Analysis of the Dispersion Characteristics of the Photonic Crystal in the Generator with Intense Relativistic Electron Beam

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Abstract: *We have investigated of the electrodynamic characteristics of a photonic crystal, which is a system of thin metal plates alternating in two dimensions or pins. In particular, we obtained the dispersion characteristics of the photonic crystal under consideration for a number of the first working modes, and their evolution was studied when the geometric parameters of the system were changed. We have numerically studied the processes of interaction of a beam with an electromagnetic field in a photonic crystal.*

Keywords: Relativistic electron beam, virtual cathode, virtual cathode oscillator, vircator, photonic crystal, high-power microwaves

Introduction

Generators with an electron stream with a supercritical current (vircators, reflective triodes, reditrons, etc.) are very perspective and, as a result, investigated actively by powerful sources of electromagnetic signals in the microwave range. Devices of this kind can be used in devices for accelerating ion fluxes, for studying electromagnetic compatibility, for probing the atmosphere, etc. [1].

It should be noted that the main advantages of vircators are: high output power, simplicity of management of spectral and power generation characteristics, in certain modes - a wide frequency band of generated signals and simplicity of design (including the possibility of functioning without external magnetic fields).

However, the main disadvantage of generators with an electron flow with supercritical current is their low efficiency (about 1%). There are several reasons for such low efficiency. The main, in our opinion, are: low efficiency of the virtual cathode interaction with the field of the electrodynamic structure and low efficiency of electromagnetic field output from the virtual cathode interaction field with the electromagnetic field into the output waveguide path due to incoherence of the virtual cathode radiation.

One possible solution of the problem of low efficiency is to indicate the modification of old schemes or the development of new ones of beam-plasma systems using the newly discovered regularities of the dynamics of REB. In this paper, we investigate the perspective scheme of a relativistic vircator with a photonic crystal, a preliminary study of which shows a significant increase in the efficiency of generation. The basic idea of using a photonic crystal in an axial vircator scheme is to increase the efficiency of sub-THz generation in this scheme by excitation of electromagnetic waves in a photonic crystal through a portion of the electron beam passing through the VC and their interaction with the REB [2,3].

System Under Study

A detailed study was made of the electrodynamic characteristics of a photonic crystal in a cylindrical waveguide. When developing a numerical model of a relativistic vircator system with a photonic crystal(PC), we based on the experimental prototype developed in the work [4]. A photonic crystal is a system of thin metal plates alternating in two dimensions or pins. This three-dimensional structure has two spatial periods (Fig. 1). The photonic crystal has 15 periods in the beam propagation direction, each of which consists of 5 alternating plates. The dispersion characteristics of the photonic crystal under consideration for a number of the first working modes were obtained and their evolution was studied with a change in the geometric parameters of the PC, such as the length of the plates l_g (the radius of the pins R_c) in the longitudinal direction, the distance between the plates (pins) in the longitudinal lz and transverse ly directions relative to propagation relativistic electron beam.

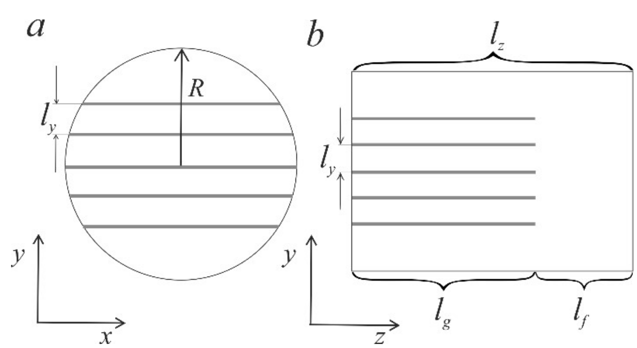

Figure 1. Schematic representation of the investigated model of the photonic crystal. (*a*) View of the photonic crystal in the xy plane. (*b*) One period of the photonic crystal in the longitudinal direction. l_z is the longitudinal period; Ly is the transverse period; l_g and l_f the length of the plate and the distance between the plates in the longitudinal direction, respectively;

Results

To study the dispersion characteristics, the collections of dependences *f(k)* for a number of modes were constructed, where *f* is the frequency, and *k* is the wave number. A characteristic feature typical of electrodynamic structures with a photonic crystal consisting of thin metal plates, is found. It consists in the fact that the shapes of the f (k) curves can be divided into two types: the modes inherent in the photonic crystal (Fig. 2, curve types 1); modes having the nature of a cylindrical waveguide (Fig. 2, curves of type 2. We note that these curves are mapped partially in order to see the features of curves of type 1).

Figure 2 shows the region between the wave numbers k_1 and k_2, where the features of the PC are best manifested. We note that in this region the group velocity of waves can be slowed down by more than 10,000 times, in comparison with waves in a system without PC, which is a distinctive feature of the electrodynamic structures under consideration.

Analysis of the effect of length *lg* plates and the distance between the plates in the longitudinal direction l_f on the dispersion curves *f(k)* showed that if the sum $l_f + l_g$ constant then dispersion curves *f(k)* are practically not transformed. At the same time, with a change in the longitudinal period of the photonic crystal $l_z = l_f + l_g$, characteristic transformations are observed: an increase in the longitudinal period l_z leads to a decrease in the characteristic wave number k_2 and, accordingly, to the narrowing of the characteristic region $\Delta k = k_2 - k_1$ down to its complete disappearance at a certain characteristic value l_{z_cr}. It should be noted here that, at the same time, the frequency *f* corresponding to the range between k_1 and k_2 varies slightly with the variation of l_z. The change in the transverse period l_y of the photonic crystal leads to stronger transformations of the dispersion characteristics. An increase in the transverse period l_y leads to an increase in the characteristic wave number k_1 and a decrease in the wave number k_2, which in turn leads to a faster narrowing of the region Δk, compared to the decrease of this region with increasing longitudinal period l_z. At the same time, an increase in the transverse period l_y leads to an increase in the frequencies of all the considered dispersion characteristics *f (k)*. Thus, a change in the transverse period l_y leads to two characteristic effects, namely, to the change in the region Δk and to the displacement of the dispersion characteristics of the working modes along the *f*.

The use of such characteristic features of the dispersion characteristics of a photonic crystal as a region of strong slowing of the group velocity makes it possible to increase the coupling resistance of the beam and the electromagnetic field in these regions, and also provides the condition for synchronism of the phase velocity of the wave and the relativistic electron beam over a wide range of velocities. Together, this should allow substantially increasing the efficiency of the interaction of the electron beam with the electromagnetic field.

Note that in devices of the vircator type, the beam passing through the virtual cathode has a considerable velocity spread. To improve the efficiency of these devices, one can use the features of the electrodynamic characteristics of photonic crystals. Indeed, it is possible to select the parameters of the photonic crystal in such a way that the vibration frequency of the virtual cathode in the vircator f_v coincides with the frequency of one of the modes in the region of slowing down the group velocity between k_1 and k_2. In the optimal regime, the beam line (its dispersion characteristic) corresponding to the average velocity of the electron beam must pass through the point $((k_1 + k_2) / 2, f_v)$. In this case, there should be a significant increase in the efficiency of the interaction of the electron beam and the electromagnetic field. Thus, an analysis of the features of the dispersion characteristics of a photonic crystal shows that these electrodynamic structures can be effectively used in devices of the vircator type to improve their output characteristics.

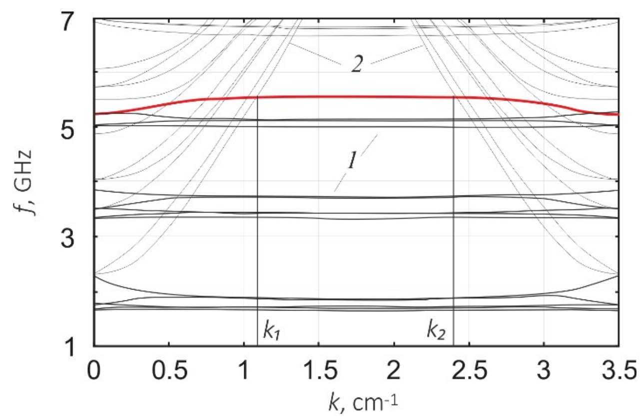

Figure 2. Numerically obtained dispersion characteristics of the photonic crystal in the considered vircator system.

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