Research of Volume Free-Electron Laser with Photonic Crystal Structure for Operation in Sub-Terahertz Range

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***Abstract*— In this work, we present the results of the numerical optimization of volume free-electron laser based on the interaction between an electron beam and periodic structure of microwave photonic crystal. The optimization aims at the advancement of such device to the sub-terahertz frequency range. We show that the reduction of characteristic geometric dimensions allows increasing the working frequency of photonic crystal fundamental mode up to 12.5 GHz. Moreover, we observe the possibility to generate microwaves at the fifth harmonic of the fundamental frequency, namely f=62.5 GHz and obtain an output power level of about 3.6 kW.**

I. INTRODUCTION

The active development of the so-called “nanoklystrons” and “nanovircators” operating in THz range is going on nowadays [1,2]. The main idea underlying the advancement of classical klystrons and vircators to a higher frequency range is reducing of device geometrical parameters up to micrometers.

The same principle of frequency increase can be applied to a prospective type of microwave sources, so-called volume free-electron lasers (vFELs), based on the interaction between an intense electron beam and periodic structure of photonic crystal (PC). In these devices, the frequency of electromagnetic field oscillations excited by electron beam, piercing PC structure, is defined by the dispersion characteristics of PC. Generally, the fundamental mode of PC is the most efficiently excited. However, in recent theoretical study, the combination of the described vFEL principles with a vircator generation mechanism allowed to increase operating frequency and generation efficiency by means of exciting higher PC eigenmodes [3]. The main advantages of such devices are relatively high efficiency of energy exchange between an electron beam and PC along with the stability of the operating frequency.

In this paper, we present the results of a numerical study aimed at optimization of vFEL geometrical parameters and the detailed investigation of electron beam dynamics to advance the generator to sub-THz frequency range. Numerical simulations have been carried out by means of self-made computational 3D electromagnetic particle-in-cell (PIC) code based on a simultaneous calculation of Maxwell equations and relativistic equations of charged particles motion.

II. RESULTS

Let us describe the design and numerical simulation details of the proposed scheme of vFEL with PC. The schematic representation of the system under study is presented in Fig.1. The scheme of the generator consists of a cylindrical drift tube of radius R_w = 6 mm, into which several single-velocity electron beams are injected with energy W and current I each. The PC is located near the injection plane and consist of periodically alternating metal pins in the longitudinal and transverse directions to the beam propagation (diameter of the pin is d_{pin} = 0.4 mm); the distance between pins in the longitudinal direction – z_p = 2 mm, in the transverse direction – y_p =1.9 mm. The power output section is located behind the PC. An external driving magnetic field is applied to the system and leads the electron beam through PC. After the beam leaves the PC, the magnetic field leads it to the walls of the waveguide.

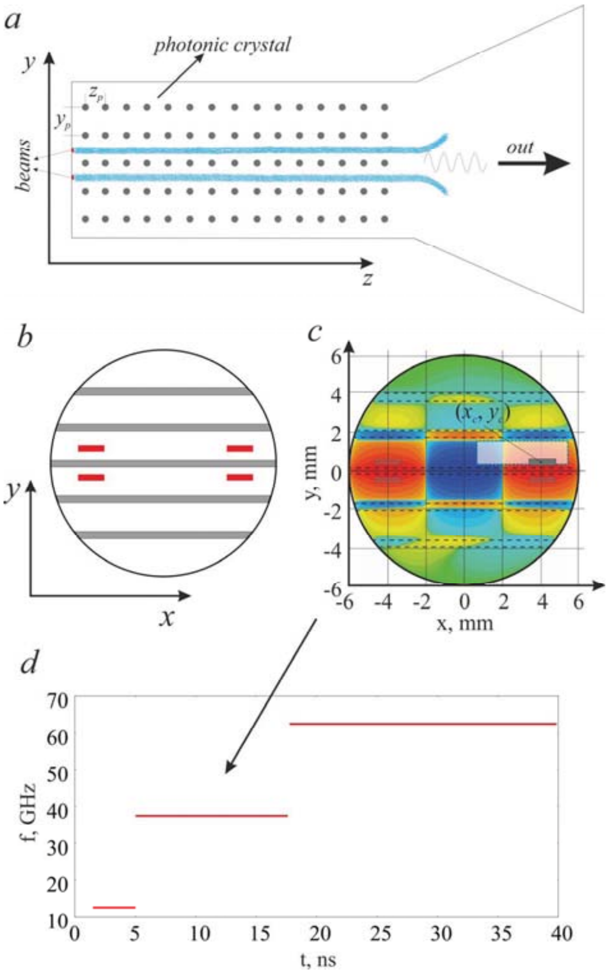

Fig. 1. The investigated model of volume free-electron laser with photonic crystal. (*a*) Schematic representation of the system under study in the YZ plane. Blue is the schematic representation of a beam; red – areas of electron beams injection. (*b*) Schematic representation of the studied configuration with four electron beams. (*c*) Distribution of electric E_z field of one of the excited modes. (*d*) Dynamics of the main radiation frequency in time.

In this work, we consider two configurations of emitters, with two or four electron beams, in order to investigate the excitation of various modes. Configuration of the system with four electron beams is schematically presented in Figure 1c. The regions corresponding to the electron beams emitters are highlighted in red, thickness of the beams – d_c=0.475 mm and the width – l_c=1.5 mm.

This study has been conducted to access the possibility of increasing the frequency of generation of vFEL with PC and its advancement to the sub-THz range due to the miniaturization of the model and work on higher modes of PC. It should be noted that the miniaturization of the model has been carried out within the limits of the capabilities of the current level of technological development and is achievable with full-scale implementation.

In order to better understand the physical processes of the interaction of an electron beam with the photonic crystal eigenmodes, consider the dynamics of the electron beam when exciting mode EH_{13}. When electron beam passes through the PC, one of the PC modes is excited, corresponding to the conditions of the best energy exchange between the beam and the wave. There is an accumulation of electromagnetic energy in the PC area and an increasing oscillation of the electron beam. First of all, the accumulation of energy is related to a strongly slowed-down group velocity of the PC eigenmodes in the excitation region. After a short time, the accumulation of energy and the increased beam oscillations lead to reflections of the electron beam. This, in turn, is accompanied by a slowing down of the average beam velocity and the appearance of the so-called "squeezed state" [5], i.e. the region in which there are a strong deceleration of the electron beam, an increasing space-charge density, and a strong scatter in the velocities (Fig. 2).

A strong scatter in beam velocity, combined with a high space charge density, leads to simultaneous fulfillment of the synchronism conditions for a variety of spatial harmonics of different modes. This is accompanied by the formation of electron bunches in the electron beam actively interacting with electromagnetic fields. It should be noted that the fundamental mode of the PC is excited in the injection area, supporting intense oscillations of the electron beam, but as it propagates through the PC, the stored energy is transferred to the EH_{13} mode via the formed "squeezed state". So, the absorption of the fundamental mode and the excitation of the EH13 mode occurs in the beam in the case under consideration. Thus, a "squeezed state" can be considered as an active medium where the cascade amplification of the electromagnetic wave occurs due to the volume distributed feedback and the adjustment of the electron beam configuration to the excited mode structure.

Also, it was obtained effective generation at the frequency $f_n = n*f_0 = 62.5$ GHz (where $f_0 = 12.5$ GHz is the frequency of the fundamental mode, $n = 5$) in the vFEL model with PC. The most efficient excitation has been achieved using four beams located in the maxima of the longitudinal electric field of the EH_{15} mode. The output power has reached 3.6 kW with a total beams current of 6 A and an accelerating voltage of 108 kV. In this case, it is observed consistent switching of frequency generation of an electromagnetic field. We have found out that the frequency switching is related to the excitation of different eigenmodes of PC. Thus, the dynamics of electromagnetic radiation is following. In early time moments, the generation frequency is mainly determined by the frequency of the fundamental mode EH_{11} (12.5 GHz). Next, it happens the switching of generation frequency and the excitation of the mode EH_{13} (37.5 GHz). Finally, after some time, the switching to the eigenmode EH_{15} occurs accompanied by the appearance of radiation frequency at 62.5 GHz (Fig. 1*d*). Note, the selection of mode is determined mainly by emitters configuration and the described above processes of electron beam dynamics.

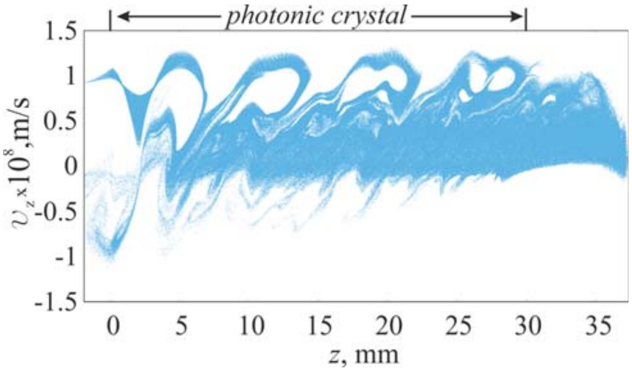

Fig. 2. The phase portrait of the system in the plane (V_z, z).

It should be noted that the obtained results are not the limit for the considered system: it is possible to excite modes of a higher order while more precise optimization of the system parameters.

In conclusion, we have shown that the excitation of various photonic crystal eigenmodes requires fine-tuning of the configuration of emission sources in accordance with the spatial distribution of electromagnetic fields of a particular mode. Due to the presence of strong distributed feedback, the electron beam is divided into bunches, and coherent electromagnetic radiation is generated. It should be noted that guided by the principles described above and more fine-tuning the configuration of electron beams, it is possible to excite higher order modes. The optimization of the system parameters for the configuration with four electron beams and generation frequency of 37.6 GHz has shown that it is possible to achieve electronic efficiency up to 28%.

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