UDC 621.385.62

COMPUTER SIMULATION OF NOISE GENERATION IN MAGNETRON

G.I. CHURYUMOV, A.V. GRITSUNOV AND A.I. EKEZLY

This paper describes possible approaches to the computer simulation of fluctuation processes in a magnetron operating in π-mode. The use of computer simulation (TULIP particle-in-cell simulation code) allows carrying out comparative analysis of output spectrum and phase focusing of electron flow in different operating conditions of the magnetron. It is shown that the regularization of electron flow motion associated with decreasing its turbulence, leads to minimizing the noise level in the range of up to - 60 dB relative to a level of operating signal. A circuitry model of the magnetron is established for more detailed study of physical processes and understanding the influence of fluctuation processes in re-entrant electron flow on the quality of the output spectrum.

Keywords: magnetron, simulation, noise, fluctuation, PIC method, circuit method, output spectrum.

I. INTRODUCTION

Various magnetrons as the most popular vacuum tubes keep attracting attention of the researchers in vacuum electronics worldwide (see, e.g., [1–4]). Traditional research and developments of magnetrons are focused on the following topics: enhancement of energy efficiency, increase of output power and working frequency; advancing technologies for anode & cathode and magnetron magnet systems, etc. Nowadays, one may see increasing interest to the research focused on improvements in frequency characteristics of the magnetrons, including enhancement of frequency stability and quality of the output spectrum; suppression of the spurious oscillations and both the amplitude and phase noise, etc. [2, 5–7]. On the other hand, the idea of using magnetrons for generation of oscillations with increased level of the noises and design on this basis the microwave noise generators did not lost its relevance yet [8].

The main objective of this paper is to make choice of a method for computer simulation of the fluctuation processes in the magnetrons for adequate describing the chaotic behavior of electron flow and the study of existing regularities between the space charge spokes form and levels of the spurious oscillations in the output spectrum of the magnetron.

II. STATEMENT OF THE PROBLEM

For understanding the need of investigation of the fluctuation processes in the magnetrons we might study in details the output waveform of the magnetron and features of its frequency spectrum.

Fig. 1 shows the distributions of instantaneous values of the RF amplitudes for the ideal (a) and actual (b) the output waveform in the time and frequency domains.

As is seen, in case of the actual waveform we have spurious amplitude and frequency (phase) modulations of the output signal. As a result, at the output of the magnetron instead of the ideal monochromatic oscillation

$$\tilde{U}(t) = \tilde{U}_m \cdot \cos\omega_0 t \,, \qquad (1)$$

where $\tilde{U}(t)$ is the instantaneous RF amplitude; $\tilde{U}_m$ is the voltage of microwave oscillation in the steady state operation of the magnetron; ω_0 is the oscillation frequency of the magnetron, we have randomly modulated oscillation

$$\tilde{U}(t) = \tilde{U}_m \cdot \left[1 + \alpha(t)\right] \cdot \cos\left[\omega_0 t + \varphi(t)\right] , \qquad (2)$$

where $\alpha(t)$ is the dimensionless coefficient that determines the instantaneous depth of the chaotic amplitude modulation ($\alpha(t) << 1$); $\varphi(t) = \int_{-\infty}^{t} \Delta f(\tau) d\tau$ is the function that determines the variations of the output signal phase; $\Delta f(\tau)$ is the instantaneous frequency deviation.

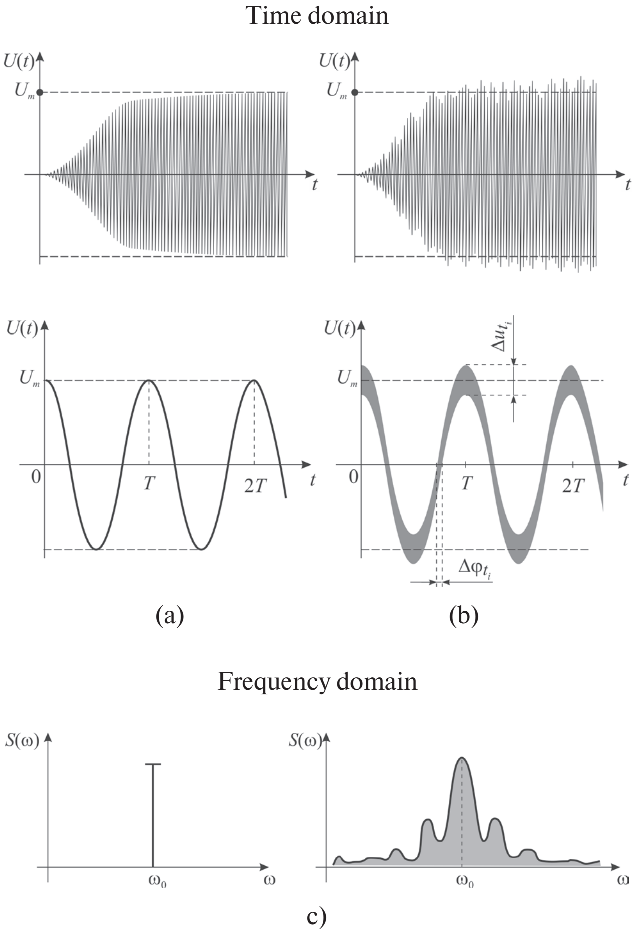


Fig. 1. The ideal (a) and actual (b) waveform output signals and their spectrum (c)

Analysis of the expression (2) shows that the availability of amplitude modulation of the output signal leads to expansion of its spectrum. With increasing complexity of waveform $\tilde{u}(t) = \tilde{U}_m \cdot \alpha(t)$ increases the number of spectral components in the output spectrum $\tilde{U}(t)$ and its quality deteriorates. Stochastic fluctuations of the phase in (2) are determined by the type of dependence $\varphi(t)$ (phase noise) and are one of the criteria for frequency stability of the magnetron.

For determining a spectrum of the output signal (2) necessary to analyze the waveform $\tilde{u}(t)$. In the case when the waveform is periodic we can represent it as a Fourier series

$$\tilde{u}(t) = U_0 + \sum_{k=1}^{\infty} \tilde{U}_{mk} \cdot \sin(k\Omega t + \psi_k), \qquad (3)$$

where U_0 is the constant component of the voltage ($U_0 = 0$); $\Omega = \dfrac{2\pi}{T}$ is the fundamental frequency; $\tilde{U}_{mk}$ and ψ_k are the amplitude and phase of the k-th harmonic of the fundamental signal. The set of values $\tilde{U}_{mk}$ is defined as the amplitude spectrum of the output signal.

For spectral decomposition of a non-periodic waveform $\tilde{u}(t)$ we use a Fourier integral

$$\tilde{u}(t) = \frac{1}{2\pi} \cdot \int_{-\infty}^{\infty} S(\omega) \cdot e^{j\omega t} d\omega, \qquad (4)$$

where

$$S(\omega) = \int_{-\infty}^{t} \tilde{u}(t) \cdot e^{-j\omega_0 t} dt. \qquad (5)$$

The value $S(\omega)$ is the spectral density, and its absolute value $|S(\omega)|$ determines the output frequency spectrum of the magnetron.

The presence of random fluctuations of the voltage $\Delta\tilde{U}_{t_i}$ and the phase $\Delta\varphi_{t_i}$ of the RF output signal can be considered as demonstration of the noise caused by the influence of internal and external destabilizing factors (stochastic fluctuations).

The main sources of the intrinsic destabilizing factor (noise) in the magnetrons are re-entrant electron flow with inherent discrete nature of electric charge and probabilistic nature of electron emission from the cathode. This causes an appearance of the fluctuation noise including the shot noise, distribution noise as well as secondary electron emission noise. Besides, the stochastic local changes of work function of cathode material and consequent the spontaneous modulation of the space charge are the reasons for electron emission current fluctuations (flicker noise) and noise associated with the presence of positive ions in the electron flow near a cathode of the magnetron [5, 7, 9]. Among external destabilizing factors affecting the magnetron operation one has to note the deterministic fluctuations or noise caused by an influence of magnetron power supply circuits, vibrations, temperature changes, etc.

Level of the noise in magnetrons is the result of composition of all the above mentioned sources of. For a quantitative assessment and comparative noise analysis of the noise level we use the dimensionless parameter as the ratio of signal power to noise power (signal/noise)

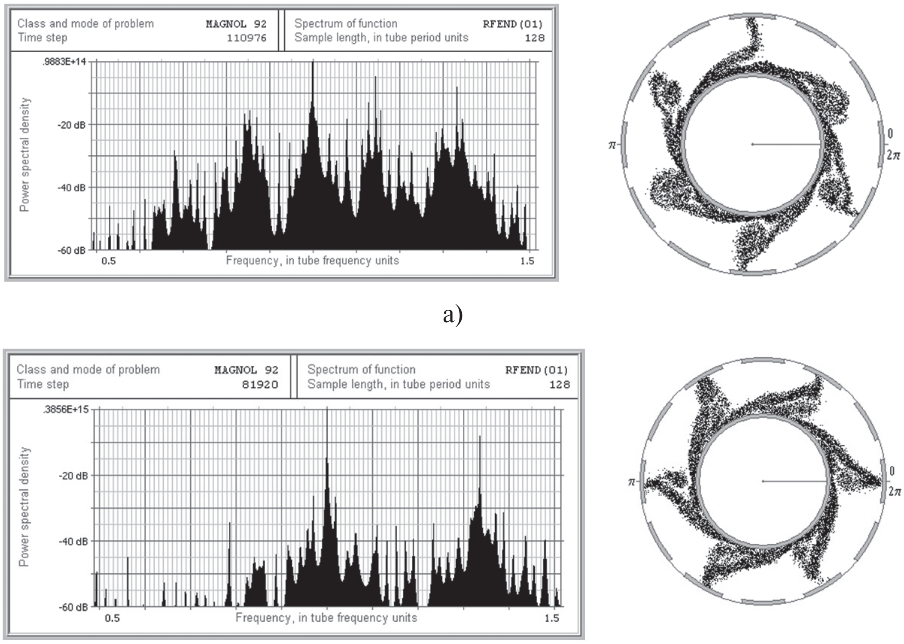
$$SNR(dB) = 10 \cdot \lg\left[\frac{P_{signal}}{P_{noise}}\right] = 20 \cdot \lg\left[\frac{U_{signal}}{U_{noise}}\right]. \qquad (6)$$

III. RESULTS OF COMPUTER SIMULATION

The computer simulation of fluctuation processes in the magnetrons is usually performed using both analytical methods (see, e.g. [4]) and numerical methods based on the FTTD technique for an electromagnetic field simulation and particle-in-cell (PIC) method for the simulation of electron flow [3]. It should be noted that the computer simulation allows studying the various noise sources. However, the computational experiment has a significant drawback that limits its application for studying electron-wave processes in low field operation. This is because high level of the so-called “computing noise” inherent in this approach due to calculation errors of the electrical and magnetic components of electromagnetic field and the coordinates and velocities of charged particles as well as value of space-charge field at the points of discrete space-time grid. Therefore, the use of computational experiment to study the noise processes is possible in a case when the level of physical noise will dominate compared to “computational noise”. As it is shown in [3], it is possible to analysis the noise in high-power microwave tubes, such as the magnetron amplifiers. On the other hand, this ability is achieved by increasing the accuracy of calculations and related to the use of computational algorithms that provide programmable level of the calculation errors as well as available hardware capabilities of the computers (for example, carrying out calculations with double precision).

Fig. 2 shows the results of the computer simulation of the electron bunching and output spectrum for different operating conditions of the 4J33 magnetron. These results have been obtained with 2D PIC simulations using the TULIP code created for full-format and spectral computer simulation of the magnetrons [10].

As illustrated in Fig. 2, the quality of the output spectrum of the magnetron is largely dependent on conditions of its operation. Regularization of motion of the electron flow associated with decreasing its turbulence is achieved by choosing the optimal anode voltage. As a result we have a significant reduction of the noise level in the output spectrum (Fig. 2, b). Analysis of kinematic characteristics of the electron flow shows that in optimal conditions operating reduces velocities spread of electrons and increases laminar nature of its motion in area of the electron spokes relative to the fixed coordinate system. Unfortunately, in the case of the noise process studying via the computational experiment it is difficult (and in some cases impossible) to understand and define the role of specific factors and their effects on a noise level



a)

b)

Fig. 2. The distribution of space charge and output spectrum of the 4J33 magnetron at $B_0 = 0.25$ T; U_a = 24,0 kV (a) and U_a = 28,0 kV (b)

taking into account that all factors are interrelated and it is not possible unambiguously to determine the causes of these changes. Therefore, there is a need for further development of more simple and physically adequate mathematical models for studying the noise processes in the magnetrons.

IV. CIRCUITRY MODEL OF MAGNETRON

When studying the fluctuation processes in steady state mode of the 4J33 magnetron we assumed that π–mode is the main operating mode for which the space charge distribution in the interaction space can be presented as $N/2$ formed electron spokes. The general view of the formed electron spokes in the moving coordinate system is shown in Fig. 2, b. For analytical calculations of induced current let us consider a more simple form of the electron spokes representation in the interaction space.

Fig. 3 shows two electron spokes over one period of the anode resonant system: 1 denotes the form of electron spoke that is used for the analytical model of the magnetron and 2 denotes the electron spoke obtained with the help of the PIC method. The electron spokes revolve around the cathode and induce current on the segments of the anode resonant system in accordance with the Shockley-Ramo theorem. In the two-dimensional approximation, we obtain that

$$i(t) = h\int_S \rho(r,\varphi)\,\vec{v}(r,\varphi)\,\vec{E}(r,\varphi)\,dS\,, \qquad (7)$$

where $\vec{E}(r,\varphi) = \tilde{E}_r\vec{r}_0 + \tilde{E}_\varphi\vec{\varphi}_0$ is the expression for π–mode field intensity [11]; $\rho = \rho(r,\varphi)$ is the distribution of the space charge density; $\vec{v} = \vec{v}(r,\varphi)$ is the distribution of the velocities in the electron bushing and spokes of space charge; h is the height of the anode block of the magnetron.

In order to determine the dependencies $\rho = \rho(r,\varphi)$ and $\vec{v} = \vec{v}(r,\varphi)$ we use the results of numerical simulation of bunching processes of the space charge which have been described in [12]. These dependencies (curves 1) and the results of their more simple approximation (curves 2) are shown in Fig. 4.

The expression for the radial distribution of the space charge density in electron spoke can be written as

$$\rho(r) = \rho_{\max} e^{-\alpha(r-r_c)}\,, \qquad (8)$$

where

$$\alpha = \frac{1}{(r_a - r_c)}\cdot\ln\left(\frac{I_{em}}{I_a}\right), \qquad (9)$$

$\rho_{\max}$ is the maximal electron flow density near the cathode (in area of virtual cathode); I_{em} is the total current from the cathode, providing a space-charge-

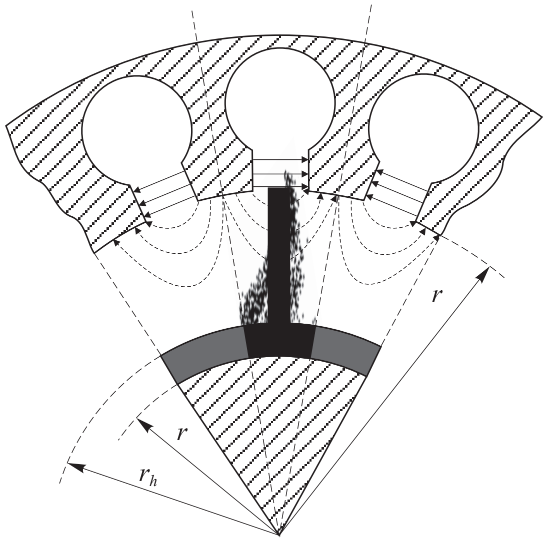
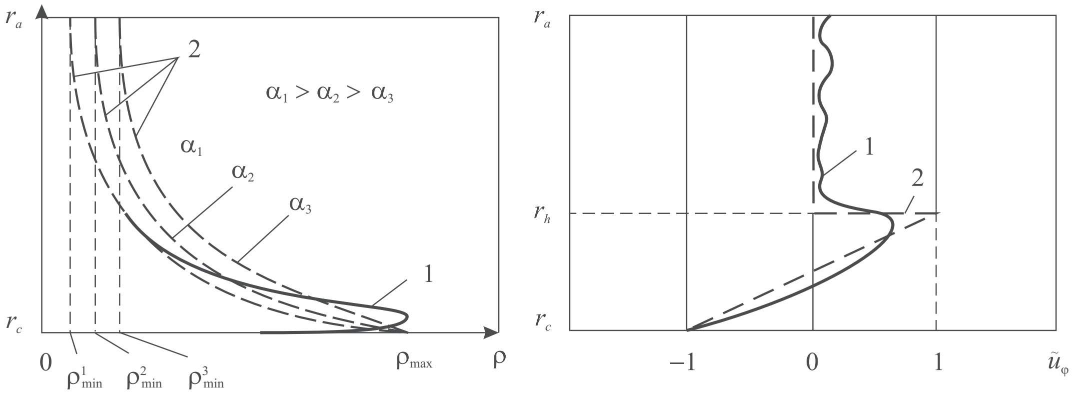


Fig. 3. The distribution of space charge and output spectrum of the 4J33 magnetron at $B_0 = 0.25$ T; U_a = 24,0 kV (a) and U_a = 28,0 kV (b)



a) b)

Fig. 4. The radial distributions of space charge density and azimuthal velocity of the electron cloud

limited emission regime; I_a is the anode current of the magnetron.

Analysis of the electron flow in the magnetron shows that in the steady-state operation exist two stable regions in the flow. These are two region of the electron bushing: in the first one $r_c < r < r_h$, predominates double-flow state of the electron flow, while in the second one $r_h < r < r_a$ the electrons motion is close to laminar one (quasi-laminar electron flow) [12]. The results obtained via computer simulation showed that in the area of the electron bushing linear azimuthal velocity increases from zero at the $r = r_c$ to (1.1 – 1.3) $\cdot \bar{v}_e$ on the top of the electron bushing at the $r = r_h$, where $\bar{v}_e = \dfrac{U_a}{r_a \cdot B_0 \cdot \ln(r_a/r_c)}$ is the average drift velocity of the electron flow at the anode. In the area of the electron spokes in the area of $r_h < r < r_a$, as illustrated in Fig. 4, b, predominates quasi-laminar motion of the electron flow. For this area the azimuthal velocity is equal

$$v_\varphi = \bar{v}_e + \Delta\tilde{v}_e\,, \tag{10}$$

where $\Delta\tilde{v}_e$ is oscillation of the azimuthally velocity related to radial motion of the electrons.

The expression for the current induced by the one electron spoke on the segments of the anode resonant system can be written as

$$i(t) = h\cdot\rho_{\max}\cdot\bar{v}_e\cdot\left\{\int_{r_c}^{r_a}\int_{-\frac{\pi}{2}}^{+\frac{\pi}{2}} r\cdot e^{-\alpha(r-r_c)}\cdot\tilde{E}_\varphi d\Phi dr + \right. \tag{11}$$

$$+\int_{r_c}^{r_a}\int_{-\pi}^{-\frac{\pi}{2}} r\cdot\left\{1-\cos\left[\frac{(r-r_c)}{(r_h-r_c)}\right]\cdot\pi\right\} e^{-\alpha(r-r_c)}\cdot\tilde{E}_\varphi d\Phi dr +$$

$$\left. +\int_{r_c}^{r_h}\int_{+\frac{\pi}{2}}^{+\pi} r\cdot\left\{1-\cos\left[\frac{(r-r_c)}{(r_h-r_c)}\right]\cdot\pi\right\} e^{-\alpha(r-r_c)}\cdot\tilde{E}_\varphi d\Phi dr\,.\right.$$

In the steady state operation of the magnetron the current to be induced by the electron spokes on the anode are periodic sequence of the current pulses, which can be expanded in Fourier series

$$i(t) = I_0 + \sum_{n=1}^{\infty} I_n e^{jn\Omega_e t}\,, \tag{12}$$

where n is the number of current harmonic; I_0 is the dc component of the induced current (anode current); $\Omega_e = \dfrac{\omega}{\gamma}$ is the angular velocity of rotation of the electron spokes (condition for re-entrant electron flow); $\gamma = \dfrac{N}{2}$ is the propagation constant corresponding π-mode.

The expression for a synchronous harmonics of the induced current can be written as

$$I_n = \frac{1}{2\pi}\cdot\int_{-\pi}^{+\pi} i(t)\cdot e^{-jn\Omega_e t} dt\,, \tag{13}$$

Fig. 5 shows the equivalent circuit of the magnetron corresponding the excitation of the π-mode. This equivalent circuit comprises current sources $I_\omega(t)$ and voltage sources $U_a(t)$ and $\tilde{U}_\pi(t)$. The number of the current sources corresponds to the number of the electron spokes, i.e. $\dfrac{N}{2}$, where N is the number of the cavities (in our case $N = 12$). The value of the current which induces by the current sources $I_\omega(t)$ corresponds to the synchronous harmonic of the induced current (13).

The value $I_\omega(t)$ can be written as

$$I_\omega(t) = \bar{I}_\omega + \Delta\tilde{I}_\omega(t)\,, \tag{14}$$

where $\bar{I}_\omega$ is the value of the induced current corresponding the constant emission current from the cathode; $\Delta\tilde{I}_\omega(t)$ is the fluctuations of the induced current associated with influence of oscillatory processes in the electron flow (shot effect, the phenomenon of the current distribution and the secondary emission).

As the sources of voltage in Fig. 5 we consider the source of anode voltage $U_a(t)$ and the synchronous voltage source $\tilde{U}_\pi(t)$ that excites the mode oscillations in the anode resonant system of the magnetron, i.e.

$$U_a(t) = U_a + \Delta U_a(t)\,, \tag{15}$$

$$\tilde{U}_\pi(t) = \tilde{U}_{\pi m}\cos\left[\omega t + \psi(t)\right]\,, \tag{16}$$

where U_a is the constant anode voltage; $\Delta U_a(t)$ is the anode voltage fluctuations caused by an instability of the power supply; $\tilde{U}_{\pi m}(t)$ is the instantaneous amplitude of the π-mode in the steady state of the magnetron; $\psi(t)$ is the parameter determining the phase shift between the voltage of the π-mode and the synchronous harmonic of the current (13).

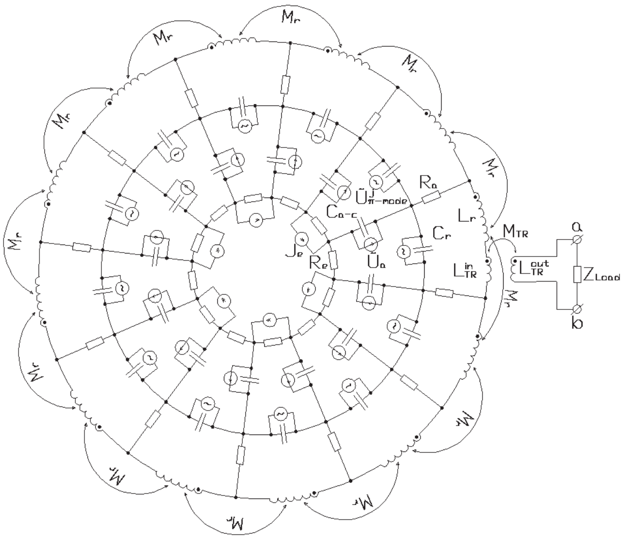


Fig. 5. Equivalent circuit of "hot" magnetron

For determining the values of the capacitances of the interaction space $C_{a-c}(t)$ and resonators $C_r(t)$ we use the expression for a capacitance of the parallel-plate capacitor, i.e.

$$C_{a-c}(t) = \frac{\varepsilon_e^{a-c}(t)\cdot S_{a-c}}{4\pi d_{a-c}}, \qquad (17)$$

$$C_r(t) = \frac{\varepsilon_e^{r}(t)\cdot S_{r}}{4\pi d_{r}}, \qquad (18)$$

where S_{a-c} is the cross-sectional area of a vane; S_r is the slit area of a resonator; $d_{a-c} = r_a - r_c$ is the distance between the cathode and anode; d_r is the distance between the vanes at the $r = r_a$; r_a and r_c are the anode and cathode radiuses; $\varepsilon_e^{a-c} = \overline{\varepsilon}_e^{a-c} + \Delta\tilde{\varepsilon}_e^{a-c}(t)$ and $\varepsilon_e^{r} = \overline{\varepsilon}_e^{r} + \Delta\tilde{\varepsilon}_e^{r}(t)$ is the dielectric constant of the electron flow in cathode-anode space and between the vanes; $\overline{\varepsilon}_e^{a-c}$ and $\overline{\varepsilon}_e^{r}$ is the average values of dielectric constants of the electron flow; $\Delta\tilde{\varepsilon}(t)$ is the fluctuations of the dielectric constant of the electron flow resulting from oscillations in the electron density of the space charge.

In general, it should be noted that the capacitance values $C_{a-c}(t)$ and $C_r(t)$ have a non-linearly dependence on the anode voltage U_a. The nature of the nonlinearity depends on the state of the electron flow and distribution of the space charge density in the space between the cathode and anode.

To convert the equivalent circuit of "hot" magnetron to the form convenient for calculations it is necessary to exclude the magnetic coupling between the inductances L_r of the coupled cavities of the anode resonator system as well as input L_{tr}^{in} and output L_{tr}^{out} inductances of output linear transformer which provides matching the anode resonant system with the output load

$$Z_{load} = R_{load} + jX_{load}\,. \qquad (19)$$

The matching condition of the magnetron is given by the

$$R_{load} = \mathrm{Re}\left(Z_{in}^{a-b}\right), \qquad (20)$$

where Z_{in}^{a-b} is the value of input impedance of the anode resonant system of the magnetron (Fig. 5).

In order to describe the electrical circuit we apply Kirchhoff's laws, writing equations for the instantaneous values of the induced currents using the mesh-current method. Consequently, the numerical solutions of the equations we get the complex values of the instantaneous induced current in the each circuit of the electrical network.

The instantaneous value of the active power at the matched load equal

$$P_a(t) = \frac{I_{\omega load}^{\,2}(t)\cdot R_{load}}{2}, \qquad (21)$$

where $I_{\omega\ load}$ is the instantaneous value of the induced current in the output circuit of the magnetron to be found from solution of the set of equations for the loop currents

V. SUMMARY

A novel approach for investigation of the noise processes in magnetrons has been proposed. This approach is based on a combination of numerical and analytical simulation of deterministic and stochastic fluctuation processes. The use of numerical methods (computational experiment) showed that the noise level depends on the operating conditions of the magnetron and decreases for the electron flow available lower parameter of turbulence (quasi-laminar electron flow). At the same time the possibility of computational experiment for analyzing an interaction of the electron flow with lower electromagnetic fields are limited. This is due to the errors of calculation that accumulate ("computational noise") and can become a cause of the appearance of "non-physical" effects (e.g., the spurious generation of additional components in the output spectrum of the magnetron). In order to carry out analytical simulation of the fluctuation processes in the magnetrons proposed an analytical model based on the equivalent circuits method. This model allows studying the influence of fluctuations of electron emission parameters (emission current density, including a secondary electron emission), the characteristics of electron flow (coordinates and velocities of electrons, space-charge density) as well as the parameters of external electric circuit (power supply voltage and induced external electromagnetic signals) into the operation mode of the magnetron (π-mode).

References

[1] O.A. Morozov, and other, The second born of magnetron direction. Electronnaya Technika. Ser.1. SVCh Technika, No 3 (496), 2008, pp. 3–9 (in Russian).

[2] I. Tahir, A. Dexter, R. Carter, "Noise Performance of Frequency and Phase Locked CW Magnetrons Operated as Current Controlled Oscilators," IEEE Trans. on Electron Devices, vol. ED-52, November, 2005.

[3] Cherrnin D.P. Computer Simulation of Low Noise States in a High-Power Crossed-Field Aplifer. IEEE Trans. On Electron Devices. Vol. 43, # 11, November 1996, pp. 2004 -2010.

[4] Li D., Chen X. Study of Non-Linear Dynamics in Magnetron by Using Circuitry Model. Physics of Plasma 19, 2012, pp.2004 – 2010.

[5] K. Yamamoto, H. Kuronumo, T. Koinumo, and N. Tashiro, A Study of Magnetron Noise. IEEE Trans. On Electron Devices. Vol. ED-34, No 11, May 1987, pp. 1223-1226.

[6] G.I. Churymov, O.M. Nikitenko, and V.N. Zin'kovski, Noise in Crossed-Field Devices. Proceedings of NRT - 2002. Yalta. Ukraine, 2002.

[7] G.I. Churyumov and other, Magnetron – EMI Sources: Computer Modeling and Experimental Investigations. Proceedings of EMC Europe. Eindhoven. Netherlands, 2004.

[8] Yu.V. Anisimova and other, Shumotron, Radiotechnika, № 2, 2000, pp. 19–22 (in Russian).

[9] A.N. Malahov, Fluctuatsii v avtokolebatel'nych sistemach. – Moscow: Nauka. 1968, 660 p. (in Russian).

[10] A.V. Gritsunov, Exitation of Electromagnetic Oscillations of Arbitrary Spectral Contents by Re-entrant Electron Beams in Crossed-Field Systems. Thesis for a doctor's degree. – Institute of Radiophysics and Electronics of National Academy of Science of Ukraine, Kharkov, 2005 (in Russian).

[11] G. B. Collins, Microwave Magnetrons. New York: McGraw-Hill, 1948, ch. 19.

[12] G.I. Churyumov, Ways and Methods of Increase of Interaction Efficiency of of Electron Beam with Slowed Electromagnetic Waves in the Crossed-Field Systems. Thesis for a doctor's degree. – Institute of Radiophysics and Electronics of National Academy of Science of Ukraine, Kharkov, 2005 (in Russian).

Manuscript received February, 28, 2013

Gennadiy I. Churyumov (M'96, SM'00) received the Cand. Sc. degree (Ph.D.) in 1981 from the Kharkov State Technical University of Radio Electronics, Kharkov, Ukraine; and the Doctor of Sc. degree in 1997 from Institute of Radio Physics and Electronics of NASU, Kharkov. He is currently a Professor and the Head of the Microwave & Optoelectronics Laboratory at the Department of Electronics Engineering, Kharkov National University of Radio Electronics. His general research interests lie in the area of 2-D and 3-D computer modeling of electron-wave processes in vacuum tubes, simulation techniques of electromagnetic problems and nonlinear phenomena, electromagnetic compatibility. His current activity concentrates on the practical aspects of application of the vacuum tubes. Prof. Churyumov is a member of the European Microwave Association.

Gritsunov Alexander Valentinovich received the M.S. degree in electronic engineering in 1979, the Ph.D. degree in radio physics in 1984, and the D.Sc. degree in physical electronics in 2006, all from the Kharkiv National University of Radio Electronics. Since 1977, he deals with the computer simulations of crossed-field devices. Now he also introduce his spectral methodic into the numerical modeling of signal spectra in TWT's and klystrons.

Andrew I. Ekezly is a junior researcher of the Kharkov National University of Radio Electronics. His research work is focused on computer modeling of microwave devices.

УДК 621.37

Математическое моделирование генерации шума в магнетроне / Г.И. Чурюмов, А.В. Грицунов, А.И. Экезли // Прикладная радиоэлектроника: науч.-техн. журнал. – 2013. – Том 12. – № 1. – С. 58–63.

В данной статье рассматриваются возможные подходы к моделированию флуктуационных процессов в стационарном режиме работы магнетрона на основном виде колебания. Применение вычислительного эксперимента (программа TULIP) позволяет провести сравнительный анализ выходного спектра магнетрона и состояния фазовой группировки электронного облака в различных режимах работы магнетрона. Показано, что регуляризация движения электронного потока, связанная с уменьшением его турбулентности, приводит к минимизации уровня шума в диапазоне значений до –60 дБ по отношению к уровню основного сигнала. Описана математическая модель магнетрона на основе метода эквивалентных схем для более детального изучения и понимания влияния флуктуационных процессов в электронном облаке на качество спектра выходного сигнала.

Ключевые слова: магнетрон, моделирование, шумы, колебания, PIC метода, метода цепи, выходной спектр.

Ил. 5. Библиогр.: 11 назв.

УДК 621.37

Математичне моделювання генерації шума в магнетроні / Г.І. Чурюмов, О.В. Грицунов, А.І. Екезлі // Прикладна радіоелектроніка: наук.-техн. журнал. – 2013. – Том 12. – № 1. – С. 58–63.

У даній статті розглядаються можливі підходи до моделювання флуктуаційних процесів у стаціонарному режимі роботи магнетрона на основному виді коливання. Застосування обчислювального експерименту (програма TULIP) дозволяє провести порівняльний аналіз вихідного спектра магнетрона та стану фазового групування електронного потоку в різних режимах роботи магнетрона. Показано, що регуляризація руху електронного потоку, пов'язана зі зменшенням його турбулентності, призводить до мінімізації рівня шуму в діапазоні значень до –60 дБ по відношенню до рівня основного сигналу. Описано математичну модель магнетрона на основі методу еквівалентних схем для більш детального вивчення та розуміння впливу флуктуаційних процесів у електронному потоці на якість спектра вихідного сигналу.

Ключові слова: магнетрон, моделювання, шуми, коливання, PIC методу, методу ланцюга, вихідний спектр.

Іл. 5. Бібліогр.: 11 найм.