Nanovircator: Promising THz Electromagnetic Radiation Source

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***Abstract*— We suggest the new approach of sub-THz and THz signals generation based on intense electron beams containing oscillating virtual cathode. In this work we discuss the results of numerical simulation and optimization of the novel device called “nanovircator” that have been carried out. The results of the numerical study show the possibility of “nanovircator” operation at 0.1-0.4 THz frequency range.**

I. INTRODUCTION

At the present time there is “the Terahertz Gap” of rather powerful high-frequency signals generation technologies [1]. The important problem of the present-day microwave electronics is the research and design of the compact sources of radiation in the sub-THz and THz frequency range to fill this “gap”. In particular, the active development of the so-called “nanoklystrons” to operate in the THz range is going on nowadays [2-4]. The same idea based on the scaling of the device geometrical parameters to micrometers can be used to advance another perspective class of microwave devices, vircators, to the sub-Thz and THz frequency range.

The key features of this device operation that single out vircators are the construction simplicity, the ability of operation without external magnetic field, low demands on the quality of the electron beam and the ease of oscillation regimes switching by the variation of controlling parameters [5,6]. Also it is well-known that the vircator generation frequency is rather low and does not exceed usually 20-40 GHz, so the frequency gain of virtual cathode oscillators (VCOs) is the important goal of modern electronics. The generation frequency of virtual cathode oscillator is close to the beam plasma frequency f_{vc}~f_p and plasma frequency is proportional to the space charge density of the beam ρ_b. So, obviously, there are two ways to increase the vircator operation frequency: the increasing of space charge density by gain of beam current I_0 or by decreasing the beam surface at fixed value of I_0. As the growth of I_0 may lead to undesirable consequences such as electric discharges and breakdowns, we choose the second way of vircator frequency gain based on the scaling of geometric parameters. As we have shown the suggested approach allows to propagate virtual cathode oscillators to sub-THz frequency range.

In this Report the prototype scheme of the micrometer-scale virtual cathode oscillator (“nanovircator”) is simulated and optimized in the framework of CST Particle Studio.

II. RESULTS

The numerical particle-in-cell simulation of the "nanovircator" dynamics in the framework of CST Particle Studio (PS) has been carried out. In Fig. 1 the scheme of the simulated VCO, containing electron beam with overcritical current is presented. One can see that the proposed "nanovircator" has a simple construction.

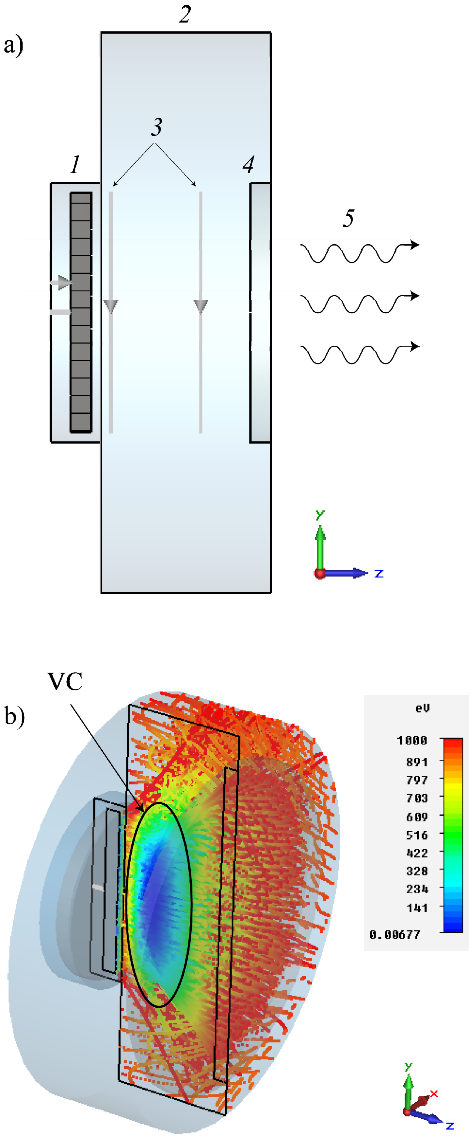

Fig. 1. (a) The cross-section of the “nanovircator” model: 1 - electron gun; 2 – drift tube; 3 – Rogowski coils; 4 – collector; 5 - RF output (coaxial waveguide). (b) "Nanovircator" in the presence of charged particles simulated in the framework of CST PS. Here “VC” denotes the virtual cathode.

We can divide it into two parts: the electron gun and the drift space. The field-emission carbon nanotube cathode with radius r_c is used for electron beam injection in the framework of the observed model. According to the works [3,7] carbon nanotube cathodes are the effective sources for generation of high-density electron beams with reference to the vacuum microelectronics goals. Such cathodes are able to emit beams with the values of current density about several kA/cm^2.

The formation and oscillation of low-energy electron cloud (virtual cathode) in the electron beam with overcritical current take place in the short cylindrical drift tube (r_{dt} and L_{dt} are the radius and the length of the drift tube respectively). The output electromagnetic radiation is extracted with the help of the coaxial waveguide located at the far end of the device. The inner conductor of the coaxial waveguide is the collector.

The radius of the collector r_{coll} has been optimized to balance between the optimal impedance of the waveguide and minimization of the amount of charged particles in the waveguide. So, the values of geometric parameters of the described "nanovircator" model are $r_{\mathrm{c}} = 0.12$ mm, $r_{\mathrm{dt}} = 0.28$ mm, $L_{\mathrm{dt}} = 0.15$ mm, $r_{\mathrm{coll}} = 0.25$ mm. The beam is accelerated due to the voltage $V_0 = 1$ kV between the electrodes of the electron gun.

The fundamental frequency of the virtual cathode oscillations in the “nanovircator” is close to the beam plasma frequency that is proportional to the beam current I_0: $f_{\mathrm{vc}} \sim f_{\mathrm{p}}$. Variation of I_0 changes the fundamental frequency of output radiation in the range of 0.05÷0.15 THz with average power ~0.5 W (Fig. 2). “Nanovircator” oscillations spectrum at high beam currents has the strong single component corresponding to the frequency of the virtual cathode oscillations. Notable, that the growth of the beam current value leads to the increase of both fundamental frequency of output radiation and the power level of the proper component in the spectrum.

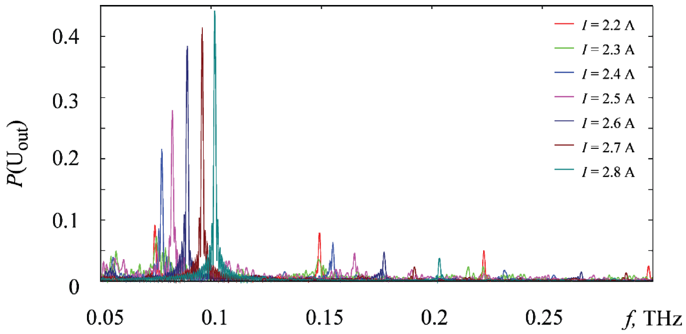

Fig. 2. Spectra of "nanovircator" output radiation corresponding to the different values of beam current.

Interesting operating regime of the proposed THz oscillator is observed when the beam current is low enough (at the edge of the generation zone) and exceeds slightly the value of critical current (see Fig. 3). The oscillations of the virtual cathode are rather weak at low currents. Nevertheless, a number of the higher harmonics of the fundamental frequency are effectively excited in this case.

Fig. 3 illustrates the typical “nanovircator” spectrum that is rich in the intense highest harmonics of the fundamental frequency. As it can be observed, higher harmonics are excited in the frequency range of 0.2÷0.9 THz.

Let us note, that the “nanovircators” as the compact THz sources are of interest in terms of the creation of the nonlinear antennas and arrays of oscillators due to the complex beam dynamics and the possibility of the switching of oscillation regime by changing beam parameters [8].

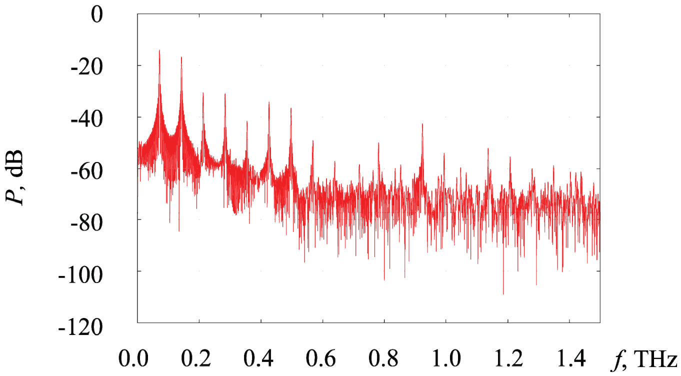

Fig. 3. Spectrum of "nanovircator" output radiation at low beam current I_0=2.1 A.

III. SUMMARY

The results of carried out numerical simulations of the novel device of vacuum microelectronics, the so-called "nanovircator", show that the micrometer-scale virtual cathode oscillators are the promising compact sources of mmw-to-THz electromagnetic radiation.

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