Perspective sub-THz powerful microwave generator "nanovircator" for T-rays biomedical diagnostics

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ABSTRACT

In this paper we suggest the new approach of powerful sub-THz signal generation based on intense electron beams containing oscillating virtual cathode. Suggested compact microwave source complies with a number of biomedical applications such as imaging, preventive healthcare, etc. 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.

Keywords: Virtual cathode oscillator, sub-terahertz radiation, microelectronics, biomedical diagnostics

1. INTRODUCTION

A large number of practical tasks requires the development of the high-power high-frequency signal generation technologies. The broad range of scientific and applied areas of biomedicine such as spectroscopy, imaging, biomedical diagnostics, etc., are of the strong commercial and theoretical interest.[1–4] Recent review[5] shows the growing interest of terahertz technology research for biomedical applications. Pharmaceutical quality control, protein characterization and cancer detection are of special interest.[6–8] The practical applications within these areas need the compact terahertz and subterahertz devices being simple and inexpensive in production.[9] Existing microwave sources that can operate at (sub)THz frequencies, such as mmw-gyrotrons and free electron lasers (FELs),[10,11] are able to generate a powerful electromagnetic radiation, but they are heavy, not compact and need a strong magnetic field and high-voltage sources for power supply. The other type of THz devices, solid-state devices and semiconductor lasers, such as resonant tunneling diodes (RTD), Gann diodes, quantum cascade lasers (QCL), superlattices, p-Ge lasers,[12–20] comply with the mobility and compactness conditions, but in the most cases they can not demonstrate the suitable power level for the real practical applications. Additionally, the solid-state devices are extremely sensitive to the temperature and require the delicate tuning.[21]

Therefore, there is presently the challenging task to develop the class of devices that would combine the advantages of both of types of THz radiation sources mentioned above. In these terms, the vacuum microelectronics provides good opportunities for the creation of the terahertz radiation sources with the required properties. One of the important ways to increase the frequency of vacuum devices with RF cavity is the reduction of the cavity dimensions. The considerable progress in the area of micromachining techniques and field electron emission sources has given rise to the active research and development of the so-called "nanoklystrons" — the vacuum high-frequency electronics devices based on the scaling down of the original klystron scheme.[22–25] The application of modern micromachining using micro-electro-mechanical systems (MEMS) technology allows to fabricate small-size resonant cavities with the characteristic dimension of about tens micrometers and field-emission cold

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cathodes to operate at sub-THz and THz ranges. The carried out theoretical studies of this microelectronic device have revealed $300 \div 400\,\mathrm{mW}$ power level at $300\,\mathrm{GHz}$ with the value of the beam current $I_0 = 0.28$ mA and accelerating voltage $V_0 = 0.75\,\mathrm{kV}$.[25]

In our work we propose to use the same idea based on the scaling of the device geometrical parameters to micrometers to advance the another perspective class of microwave devices, virtual cathode oscillators or vircators,[10,11,26–28] to the sub-Thz and THz frequency range. Vircators are the specific class of high-power bremsstrahlung microwave electronics devices that have a number of advantages, such as construction simplicity, the possibility of operation without the external magnetic field, low demands on the quality of electron beam and the possibility of the control of the output characteristics by the variations of the system parameters (beam current, magnetic field, etc.)[27,29–33] or the application of the external force.[34–37] Usually, vircators are considered as relativistic beam-plasma generators of high-power microwave electromagnetic pulses.[10] However, we have shown recently the possibility of vircator operation with low-voltage electron beams and additional braking of electrons.[38] Such devices, the so-called low-voltage vircators,[38–40] are considered as the perspective sources of wide-band microwave radiation including chaotic pulses[39,41] for different tasks, for example, for communication systems with chaotic carriers.[42]

The problems of the miniature small-size electrodynamic systems creation, the thermal dissipation and the electron velocity spread are known to become more significant at THz frequencies in comparison with lower frequencies. These factors do not lower the vircator operation efficiency considerably. For example, vircator can operate without external magnetic field[43,44] in superdimentional electrodynamic system in respect of the wavelength corresponding to the vircator fundamental frequency,[44,45] and in the presence of relatively high electrons velocities and angles spread.[46–48] However, vircators have the fundamental shortcoming: the vircator oscillation frequency is relatively low and does not exceed 20–40 GHz usually. So, the frequency gain of virtual cathode oscillators (VCOs) is one of the topical goals of the vacuum and plasma high-power electronics. It is well-known that the generation frequency of vircator is determined by the beam plasma frequency $f_{vc} \sim kf_p$, where k is the proportional coefficient which lies usually in the range $[1.5, 4.0]$.[10,45] The plasma frequency, in turn, is proportional to the space charge density of the beam ρ_b. Obviously, there are two ways to increase the vircator operation frequency: the increase of the space charge density (1) by the gain of the beam current I_0 or (2) by decreasing the beam surface at fixed value of I_0. As the growth of I_0 may lead to the undesirable consequences, such as electric discharges and breakdowns, we have chosen for the analysis the second way for the vircator frequency gain based on the scaling of geometric parameters. Nevertheless, the value of the beam current density j_0 that is necessary for the formation of the oscillating virtual cathode in the proposed micrometer-scaled vircator system is quite significant and reaches values of several $\mathrm{kA/cm^2}$. While speaking about the field electron emission, the highly-ordered carbon nanotube cathodes are used in microelectronics to form the high-density intensive electron beams according to their outstanding emission properties.[49] With the emitted current $100\,\mathrm{nA}$ per nanotube and the array density of about $10^{11}\,\mathrm{cm^{-2}}$ the values of the total current density emitted from the cathode up to $10\,\mathrm{kA/cm^2}$ are available.[22]

In this paper we present the prototype scheme of the micrometer-scaled virtual cathode oscillator for terahertz diagnostics, which we have called "nanovircator" by analogy with nanoklystron ,[22–25] and the results of its numerical simulation in the framework of the particle-in-cell code integrated in the Program Suite CST Particle Studio (CST PS). Using the CST PS, we have numerically investigated the virtual cathode formation and oscillations conditions, obtained the main parameters of the output electromagnetic radiation and carried out the numerical optimization of "nanovircator" geometrical parameters by means of the well-known optimization algorithms.

2. NANOVIRCATOR DESIGN

The designed construction of the proposed nanovircator shown in Fig. 1(a) is based on the classical vircator scheme,[10] i.e. the low-voltage electron beam with overcritical current is emitted from the electron gun into the drift space, where the virtual cathode (VC) is formed under the influence of the space-charge forces. The formation of a VC in the electron beam is illustrated in Fig. 1(b),(c), where the particles colored according to their energy (Fig. 1(b)) and electron beam phase portrait (Fig. 1(c)) are presented. One can see that the formation of the VC takes place near the anode grid in the drift space.

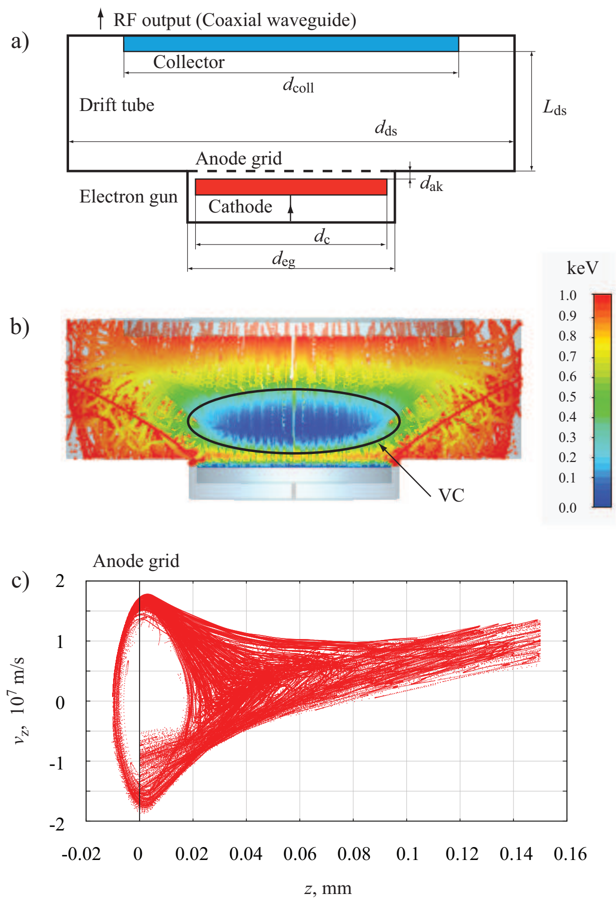

Figure 1. The illustration of nanovircator construction (a), the snapshot ($t = 1.2\,\text{ns}$) of nanovircator simulated in the framework of CST PS in the presence of the electron beam (b), the phase portrait of the electron beam in the coordinates (z, v_z) at $t = 1.2\,\text{ns}$

The electron beam is accelerated by the voltage pulse $V_0 = 1.0\,\text{kV}$ applied for $1.5\,\text{ns}$ between the anode grid and cathode with the distance between them being $d_{ak} = 0.01\,\text{mm}$. The diameters of the cathode and electron gun tube are $d_c = 0.24\,\text{mm}$ and $d_{eg} = 0.26\,\text{mm}$, respectively. The drift space of the nanovircator is a perfect electric conducting (PEC) cylindrical cavity loaded on the coaxial waveguide at the remote wall to extract the output electromagnetic radiation of VC oscillations. The oscillations of VC excite the fundamental mode of the coaxial waveguide. The outer diameter of the coaxial waveguide is equal to the diameter of the cavity $d_{ds} = 0.56\,\text{mm}$. The inner conductor of the output coaxial waveguide is a PEC collector with the diameter $d_{coll} = 0.42$ mm. The diameter of the collector d_{coll} has been optimized from the point of view of the balance between the optimal impedance of the waveguide and the minimization of the amount of the charged particles penetrating into the waveguide. The length of the drift space is $L_{ds} = 0.15\,\text{mm}$. The geometrical parameters of the nanovircator scheme mentioned above are chosen according to the results of the mathematical optimization with the help of Trust Region Framework and Particle Swarm algorithms integrated in CST PS.

During the 3D electromagnetic particle-in-cell simulation of the proposed nanovircator the cold cathode acts as a particle source with field emission model. For this vircator system the injected beam current has been limited as $2.1\,\text{A} < I_0 < 2.8\,\text{A}$. The bottom limit of the beam current is determined by the space-charge limiting current $I_{SCL} = 2.1\,\text{A}$ above which the non-stationary VC is formed in the drift space. The upper bound of the beam current ($2.8\,\text{A}$) corresponds to the present limits of the carbon nanotube cathode emission properties.

3. RESULTS OF THE NUMERICAL SIMULATION

We have analyzed the output microwave radiation characteristics of nanovircator (spectrum, oscillation form, power level) and their evolution with the change of the beam current I_0. The typical oscillations and spectra of nanovircator electromagnetic radiation are shown in Fig. 2. It is well known that the fundamental frequency of the virtual cathode oscillations in VCOs is determined by the beam plasma frequency that is proportional to the beam current I_0: $f_{VC} \approx f_p$, $f_p \sim I_0$. The estimated values of the beam plasma frequency for the chosen values of the beam current lie within the range of $f_p = 0.07 \div 0.1$ THz. It is important that the resonant properties of the drift space cavity do not appear in this vircator system because the VC oscillation frequency is much lower than the cavity eigenmodes frequencies. This fact allows to tune the output radiation frequency by the simple variations of the beam current. The results of the numerical simulations shown in Fig. 2(b) are in a good agreement with the carried out theoretical estimations: the increase of the beam current value leads to the growth of the main frequency of nanovircator. It also leads to the growth of the amplitude of the main spectral component. Noticeable that the spectra of nanovircator output electromagnetic radiation have a number of higher harmonics of the fundamental VC oscillations frequency. The presence of the higher harmonics in the radiation spectra is caused by the relaxation-like oscillations form being character for the VCOs as shown in the insert in Fig. 2(a) (see also Ref.[45]). Fig. 3 illustrates the typical spectrum of output radiation of nanovircator in the logarithmic scale containing a large number of higher harmonics of the fundamental frequency. It is clearly seen that the higher harmonics of the main frequency with the suitable power level (greater than −30 dB) can reach up to 0.47 THz.

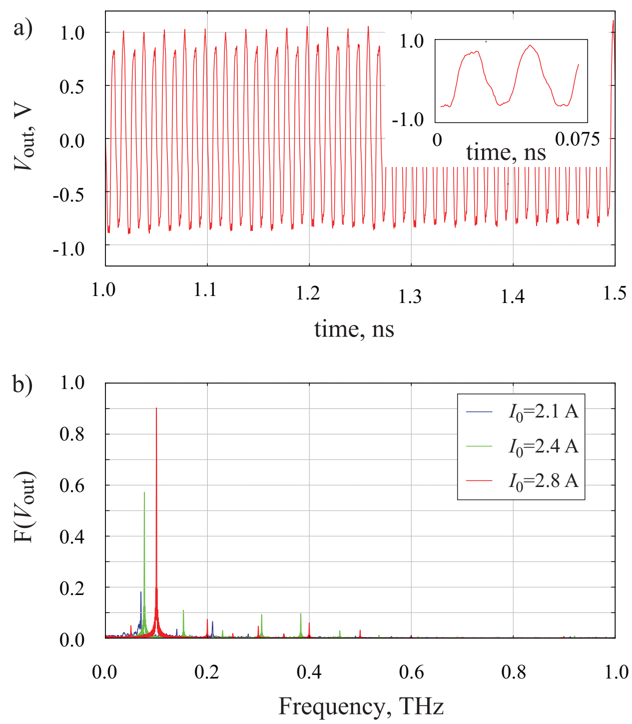

Figure 2. Output microwave radiation of nanovircator for $I_0 = 2.8$ A (a) and the amplitude spectra of output radiation obtained for the different values of I_0 (b). The insert demonstrates two typical periods of microwave oscillations

The dependencies of the spectral components frequencies with power level greater than −30 dB on the beam current are shown in Fig. 4(a). One can see that the number of the higher harmonics of the VC oscillations fundamental frequency with sufficient magnitudes depends on the beam current. For low currents $I_0 = 2.1 \div 2.2$ A three higher harmonics (f_2–f_4) of the main frequency $f_1 = f_{VC}$ are effectively excited. There is the area of the high frequency harmonics excitation (f_5 and f_6) at $I_0 = 2.2 \div 2.4$ A. In this area the frequency of the highest excited harmonic reaches 0.47 THz approximately. At $I_0 = 2.4 \div 2.6$ A the VC oscillations are characterized by the chaotic noise-like form with rather high level of noise in the spectrum, that is typical for the systems with VC,[36,39] and only the second harmonic of main frequency f_1 is excited at such beam currents. In the area $I_0 = 2.6 \div 2.8\,\mathrm{A}$ the beam dynamics becomes regular and the higher harmonics of f_{VC} are excited again.

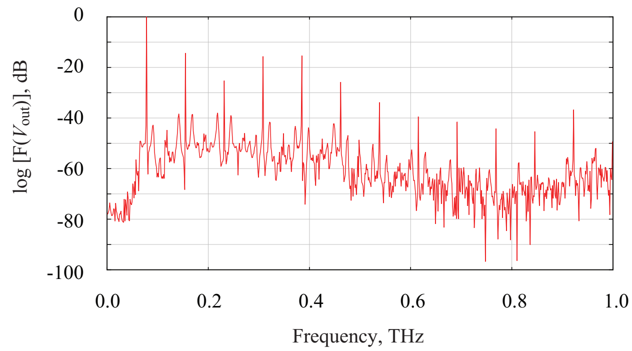

Figure 3. The amplitude spectrum of nanovircator microwave radiation in the logarithmic scale for the beam current $I_0 = 2.4\,\mathrm{A}$

We have also analyzed the dependence of the power of each harmonic on the beam current (see Fig. 4(b)). It is clearly seen that the power of the microwave oscillations at the fundamental frequency, $P_{VC} = P(f_1)$, is about several hundreds mW and even reaches 0.9 W at high currents. At the same time, the microwave power of VC oscillations at higher harmonics is significantly smaller (about several tens mW and smaller). It is important to note that both the fundamental frequency and the power at fundamental frequency depend linearly on the beam current I_0 for the relatively high current values $I_0 > 2.5\,\mathrm{A}$. Though the values of the higher harmonics frequencies depend on the beam current approximately linearly, their power has a nonlinear dependence on I_0. Such behavior of the power of higher harmonics is related to the strong nonlinearity of the processes taking place in the low-voltage electron beams with VC.

Having based on the presented results of the numerical investigations of the nanovircator output characteristics, one can choose the value of the control parameter I_0 to obtain the high frequency microwave radiation being suitable for a given problem. The optimal parameter to obtain the relatively powerful sub-THz radiation is $I_0 = 2.8$ A with 0.9 W at 0.1 THz (the fundamental frequency oscillations). For the higher frequencies: a) $I_0 = 2.7$ A — the third harmonic with 10 mW at 0.27 THz; b) $I_0 = 2.4$ A — the fourth harmonic with 8 mW at 0.31 THz; c) $I_0 = 2.4$ A — the fifth harmonic with 7 mW at 0.38 THz; d) $I_0 = 2.7$ A — the fifth harmonic with 4 mW at 0.47 THz. So, the obtained results show the possibility of the use of nanovircator for the generation of sub-Thz and in perspective THz electromagnetic radiation for different purposes, and in spite of the output power at higher harmonics is relatively low at this stage, the further complex optimization of nanovircator (in particular, power output) will allow to raise it essentially.

4. CONCLUSIONS

The results of the carried out numerical simulations of the novel device of vacuum microelectronics, the nanovircator, show that the micrometer-scaled virtual cathode oscillators are the promising compact sources for the wide area of biomedical tasks that require T-rays. We should also make some technical remarks in conclusion. The complete vacuum microelectronic nanovircator with cold cathode, anode grid, cavity space and collector could be fabricated by microelectronic technology on silicon, using micromachining.[22] The cathode of nanovircator could be composed of a carbon nanotube field emitter array with integrated grid as in the vacuum nanoklystrons or microtriodes. The cavity and output waveguide are etched from two silicon wafers, which are later joined by thermocompression bonding. The cathode are drop-in-parts and vacuum sealing is performed in the last step.

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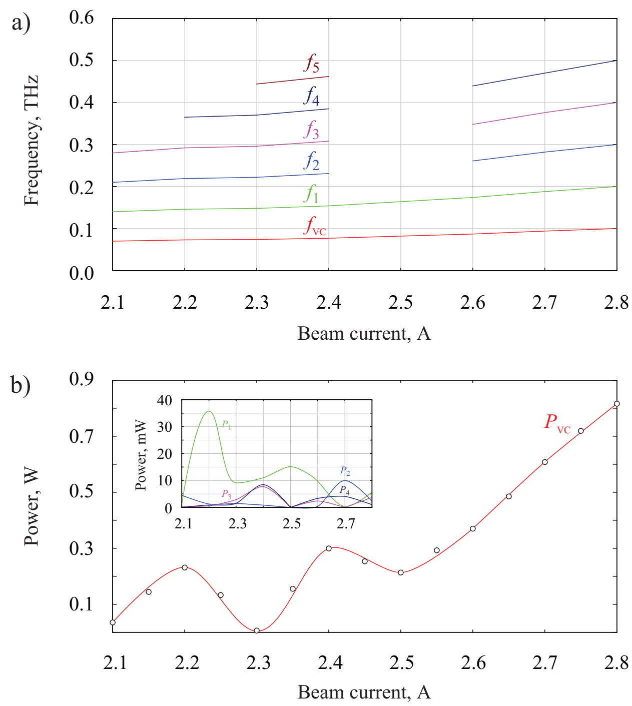

Figure 4. The dependence of the fundamental frequency f_{VC} of VC oscillations and its higher harmonics $f_2 - f_6$ on the beam current I_0 (a) and the dependence of the fundamental frequency power, P_{VC}, on the beam current I_0 (b). The insert in Fig. 4(b) shows the dependencies of the higher harmonics power $P_2 - P_5$ on the beam current I_0

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