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Nonlinear Dynamics of a Generator on a Virtual Cathode with Modulated Emission

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Abstract—A numerical study of a low-voltage vircator with controlled emissions from a thermocathode is performed for when an external signal effects on the electron beam and modulates the emission. The strong influence of the modulation parameters on characteristics of oscillations of the beam with virtual cathode is noted. It is shown that when the modulation frequency is tuned to the one of harmonics of a virtual cathode's free oscillations, there is a considerable increase in the power of high-frequency harmonics of the virtual cathode's free oscillations in the output spectrum.

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INTRODUCTION

Increasing the intensity, power and frequency of a generator equipped with a virtual thermocathode (vircator) is a key problem in today's high-power electronics. Vircators are promising sources of high-power microwave radiation [1, 2]. Of current interest as well is developing methods for controlling the generation characteristics of vircators for different applications, e.g., probing the atmosphere, investigating electromagnetic compatibility, various technological processes, and long-range radiolocation. Early investigations of vircators equipped with external resonant systems showed [3–5] that one effective approach is modulating the velocity in generators containing virtual cathodes (VCs) [3, 4, 6–8] and modulating the density of the electron beam [5]. In the latter case, it is convenient to use an electron source with modulated emissions that allow us to achieve deep modulation of the beam density via an external low-power signal. In this work, we performed a numerical study of a low-voltage vircator with controlled thermionic emissions of a cathode for when an external signal affects the beam, modulating the radiation in the region of beam formation.

INVESTIGATED SYSTEM AND NUMERICAL MODEL

The investigated system was the drift area of an electron beam in the form of a segment of a cylindrical waveguide with length L and radius R, closed at both ends by grid electrodes transparent to the electron beam. An axially-symmetric continuous monoenergetic electron beam with radius R_b, current I, and modulated density was injected into the drift region through the left grid and exited through the right grid. The beam can also be deposited onto the sidewalls of the interaction area. A uniform external focusing magnetic field with induction B was applied along the axis of the system. Numerical simulation of time-dependent processes was performed for large particles using a program developed for studying generators with electronic feedback [12, 13]. The program was based on solving a self-consistent system of dynamics equations for large particles and the Poisson equation within two-dimensional cylindrical geometry. In our calculations, we used the following geometric parameters: $L = 50$ mm, $R = 12.5$ mm, and $R_b = 6.25$ mm; the accelerating voltage was 2.1 kV, corresponding to the experimental model of a low-voltage vircator in [9–11]. Density was modulated using the external harmonic modulation signal of the accelerating voltage in an electron gun equipped with a thermocathode. The main control parameters of the vircator system with modulated emission were A, the beam current's supercriticality, which was equal to the ratio of the beam current to the critical value at which a VC is formed in the electron flow; D the depth of depth current density modulation (%), which was equal to the ratio of the difference between the maximum and minimum values of the current density; and ω, the modulation frequency.

DYNAMICS OF THE SYSTEM

Numerical simulations showed that upon deep modulation ($D > 80\%$) of the beam's current density and relatively low values of the supercriticality parameter, $1 < A < 3$, the spectral composition of the output radiation is determined by the frequency of the modulating harmonic signal and contains the first three harmonics of this frequency. For example, at $A = 2.1$, which corresponds to $I = 11$ A, $D = 100\%$, and $\omega = 1.03$ GHz (see Fig. 1a), the output spectrum contains harmonics at frequencies of 1, 2, and 3 GHz with a 6 : 3 : 1 ratio of amplitudes, while the frequency of free VC oscillations is 1.4 GHz. At certain parameters, the spectrum can also contain combinations of the harmonics of the modulation signal frequency and those corresponding to free VC oscillations (in a system without modulation), but their amplitude is negligible. For deep modulation of the current density ($D > 80\%$) at relatively low values of the supercriticality parameter, the mechanisms of VC formation therefore disappear. The electron flow is injected into the system in the form of a series of electron clusters with the repetition frequency and density determined by the parameters of the modulation signal. This reduces the density of the charge in the area of interaction, and a virtual cathode has no time to form during a single pulse of the current. This effect is most pronounced for large periods of the modulation signal. The time preceding the modulation signal is in the negative phase, and new electrons are not injected into the system. The space charge virtually disappears from the system and the critical charge density necessary for VC formation is not achieved. Simultaneously with this, the modulated electron beam in the form of a sequence of bunches effectively excites the generator's electrodynamic system at the frequency of modulation and the harmonics of this frequency. The generator system is, e.g., in the form of a spiral slow-wave structure. In other words, the external modulation signal imposes its own dynamics, disrupts the mechanism of VC formation, and affects the spectrum of the output radiation.

A virtual cathode begins to form again upon a further increase in the supercriticality parameter in a system with deep modulation of emissions. At $A > 3$ and $D = 100\%$, the form of the output spectrum is thus transformed qualitatively, relative to the above example of a smaller supercriticality parameter (Fig. 1b). The harmonics of free VC oscillations begin to appear in the spectrum along with components that correspond to the modulation frequency and its harmonics. In addition, the amplitudes of the latter harmonics prove in most cases to be maximal, indicating a strongly nonlinear regime of system functioning. At $A = 6.4$, $D = 100\%$, and $\omega = 0.51$ GHz, the spectrum of the output radiation (Fig. 1b) thus contains a component with a frequency of 0.5GHz and a dimensionless amplitude of 2, corresponding to frequency modulation with an external signal; a component with a frequency of 1.5 GHz and a dimensionless amplitude of 2.5, corresponding to the frequency of free VC oscillations; and a component with a combinational

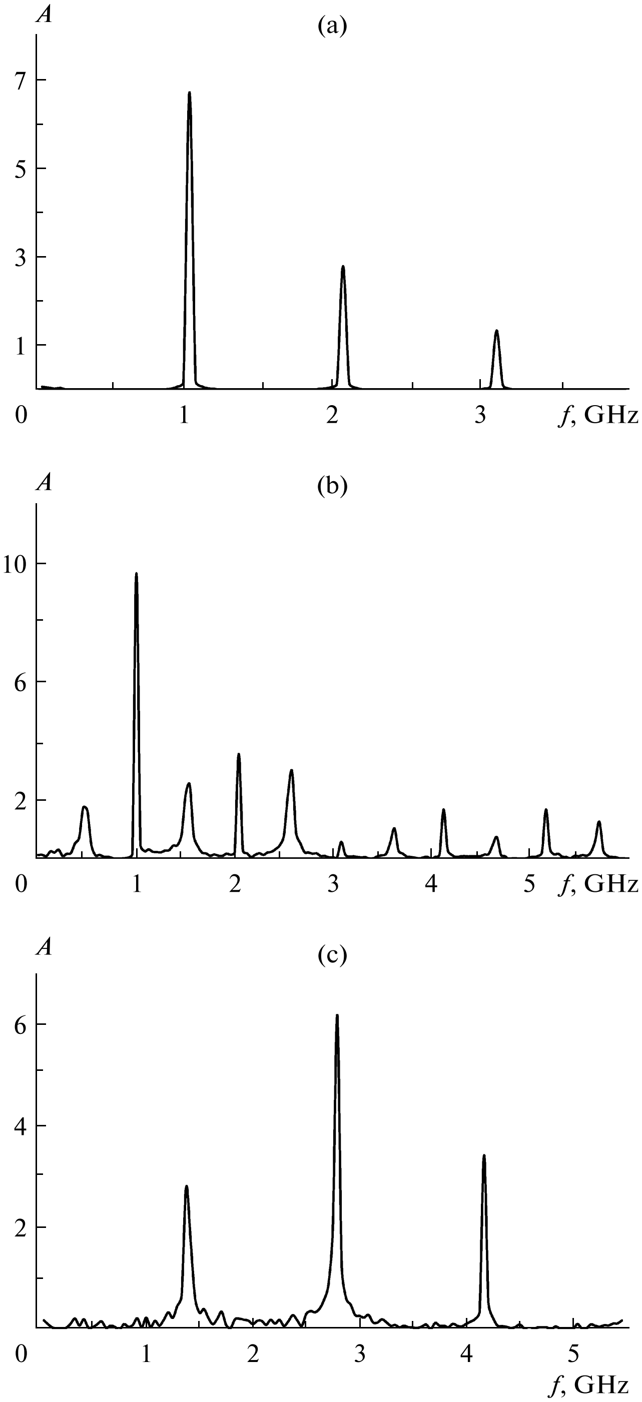

Fig. 1. Spectra of the electric field oscillations in the region of a VC at $A = 2.1$, $D = 100\%$, (a) $\omega = 1.03$ GHz; (b) $A = 6.3$, $D = 100\%$, $\omega = 0.51$ GHz; (c) $A = 4.9$, $D = 80\%$, $\omega = 1.38$ GHz.

frequency of 1 GHz and an amplitude of 9.7, corresponding to a half the sum of the first two harmonics. In addition, the output spectrum contains the second harmonics of a combinational frequency of 2 GHz and an amplitude of 3.6. The maximum energy of the output signal (about 50%) is concentrated within the combinational spectral harmonics at a frequency of 1 GHz, and the rest of the energy is almost uniformly distributed between the other spectral components. In a vircator system with deep modulation of emissions and a high supercriticality parameter, there is thus nonlinear interaction between two processes: (i) vircator oscillations that start to form in the system upon modulation due to an increase in supercriticality (these oscillations are proportional to the plasma frequency of the beam) and (ii) the dynamics of electron clusters with the frequency of repetition determined by the modulated voltage frequency. This gives rise to intense combinational components in the spectrum of the VC system's output radiation.

It is worth noting separately the situation where emission at $D > 80\%$ is modulated at the frequency of free VC vibrations. In this case, the spectrum of the output signal is considerably simplified and contains the first three harmonics of this frequency, in which more than 80% of energy is concentrated. This result is understandable from a physical point of view, since the electron clusters in the modulated electron flow arrive at the region of VC in phase with its oscillations. The generation efficiency coefficient in this regime is higher than the one for free VC oscillations.

Let us consider the results from studying a vircator system with current-modulated emission at lower depths of modulation ($50\% < D < 80\%$) and medium values of supercriticality ($1 < A < 5$). When the frequency of the modulated signal is not a multiple of the frequency of free VC oscillations, the spectrum of the output emissions is similar to the abovementioned case of high supercriticality and depth of modulation, and contains harmonics of the modulated signal (those of VC oscillations and their combinations). Of greatest interest is the case where the frequency of the modulated signal is tuned to one of the harmonics of free VC oscillations. At such parameters, there is a considerable increase in the amplitude of the highest harmonics of the frequency of the output spectrum's free VC oscillations when the amplitude of the first harmonics is reduced. At $A = 4.9$, $D = 80\%$, and $\omega =$ 1.38 GHz (Fig. 1c) corresponding to the frequency of free VC oscillations, the amplitude of the third harmonics in the output spectrum at a frequency of 4.14 GHz thus grows by a factor of 2, the amplitude of the second harmonics remains virtually the same, and the amplitude of the first harmonics shrinks by a factor of 2, relative to when there is no modulation. Energy is therefore transferred from the low- to the high-frequency harmonics. We can raise the power of spectral components with still higher frequencies that are not multiples of the VC frequency by tuning the frequency of modulation to the VC's higher-frequency harmonics. A vircator regime with modulated emission is necessary when we need to raise a unit's frequency of generation substantially, e.g., when modifying a VC generator to produce a vircator frequency multiplier.

From a physical point of view, initial preliminary modulation of the electron flow at a frequency that is a multiple of the frequency of free VC oscillations promotes the formation of the electron beam, since new additions to the spatial charge arrive at the VC in the form of electron bunches when it is in the charge accumulating phase. The grouping of the beam near the VC is thus considerably improved, and the corresponding harmonics of spatial charge oscillations in the region of the VC rise sharply due to better concentration of the flow. Reducing the depth of modulation allows us to inject current sufficient to form and maintain a VC in the system. It is known that a VC exhibits complex relaxation-type oscillations with a spectrum enriched in higher harmonics [7, 14]. Modulation of the flow at a frequency that is a multiple of that of free VC oscillations thus raises the amplitude of the other harmonics of this frequency in the output spectrum.

CONCLUSIONS

We established the strong effect the parameters of modulation for the emissions of a vircator have on the oscillation characteristics of a beam with a virtual cathode. It was shown that when the modulation frequency is tuned to the one of harmonics of the VC's free oscillations, there is a considerable increase in the power of its high-frequency harmonics of free oscillations in the output spectrum. This mode of a vircator with modulated emission can be used to raise the frequency of generation substantially when modifying a VC generator to produce a vircator frequency multiplier.

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