Photonic Crystal and Bragg Waveguides for THz Electron Devices

Eugene N. Odarenko
Kharkiv National University of Radio Electronics
Kharkiv, Ukraine
Email: e.n.odarenko@gmail.com

Alexander A. Shmat'ko
V.N. Karazin Kharkiv National University
Kharkiv, Ukraine
Email: sh47@ukr.net

***Abstract*—Dispersion characteristics and spatial field distributions in the photonic crystal waveguides and Bragg ones are considered. It is shown that these waveguides can be used as slow-wave systems in the THz vacuum electron devices.**

Keywords—photonic crystal; THz device; Bragg waveguide; slow-wave system; dispersion diagram

I. Introduction

Development of the effective terahertz electron devices (generators and amplifiers) is the one of basic tendencies of the modern vacuum electronics [1, 2]. Efficiency of the classical microwave devices decreases in this frequency range. The most critical problems are the slow-wave structures fabrication and coupling impedance decrease. These problems stimulate the searching of the novel electron devices schemes with more effective beam-wave interaction.

We propose the method to increase the interaction efficiency based on the application of the electrodynamics systems containing photonic crystal and Bragg waveguiding structures.

Results of the numerous experimental and theoretical investigations of the photonic crystals and Bragg waveguides show possibilities of their wide application in active and passive elements for different frequency ranges [3, 4].

In this report the different schemes of the photonic crystal and Bragg structures that can be used for interaction with sheet electron beams in terahertz electron devices are investigated.

II. Photonic Crystal Waveguide

The application of photonic crystal structures for the formation of electrodynamics systems of the terahertz devices can overcome one of the main factors that reducing the interaction efficiency in electronic devices with increasing frequency – decrease of the interaction impedance due to the localization of high-frequency field near the surface of slow-wave structures.

Due to the periodicity of the material parameters changes in one or more dimensions in photonic crystals formed band gaps in which the radiation propagation becomes impossible. This physical phenomenon is used to form a quasi-optical and optical waveguides and cavities based on defects in photonic crystals, i.e. violations of translational symmetry.

Different kinds of the linear defects that can be used for transmission of the electron beam and its interaction with the electromagnetic field are considered. The dispersion characteristics and spatial distributions of the electric field for the localized modes of the photonic crystal waveguides are calculated. Numerical calculations were performed using free software packages MIT Photonic Bands (MPB) [5].

Fig. 1(a) is a scheme of the photonic crystal waveguide which is used as a channel for passing the sheet electron beam with initial longitudinal velocity $\vec{v}_0$ along *Ox* axis. Here two-dimensional photonic crystal of square lattice airholes in dielectric with permittivity $\varepsilon = 12$ is considered. This structure exhibits the photonic band gaps for radiation with TE polarization. In this case electric field vector have a component along axis *Ox* that parallel to the direction of the electron beam passing. Fig. 1(b) shows the dispersion diagram of photonic crystal waveguide. *a* is the lattice constant of photonic crystal.

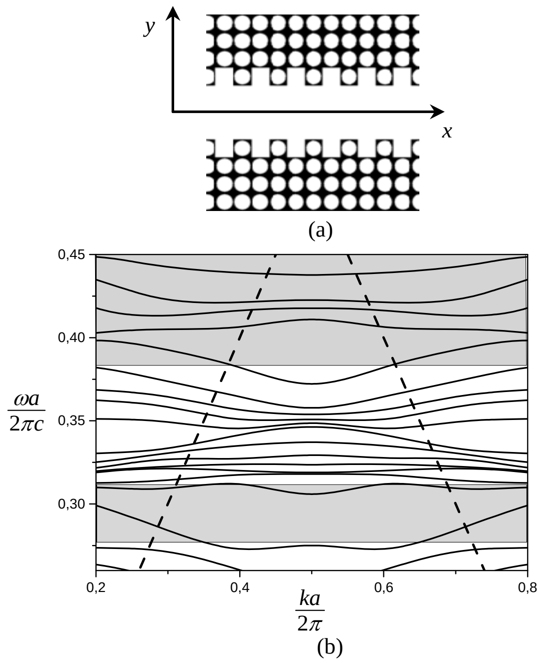

Fig. 1. Photonic crystal waveguide scheme and dispersion diagram.

978-1-5090-1009-7/16/$31.00 ©2016 IEEE

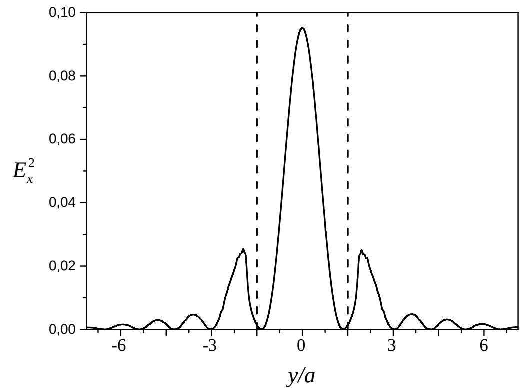

Fig. 2. Spatial distribution of the longitudinal electric field intensity squared.

The shaded areas show the forbidden zones of the bulk photonic crystal for the TE polarization of the radiation. Sloping dashed lines represent light lines for positive and negative spatial harmonics. Dispersion diagram shows that the slow wave modes exist in the photonic crystal waveguide (phase velocity less than the speed of light). Furthermore this modes lie within the both band gaps.

Fig. 2 displays spatial distributions of the electric field amplitude squared in the cross-section of the photonic crystal waveguide shown in Fig. 1(a). Dashed lines indicate the boundaries of hollow waveguide channel where sheet electron beam is passed. In this case we can see the localized mode of the phonic crystal waveguide. Furthermore the phase velocity for this mode is less than speed of light.

As seen in Fig. 2 the dependence of electric field amplitude on transversal coordinate has a maximum in the center of the channel. Therefore this localized mode of the photonic crystal waveguide is not a surface mode in the ordinary sense. At the same time modes of the conventional metal slow-wave systems are purely surface. This fact results in the coupling resistance decrease and complicate the usage of the metal electrodynamic systems in the terahertz electron devices.

It is clear from Fig. 2 that in the photonic crystal slow-wave systems electron beam may be passed in the center of the waveguide channel.

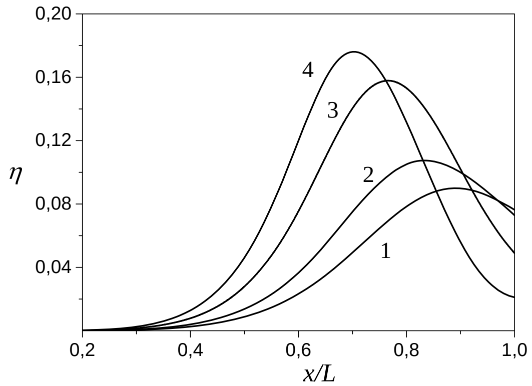

Fig. 3. Beam-wave interaction efficiency vs longitudinal coordinate.

This configuration is suitable for miniaturized electron devices since in this case strong requirements for current density, electron beam sizes and electron-optical system are absent.

Fig. 3 shows effect of the electron beam thickness Δ on the beam-wave interaction efficiency. L is the interaction space length. Curves 1-4 correspond to different values of normalized electron beam size Δ / D along axis Oy. Here D – width of the waveguide channel. Curve 1 – $\Delta / \mathrm{D} = 1$; 2 – $\Delta / \mathrm{D} = 0.75$; 3 – $\Delta / \mathrm{D} = 0.5$; 4 – $\Delta / \mathrm{D} = 0.25$. It is clear that decrease of the parameter Δ / D results in the efficiency enhancement. Moreover efficiency maximum is reached in the interaction space for less longitudinal coordinate.

Numerical calculations were performed on the basis of the nonlinear multidimensional theory of the resonant O-type vacuum electron devices with prolonged beam-wave interaction and arbitrary spatial distribution of the focusing magnetostatic field [6].

III. Bragg Waveguide

Bragg waveguides is one of the numerous kinds of the photonic band-gap waveguides. These structures may to have cylindrical or planar configurations. We consider the hollow-core planar Bragg waveguide. In this case the vacuum layer is surrounded by Bragg cladding layers (Fig. 4). Localization of the electromagnetic energy in the waveguide channel is determined by the photonic band gap of the Bragg structure. Additional layers adjacent to the vacuum core provide the supporting of the modes with phase velocity that less than speed of light [7]. Moreover these layers can be use as matching layers for effective control of the core field spatial distribution [8].

Bragg waveguides were first analyzed by Yeh and coauthors [9]. Electrodynamical analysis of the periodic multilayer structures based on the ABCD matrix method has been resulted in analytical expressions for dispersion relations. This method also allows obtaining dispersion equation for structure in Fig. 4. The layers permittivities are 12 and 1 that correspond to black and white colors. Corresponding thickness of the alternating layers are 0.33*a* and 0.67*a*.

It should be noted that two kinds of modes are existing in this waveguiding structure – even and odd. Application of the Bragg waveguide in the O-type beam-wave systems demands to use even modes only because in this case electric field maximum is realized in the center of the hollow channel.

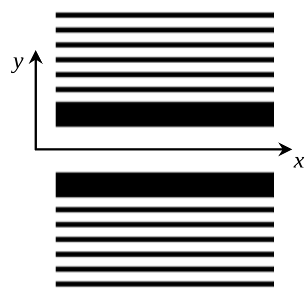

Fig. 4. Scheme of the planar Bragg waveguide

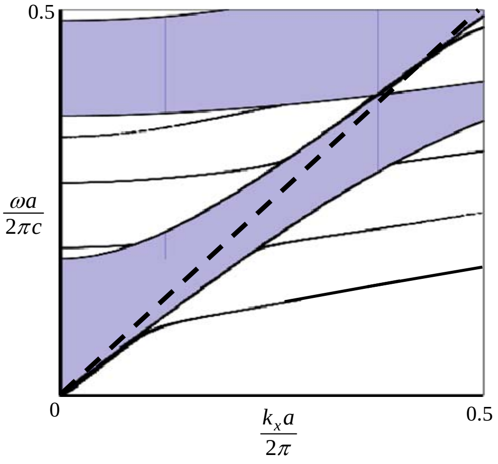

Fig. 5. Dispersion diagram of the planar Bragg waveguide.

Fig. 5 shows the calculated photonic band structure of the planar Bragg waveguide. Shaded regions represent modes penetrating through the periodic cladding. Dashed line indicates the “light line” that distinguishes waveguide modes and surface ones.

It is clear from Fig. 5 that these modes lie within the forbidden zones of the dispersion diagrams. It should be noted that we obtain the localization of the electromagnetic field in the hollow channel as for waveguide modes (fast waves) as for surface modes (slow waves). Only modes with phase velocity less than speed of light are suitable for beam-wave interaction in the system under consideration.

Transversal spatial distributions of the surface modes electric field in Bragg waveguide are shown in Fig. 6 for different values of the vacuum channel width *D* = *a;* 2*a;* 4*a*. It is apparent that additional dielectric layers enhance the localization of the electromagnetic field in the waveguide channel. An increase of the parameter *D* results in decrease of the electric field intensity at the center of the waveguide.

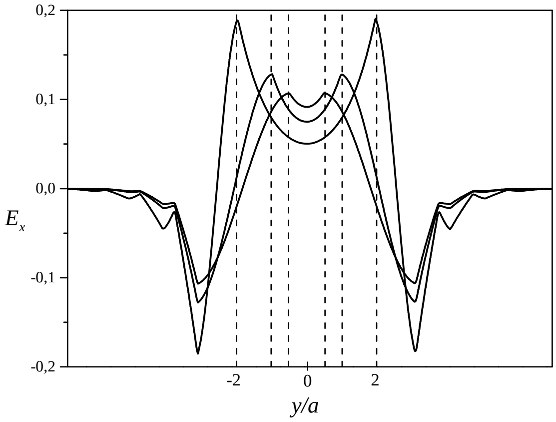

Fig. 6. Spatial distribution of the electric field in the Bragg waveguide channel

However this field attenuation is not significant. Indeed the fourfold widening of the vacuum channel corresponds to field intensity reduction no more than twice as much.

Therefore this band-gap waveguide may be used for support of effective beam-wave interaction in the vacuum THz devices. For example if electron beam fills the entire waveguide channel ($\Delta / D = 1$) then electric field intensity varies no more than fourfold within the electron beam thick. This result provides significant reduction of the electron beam high-frequency layering in comparison with conventional electrodynamical systems of the THz vacuum electron devices.

IV. Conclusion

It was found that in the photonic crystal waveguides can be implemented regime of slow waves with a transverse electric field amplitude distribution, which provides the increase of the coupling resistance compared to standard electrodynamics systems of vacuum terahertz devices.

Application of the Bragg waveguide with additional dielectric layers for beam-wave interaction provides the decreasing of the electron beam layering. Therefore the efficiency enhancement is possible for this electrodynamic system in comparison with conventional metal slow-wave systems of THz vacuum electron devices.

References

[1] R. Letizia, M. Mineo, C. Paoloni, “Photonic Crystal-Structures for THz Vacuum Electron Devices,” IEEE Trans. on Electron Dev., vol. 62, no. 1, pp. 178-183, 2014.

[2] J. T. Donohue, J. Gardelle, “Simulation of Smith-Purcell terahertz radiation using a particle-in-cell code,” Phys. Rev. ST Accel. Beams, vol. 9, 060701, 2006.

[3] B. M. Cowan, “Two-dimensional photonic crystal accelerator structures,” Phys. Rev. ST Accel. Beams, vol. 6, 101301, 2003.

[4] J. D. Joannopoulos, R. D. Meade, J. N. Winn, Photonic Crystals: Molding the Flow of Light. Princeton, NJ: Princeton Univ. Press, 1995.

[5] S. Johnson, J. Joannopoulos, “Block-iterative frequency-domain methods for Maxwell’s equations in a planewave basis,” Optics Express,. vol. 8, no. 3, pp. 173-190, 2001.

[6] Ye.N. Odarenko, A.A. Shmat’ko, “Nonlinear theory of O-type microwave oscillators with nonuniform magnetostatic field (two-dimensional model),” J. of Communication Techn. and Electronics, vol. 39(9), pp. 1-8, 1994.

[7] E.I. Smirnova, B.E. Carlsten, L.M. Earley, “Design, Fabrication, and Low-Power Tests of a W-band Omniguide Traveling-Wave Tube Structure,” IEEE Trans. on Plasma Sc., vol. 36, no. 3, pp. 763-767, 2008.

[8] A. Mizrahi, L. Schächter, “Bragg reflection waveguides with a matching layer,” Optics Express,. vol. 12, no. 14, pp. 3156-3170, 2004.

[9] P. Yeh, A. Yariv, C.-S. Hong, “Electromagnetic Propagation in Periodic Stratified Media. I. General Theory,” J. Opt. Soc. Am., vol. 67, no. 4, pp. 423-438, 1977.