

Localized Field Enhancement in Slow-wave Modes of Modified Bragg Waveguide

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Abstract—Modified scheme of Bragg reflection waveguide with additional layers between the hollow core and cladding is considered. Dispersion diagrams are calculated on the base of dispersion equations solutions for ordinary and modified Bragg waveguides. Slow-wave regimes are considered for both kinds of structure. Electric field spatial distributions for localized slow-wave modes of Bragg reflection waveguide are obtained. It is shown that modified scheme of Bragg waveguide provides the enhanced localization of the surface modes field in the hollow core. Therefore modified Bragg waveguide is the promising electrodynamic system not only for laser-driven accelerators but also for the vacuum electron devices where usual slow-wave structures are inconvenient.

Keywords—Bragg reflection waveguide; additional layers; dispersion equation; slow waves; mode field spatial distribution

I. INTRODUCTION

Bragg waveguides are one of variations of the photonic band-gap waveguides. Increasing interest to these structures is bound with unique physical properties, which are caused by energy localization mechanism in a waveguide channel. In a case of hollow-core waveguide this mechanism is determined by photonic band gaps of the periodic cladding. Bragg waveguides are investigated by many authors. Their aims were determination of the electrodynamic characteristics and the main directions of practical applying such structures [1 – 10]. First investigations have been carried out by Yeh and co-authors [1, 2]. The analytical expressions for dispersion relations both infinite structure and different optical waveguides with multilayers periodic cladding were obtained. The ABCD method is used for theoretical analysis.

Modified variant of Bragg waveguide is investigated theoretically by Mizrahi and Schachter [11]. The scheme with matching layers, which allows governing spatial field distribution in the hollow waveguide channel, is studied. Moreover this modified Bragg waveguide was analyzed as a system with hybrid guiding mechanism [12]. The capabilities to use the modified Bragg waveguide in laser-driven vacuum-accelerators are also considered [13, 14].

The cylindrical variant of such waveguide have been investigated by Smirnova and co-authors to form slow-wave system of traveling wave tube [15]. Electron beam is synchronized with slow wave traveling at about half of the speed of light. Important advantages of the dielectric slow-wave system over the conventional metallic one are considered. It concerns both electrodynamic characteristics and thermal regimes of the beam-wave system.

Thus Bragg waveguides are perspective in both planar and cylindrical beam-wave systems. High field concentration extent in the hollow core allows increasing of coupling impedance and thereby enhances the beam-wave interaction efficiency.

Furthermore the electrodynamic properties of the hollow core Bragg waveguide with additional (defect) layers provide the sensitivity enhancement of the system transmittance to physical properties of these layers in terahertz band [16]. This phenomenon stipulated by resonant power transfer between the waveguide core modes and defect layers ones. Therefore the further investigations of the modified Bragg waveguides are required for developing of the novel electrodynamic systems for various applications.

In the area of the nonlinear processes Bragg reflection waveguides with matching layers are used for enhancing the effective second-order optical nonlinearity [17, 18]. Apart from another advantages this waveguide scheme provides the increase of the field confinement factor [18]. Therefore one can expect enhancement of the interaction efficiency between the localized modes and some nonlinear or active media in the waveguide core.

Electrodynamic characteristics of the modified planar Bragg waveguide with additional dielectric layers placed between the hollow core and periodic cladding are considered in this report. This structure supports the slow waves, which can be synchronized with sheet electron beams. It is perspective to use this scheme of the beam-wave system in terahertz band, where conventional metallic slow-wave systems are ineffective because of principled physical and technical restrictions.

II. ORDINARY BRAGG WAVEGUIDE

The hollow core Bragg waveguide consists multilayer periodic cladding, which provides electromagnetic wave localization in the vacuum waveguide channel. In this case waveguide works in frequency range within forbidden zone of Bragg structure. Ordinary Bragg waveguide scheme, which is investigated in [1], is shown in Fig. 1. Dielectric layers with permittivities ϵ_1 and ϵ_2 have thicknesses a and b respectively. $L = a + b$ – period of Bragg structure. $2d$ is the waveguide channel width.

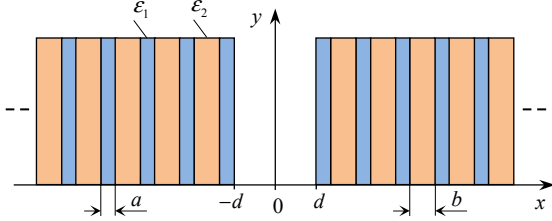


Fig. 1. Scheme of the hollow-core planar Bragg waveguide.

Dispersion relation for this waveguide is obtained in [1] for even and odd modes. Dispersion relation for field polarization with longitudinal components of electrical field for even modes can be written as:

$$e^{iKL} = A + B \frac{k_1 - i\epsilon_1 k_0 \operatorname{tg}(k_0 d)}{k_1 + i\epsilon_1 k_0 \operatorname{tg}(k_0 d)}, \quad (1)$$

$$A = e^{ik_1 a} \left[\cos k_2 b + \frac{i}{2} \left(\frac{\epsilon_2 k_1}{\epsilon_1 k_2} + \frac{\epsilon_1 k_2}{\epsilon_2 k_1} \right) \sin k_2 b \right],$$

$$B = e^{-ik_1 a} \left[\frac{i}{2} \left(\frac{\epsilon_1 k_2}{\epsilon_2 k_1} - \frac{\epsilon_2 k_1}{\epsilon_1 k_2} \right) \sin k_2 b \right],$$

$$k_0 = \sqrt{\left(\frac{\omega}{c}\right)^2 - \beta^2}, \quad k_{1,2} = \sqrt{\left(\frac{\omega}{c}\right)^2 \epsilon_{1,2} - \beta^2}.$$

Here k_1 and k_2 – wave vector components along axis Ox in the layers with permittivities ϵ_1 and ϵ_2 respectively; K – Bloch wave number; β – longitudinal wave number. Coefficients A and B form the first row of the ABCD translation matrix.

In this case only even modes present practical interest since their spatial electrical field distribution unequal zero in the middle of waveguide channel. We computed the dispersion diagram of a waveguide on the basis of equation (1). Calculations results are shown as black solid curves in Fig. 2 for even modes. Uncolored parts of the diagram show the forbidden zones where no propagating modes can exist. Bloch

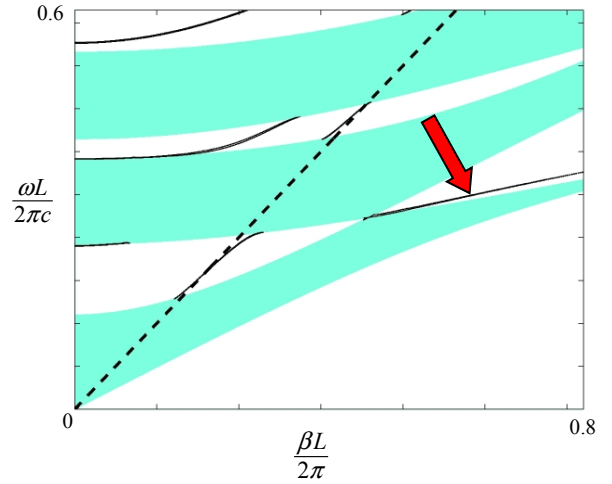


Fig. 2. Dispersion diagram of Bragg waveguide.

wave number is complex within these zones. In the colored regions waves penetrate through the Bragg structure. Therefore the Bloch wave number is real in this case. Naturally, solutions of the dispersion equation (1) lie within forbidden zones (solid black curves).

Sloping dashed line in Fig. 2 indicates the “light line” that used to divide a dispersion diagram into a region of bulk waves and a region of slow ones.

We can see that there are both bulk waves and slow ones in Bragg waveguide. Red arrow indicates dispersion curve of surface slow waves. Only slow (Bloch surface) waves can be synchronized with relativistic and nonrelativistic electron beams in the waveguide channel. Longitudinal electric field intensity within the cross section of the electron beam determines the efficiency of the beam-wave interaction.

Fig. 3 shows the spatial distributions of the electric field of the surface waves in Bragg waveguide for different values of the channel width. It should be note that field distributions are shown qualitatively in the terms of MIT Photonic Bands package [19]. Fig. 3a and Fig. 3b correspond to values

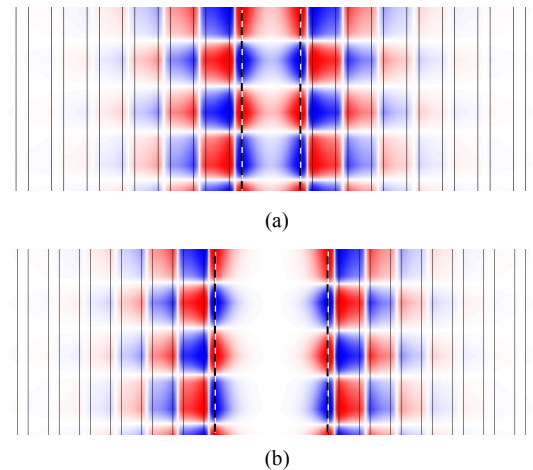


Fig. 3. Electric field spatial distribution for surface waves in Bragg waveguide.

$2d = 1.67L$ and $3.67L$ respectively. Dashed lines indicate the boundaries of the waveguide channel. The areas of blue and red color in the figures correspond to the opposite signs of the field amplitude. The white color corresponds to zero field amplitude.

It is apparent that increase of the parameter d results in strong decrease of the electric field intensity in the center of the waveguide channel due to exponential decay of the electric field away from the channel boundaries. Analogous situation realizes in the usual metallic slow-wave systems and forces the electron beam passing as close as possible to the grating surface. It entails a number of problems and incites to develop novel electrodynamic systems for electron devices especially in terahertz band.

III. MODIFIED BRAGG WAVEGUIDE

Scheme of the planar Bragg waveguide with additional dielectric layers allows forming spatial distributions of the electric field intensity in the hollow core that can provide more effective interaction with linear electron beams. Outline of the modified Bragg waveguide is shown in Fig. 4. Here h is the width of the additional dielectric layers. ϵ_g is the permittivity of these layers.

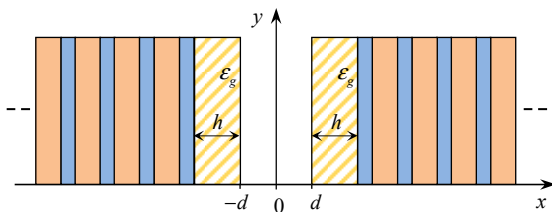


Fig. 4. Scheme of modified planar Bragg waveguide.

Dispersion equation for this structure is also obtained within the framework of ABCD matrix technique. Then we can write equation in such form for even modes:

$$e^{iKL} = A + B \frac{k_1 \epsilon_g - ik_g S}{k_1 \epsilon_g + ik_g S}, \quad (2)$$

$$S = \frac{k_0 \epsilon_g \cos(k_g h) \operatorname{tg}(k_0 d) + k_g \sin(k_g h)}{k_0 \epsilon_g \sin(k_g h) \operatorname{tg}(k_0 d) - k_g \cos(k_g h)},$$

$$k_g = \sqrt{\left(\frac{\omega}{c}\right)^2 \epsilon_g - \beta^2}.$$

Fig. 5 shows dispersion diagram of the modified Bragg waveguide for such parameters: $2d = 3L$; $a = 2b$; $\epsilon_1 = 3$; $\epsilon_2 = 18$; $\epsilon_g = 14$; $h = 2.5L$. Obviously in this case there are some even slow-wave modes within the forbidden zones. Red

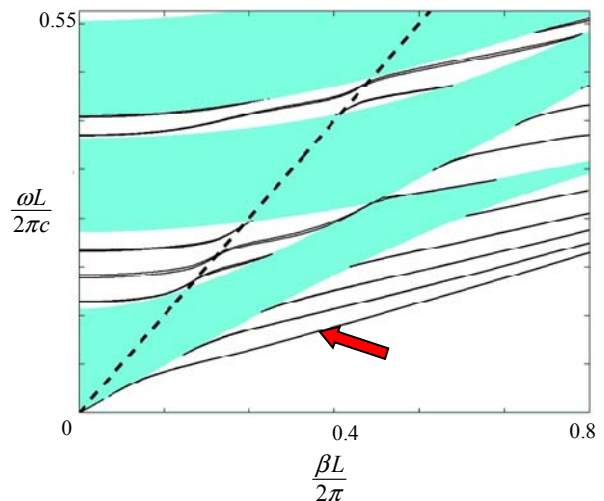


Fig. 5. Dispersion diagram of modified Bragg waveguide.

arrow indicates the dispersion curve of surface waves with lowest phase velocity. Slow-wave modes lie in the region under the light line on the dispersion diagram.

To investigate the capability of slow-wave modes for effective interaction with electron beam we computed the transversal spatial distributions of the electric field intensity in Bragg waveguide.

Fig. 6 shows qualitative characteristics of spatial distribution for even slow-wave modes that correspond to three different values of the waveguide channel width $2d$. Fig. 6a, Fig. 6b and Fig. 6c correspond to values $2d = 1.5L$; $3L$ and $5L$ respectively. Phase velocity of these modes is about $0.4c$. Vertical dashed lines indicate the boundaries of the waveguide hollow core.

Using additional layers in Bragg reflection waveguide results in the increase of the surface wave electric field intensity at the hollow core compared with ordinary Bragg waveguide. In Fig. 6a we can see almost uniform spatial distribution of the electric field intensity in the waveguide channel. But in this case channel is quite narrow and electron beam passing is difficult. Increase of the parameter d results in slight decrease of the electric field intensity in the hollow core center (Fig. 6b and Fig. 6c). Therefore in this case one can use modified Bragg waveguide with more wide hollow core as a slow-wave electrodynamic system for vacuum electron devices.

Furthermore electric field confinement also realized in the additional layers where we can see typical odd mode of the planar dielectric waveguide. Field spatial distribution within the layers corresponds to slow bulk waves with phase velocity that is less than light velocity in air. Electric field intensity decays exponentially outside of these layers in Bragg cladding but in the hollow core one can see the even mode with more uniform field spatial distribution than in Fig. 3. Thus in this case electric field spatial distribution of Bragg surface waves is modified by additional layers. It should be noted that

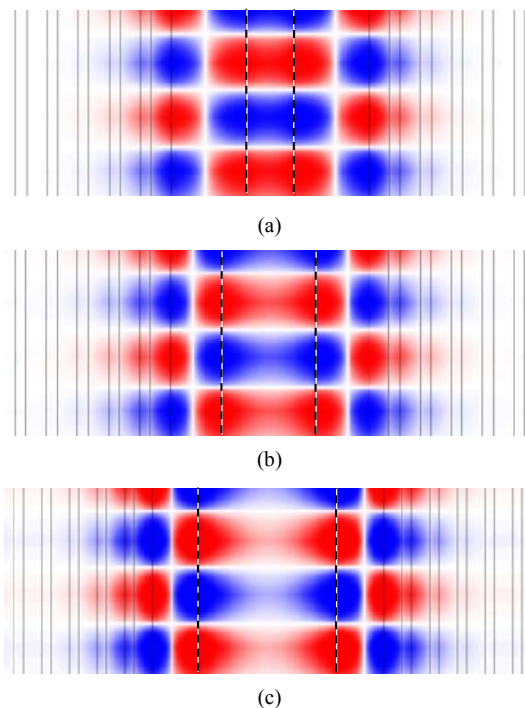


Fig. 6. Electric field spatial distribution for slow waves in modified Bragg waveguide.

electromagnetic energy distributes predominantly between the waveguide hollow core and these layers. Therefore estimation of the energy flux in these areas will allow defining the efficiency of the modified Bragg waveguide using in the beam-wave systems.

Changing the electric field spatial distribution is expected to effect the losses in composite cladding of the hollow-core waveguide. Comparative analysis of the Fig. 3 and Fig. 6 shows that substantial part of losses in modified Bragg waveguide occurred in the additional layers, whereas in ordinary waveguide losses are defined by Bragg structure properties. The appropriate choice of the material for additional layers fabrication will allow decrease the dissipation losses.

IV. CONCLUSIONS

Localization of the slow wave's field in the hollow core of the Bragg reflection waveguide is considered. Using the additional layers between core and periodic cladding results in the modification of the slow wave's field spatial distribution in the hollow waveguide channel. Enhanced field localization occurs both in the additional layers and in the hollow core. In this case field spatial distribution combines three types of the slow waves: surface waves in the hollow core, bulk waves in the additional layers and Bloch surface waves in the periodic cladding. Spatial distribution of the core wave's field is more uniform than in the ordinary Bragg waveguide with same

channel width. Thus localized slow-wave modes of the modified Bragg waveguide can be used for interaction with linear electron beams in terahertz beam-wave system.

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