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

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***Abstract*—In this work we present the results of numerical optimization of volume free-electron laser based on the interaction between electron beam and periodic structure of microwave photonic crystal. The optimization aims at advancement of such device to sub-terahertz frequency range. We show that reduction of characteristic geometric dimensions allows to increase the oscillation frequency of photonic crystal fundamental mode f_0 up to 12.5 GHz. Moreover, we observe the possibility to generate microwaves at higher harmonics of fundamental frequency, namely at $f_5 = 5 \times f_0 = 62.5$ GHz, and obtain output power level of about 3.6 kW.**

***Index Terms*—volume free-electron laser, photonic crystal, relativistic electron beam, sub-terahertz radiation**

I. Introduction

The so-called “the terahertz gap” is a definition of a particular problem in microwave electronics, which describes a lack of rather powerful high-frequency signal generation technologies in terahertz (THz) frequency range [1]. At the same time, the research and design of the compact sources of radiation in the sub-THz and THz frequency ranges is of strong interest in a broad range of scientific and applied areas such as spectroscopy, imaging, biomedical diagnostics, broadband communication etc. [2]–[4]. Therefore, researchers develop new and modify existing devices to fill this “gap” [1]. In particular, active development of the so-called “nanoklystrons” and “nanovircators” operating in THz range is going on nowadays [5]–[8]. The main idea underlying the advancement of classical klystrons and vircators to a higher frequency range is a significant reducing of device geometrical parameters to micrometers.

The same principle of frequency increase in well-known devices can be applied to a prospective type of microwave sources – so-called volume free-electron lasers (vFELs), based on the interaction between intense electron beam and periodic structure of photonic crystal (PC) [9], [10]. In this devices, frequency of electromagnetic field oscillations excited by means of electron beam piercing PC structure is defined by the dispersion characteristics of PC [11]. Generally, fundamental mode of PC is the most efficiently excited. However, in recent theoretical study, combination of described vFEL principles with vircator generation mechanism allowed to increase operation frequency and generation efficiency by means of exciting higher PC eigenmodes [12]. So, the main advantages of such devices are high efficiency of energy exchange between electron beam and PC along with stability of operation frequency.

In this study, we present the results of numerical study aimed at mathematical optimization of vFEL geometrical parameters to advance 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 simultaneous calculation of Maxwell equations and relativistic equations of charged particle motion.

II. Results

In this work, we have considered multibeam modification of the vFEL scheme proposed in [9]. In particular, microwave device consists of cylindrical drift tube with multibeam injector located at the left side. PC is placed inside drift tube to the right from multibeam injector and consists of periodically located metal pins in the longitudinal and transverse direction to the beam propagation. The output waveguide is located at the right end of the drift tube. Optimized geometry parameters of this scheme will be listed further.

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. To ensure mode selection when operating at higher modes, it is necessary to realize the best energy exchange between the high-order mode being excited and the electron beam. To obtain the regime of effective interaction between the beam and electromagnetic field oscillation at the desired mode, it is necessary to ensure the equality of the phase velocity of the electromagnetic wave and the velocity of the beam at the point where the group velocity is slowed the most. Moreover, the electron beams should be positioned so that they pass in the field antinodes, where the electric field is directed parallel to the beam propagation, and the shape of the electron beams should ideally correspond to the geometric dimensions of the field maxima. Guided by these principles, in the vFEL model with PC, it was possible to obtain effective generation at the frequency $f_n = n * f0 = 62.5$ GHz, where $f_0 = 12.5$ GHz is the frequency of the fundamental mode, $n = 5$. The most efficient excitation has been achieved using four beams located in the maxima of the longitudinal electric field. The output power has reached 3.6 kW with a total beams current of 6 A and an accelerating voltage of 108 kV. It should be noted that the results obtained are not the limit for this system: with more precise optimization of system parameters, one is possible to excite modes of higher order. In this study, we have not consider excitation of higher-order modes (n¿ 5) due to limitations on computing resources necessary for correct modeling of the processes of electron-wave interaction in these modes.

A multiparameter optimization of the vFEL model has been carried out, on the basis of which the following optimal PC parameters have been determined: drift tube radius $R = 6$ mm, pin radius $R_c = 0.2$ mm, spacing in the transverse direction $l_y = 1.9$ mm, spacing in the longitudinal direction $l_z = 1.6$ mm, the number of periods in the longitudinal direction is 15, in the transverse direction – 4. The configurations and the number of beams for the effective excitation of various modes depend on the spatial structure of the excited mode. For example, for the excitation of the main mode of the PC, it is optimal to use two beams located near the center pin of the PC, since in these regions, the maxima of the longitudinal component of the electric field are observed.

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