

Optical-electronic generator of determinative chaos based on bipolar field transistor structure with negative differential resistance

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ABSTRACT

The paper proposes and investigates a new scheme of an optoelectronic generator of deterministic chaos based on a bipolar field-effect transistor structure with negative differential resistance, which has a short settling time of stationary oscillations (15.36 – 19.82 ns). A mathematical model has been developed of an optoelectronic generator of deterministic chaos in the form of first-order differential equations, which allows determining the value of the output signal frequency depending on the control voltage, as well as the parameters of the main elements of the oscillator at any time. Using a software package MATLAB computer-aided circuit-technical study of the parameters and characteristics of generated electrical oscillations in a chaotic mode was carried out. Compared to analogues, the proposed and investigated opto-electronic generator of deterministic chaos has improved load capacity and higher speed.

Keywords: oscillator, deterministic chaos, transistor structure, negative differential resistance, optoelectronic oscillator

1. INTRODUCTION

The need for secure communication systems has grown exponentially over the past decade. This growth is driven by the critical role of electronic communications and radio systems in global communications, as well as the growing use of devices and systems in the Internet of Things (IoT)¹. Reliable and secure transmission of information signals has become a major challenge, especially given the increasing cyber threats and privacy concerns. Currently, traditional methods and means of ensuring secure communication often rely on standard encryption methods that can be vulnerable when using large computing power, such as those provided by quantum computing². Currently, encryption usually uses higher protocol layers and leaves the physical layer of the transmitted information signal relatively unprotected. Therefore, the use of deterministic chaotic communication can be a promising way to solve this problem, using the inherent unpredictability and nonlinearity of deterministic chaotic signals to improve security³.

Deterministic chaotic systems have good characteristics and parameters that make them suitable for secure applications in electronic communications and radio systems⁴. Their nonlinear and noise-like behavior allows for sufficient unpredictability, as well as their sensitivity to boundary and initial conditions, the deterministic nature of the output signal provides inherent encryption capabilities, which significantly adds to the difficulty of breaking a communication system or decoding a system without precise knowledge of the parameters. Such systems exhibit low autocorrelation, as well as low inter-signal correlation and wide bandwidth, which further enhances their potential as secure information carriers in electronic communications and radio systems with immunity to interference and providing a sufficient level of security of the physical channel itself for wireless data transmission⁵.

2. MATHEMATICAL MODEL OF OPTO-ELECTRONIC GENERATOR DETERMINATIVE CHAOS BASED ON BIPOLAR FIELD-EFFECT TRANSISTOR STRUCTURE

The development of devices for generating signals with chaotic dynamics is a relevant scientific direction. Self-oscillating devices and deterministic chaos systems demonstrate high efficiency, since they respond sensitively to small

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disturbances, therefore they are able to generate and form signals with a small amount of energy^{6,7,8}. The same self-oscillating system of deterministic chaos with small changes in the initial conditions or system parameters is able to generate different output information signals⁹. In contrast to the known methods of modulation, manipulation and coding of analog signals, deterministic chaos signals have a greater information capacity and noise immunity, and in many cases chaotic signals are orthogonal^{8,9}. One of the applied applications of the achievements of the theory of deterministic chaotic systems is the field of quantum-optical communications¹⁰. A significant advantage of chaotic optoelectronic systems is that there is no restriction on the spectrum of frequency bands of information signals, and therefore the number of available communication channels can be greater than the number of radio frequency channels in classical communication systems^{11,12}. The only limit to the coding of chaotic optoelectronic signals is the ability of receivers to distinguish between different chaotic states. Table 2 shows the font sizes and highlighting in a typical manuscript. These font "styles" are contained with this sample manuscript. Use Times Roman or another standard and embedded font to avoid font errors.

The electrical circuits of optoelectronic generators of deterministic chaos must be simple enough to be synchronized. A feature of generating and shaping deterministic chaos signals by analog devices is the use of their nonlinear static ordynamic characteristics. Simplicity of circuit solutions of deterministic chaos generators is a necessary condition for reducing instabilities in the operation of electronic and optical devices, which are caused by the concentration of impurities, the rate of recombination of carriers, crystal defects, and others, which leads to the transition of the self-oscillating system from chaotic oscillations to stochastic ones. The paper considers the possibility of obtaining a chaotic mode in an opto-electronic generator based on a bipolar field-effect transistor structure with negative differential resistance, the electrical circuit of which is presented in Fig. 1. The self-oscillating system has three dynamic variables, two of which are voltages on equivalent capacitances of a transistor structure with negative differential resistance (respectively, on the drain electrodes of the field-effect transistor VT2 - the collector of the bipolar transistor VT1), and the third is the current of the inductance L1. The dynamic processes of deterministic chaos are determined by the reactive properties of the bipolar field-effect transistor structure with negative differential resistance and are close in nature to chaotic processes in the generator according to the capacitive three-point scheme. To change the dynamics of chaotic oscillations and expand the working volume of the phase space, the R5C3 circuit was added, and a circuit of light-emitting diodes connected in series was added to the inductive branch of the basic circuit of the generator based on the bipolar field-effect transistor structure with negative differential resistance. The C1R3 circuit was introduced to thermally stabilize the generator operation. The ratings of the radio electronic components were selected for the following reasons: 1) to ensure the maximum length of the falling section of the static I-V characteristics; 2) to ensure a wide change in the equivalent capacitance of the transistor structure.

The generated chaotic voltage is removed from the drain of the transistor VT2 (the main output of the generator). In this case, the chaotic dynamics is controlled by changing the voltage of the power sources V1 and V2. When connecting the load resistance, it is necessary to take into account the active and reactive resistance introduced by it to the oscillatory circuit of the generator. The use of an LED allows for galvanic isolation of the output of the deterministic chaos generator with the load. In this case, the generator operates in idle mode on the main output, which allows it to be widely used in the circuits of measuring and control devices and automation. To analyze the statistical characteristics of the generated chaotic pulses, a mathematical model was developed, the further calculations of which were carried out in MATLAB R2018a.

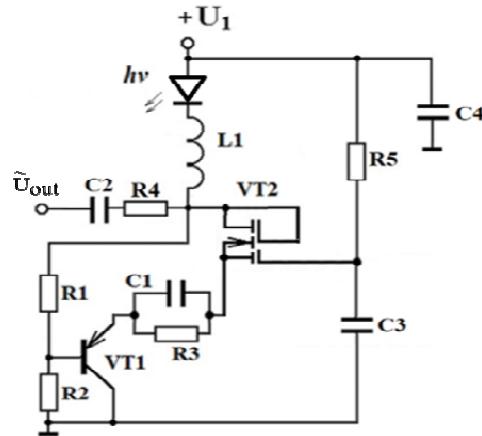


Figure 1. Electrical diagram of an optoelectronic generator of deterministic chaos based on a bipolar field-effect transistor structure.

During the analysis of the optimal variant of the deterministic chaos generator design, it was concluded that it is advisable to use the frequency information conversion method, which will allow to increase the output power of the oscillator, as well as to expand the frequency range of the generated signal. Theoretical studies have shown that as circuits of deterministic chaos generators it is advisable to use oscillator circuits based on the reactive properties of transistor structures with negative differential resistance^{13,14,15}, which implement the frequency conversion principle. In principle, oscillator transistor structures with negative differential resistance are a transistor analogue of a negatron, the I-V characteristic of which has a falling section that corresponds to the negative differential resistance, which is provided by internal feedback and serves to compensate for energy losses on the active resistances of the circuit. The complex resistance of such a structure, depending on the form of its current-voltage characteristic, has a capacitive or inductive nature, and the value depends on the voltage applied to its input. When such a structure is connected to an inductance (or, in another case, to a capacitance), a resonant oscillatory circuit is formed. If the magnitude of the voltage drop and the magnitude of the complex resistance of the transistor structure depend on the magnitude of the control voltage.

Figure 2 shows a diagram of an optoelectronic generator of deterministic chaos based on a bipolar field-effect transistor structure with the introduction of a control voltage source for the development of a mathematical model of this generator. Finding the optimal operating power point of such a circuit is carried out using two sources of constant voltage: the supply voltage U_1 and control voltages U_2 (Figure 2).

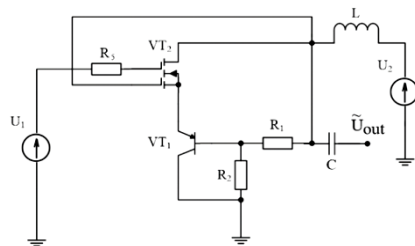


Figure 2. Electrical diagram of an optoelectronic generator of deterministic chaos.

The equivalent capacitance is part of the total capacitance of the transistor structure with negative differential resistance, which arises at the electrodes of the drain of the double-gate MOSFET transistor - the collector of the bipolar transistor, which together with the inductance L form a resonant oscillatory circuit. $L-C$ circuit, which, in view of the above, has a resonant frequency of oscillations dependent on the control voltage. To create a mathematical model of an optoelectronic generator of deterministic chaos, a nonlinear equivalent circuit is shown in Figure 3.

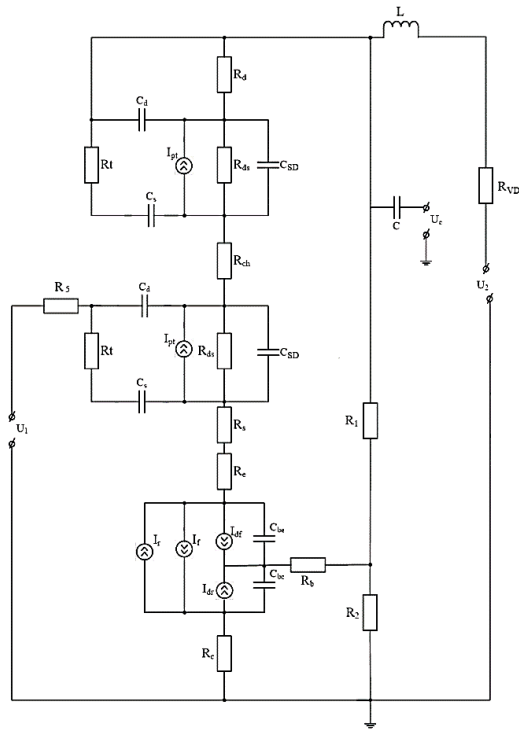


Figure 3. Nonlinear equivalent circuit of an optoelectronic generator of deterministic chaos based on a bipolar field-effect transistor structure.

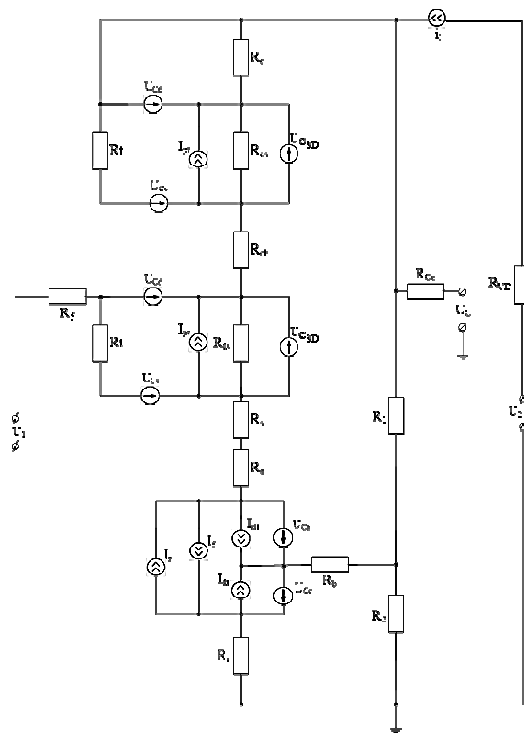


Figure 4. Converted equivalent circuit of an optoelectronic generator of deterministic chaos based on a bipolar field-effect transistor structure.

The elements of the equivalent circuit are described as follows: L – inductance; R_{VD} – internal resistance of the light-emitting diode; R_1, R_2 and R_3 – load resistances of the drain–source and base–collector junctions of transistors; R_{ds}, R_d, R_s – volume resistances of the channel, drain, and source of a two-gate MOSFET transistor; R_e, R_c, R_b – volume resistances of the emitter, collector and base of a bipolar transistor; C_e, C_c – capacitances of the emitter and collector junctions of a bipolar transistor; C_s, C_d – lock-inlet and lock-outlet tanks; C_{SD} – capacitance of the MOSFET transistor channel; I_f, I_r – forward and reverse current of a bipolar transistor; I_{dr}, I_{df} – currents of internal base–collector and base–emitter junctions; I_{pt} – channel current of a two-gate MOSFET transistor; U_1, U_2 – power sources.

To build a mathematical model of an optoelectronic generator of deterministic chaos based on a bipolar field-effect transistor structure, we will use the state variable method, which allows us to determine the values of voltages and currents of circuit elements at each moment of time. Therefore, using the state variable method, we will present a transformed equivalent circuit (Fig. 4), in which all capacitances are represented as independent voltage sources, and inductances are current sources¹⁶. In order to consider the properties of the proposed circuit and create its mathematical model, a transformed equivalent circuit for direct current was created, shown in Fig. 4¹⁷. The following simplification is made in the equivalent circuit: $I_{bt} = (I_f - I_r) / QB$, where QB – coefficient of non-ideality of the junctions of a bipolar transistor.

Having chosen the directions of bypassing the circuits and indicating the corresponding currents, we will write a system of equations according to Kirchhoff's laws (its variant - the circuit current method). We will use the resulting system of equations to analyze the circuit using the state variable method.

$$\left\{ \begin{array}{l} U_L = U_1 - (i_{R_2}(R_1 + R_{C_c}) + i_{R_3}R_2 - i_LR_{VD}); \\ i_{R_3} = i_{R_2} - i_{R_b}; \\ i_{R_{ds}} = (-U_{C_{SD}}) / R_{ds}; \\ i_{c_d} = (U_{c_s} - U_{C_{SD}} - U_{c_d}) / R_t; \\ i_{R_d} = (U_{C_{SD}}) / R_d; \\ i_{R_2} = i_{c_d} + i_{R_d} + i_L; \\ i_{R_b} = (-U_{c_c} - i_{R_c}R_c - i_{R_3}R_3) / R_b; \\ i_{R_c} = (-R_s(i_{c_d} + i_{c_s}) - i_{R_e}(R_e + R_s) - (U_2 + U_{c_s} + U_{c_c} + U_{c_e})) / R_c; \\ i_{R_1} = i_{c_d} + i_{c_s}; \\ i_{c_s} = -I_{pt} - i_{R_{ds}} + i_{c_{ds}} + i_{R_e}; \\ i_{c_{ds}} = i_{R_d} + I_{pt} - i_{c_d} + i_{R_{ds}}; \\ i_{c_c} = i_{R_c} + I_{bt} - I_{dr}; \\ i_{c_e} = i_{R_e} + I_{bt} + I_{df}; \\ i_{R_e} = i_{R_c} - i_{R_b}. \end{array} \right. \quad (1)$$

Assuming that the corresponding values of the voltages on the capacitors and the current through the inductance are given, we solve the system of equations (1) with respect to the following quantities: $U_L, i_{c_d}, i_{c_s}, i_{c_{ds}}, i_{c_c}, i_{c_e}$, making the following substitutions:

$$A_1 = \frac{-U_{C_{SD}} + U_{c_s} - U_{c_d}}{R_t} + I_{pt} + \frac{U_{c_d}}{R_d} - \frac{U_{C_{SD}}}{R_{ds}}; \quad A_2 = I_{bt} + I_{df}; \quad A_3 = U_2 + U_{c_s} + U_{c_c} + U_{c_e}; \quad A_4 = i_{c_d};$$

$$\begin{aligned}
A_5 &= -R_1 A_4 + I_{pt} - A_1 - \frac{U_{C_{SD}}}{R_{ds}} - A_3, \quad A_6 = R_e + R_s + R_1; \quad A_7 = 2U_{C_{SD}} + U_{C_e} + U_{C_d} + U_{C_c}; \\
A_8 &= \left(\frac{U_{C_s} - U_{C_{SD}} - U_{C_d}}{R_t} + \frac{U_{C_d}}{R_d} + i_L \right) (R_2 + R_3); \quad A_9 = 1 - A_6 - \frac{A_6}{R_b} (2R_2 + R_3), \quad A_{10} = A_5 + A_6 A_7 + A_6 A_8 + \frac{A_6 U_{C_c} (2R_2 + R_3)}{R_b}; \\
A_{11} &= (A_6 (2R_2 + R_3)) / R_b; \quad A_{12} = (A_4 + U_{C_d} / R_d) (R_2 + R_3); \quad A_{13} = U_{C_c} A_9 + A_{10}; \quad A_{14} = -A_7 A_9 - A_{10} + A_4 A_9 - \frac{U_{C_d}}{R_d} A_9; \\
A_{15} &= A_9 (2R_s + R_e); \quad A_{16} = A_{11} R_3 + A_9 R_3; \quad A_{17} = \frac{-U_{C_c} A_9 - A_{10} - 2A_{14} R_b - A_{15} R_b (I_{bt} + I_{pt}) + A_5 A_1 R_b + A_{15} R_b I_{dr} + \frac{A_{15} R_b U_{C_{SD}}}{R_{ds}}}{2A_{16} R_b + A_{11} R_3 + A_9 R_3}.
\end{aligned}$$

$$\begin{cases}
i_{c_d} = A_4; \\
i_{c_c} = (A_{10} + A_{11} R_3 A_{17}) / (A_9 R_c); \\
i_{c_e} = (A_{14} + A_{16} A_{17}) / A_{15} + I_{bt} - I_{dr}; \\
i_{c_s} = (A_{14} + A_{16} A_{17}) / A_{15} + I_{pt} - A_1 - U_{C_{ds}} / R_{ds}; \\
i_{c_{ds}} = A_1; \\
U_L = U_1 - (A_{12} + i_L (R_1 + R_2 + R_{VD})) + A_{17}.
\end{cases} \quad (2)$$

Since the voltages and currents of the circuit of the optoelectronic generator of deterministic chaos based on the bipolar field-effect transistor structure change in time, then, taking into account that the capacitance current and the voltage on the inductance are described by the expressions: $i_c = C \frac{dU_c}{dt}$, $U_L = L \frac{di_L}{dt}$. If we take into account that each instantaneous value of voltage and current in the equivalent circuit is a function of time, then we can write the left-hand sides of the equations in the form of first-order differential equations and system (2) can be rewritten as follows:

$$\begin{cases}
C_d \frac{dU_{C_d}(t)}{dt} = \frac{U_{C_s}(t) - U_{C_{SD}}(t) - U_{C_d}(t)}{R_t}, \\
C_c \frac{dU_{C_c}(t)}{dt} = \frac{U_{C_e}(t) - U_{C_{SD}}(t) - U_{C_d}(t)}{R_t} + I_{bt} - I_{dr}, \\
C_e \frac{dU_{C_e}(t)}{dt} = A_1 + I_{bt} - I_{dr}, \\
C_s \frac{dU_{C_s}(t)}{dt} = -I_{pt} - \frac{U_{C_{SD}}(t)}{R_{ds}} + A_3, \\
L \frac{di_L(t)}{dt} = U_2 - i_L(t) \cdot R_4 - \frac{U_{C_e}(t) + U_{C_c}(t) + U_{C_s}(t)}{R_e + R_s}, \\
C_{SD}(t) \frac{dU_{C_{SD}}(t)}{dt} = \frac{U_{C_d}(t)}{R_d} + I_{pt} - \frac{U_{C_s}(t) - U_{C_{SD}}(t) - U_{C_d}(t)}{R_t} + \frac{U_{C_{SD}}(t)}{R_{ds}}.
\end{cases} \quad (3)$$

Given that the system of equations (3) contains terms that describe nonlinear elements (current sources), the system is nonlinear. Nonlinear circuit elements describe the currents of nonlinear internal sources of circuit elements. The forward and reverse currents of the junctions of a bipolar transistor are described by equations (4)¹⁷:

$$I_f = I_s \left(e^{\frac{U_{BE}}{U_T \cdot NF}} - 1 \right); \quad I_r = I_s \left(e^{\frac{U_{BK}}{U_T \cdot NR}} - 1 \right). \quad (4)$$

The currents of the internal junctions of a bipolar transistor, base-emitter and base-collector, are described by equations (5):

$$I_{DF} = \frac{I_f}{BF}; \quad I_{DR} = \frac{I_r}{BR}. \quad (5)$$

where BF, BR – maximum current transfer coefficients for the common emitter switching scheme.

The channel current of a double-gate MOSFET transistor is represented in the form of a nonlinear piecewise approximation¹⁶:

$$I_{pt} = \begin{cases} 0, U_{GS} - U_{VTO} \leq 0 \\ \beta \cdot (U_{GS} - U_{VTO})^2, U_{GS} - U_{VTO} \leq U_{DS} \\ \beta \cdot U_{DS} \cdot [2 \cdot (U_{GS} - U_{VTO}) - U_{DS}], U_{GS} - U_{VTO} > U_{DS}, \end{cases} \quad (6)$$

where NF, NR – coefficients of non-ideality of the MOSFET transistor in the forward and inverse modes of operation;

BF, BR – maximum current transfer coefficient; U_{VTO} – threshold voltage; $\beta = \frac{1}{2} S_C W_{pL}$ is the steepness of the characteristics of the two-gate MOSFET transistor, where S_C – specific slope of the characteristic; W_{pL} – the ratio of the channel width to its length; $U_{GS} = U_G - U_S$ – voltage at the internal gate-source point; $U_{DS} = U_D - U_S$ – voltage at the internal drain-source point.

Any capacitance of a bipolar transistor has a diffusion and barrier component in the linear mode of operation. Collector junction capacitance C_c is described by the expression:

$$C_c = C_{c_{diff}} + C_{c_b} \quad (7)$$

where $C_{c_{diff}} = ((I_r + I_s) \cdot TR) / (U_t \cdot NR)$

$$C_{c_b} = \begin{cases} \frac{CJC}{(1 - (U_{BC})/V_{JC})^{MJC}}, U_{BC} < 0 \\ C_{JC}, U_{BC} \geq 0 \end{cases} \quad (8)$$

where U_t – temperature potential of the p-n junction.

Emitter junction capacitance C_e is described by the expressions [16]:

$$C_e = C_{e_{diff}} + C_{e_b}; \quad C_{e_{diff}} = ((I_r + I_s) \cdot \tau_{inv}) / (U_t \cdot \tau_{nor}). \quad (9)$$

$$C_{e_b} = \begin{cases} \frac{CJE}{(1 - U_{BE}/V_{JE})^{MJE}}, U_{BE} < 0 \\ C_{JE}, U_{BE} \geq 0 \end{cases} \quad (10)$$

where $C_{e_{diff}}, C_{e_b}, C_{c_{diff}}, C_{c_b}$ – differential and barrier capacitance of the emitter and collector junctions of a bipolar transistor; τ_{inv}, τ_{nor} – charge transfer time through the base region in the inverse and normal operating modes; U_{JE}, U_{JC} – contact potential difference of the emitter and collector junctions of a bipolar transistor; C_{JE}, C_{JC} – capacitances of the emitter and collector junctions of a bipolar transistor; M_{JE}, M_{JC} – coefficients of smoothness of the emitter and collector junctions of a bipolar transistor.

The dynamic model of an optoelectronic generator of deterministic chaos (system of equations (3)) allows us to determine the value of the frequency of the output signal depending on the control voltage, as well as the parameters of

the main elements of the oscillator at any time. Using a software package MATLAB computer-aided circuit engineering study of the parameters and characteristics of generated electrical oscillations in a chaotic mode was carried out. Figure 5 shows the simulated output signal of the optoelectronic generator of deterministic chaos.

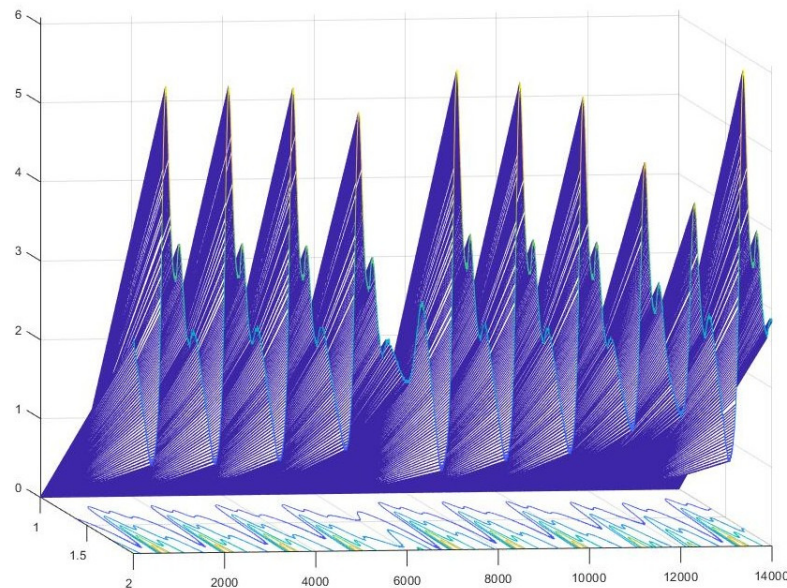


Figure 5. Modeled output signal of an optoelectronic generator of deterministic chaos.

Experimental studies conducted opto-electronic generator of deterministic chaos based on a bipolar field-effect transistor structure with negative differential resistance, it was shown that this circuit solution allows to reduce the settling time of stationary oscillations and expand the frequency range of chaotic oscillations. This circuit solution has a short settling time of stationary oscillations (15.36 – 19.82 ns). Fig. 6 shows experimental oscillograms of chaotic oscillations of the self-oscillating system.

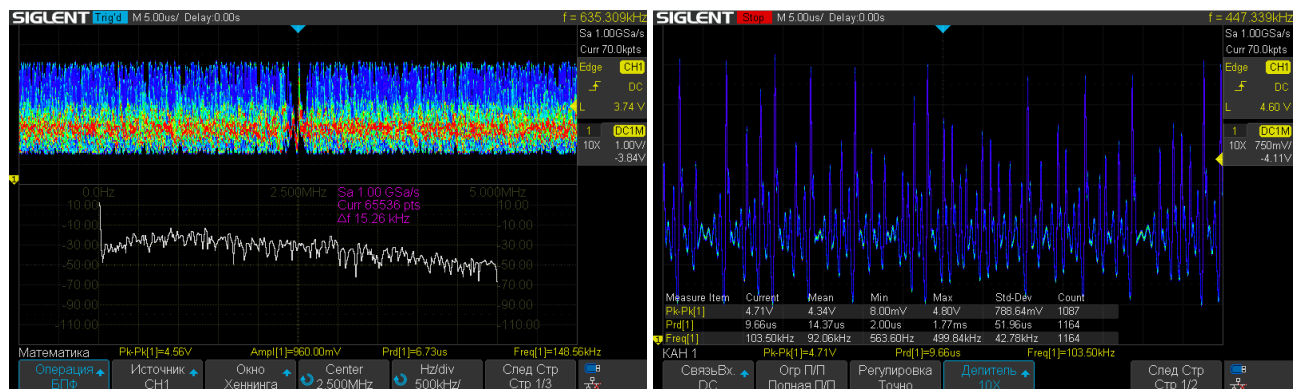


Figure 6. Oscillograms of an optoelectronic generator of deterministic chaos based on a bipolar field-effect transistor structure.

3. CONCLUSIONS

The paper proposes a new circuit solution for an optoelectronic generator of deterministic chaos based on a bipolar field-effect transistor structure with negative differential resistance, which has a short settling time of stationary oscillations (15.36 – 19.82 ns). A mathematical model has been developed of an optoelectronic generator of deterministic chaos in the form of first-order differential equations, which allows determining the value of the output signal frequency depending on the control voltage, as well as the parameters of the main elements of the oscillator at any time. Using a software package MATLAB computer-aided circuit-technical study of the parameters and characteristics of generated

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