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Higher-order modes excitation in generator with photonic crystal

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ABSTRACT

We revealed physical processes responsible for the excitation of higher-order modes in volume free-electron laser with photonic crystal. We discovered the new approach for the selection of the electromagnetic modes in volume free-electron laser with photonic crystal based on the choice of the emitter configuration. This approach allows essential multiplying the generation frequency. We found that the regimes with developed higher-order modes are accompanied by complex squeezed-like beam dynamics. Also, we present the results of the optimization of volume free-electron laser with photonic crystal in terms of excitation of high-order modes. In particular, we investigated the influence of the location of electron beams on the excitation of photonic crystal eigenmodes.

Introduction

Currently, there is special interest in the development of compact powerful sources of electromagnetic radiation from the millimeter wavelengths to the terahertz frequency range [1–4]. Primarily, this is due to the fact that electromagnetic fields of this range have a wide ambit of applications in various areas, including monitoring, and security, remote sensing of the atmosphere, high-speed transmission of information, etc. [7,4–6,3,8,9]. At the same time, the most pressing issues of modern vacuum and plasma electronics are increasing the operating frequency and output power of generators and amplifiers of electromagnetic radiation, increasing their efficiency and stability of operation [1,10]. The solution of the formulated problems is difficult without attracting new ideas and approaches which will allow overcoming partially the existing limitations of well-known vacuum and plasma electron devices [1,4,11–16].

This work is devoted to the development of the promising approach for higher-order modes excitation based on the using of photonic crystal (PC) as an electrodynamic structure of microwave generator. Many of the unique properties of photonic crystals are well-known and widely described in the literature [17–21]. The most important among them are bandwidth availability, high coupling impedance at bandwidth, localization of electromagnetic fields in the electrodynamic system, high stability of generation when used PCs [22–31]. For example, it was shown in Ref. [29] that PC located in the drift tube of an axial vircator permits to significantly improve the efficiency of microwave generation due to a number of factors: (i) high interaction impedance with passing electron beam, (ii) distributed electromagnetic feedback with virtual cathode, (iii) efficient electromagnetic energy output compared to traditional cylindrical waveguide.

Photonic crystals have been already successfully used in volume free electron lasers (vFELs) [28], and free electron masers, which demonstrate high output power and operating efficiency in a wide frequency range [27,29,32]. In such systems, the electromagnetic modes that effectively interact with an electron beam are excited. This is due to the fact that group velocity of PC eigenmodes demonstrates a strong deceleration at the certain parameters of the system [18,27,33,34]. An electromagnetic wave is continuously reflected on the periodic planes of the photonic crystal in these regimes, lingering in the region of interaction of the electron beam with the electromagnetic wave. So, a PC provides distributed feedback and the interaction of electron beam with electromagnetic fields occurs more efficiently [27,35]. At the same time, the presence of the PC leads to the distribution of electromagnetic energy over a larger volume and reduces the local energy load on the system elements.

However, there are still a number of crucial issues related to the processes of generation of electromagnetic radiation in the devices with PCs. In particular, there is the problem of effective excitation of high-order modes in vFELs for essential increasing of generation frequency.

This paper presents the results of investigation of physical processes responsible for the excitation of higher-order modes in the proposed scheme of vFEL with PC and development of the approach which will

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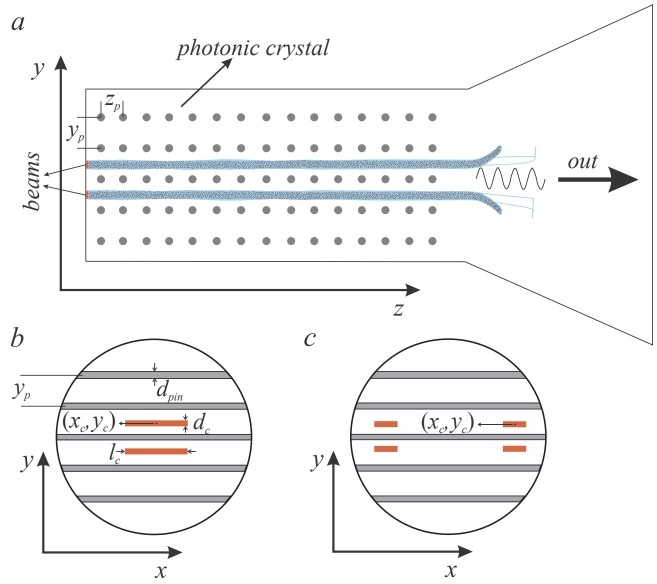

Fig. 1. The scheme of the model under study—volume free electron laser with a photonic crystal. (a) Schematic representation in YZ plane. Blue areas correspond to schematic representation of ribbon electron beams; red ones—to the electron beams emitters. $y_p = 1.9$ mm, $z_p = 2$ mm are the distances between the pins of the PC in the transverse and longitudinal directions, respectively, relative to the direction of the electron beam propagation. (b), (c)—schematic representation of two considered configurations of emission source: with two or four electron beams, respectively. l_c is the width of the beam, d_c is the thickness of the beam, $d_{pin} = 0.4$ mm is the diameter of the conductive pins, (x_c, y_c) – coordinate of the center of one of the electron beams.

allow essential increasing the generation frequency. Also, we discuss the features of nonlinear dynamics of electron beams interacting with eigenmodes of PC.

System under study

The study of the considered systems by analytical methods is extremely difficult and inefficient due to the presence of strongly nonlinear and nonstationary self-consistent interaction of the electron beams with electromagnetic fields of PC. In this regard, we use a 3D fully electromagnetic particle-in-cell (PIC) code for simulation of the electron-wave interaction [36]. This method is based on the joint solution of the Maxwell equations and the relativistic equations of particles motion and characterized by a high degree of accuracy and reliability.

Let us describe the design and the details of numerical simulation of the proposed model of vFEL with PC. The scheme of the device (see Fig. 1) consists of cylindrical drift tube of radius $R_w = 6$ mm into which several single-velocity electron beams are injected (from red areas in Fig. 1a) with energy W and current $I = 1$ A each. The PC is located near the injection plane and composed of periodically alternating metal pins in the longitudinal and transverse directions relative 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 structure. An external driving magnetic field with induction of 2 T 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 horn. In order to investigate excitation of different electromagnetic modes, we consider two configurations of the vFEL in this work: with two or four emitters of an electron beam. They are presented schematically in Fig. 1b and c, respectively. The regions corresponding to the electron beams emitters are highlighted in red, the thickness of the beams – $d_c = 0.475$ mm and the width – $l_c = 1.5$ mm.

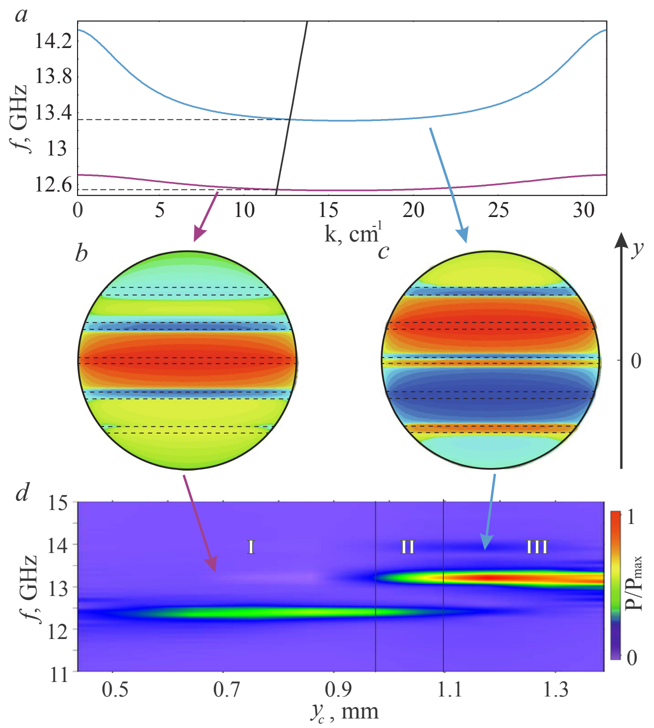

Fig. 2. (a) Numerically obtained dispersion characteristics of the hybrid electromagnetic modes EH_{11} and EH_{12} of the PC and (b), (c) corresponding distributions of electric field (E_z component). The distributions of the field are built in the region between the pins of the PC. The dotted lines in (b) and (c) indicate the locations of the PC pins. The bold black line in (a) corresponds to the undisturbed drifting electron beam with energy 12.67 keV and is defined as $f(k) = v_b k/2\pi$, where v_b is the beam drift velocity. (d) The dependence of the electromagnetic radiation frequency on the position of the electron beams y_c along the y-axis for the system configuration with two electron beams (see Fig. 1b). Roman numerals denote three characteristic areas corresponding to different generation regimes: I – single-frequency generation at the frequency of 12.4 GHz, II – two-frequency generation regime at 12.4 GHz and 13.35 GHz, III – single-frequency generation at 13.35 GHz.

Key results

Mechanisms of modes competition

The main difficulty when a microwave device operating at higher modes is the occurrence of modes competition which is usually caused by the simultaneous fulfillment of excitation conditions for several modes [1]. Indeed, it is rather simple to ensure synchronism of the beam and wave in the studied system for several eigenmodes of PC simultaneously. In particular, such regime is observed when the electron beams energy is $W = 12.67$ keV that is clearly seen from the dispersion dependencies for the hybrid electromagnetic modes EH_{11} and EH_{12} of the PC (see Fig. 2). Note, the beam energy $W = 12.67$ keV corresponds to the optimal excitation of fundamental mode EH_{11}.

We should note that the system configuration with two electron beams symmetrically located relative to the central conductor of the PC was chosen based on the distribution of the electric field longitudinal component E_z of the fundamental mode EH_{11}. We have found out that such configuration of electron beam emitters is optimal in terms of excitation of this mode.

We have discovered the switching of the generation frequency associated with competition between EH_{11} and EH_{12} PC modes (see Fig. 2d) that is observed with increasing distance of the electron beams from the central conductor (y_c) due to changes in the efficiency of the energy exchange between the electron beams and the eigenmodes of PC. Thus, the single-frequency generation regimes I and III are realized in the case of strong coupling of the electron beams with one of the considered PC eigenmodes. At the same time, in the case of relatively strong coupling of the electron beams with both modes, the system demonstrates the two-frequency regime (region II in Fig. 2d).

The change in the efficiency of the energy exchange between the electron beam and the PC eigenmode with a change in the position of the emitters is due primarily to differences in the spatial distributions of the electromagnetic fields of the modes. Actually, the modes under consideration have vertically shifted maxima of E_z component (see Fig. 2b, c), therefore as the distance between the electron beams and the center conductor increases, their removal from the maximum of the electric field longitudinal component of the EH_{11} mode and approaching to the extremums of the EH_{12} mode occur simultaneously. So, we have found out that separate and simultaneous excitation of both modes is possible in the considered scheme of vFEL with PC.

System optimization and underlying physical processes

We have discovered that based on the described above mechanisms it is possible to excite effectively higher frequency modes in the vFEL with PC. The main idea here is the using of a larger number of electron beams that will provide optimal coupling with the desired mode. Let us consider a specific example. For the excitation of the EH_{31} mode at 37.6 GHz the most optimal way is the using of 4 electron beams symmetrically injecting into the system with respect to x- and y-axes. We note that the use of four beams instead of six located at each antinode of the electric field of the mode EH_{31} (see Fig. 3a) is due to the need to reduce the coupling with the fundamental PC mode which is characterized by the electric field maximum in the center of the waveguide.

Further, we optimized the control parameters of the system, such as energy and currents of the beams, and their location in order to increase the excitation efficiency of the EH_{31} mode. We analyzed the influence of the location of the electron beams emitters on the generated electromagnetic radiation power and its spectral composition for configuration with four electron beams. Due to symmetry, it is convenient to represent the location of the electron beams by the definition the center coordinates (x_c, y_c) of one of them (see Fig. 3a). We revealed (see Fig. 3b) that more than 95% of the power is concentrated at the frequency of 37.6 GHz when the coordinate (x_c, y_c) is in the region of the power maximum. Thus, the maximal output power is achieved when the electron beams are located near the maxima of the longitudinal component of the electric field strength of the mode EH_{31}. In aggregate, this indicates an effective energy exchange between the electron beams and the mode EH_{31} being excited.

We have found out that the most efficient excitation of the high-order eigenmodes in the considered system (particularly, EH_{31} mode) is accompanied by a complex beam dynamics close to the so-called “squeezed state” [37–40].

Let us consider the dynamics of the electron beams in more detail. When an electron beam passes through the PC, one of the PC modes corresponding to the conditions of the best energy exchange between the beam and the wave is excited. At the initial stage, this is the mode EH_{11} because it is characterized by the maximal value of Q-factor. This is expressed in the presence of the maximum in the output power spectrum at the frequency 12.4 GHz corresponding to this mode (see Fig. 4a). Phase portrait demonstrates at the initial stage the characteristic process of the electron beam bunching inside the PC area (Fig. 4b, $t = 10$ ns).

As the mode excitation rate is proportional to its Q-factor value, the high-order mode EH_{31} ($f = 37.6$ GHz), which is characterized by a lower Q-factor, develops longer in time. It begins to prevail at $t > 15$ ns (Fig. 4a). The predominance of a high-order mode over a fundamental one is ensured by the preliminary special adjustment of the position of the areas of electron beams emission.

Meanwhile, the electron beams demonstrate complex dynamics in this developed regime (Fig. 4b, $t = 99$ ns) due to the accumulation of electromagnetic energy and increasing oscillations (overmodulation) of the electron beams in the PC area leading to reflections of electrons in the beam. The accumulation of energy is related, first of all, with a close to zero group velocity of the PC eigenmodes in the excitation region (see Fig. 2a). Actually, the electrodynamic structure in the form of the photonic crystal demonstrates the properties of a resonator that is transparent to the electron beam but accumulating electromagnetic energy. In turn, this is accompanied by a slowing down of the average beam velocity and increasing space-charge density. Moreover, the nonlinear process of the modes competition leads to an additional complication of the beams dynamics.

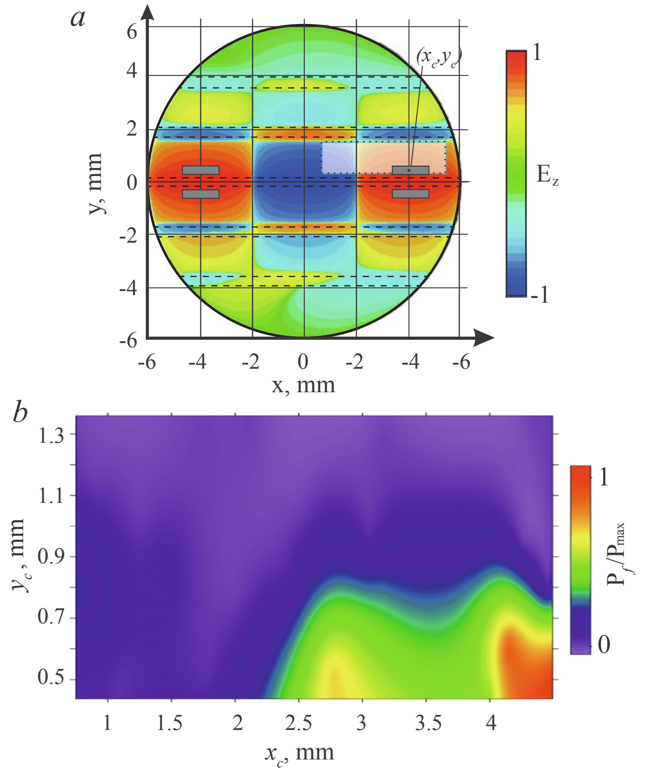

Fig. 3. (a) The example of the system with 4 electron beams upon excitation of the mode EH_{31}; the distribution of E_z component is shown in the figure. The locations of the electron beams are marked by the dark grey rectangles; (x_c, y_c) – coordinate of the center of one of the electron beams; the semi-transparent grey rectangle area in Fig. (a) corresponds to the range of the investigated change in the center coordinates of one of the electron beams. (b) The dependency of normalized power of output electromagnetic radiation P_f/P_{max} at the frequency of 37.6 GHz on the location of the electron beams centers for the configuration with four electron beams; P_f – power at the frequency of 37.6 GHz, P_{max} – the maximal value of output power. Electron beam energy is 26 keV (this is the optimal value for the effective excitation of EH_{31} mode).

Conclusion

In conclusion, we have shown that the excitation of the specific PC eigenmode in the vFEL scheme requires tuning of the configuration of the emission sources in accordance with the spatial distribution of the electromagnetic field of the particular mode. This principle is taken as the basis of the approach to mode selection in the generator with PC, which allows one to increase essentially the generation frequency due to the excitation of higher modes. It was found that the regimes, characterized by effective mode selection, are accompanied by the complex electron beam dynamics. The optimization of the system parameters for the configuration with four electron beams has shown that it is possible to achieve electronic efficiency (i.e. the ratio of power transferred from the electromagnetic fields to the electrons to the beam

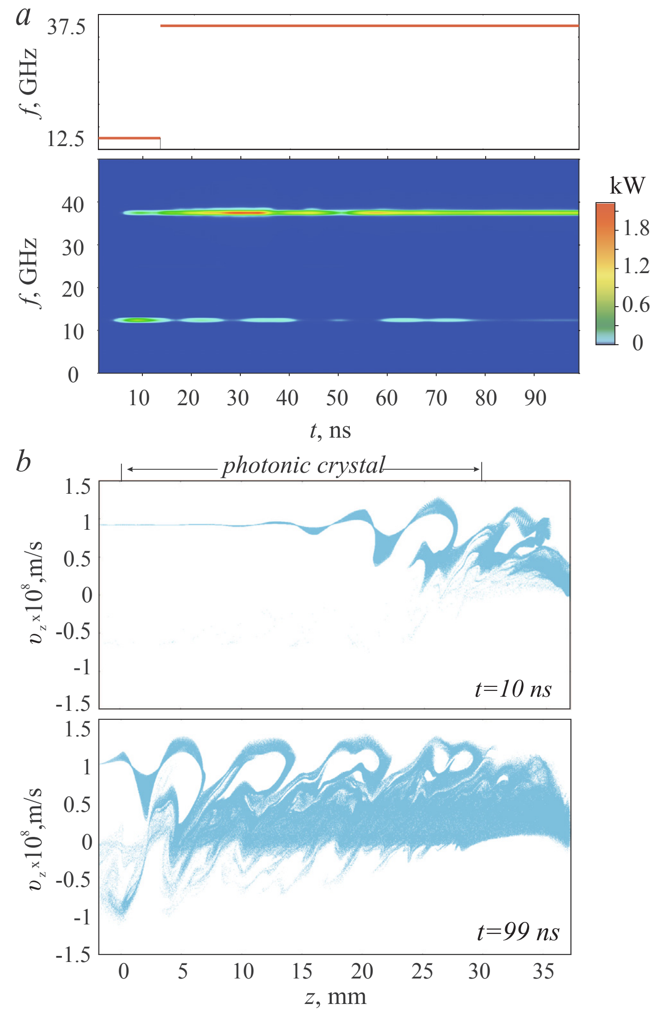

Fig. 4. (a) The dependence of the frequency value of the most powerful spectral component (skeleton) and spectral composition of output electromagnetic radiation on time. (b) The phase portrait of the system with four beams on the plane (z, V_z) at the time moments 10 ns and 99 ns. Electron beam energy is 26 keV.

power) up to 28% for the generation frequency 37.6 GHz.

Concerning the experimental realization of the proposed scheme of vFEL, we would like to note several important points. First, at large values of beam energy and current one can face with overheating of the elements of the electrodynamical structure by an intense electron beam. In the considered system, one of the ways to avoid this problem is using of thicker metal pins. In this case, heating is not critical and, at the same time, the dispersion properties of PC are mainly conserved. Second, a separate task is the formation in the electron gun of electron beams of the required configuration. From this point of view, the advantage of the proposed vFEL scheme is the low requirements for the quality of electron beams both in terms of geometry and velocity scatter. This is a consequence of the development of complex beam dynamics, the characteristics of which weakly depend on the initial conditions (including the parameters of the beams) and are determined mainly by the current and the initial energy of the electron beams [38,40,41].

CRediT authorship contribution statement

Artem A. Badarin: Investigation, Software, Validation, Writing - original draft. **Semen A. Kurkin:** Conceptualization, Supervision, Writing - original draft. **Alexey A. Koronovskii:** Project administration, Methodology, Visualization. **Alexander E. Hramov:** Methodology, Writing - review & editing. **Alexey O. Rak:** Validation, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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