EXPERIMENTAL AND THEORETICAL STUDY OF CHAOTIC MICROWAVE SIGNAL GENERATION IN ELECTRON SYSTEM WITH VIRTUAL CATHODE

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Abstract

Generation of chaotic signal in the electron system with non-relativistic electron beam with a virtual cathode is experimentally and theoretically studied. Nonlinear non-stationary processes in this electron system are investigated by means of numerical analysis of the 1D and 2D model. The chaotic microwave processes are described and interpreted with regard to formation and interaction of structures in the electron flow. The theoretical results are qualitatively confirmed by the experimental data showing that the investigated system can be considered as a promising controlled source of wideband chaotic oscillations in the microwave diapason.

Key words

Chaotic microwave generation, electron beam, experiment, numerical simulation.

1 Introduction

Investigation of the possibility of chaotic generation in microwave diapason is an important and actual application of nonlinear dynamics to modern problems of radiophysics and microwave electronics. Significance and timeliness of creation of microwave sources of chaotic wideband signals is determined by wide application of such systems in modern devices of information transmission based on the ideas of dynamical chaos, noise radiolocation, non-linear antennas etc.

Among the prospective sources of chaotic signals of microwave diapason there are systems using intensive beams of charged particles with virtual cathode. The analysis of oscillation processes in spatially extended intensive beams of charged particles in the regimes of virtual cathode (VC) formation is an important and actual problem of modern nonlinear dynamics [1–3]. It is well known [1–5] that the systems with VC are characterized by complex dynamics and can demonstrate a wide range of nonlinear phenomena, including dynamical chaos.

Among the different electron systems with virtual cathode the special interest is caused by low-voltage vircator, in which additional braking of electron beam is used for the forming of virtual cathode. In such systems the VC may be formed in the beams with low current and space charge density. In spite of that, such systems may generate periodic, narrow-band and wideband chaotic oscillations (WBCO) of the low value of power. As mentioned above, the WBCO-sources with VC have considerable interest in practice for the systems of radiolocation, systems of electronic counter measure, communication systems, industrial and medicine application.

The present report deals with theoretical and experimental research of oscillatory processes in low-voltage electron beam with VC. The complex dynamics of non-relativistic electron beam with VC in diode space with retarding field is studied experimentally and theoretically.

2 Theoretical study of the chaotic electron system with virtual cathode

The numerical simulation is carried out by using 1D and 2D models of electron beam which moves between two grids. The electron beam is characterized by Pierce parameter $\alpha=\omega_p L/v_0$, which is proportional to beam current (ω_p and v_0 are the plasma frequency and the velocity of electron beam, L is the distance between grids). The distribution of retarding potential between the grids in each moment of time is obtained by solving the Poisson equation. This equation is accompanied with the following boundary condition: on the left bound (first grid) we assume that the potential is equal to the accelerating potential value V_0, on the right bound (second grid) the potential V_t is less than V_0. The difference $\Delta\varphi=V_0-V_t$ is the value which characterizes the retarding field.

The numerical simulation of processes in the electron beam with an overcritical perveance has shown that the dynamics of the beam with VC is rather complex and depends on the value of retarding field $\Delta\varphi$ and on the value of beam current. As the value of retarding potential $\Delta\varphi$ increases, the complexity of the system dynamics rises, too. The small value of $\Delta\varphi$ corresponds to regular oscillations in the system (see Fig. 1*a*). The oscillation power spectrum is discrete and phase-plane portrait conforms to regular oscillations. As we increase $\Delta\varphi$, the oscillations become more complex (Fig. 1*b*) and when $\Delta\varphi$ reaches the critical value, chaos appears in the system (see Fig. 1*c*). The further increasing of $\Delta\varphi$ is accompanied by the transforming of chaotic oscillations to regular ones. With the overcoming of the critical value of $\Delta\varphi$ the oscillations damp and the regime of stationary VC takes place.

Fig.2 illustrates the characteristic regimes of oscillations of the electron beam on the plane of the parameters α and $\Delta\varphi$, which are accordingly the dimensionless beam current and the braking potential difference between the grids.

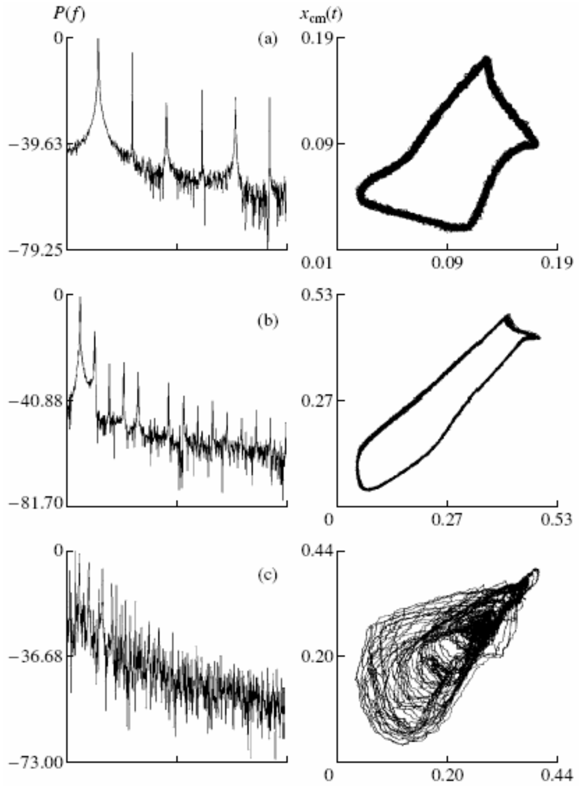

Figure 1 Spectra (left-hand panels) and phase-plane portraits (right-hand panels) for the control parameter α= 0.9 (альфа, что ли?) and the braking potential $\Delta\varphi$= (a) 0.37, (b) 0.43, and (c) 0.50.

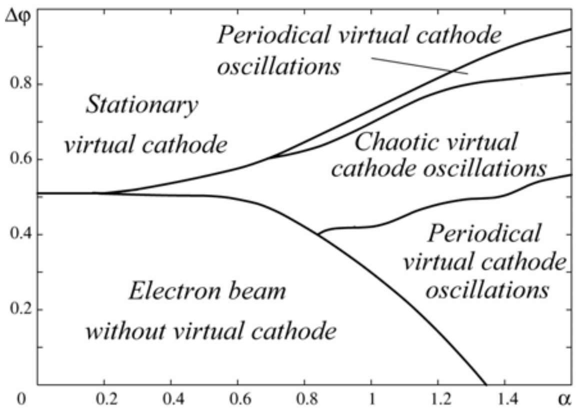

Figure 2 Characteristic regimes of the behavior of electron beam inside diode gap with decelerating field in the "Pierce parameter–decelerating potential difference" plane (numerical simulation)portraits (right-hand panels) for the control parameter α= 0.9 and the braking potential $\Delta\varphi$= (a) 0.37, (b) 0.43, and (c) 0.50.

The numerical simulation shows that the system output power increases as the value of retarding field grows. At the same time the small values of $\Delta\varphi$-parameter correspond to linear growth of power and to the regular oscillations in the system. At the point

$\Delta\varphi \approx 0.5$ the power reaches its maximum value in chaotic regime. As $\Delta\varphi$ increases the value of power slowly decreases until the stationary VC appears in the system. It is significant that the power in this work is defined as the kinetic energy of charged particles in diode space except for the left ones.

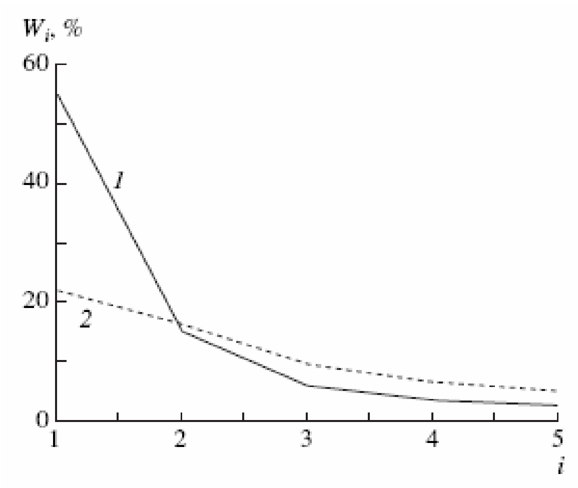

Figure 3 Mode energies *Wi* vs. mode number *i* for $\Delta\varphi$ = (*1*) 0.37 and (*2*) 0.43 (regular and chaotic signal generation, respectively).

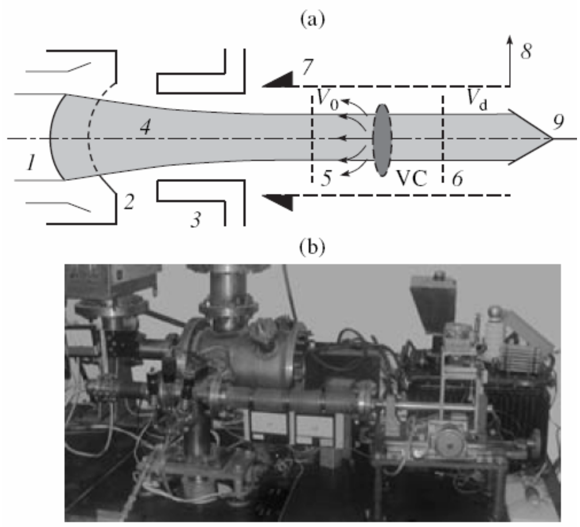

Figure 4 (a) Design and (b) photograph of the experimental setup for studying chaotic oscillations: (1) the cathode, (2) the grid, (3) the second anode of the electron gun (4) the electron beam, (5) the input grid of the diode, (6) the output grid of the diode gap with decelerating potential, (7) the matched absorber, (8) the energy output, and (9) the collector.

The method of orthogonal decomposition of Karhunen-Loeve (KL) [6] shows that in the electron beam with VC a number of KL-modes with their own space distributions and time dynamics is formed. It is shown that the forming and interaction of KL-modes defines the complex dynamics of the VC in the electron beam. KL-decomposition of the spatio-temporal data has shown that the energy of oscillation modes is redistributed from higher to lower modes as the retarding potential increases in some range of parameters ($\Delta\varphi$, beam current). In Fig. 3 the values of relative energies of the 5 highest K-L modes for the regular and chaotic oscillation regimes are shown. One can see distinctly that the energy of the first K-L mode (describing the behaviour of the main structure in the electron beam – the virtual cathode) slumps when the system passes to the chaotic regime; at the same time the energies of the lower modes (corresponding to the secondary structures regarding to the VC) increase [7]. Such increasing of a number of KL-modes is accompanied by special behaviour of VC in diode space, which differs from the case of other values of parameters. Thus, we may say that the complex dynamics of VC is caused by the forming and interacting of spatio-temporal structures in the electron beam.

3 Experimental study of the chaotic signal generation

In our work we have investigated the oscillations in the electron beam with VC injected into diode space with retarding field. The experimental device has the following characteristics: accelerating potential - 1.5÷2 kV, beam current - 50÷100 mA. The output characteristics of the device are: output power – 200÷600 mW, frequency – 1÷10 GGz, frequency bandwidth – 1÷2 octave in the chaotic regime. The VC is formed in the space between grids. The value of the retarding potential V_t is changed during the experiment from zero to the value of the accelerating potential V_0. The experimental scheme is shown in Fig. 4.

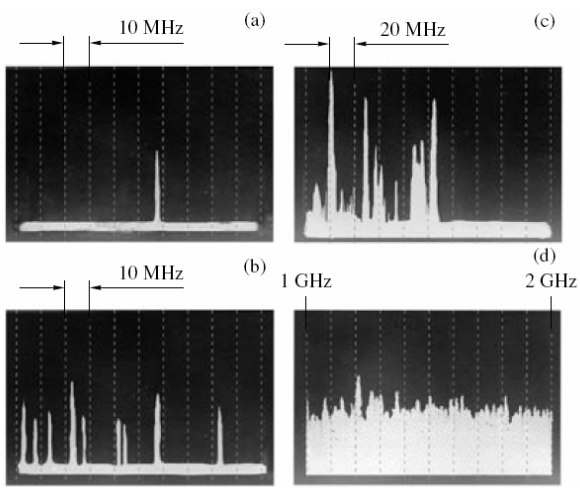

Figure 5 Experimental power spectra of microwave oscillations in non-relativistic electron beam with virtual cathode obtained at V_t/V_0: (a) 0.25. (b) 0.3 (c) 0.4 (d) 0.55

The experimental investigation shows that the output power and spectrum depend essentially on the value of the retarding field (see Fig. 5). The complexity of the energy spectral distribution increases with the growth of the retarding field value. As the retarding field grows, the regular oscillations are replaced by the chaotic ones and then the stationary virtual cathode forms in the system. At the same time, the output power increases. At the point where V_t is equal to the half of the accelerating potential value, the output power and the oscillation's complexity reach their maximum value. After this point, the complexity and output power decreases slowly. Also, as the V_t decreases the frequency bandwidth grows and reaches its maximum in the chaotic regime (see Fig. 6).

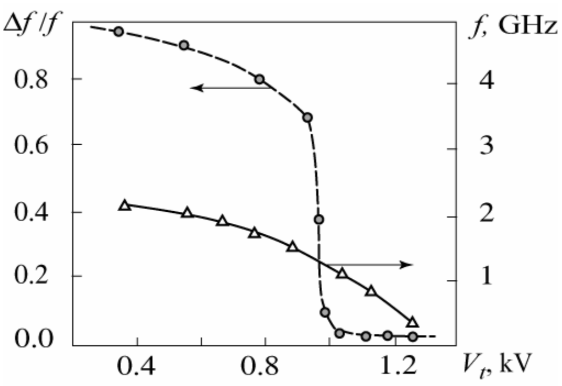

Figure 6 Characteristic frequency and bandwidth of chaotic oscillations in a beam with VC as functions of the potential difference.

4 Chaotic wide-band generation in traveling wave tube with collector-oscillator in regime of virtual cathode formation

The scheme considered in section III demonstrates the regimes of wideband chaotic generation but has one essential defect: the output power of such microwave electron generator is rather small. The experimental model with beam current 200 mA and accelerating voltage 1.5 kV gives microwave oscillations in diapason 1–3 GHz with power near 0.2–1.0 W and electron efficiency not more than 1-2%.

Solving this problem may be using a hybrid scheme based on wideband microwave amplifier (traveling-wave tube, TWT), one of the elements of which is a multi-stage collector, allowing the forming of a VC in its space at the expense of braking the electron beam coming out the interaction space of the TWT.

It Fig. 7 one can see the construction of the proposed microwave device based on wideband electron amplifier with collector-generator. The device consists of a number of functional modules: source of electrons (electron gun) 1, powerful wideband amplifier of microwave signal 2, collector-generator 3 and coupling element 4. The amplifying module of the device (TWT) includes source of electrons 1 forming the electron beam, which comes into the interaction space 2 with a section of delay-line. Then the exhausted beam comes to the area of multi-step collector 3, which combines the functions of microwave generator on VC (low-voltage vircator). The microwave signal, taken from the collector-generator with the help of wideband coupling element (spiral of diaphragm, loaded on coaxial line) comes by the coupling line 4 (coaxial line) to the input of amplifying module (TWT). Then, being amplified by the TWT up to the power P_{out}, it is brought out by the output energy element 5 to the load.

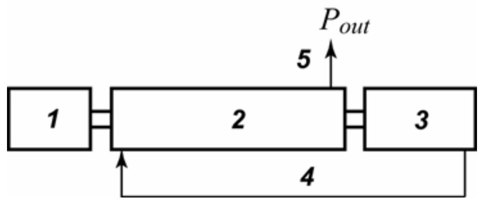

Figure 7 Block diagram of the chaotic microwave generator with TWT-amplifier

Thus, we obtain a hybrid vacuum microwave devce in which with the help of one electron beam generation and amplification of microwave signals with different spectra and power are realized at the same time. Let's note that in the studied device the *feedback path* does not present at all, which allows to create a microwave generator with the tuning of generation regimes from monochromatic to wideband chaotic signal with small irregularity and bandwidth near 1-2 octaves.

Small irregularity and wide band of generation is connected with the absence of strict phase conditions determined by the delaying feedback, as it usually takes place in the chaotic sources like TWT where the input and output are coupled with the feedback circuit and the result is that the system becomes a resonator [8]. The source of microwave oscillations in the proposed system is the non-stationary virtual cathode formed in the collector-recuperator with special wideband energy output. Controlling oscillation regimes of the VC is possible by changing the braking potential on the collector steps.

Let us consider some results of experimental investigation of generation and amplification of wideband chaotic signal in electron-wave system "TWT-amplifier with collector-generator".

In Fig 8 one can see the oscillation spectra in the beam with VC, registered at the output of collector-generator, in the dynamical regime of TWT. Fig. 8a is graphed within small braking potential on the collector steps and fig 8b – within large braking. With the increase of braking of electrons in the collector the microwave oscillations of the VC are characterized by multifrequency generation spectrum. We must mark that the dynamical regime of TWT is characterized by essential scattering of electrons' speeds values on the input of collector-generator. At that, as the experiments show, the generated signal demonstrates continuous spectrum in the bandwidth near 1 GHz and small irregularity N of the spectrum in the work bandwidth. So, the wide scattering of the electrons' speeds values in the TWT output improves the spectral characteristics of the device which conforms well with the results of the work [9].

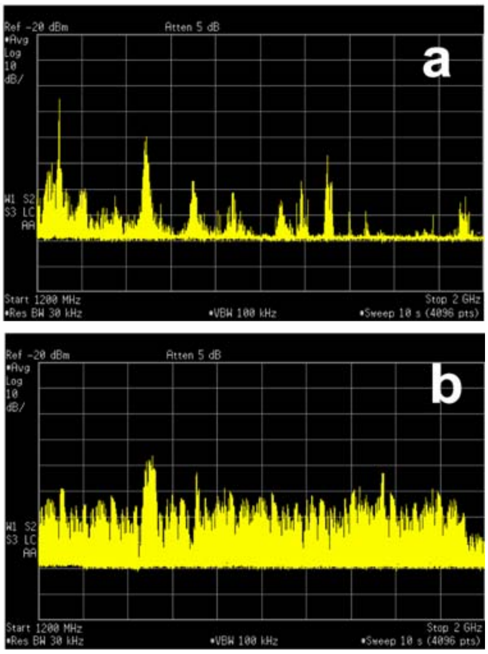

Figure 8 Spectra of the registered oscillations in collector-generator for the dynamical regime of TWT with the following potentials of three-step collector: (a) V_1/V_0=0.7, V_2/V_0=0.5, V_3/V_0=0.7; (b) V_1/V_0=0.7, V_2/V_0=0.5 and V_3/V_0=0.6 (V_0=2.5 kV – accelerating voltage).

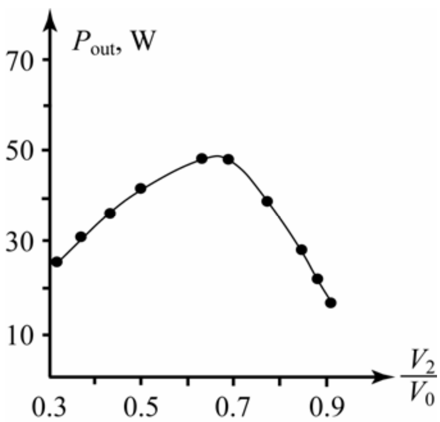

Figure 9 Output power of microwave wide-band signal vs potential of second stage of collector.

In Fig 9 the graphs of the output power of multifunctional device are shown. The integral power P_{out} of the chaotic oscillations registered in collector-generator is amplified a hundred times more and reaches 50 W, which is power amplification near 30 dB. At that the technical efficiency factor of the hybrid device is near 30%.

8 Conclusion

Our report is devoted to experimental and theoretical study of chaotic oscillations and pattern formation in the non-relativistic electron beam with VC. Comparison of the theoretical and experimental results shows good data fit. The experimental data shows that the results obtained from numerical calculating describe qualitatively the behavior of the real system with VC. The mathematical model shows that the system demonstrates complex dynamics including regular oscillations and chaos. It is shown that the complex dynamics of the system is caused by forming and interacting of the secondary KL-structures of the electron beam with the main structure (VC). Also the scheme of powerful chaotic generator based on TWT is considered, which allows to improve the characteristics of wideband generation on virtual cathode.

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