Official English translation

# Effect of low-frequency noise signal on microwave oscillator of deterministic oscillation at Si–Ge transistor

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**Aim** of this work is to show the possibility of oscillation chaotization at the effect of a low-frequency (0.1. . . 3.0 MHz) noise signal both on a feed circuit of IMPATT diode in a one-frequency IMPATT diode oscillator (IMPATT-DO) and on a feed circuit of a transistor in a one-frequency transistor oscillator. It was supposed to confirm the earlier proposed assumption that this effect, found by us for the first time for a one-frequency IMPATT-DO, can take place for any semiconductor oscillators with $p$–$n$-transition, to be more precise, its nonlinear current-voltage characteristic. **Method.** The microwave Colpitts oscillator with a simplified structure was created to solve this problem. The Si–Ge $p$–$n$–$p$-transistor was used in the oscillator as an active element. The same (0.1. . . 3.0 MHz) noise signal oscillator was used for the effect on its feed circuit as in the experiment with IMPATT-DO.

The deterministic oscillation regimes (one-frequency and two-frequencies) of the microwave Colpitts oscillator were investigated. Subsequently, the low-frequency noise signal effect on a feed circuit of a transistor was investigated and the spectra comparison of the microwave generation was made both without an effect and with it. This comparison has shown for the first time that deterministic oscillation spectra have transformed into chaotic oscillation spectra in the microwave Colpitts oscillator at the low-frequency noise signal effect on the transistor feed circuit. **Result** has fully confirmed our assumption. Therefore, this effect can take place for any semiconductor oscillators with an active element, which has $p$–$n$-transition, to be more precise, its nonlinear current-voltage characteristic.

*Key words*: microwave Colpitts oscillator, effect, low-frequency (0.1. . . 3.0 MHz) noise signal, oscillation chaotization, IMPATT diode oscillator, $p$–$n$-transition.

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## Introduction

For the first time, the possibility of generating chaotic oscillations with a wide power spectrum in the microwave range due to the nonlinear interaction of many eigenfrequencies of a multiresonance self-oscillatory system was shown in an auto-generator of two TWTs closed in a ring in which one of the lamps functioned as a non-linear element, the second one functioned as a power amplifier [1, 2]. In 2017 the 50th anniversary of this event was celebrated. It served as the starting point for the development of a new direction not only in electronics and radiophysics, but also in other areas of physics and got the general name of the nonlinear chaotic dynamics of self-oscillatory systems. So far, many diverse systems have been investigated that demonstrate chaotic dynamics [3]. Thus, with the development of solid-state microwave electronics, it was possible to create systems with even wider spectral widths in the microwave range than in TWT [4–6], using, for example, transistors. However, in the millimeter range, which the transistors are just beginning to master, it is necessary to use avalanche-span diodes (Gunned Transistor Diodes) and Gunn diodes in solid-state generators, and to implement a regime of chaotic oscillations in them, for example, in oscillators based on IMPATT (IMPATT-DO), use waveguide – coaxial cameras [7, 8], slightly changing their design [9, 10]. At present, microwave and millimeter-wave noise generators using the chaotic dynamics of active self-oscillatory systems are in demand for various fields of science and technology. Other methods were also investigated to obtain modes of oscillation randomization in IMPATT-DO.

## 1. Chaotization of oscillations in IMPATT-DO under external influence

In [11], the possibility of converting a single-frequency oscillator on an avalanche-transit diode of 7 mm wavelength range into a noise oscillator when exposed to an external narrow-band low-frequency (0.01...3.0 MHz) noise signal on an IMPATT feed circuit was shown. As for the study of this issue in the foreign literature, then, as the search conducted in [11] showed, no public access was found. In the context of explaining this effect in [11], it can be argued that this effect should "work" *for all generators with an active element containing a $p$–$n$ junction*. This refers to transistors (bipolar, field, MOS transistors), IMPATT, BARITT, tunnel diodes, etc. But, above all, this effect is important for transistor generators.

Indeed, in IMPATT-DO, this effect was associated with the possibility of adding a small noise voltage (0.1...0.5 V) to the constant voltage, which determines the operating point on the current-voltage characteristic (CVC) of the reverse-biased $p$–$n$ junction. The essence of this effect lies in the fact that it provides a significant scatter of the number of current carriers in the transit space of the diode necessary for generation at only one frequency, ensuring the generation at neighboring frequencies within the frequency band determined by the quality factor of the electrodynamic system of the generator. This situation is quite similar in substance to the scatter of current carriers in velocities, which ensures the destruction of a bunch of electrons grouped by a self-oscillating single-frequency signal in generators with instruments using electron fluxes. Particularly vividly, the result of this process, first observed near the inrush current of a 7-millimeter-wave IMPATT generator with an increase in the level of influence of a narrow-band LF noise

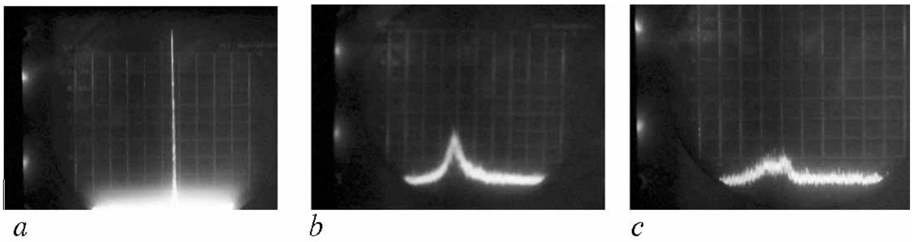


Fig. 1. Transformation of the HF signal spectra from the influence level, V: 0 (*a*), 0.02 (*b*), 0.1 (*c*)

signal [11], shows a change in the character of the spectrum of high-frequency (HF) signal presented in Fig. 1.

Therefore, it can be argued that this effect should "work" on a direct branches of the current – voltage characteristics, that is, for all generators with an active element containing a $p$–$n$ junction.

## 2. Search for popular publications on this subject

To verify this statement, a study of publications in foreign literature was conducted. However, as the search for similar publications in the Google search engine showed, such works are not publicly available abroad. Theoretical studies, as well as experimental ones, mainly relate to the transformation of the intrinsic low-frequency noise of transistors into frequent high-frequency noise of generators, for example, on field-effect transistors [12], or introducing an external signal to the input of such a generator to stabilize single-frequency generation [13].

The statement given earlier is valid and this fact is confirmed by studies of the effect of a narrow-band low-frequency generator (0.01. . . 6.0 MHz) on a system of coupled microwave generators [14], which showed the possibility of destruction of synchronous oscillations in this system under such an action. In the experiment, which was set up to test the developed theoretical model, bipolar transistors were used. As a result, the predicted breakdown in the theory of synchronous oscillations by an external low-frequency noise was illustrated by the corresponding spectrograms of the transformation of a multi-frequency spectrum into a continuous spectrum that overlaps the entire frequency band occupied by it. However, no conclusions regarding the physical processes in the transistor leading to this result have been made. There was a statement of the fact confirming the result of a theoretical study.

But it was also noted that "the frequency range of the acting noise occupies a frequency band of about 0.6% of the frequency $f$ of the autonomous generation signal and its power is $0.07P$ of the power $P$ of autonomous generation". Thus, this fact also confirms the validity of the previously proposed statement regarding generators with semiconductor devices that have a $p$–$n$ junction, in particular, for bipolar transistors. Later, the results of this theoretical study were used in [15] to create a broadband noise generator for masking the radiation of personal computers.

## 3. Chaotization of deterministic oscillations in a generator on a Si–Ge transistor

In this work, the effect of randomization of deterministic oscillations is demonstrated by the example of the impact of a narrow-band low-frequency signal on a simplified Kolpitz generator [6] on lumped elements in which a Si–Ge $n$–$p$–$n$ transistor was used. As in all generators, in which the mode of generation of chaotic oscillations could be realized, in the generator of work [6] it was preceded by the mode of single-frequency oscillations.

To conduct an experiment on the impact of a narrow-band low-frequency signal on the transistor feed circuit, a generator of the low-frequency signal was created, the spectrum of which occupied the frequency range from a few kilohertz to 3 MHz at a level of $-3$ dB and about 10 MHz at a level of $-10$ dB. The implementations of the process from the output of this generator with the help of a C1-75 oscilloscope are investigated. It was found that the probability of density distribution of the voltage amplitude $U$ obeys the Gaussian (normal) law with zero mean. The deviation of σ was determined by screen illumination and served as an estimate of the amplitude of the low-frequency signal.

To observe the spectrum of the microwave signal, we used the spectrum analyzer Hewettet Packard 8569 with a frequency measurement range from 0.01 to 22 GHz.

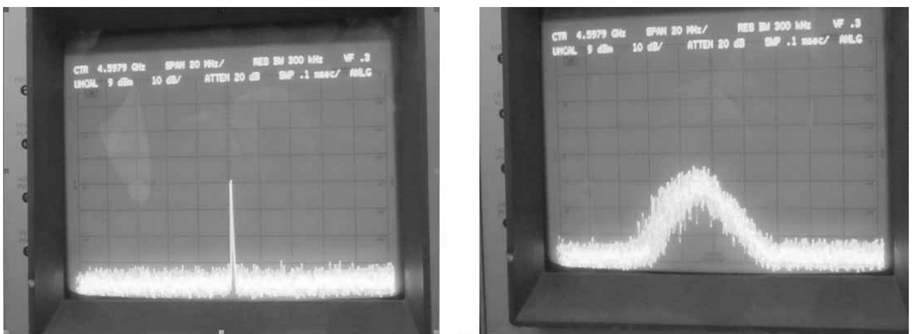
First, it was experimentally established that in autonomous generation mode at a constant emitter voltage $U_e = -2.2$ V (base is grounded) when the collector voltage changes from 0 to 1.35 V, the single-frequency generation frequency changes as follows: when $U_c = 0$, the frequency was $f_1 = 4.122$ GHz, with $U_c = +0.75$ V, the frequency is $f_2 = 4.667$ GHz and with $U_c = +1.35$ V, the frequency is $f_3 = 4.867$ GHz. Frequency changes were abrupt.

When the external noise signal of the minimum value was connected to the emitter supply at $U_c = 0$, the generation frequency abruptly shifted up to 4.667 GHz. This means that as a result of the impact, the conditions for the excitation of a higher frequency as compared with the autonomous generation mode have changed (improved), since part of the distribution of carriers has “shifted” towards the optimal value for its excitation.

The new mode required an increase in the collector voltage to $U_c = 0.28$ V, but the emitter voltage remained the same $U_e = -2.2$ V, $f_2 = 4.5979 \approx 4.6$ GHz.

In Fig. 2, *a*, *b* it is represented by generation at a frequency $f = 4.6$ GHz without an external signal and with a maximum (0.1 V) external noise signal, respectively.

As it can be seen from the figure, when an external LF noise signal is applied, the generation of a single-frequency microwave signal turns into a narrow-band noise signal with a spectrum width of about 60 MHz at $-15$ dB with a maximum at a frequency of $f = 4.6$ GHz and, judging by the distribution brightness in the spectrum, with a normal distribution law.



*a* *b*

Fig. 2. Transformation of the HF signal spectra from the influence level, V: 0 (*a*), 0.1 (*b*); $U_c = 0.28$ V

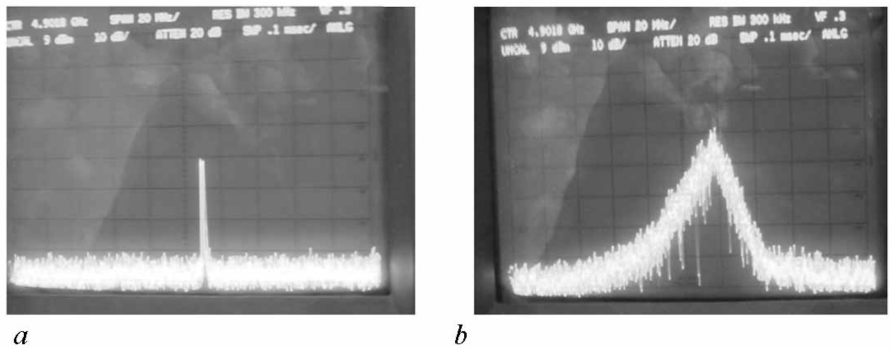


Fig. 3. Transformation of the HF signal spectra from the influence level, V: 0 (*a*), 0.1 (*b*); $U_c = 4.4$ V

With increasing collector voltage, the frequency of single-frequency generation shifts smoothly upwards. When the voltage changes to $U_c = 4.4$ V, the frequency changes smoothly to $f = 4.7$ GHz; with $U_c = 4.75$ V, a "jump" occurs to the frequency $f = 4.9$ GHz. In Fig. 3, *a*, *b* it is the generation at $f = 4.9$ GHz without an external signal and with a maximum (0.1 V) external noise signal, respectively. As it can be seen from the figure, when an external low-frequency noise signal is applied, the generation of a single-frequency microwave signal turns into a narrow-band noise signal with a spectrum width of about 30 MHz at $-15$ dB with a maximum at a frequency of $f = 4.9$ GHz and, judging by the brightness distribution in spectrum, with a normal distribution law.

Then, without an external signal, the dual-frequency generation mode $f_1 \approx 4.7$ and $f_2 \approx 4.9$ GHz was found at $U_c = 0.28$ V. But this mode exists in a narrow range of parameters. Therefore, as the collector voltage increases, the generation at the frequency $f_2 \approx 4.9$ GHz fails.

Tuning up the collector voltage with an external low-frequency noise signal switched on at an average level (0.05 V) causes the second frequency at $f_2 \approx 4.9$ GHz to be excited at $U_c = 4.4$ V and a noise mode immediately occurs along with it. In this case, the lower frequency in the spectrum is $f_1 \approx 4.7$ GHz, and the upper one is the same $f_2 \approx 4.9$ GHz, and the spectrum is shown in Fig. 4, *a*. The spectrum after increasing the level of exposure of the LF noise signal to the maximum (0.1 V) value is shown in Fig. 4, *b*.

As it can be seen from Fig. 4, *a*, *b*, the effect of a low-frequency noise signal leads in the microwave range to the overlapping of neighboring resonances at frequencies $f_1$

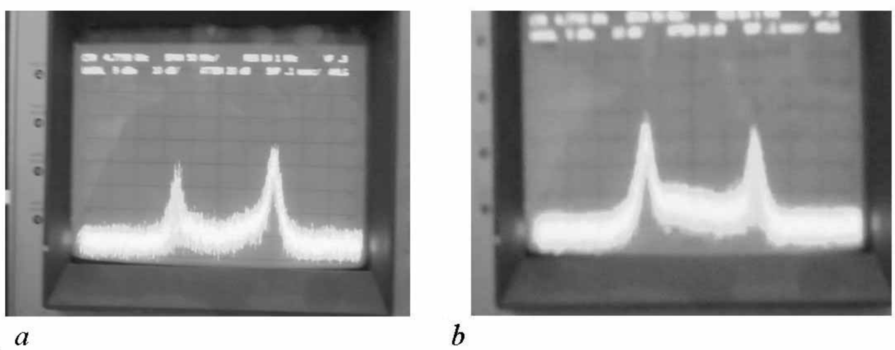


Fig. 4. Transformation of the HF signal spectra from influence level, V: 0.05 (*a*), 0.1 (*b*); $U_c = 4.4$ V

and $f_2$. An increase in the level of action leads to the "transfer" of the microwave power of the noise signal from the $f_2$ resonance to the $f_1$ resonance and to some equalization of the spectrum non-uniformity between them. However, the maximum power of the LF noise signal is not enough so that there is no "failure" between the resonant frequencies in the microwave signal spectrum.

## Conclusion

Thus, a new method to convert the mode of deterministic oscillations generation of a transistor microwave generator to noise generation with a weak nonlinearity of its active semiconductor element was proposed and demonstrated. In this case, if the generation conditions are fulfilled only for generating one frequency, then even at the maximum level of the noise signal affecting the LF signal, the spectrum width of the received noise signal is limited by a narrow band defined by the quality factor of the self-oscillating system at this frequency. In the case of excitation of two neighboring frequencies in the generator, the same maximum level of the impact of the noise signal of the noise signal is sufficient for the simultaneous randomization of oscillations of both frequencies with overlapping of their "individual" noise spectra. However, to completely overlap these spectra, the level of the external low-frequency noise signal must be greater than 0.1 V.

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