amplification cascades based on bipolar transistors 2T982 A−2, 2T937 B−2, 2T938 A−2 (https://eandc.ru/catalog/2t982a-2) were used. Microstrip

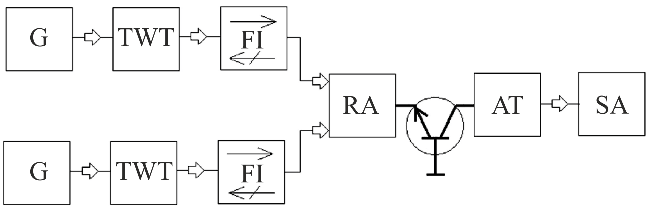

Figure 1. Block diagram of the measuring unit. G — generator; TWT — traveling wave tube; FI — ferritic isolator, RA — ring adder; AT — attenuator, SA — spectrum analyzer.

lines and matching circuits were created using standard technology on a material with a high permittivity $\varepsilon = 10$, FLAN−10 (http://www.moldavizolit.com/rus/1_mat_for_pcb/svch/flan.html).

Two single-frequency signals from standard signal generators G4−80 (https://www.meratest.ru/produktsiya/radioizmeritelnie_pribori/generatory_signalov/vch/product/g4-80/), amplified to the required power level, each with its traveling wave tube (TWT) were used as input. The biharmonic signal was supplied directly to the input of the amplification cascade through a microstrip ring adder, the summing inputs of which were connected to TWT outputs. Their outputs were connected to the inputs of the microstrip adder through coaxial ferrite isolators for decoupling. The spectrum of the output signal of the amplification cascade was observed on a spectrum analyzer C4−60.

Two different phenomena have been identified as a result of the study. The first occurs in conditions when the interval between the frequencies of the biharmonic signal F_1 and F_2 is small compared to the gain band of the transistor cascade Π, i.e. when the ratio $\Delta F = |F_1 - F_2| \ll \Pi$ is fulfilled. The second phenomenon occurs when the frequencies of the biharmonic signal F_1 and F_2 are located at the boundaries of the gain band of the transistor cascade, so that $\Delta F \approx \Pi$. This separation is determined not only by the frequency distribution of the biharmonic input signal, but also by the conditions of oscillation randomization imposed on the input signal parameters and supply voltages, which apparently determine the mechanisms of transition to chaos.

2. Biharmonic signal amplification with close frequencies

Two effects are observed when the frequency difference of the biharmonic signal is much smaller than the gain band of the transistor cascade:

– the output signal of the amplifier contains combinational components both in the gain band (with a frequency interval of ΔF) and outside this band at frequencies of $F_j = K_j|F_1 - F_2|$, where $\mathbf{K_j} = 1, 2\ldots$;

– with a certain frequency difference of the acting biharmonic signal, the output fluctuations in the gain band become chaotic.

The evolution of the output signal of the amplification cascade based on transistor 2T937B−2 with a sequential decrease of the frequency difference of the external biharmonic signal within $0 < \Delta F < 18$ MHz is shown in Fig. 2). The amplification cascade was studied with the following supply voltages: voltage between the emitter and the base of the transistor $U_{\text{eb}} = -0.4$ V, voltage between the collector and the base of the transistor $U_{\text{kb}} = 15$ V. Input signal power $P_1 + P_2 = P_{nom}$, where P_1 and P_2 are the powers of single-frequency components at frequencies F_1 and F_2, respectively, P_{nom} is the nominal output power of a single-frequency signal, at which the signal output power of the amplifier has a maximum value.

The oscillation spectra at the output demonstrate the presence of combinational components of the frequency difference F_1 and F_2 at $\Delta F > 18$ MHz. The spectrum is equidistant in this case with an interval between frequencies ΔF (Fig. 2, *a*). This is accompanied by the occurrence of modulation components with frequencies $F_j = K_j|F_1 + F_2|$, where $K_j = 1, 2\ldots$. The decrease results in the occurrence of a noise pedestal in the gain band (Fig. 2, *b*, $\Delta F = 6$ MHz) and global chaotic oscillations (Fig. 2, *c*) at $\Delta F = 3$ MHz. The envelope of the noise signal basically repeats the frequency response of the amplification cascade. Chaotic oscillation in the gain band does not lead to chaotic oscillation at the frequencies $F_j = K_j|F_1 - F_2|$, $K_j = 1, 2\ldots$. The spectrogram in this part of the range remains equidistant with a decrease of the oscillation amplitude with an increase of K_j. A further decrease of ΔF results in the weakening of the amplitude of chaotic oscillations (Fig. 2, *d*) and the usual single-frequency amplification when the frequencies of the input biharmonic signal are equal (Fig. 2, *e*).

Experiments show that chaotic oscillations in a powerful microwave amplification cascade on a transistor are possible only in case of certain values of voltage between the emitter and the base of the transistor $U_{\text{eb}} < -0.38$ V. Chaotic oscillations were observed with the following bias voltages in case of other types of amplification cascades: with at $U_{\text{eb}} < -0.58$ V for transistors of type 2T938 A−2, with $U_{\text{eb}} < -0.25$ V for transistors of type 2T982 A−2, and the transition to chaos in the amplification cascades on these transistors is similar to the one considered.

The excitation of chaotic oscillations also depends on the power of the input signal. The most developed chaos was observed with power values $P_1 + P_2 = (0.3 - 0.4)P_{nom}$ for all types of amplification cascades. At the same time, the power of chaotic oscillations P_{ch}, measured using a narrow-band filter that locks the signal at frequencies of an external biharmonic signal, was $P_{\text{ch}} \approx P_{nom}$. A decrease of the power of the biharmonic signal led to a decrease of the power of chaotic oscillations, and then to their complete disruption. However, the chaotization is still possible in case of bias voltage U_{eb} with large values of the absolute magnitude. A narrowing of the spectrum of chaotic oscillations is observed with an input signal power of more

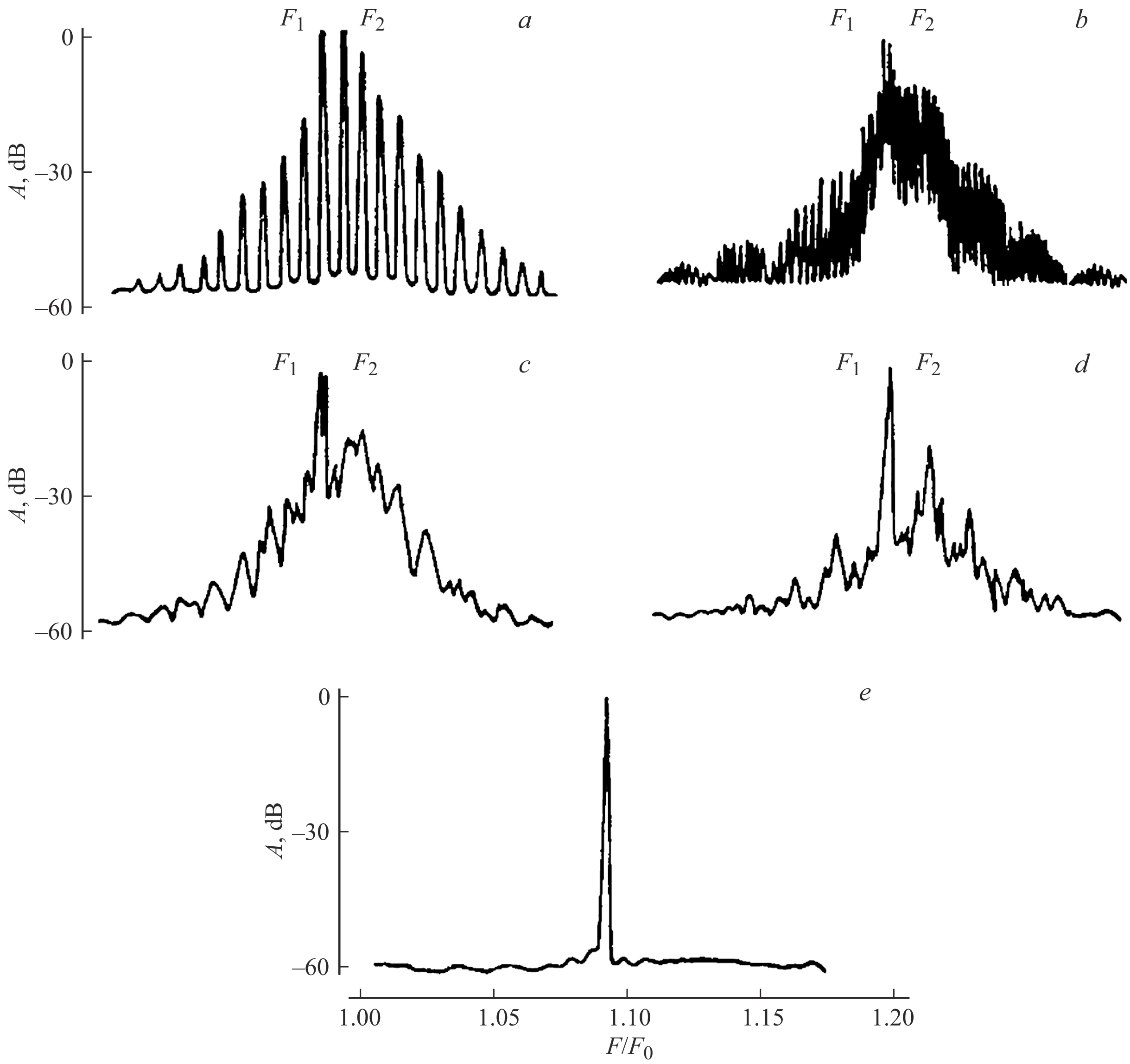

Figure 2. Dynamics of changes in the signal spectrum of the amplification cascade based on transistor 2T937 B−2 with a decrease of the frequency difference of the external biharmonic signal; ΔF, MHz: 19 (*a*); 6 (*b*), 3 (*c*), 1 (*d*), 0 (*e*).

than $0.5P_{nom}$ with a further transition to a multi-frequency mode of operation.

The diagram of the zones of existence of chaotic oscillations at ΔF, corresponding to their maximum power for the studied types of amplification cascades, depending on the power of the input biharmonic signal $P_1 + P_2$ and the bias voltage U_{eb} is shown in Fig. 3. The numbers *1−3* in this figure indicate the zones of chaotic oscillations for various types of amplification cascade on transistors 2T982 A−2, 2T937 B−2 and 2T938 A−2 respectively.

The presence of chaotic oscillation zones allows making an assumption about the mechanism of occurrence of such oscillations in powerful amplification cascade on bipolar transistors with an input biharmonic signal with close frequencies. This mechanism is based on the well-known fact that microwave generation occurs when the control voltages reach a value corresponding to the threshold, which for bipolar transistors is within the range of -0.8 V. In this case, when the frequencies of the external biharmonic signal converge and the number of combinational components increases (because of nonlinear amplification), the signal at the output of the amplification cascade acquires the character of beats with periodic alternation of relatively short intervals with large instantaneous values and time intervals during which the instantaneous values of the signal are small. The presence of periodic significant emissions in the signal causes a loss of stability and the occurrence of generation in case of a sufficient amount of constant bias (ensuring the opening of the transistor). However, such generation exists only for a limited time, determined by the duration of the intervals with large instantaneous values of the total signal at the input of the transistor. A sequence of

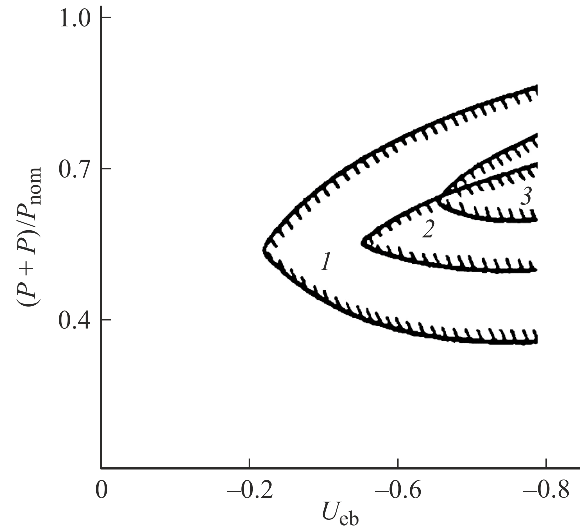

Figure 3. Chaotic oscillation zones for various types of amplification cascades on transistors 2T982 A−2 (*1*), 2T937 B−2 (*2*), 2T938 A−2 (*3*).

oscillation loops with arbitrary duration and initial phase is formed in this case.

The generation is disrupted at time intervals corresponding to small values of the total signal at the input of the transistor and occurs again at the next time interval with large instantaneous values of the total signal at the input of the transistor. In this case, bursts of generation at successive time intervals occur in the frequency range corresponding to the maximum gain. In addition, these generation arcs turn out to be out of sync with each other, as the system manages to forget the „phase" during the time between successive generation bursts. This circumstance determines the chaotic nature of the generated oscillations, which manifests itself in the formation of a continuous spectrum in the signal amplification band.

The frequency interval between the components of the biharmonic input signal, at which the most powerful chaotic oscillations were observed, is different for the studied types of amplification cascades. The values of the frequency interval ΔF corresponding to these modes were 7.0, 3.0 and 2.0 MHz for the amplification cascades on transistors 2T982 A−2, 2T937 B−2 and 2T938 B−2 respectively.

3. Amplification of a biharmonic signal with frequencies at the edge of the gain band

Characteristic spectrograms with biharmonic signal amplification at the band boundaries are shown in Fig. 4. The spectrograms were obtained by amplifying a tandem biharmonic signal by amplification cascades based on transistor 2T937B−2 with different bias voltages U_{eb}. The spectrogram in Fig. 4, *a* corresponds to the value $U_{eb} = -0.3$ V, the spectrogram in Fig. 4, *b* was obtained with a voltage of $U_{eb} = -0.6$ V. Collector voltage in both cases $U_{cb} = 15$ V. As can be seen from the above spectrograms, a noise pedestal was observed in the amplification band of the cascade, which existed within a wide range of the supply voltages of the transistor and the input powers of the external biharmonic signal. The maximum of the noise pedestal corresponded to the maximum gain of the cascade in frequency. The amplitude of the noise pedestal with a constant input signal depends most on the transistor bias U_{eb}, which determines the gain of the transistor and the degree of nonlinearity of the emitter p−n-junction. The amplification cascades based on transistors 2T982 A−2 and 2T938 A−2 demonstrated similar behavior. Reduction of the bias voltage to zero did not lead to the complete disappearance of the noise pedestal, which indicates that the mechanism of randomization in this case is different from that described earlier.

Changing the power and frequency ratio of the affected signal also affects the amplitude of the noise pedestal. Each type of amplification cascade has its own input signal power level $(P_1 + P_2)$, at which the amplitude of the noise pedestal is maximum, while its relative values were approximately the same and corresponded to the level of $P_1 + P_2 = (0.15 - 0.25)P_{nom}$. At the same time, the power of the noise pedestal, measured by a broadband bandpass filter, corresponded to the level of $\sim 0.15P_{nom}$.

The variation of the frequencies of the input signal both with the increase of the interval ΔF and with its decrease with constant input power resulted in a smooth

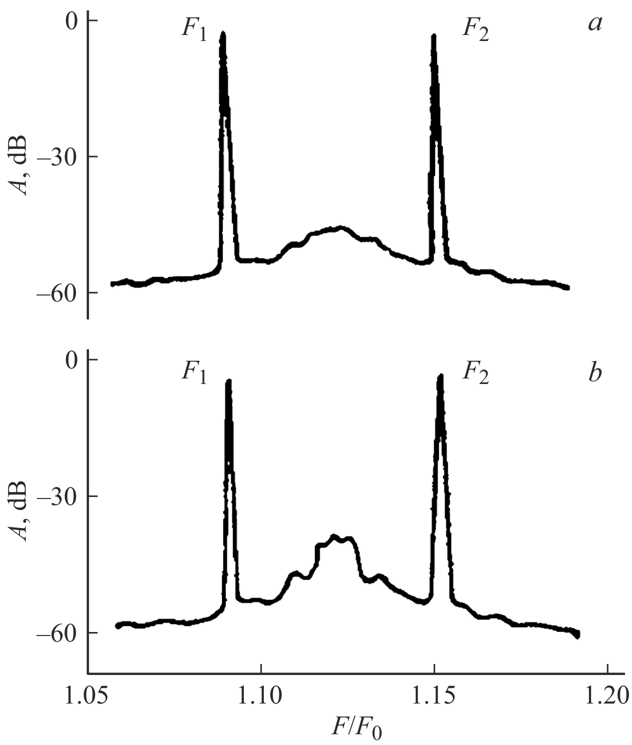

Figure 4. Spectrograms in case of amplification of a tandem biharmonic signal with amplification cascades based on transistor 2T937 B−2 with U_{eb}, V: = −0.3 (*a*) and −0.6 (*b*).

decrease of the amplitude of the noise pedestal. The maximum amplitude of the noise pedestal corresponded to the frequency range of the biharmonic signal corresponding to the condition $\Delta F = \Pi$.

Thus, the nature of the phenomenon observed in these experiments differs from the previously described case. The experiments carried out allow assuming that the main role in the mechanism of the occurrence of a noise pedestal in this case is played by the nonlinear capacitance of the emitter $p-n$-junction, which, together with the input matching circuits of the amplification cascade, forms a nonlinear circuit with a natural frequency at which the conditions of self-excitation are not fulfilled. The biharmonic input signal, acting on a nonlinear circuit, leads to a periodic change of its natural frequency. The oscillations in the circuit become chaotic with a certain sufficiently large amplitude of the effect. In this case, the contour is in a pre-excited state, which in the spectral representation is considered as a noise pedestal.

The presented mechanism of chaotic oscillations in high-power amplification cascades on bipolar transistors in case of amplification of a biharmonic signal with frequencies at the boundaries of the gain band is apparently similar to the mechanism of chaotic oscillations discussed in Ref. [7,8].

Conclusions

This paper studied complex modes of three types of amplification cascades of the centimeter wavelength range based on bipolar transistors 2T982 A−2, 2T937 B−2 and 2T938 A−2 under the impact of a powerful biharmonic signal with biharmonic components having comparable power. Two characteristic phenomena have been identified that demonstrate different mechanisms for the occurrence of chaotic oscillations in high-power amplification cascades on bipolar transistors.

The first case, which meets the condition $\Delta F \ll \Pi$, is characterized by the presence of combinational components that precede the chaotic oscillation with a decrease of the interval between the frequencies of the biharmonic signal ΔF. The chaotic mechanism in this case is based on the generation of microwave oscillation patterns with an arbitrary initial phase, and the frequency of the generated oscillations is generally uncorrelated with the frequencies of the input biharmonic signal. The power of chaotic oscillations is comparable to the power of the input signal with single-frequency amplification in this case.

In the second case, when the frequencies of the external biharmonic signal lie on the boundaries of the gain band, i.e. $\Delta F = \Pi$, the chaotic oscillation is spectrally manifested in the form of a noise pedestal in the gain band of the transistor cascade, and the power of this noise pedestal is an order of magnitude less than the power of the output signal. The main role in this case is probably played by the nonlinear capacitance of the emitter $p-n$-junction, the nonlinear dependence of which leads to chaotic modulation of the system's eigen mode, with an input tandem biharmonic signal.

The experiments conducted with three types of amplification cascades show that the observed phenomena of chaotic oscillations at their output are universal with a high degree of generality for high-power amplification cascades on bipolar microwave transistors.

These phenomena can explain in some cases the abnormally high noise levels in the output stages of high-power microwave amplifiers on bipolar transistors when amplifying complex signals.

Funding

This study was carried out under the state assignment of the Kotel'nikov Institute of Radio Engineering and Electronics of the Russian Academy of Sciences.

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] J. Henrie, A.J. Christianson, W.J. Chappell. IEEE Transactions on Microwave Theory and Techniques, **58** (5), 1230 (2010). DOI: 10.1109/TMTT.2010.2045527

[2] A.S. Kotov, P.M. Meleshkevich, A.D. Zakurdaev, M.S. Vostrov, A.V. Polyakov, A.V. Khromov, S.M. Zakharov, V.P. Motorin, V.M. Polyakova, E.M. Shipilo, E.A. Grishina, E.T. Kharabadze, N.I. Levashov. Elektronnaya tekhnika, Ser. 1, SVCh-tekhnika, **3** (526), 90 (2013) (in Russian).

[3] D.E. Root, J. Verspecht, J. Horn, M. Marcu. *X-Parameters, characterization, modeling, and design of nonlinear RF and microwave components* (Cambridge University Press, The Cambridge RF and Microwave Engineering Series, 2013)

[4] S.V. Savelyev, L.A. Morozova. ZhTF, **90** (12), 2148 (2020). (in Russian). DOI: 10.21883/JTF.2020.12.50135.418-19

[5] N.V. Stankevich, O.V. Astakhov, A.P. Kuznetsov, E.P. Seleznev. Pisma v ZhTF (in Russian), **44** (10), 46 (2018). DOI: 10.21883/PJTF.2018.10.46098.17042

[6] E.P. Seleznev, N.V. Stankevich. Pisma v ZhTF (in Russian), **45** (2), 59 (2019). DOI: 10.21883/PJTF.2019.02.47227.17473

[7] V.A. Buts, D.M. Vavriv. In: *International Kharkov symposium on physics and engineering of microwave, millimeter and submillimeter waves* (MSMW, Kharkov, 2013)

[8] A.Yu. Nemets, D.M. Vavriv. Voprosy atomnoy nauki i tekhniki (in Russian). **98** (4), 282 (2015).

[9] L.A. Belov, A.S. Kondrashov, S.V. Petushkov. Elektrosvyaz, **5**, 28 (2015). URL: https://rucont.ru/efd/419915

[10] F. Sechi, M. Bujatti. *Solid-states microwave high-power amplifiers* (Artech House Publishers; 1st edition, August 1, 2009)

Translated by A.Akhtayamov