The Effect of Additional Layers Parameters on the Modifided Bragg Waveguide Characteristics

Sashkova Y.V., Odarenko E.N.
Department of Photonics and Laser Engineering
Kharkiv National University of Radio Electronics
Kharkiv, Ukraine
E-mail: sashkovayana@gmail.com

***Abstract*— Bragg waveguide with additional layers between hollow core and periodic cladding is considered. On the base of dispersion equation solutions dispersion diagrams are obtained. The transversal spatial distributions of the electric field intensity are shown. The characteristics of Bragg waveguide respect to additional layer thickness and permittivity are considered. It is shown that increase of additional layers thickness results in increase of slow-waves number. Also field intensity decay in channel is reduced. Number of slow-waves increases respect to additional layers permittivity too. But distribution of the electric field intensity in the channel changes insignificantly. So one can tune additional layers parameters to get expected Bragg waveguide characteristics.**

***Keywords*— Bragg waveguide; additional layers; dispersion equation; dispersion diagrams; field spatial distribution**

I. INTRODUCTION

Usual fiber waveguides consist of core and cladding. Light guidance is realized due to total internal reflection. This phenomenon occurs when the refractive index of the core is greater than the refractive index of the cladding. For the case of hollow-core waveguide total internal reflection becomes impossible, so one needs another light guidance mechanism. One of the possible ways is using Bragg reflection [1–13].

Fiber waveguide, in which light confinement and guidance are realized due to Bragg reflection instead of total internal reflection was investigated by Yeh and co-authors [1, 2]. This waveguide is called Bragg reflection waveguide. It consists of a core surrounded by alternating layers of high and low refractive indices. They have obtained analytical expressions for dispersion relations both infinite structure and different optical waveguides with multilayer periodic cladding. The transfer matrix method has been used for analysis [1].

Necessity of spatial distribution and other parameters tuning is emerged in the waveguides. From the point of view of practical realization, the simplest method is using the additional layers between waveguide channel and Bragg cladding. Modification of structure symmetry results in electrodynamic characteristics changing. The parameters of additional layers can govern the transmission, optical losses and dispersion relation of the waveguide.

The influence of the intermediate layer thickness on the mode composition of propagating light and the optical loss of the hollow waveguide with a periodic cladding was investigated in [3]. The influence of refractive index and thickness of the intermediate layer on optical loss of the transmitted radiation through a multilayer waveguide was investigated in [4].

Modified Bragg waveguide with matching layer have been investigated by Mizrahi and Schachter [5]. The matching layer in his scheme is first layer of Bragg structure with adjusted width. The authors considered influence of the matching layer width on the dispersion curves. They paid their attention to regimes when phase velocity equals to speed of light due to the capabilities to use such waveguide in laser-driven vacuum accelerators [6].

The cylindrical Bragg waveguide was investigated in [7]. Authors synchronize electron beam with slow wave traveling at about half of the speed of light. Their aim was to form novel slow-wave system for millimeter waves traveling wave tube. Dielectric slow-wave system advantages over the conventional metallic one are considered in this work.

In the nonlinear processes Bragg reflection waveguides with additional layers are used for enhancing the effective second-order optical nonlinearity [8, 9].

In this paper modified planar Bragg waveguide with additional layers placed between the hollow core and periodic cladding is considered. Such structure supports the slow waves, which can be synchronized with sheet electron beams. So it is perspective to use in terahertz band where conventional metallic slow-wave systems are ineffective because of physical and technical restrictions. The effect of the additional dielectric layers parameters on the modified planar Bragg waveguide characteristics is considered.

II. SCHEME OF MODIFIED BRAGG WAVEGUIDE AND DISPERSION EQUATION

Modified Bragg waveguide consists of the hollow core, additional layers and periodic cladding. In the Fig. 1 scheme of this structure is shown. Work frequency range is located in the forbidden band of Bragg structure and therefore the light is confined in waveguide core. Here $2d$ and ε_a are the hollow

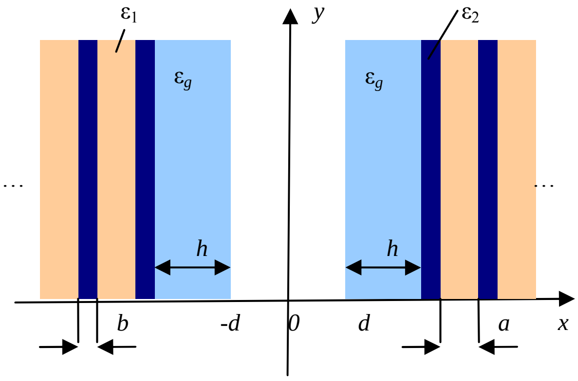


Fig. 1. Scheme of planar Bragg waveguide with additional layers.

core thickness and permittivity respectively, h is the additional dielectric layers thickness, ε_g is the permittivity of these layers; a and b are periodic cladding layers thicknesses with permittivitties ε_1 and ε_2 respectively. $L = a + b$ – period of Bragg structure.

Dispersion equation in analytical form for this structure was obtained. Using the transfer matrix method we obtained it for even and odd modes. It should be noted that only even modes present practical interest since their mode field is unequal to zero in the middle of waveguide channel. But in the specific cases odd modes can be realized with non-zero power on waveguide axis [5].

For even modes dispersion equation can be written as:

$$-\frac{ik_1(e^{-iKL}-A-B)}{\varepsilon_1(e^{-iKL}-A+B)} = \frac{k_0\varepsilon_g\sin(k_0 d)\cos(k_g h)+k_g\varepsilon_0\sin(k_g h)\cos(k_0 d)}{k_0\varepsilon_g\sin(k_0 d)\sin(k_g h)-k_g\varepsilon_0\cos(k_g h)\cos(k_0 d)} \qquad (1)$$

where

$$A = e^{ik_1 a}\left[\cos k_2 b + \frac{i}{2}\left(\frac{\varepsilon_2}{\varepsilon_1}\frac{k_1}{k_2}+\frac{\varepsilon_1}{\varepsilon_2}\frac{k_2}{k_1}\right)\sin k_2 b\right],$$

$$B = e^{-ik_1 a}\left[\frac{i}{2}\left(\frac{\varepsilon_1}{\varepsilon_2}\frac{k_2}{k_1}-\frac{\varepsilon_2}{\varepsilon_1}\frac{k_1}{k_2}\right)\sin k_2 b\right],$$

$$k_0 = \sqrt{\left(\frac{\omega}{c}\right)^2-\beta^2}\ ,$$

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

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

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

Based on the solutions of relation (1) dispersion diagrams can be computed. When Bloch wave number K is real, wave can propagate through Bragg structure. This is pass band. Complex Bloch wave number K corresponds to forbidden band. Obviously solutions of the dispersion equation (1) lie within forbidden band.

The parameters of additional layers (thickness and permittivity) can significantly affect on dispersion properties, number of slow-wave modes, the spatial field distribution, decay in Bragg structure and hollow core.

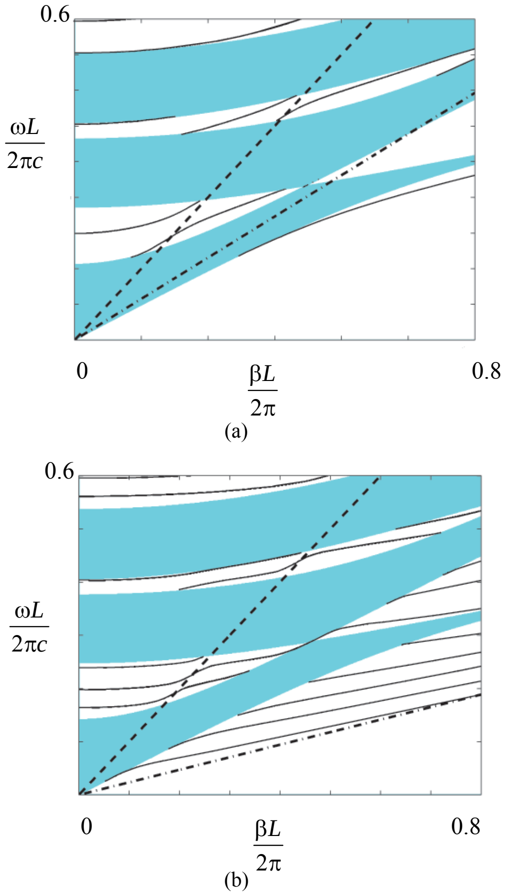
III. ADDITIONAL LAYERS PERMITTIVITY INFLUENCE ON MODIFIED BRAGG WAVEGUIDE CHARACTERICTICS

Dispersion diagrams of modified Bragg waveguide are shown on the Fig. 2. Values of the structure are: $2d = 3L$, $a = 2b$, $\varepsilon_1 = 3$, $\varepsilon_2 = 18$, $h = 2L$.

These dispersion diagrams are calculated for following permittivities values: $\varepsilon_g = 5$ (Fig. 2, a), $\varepsilon_g = 15$ (Fig. 2, b). The colored parts of diagrams are pass bands of Bragg structure, uncolored ones are forbidden bands. Solutions of the dispersion relation (1) lie within forbidden bands (solid black curves). Dashed line indicates the “light line” in the vacuum, dot-dash line indicates the “light line” in the dielectric with permittivity values $\varepsilon_g = 5$ (Fig. 2, a) and $\varepsilon_g = 15$ (Fig. 2, b). Light line in the vacuum divides dispersion diagram into two regions that correspond to slow and fast waves. The modes that lie under light line in the vacuum are slow waves.

Obviously in the both case there are some slow-wave modes within the forbidden bands. When $\varepsilon_g = 5$ there are one slow-wave mode in the 0-th forbidden band (Fig. 2, a). This mode has the lowest phase velocity. This case is similar to dispersion characteristics in [14]. When $\varepsilon_g = 15$, more than one slow-wave modes appear in 0-th zone (Fig. 2, b). Then number of slow-wave modes increases with additional layer permittivity increasing. This pattern is observed for any value of additional layer thickness.

The transversal spatial distributions of the longitudinal electric field (E_y component) intensity are shown on Fig. 3. Dashed black lines indicate the boundaries of the waveguide channel. The spatial distribution curves are obtained for different values of the additional layers permittivity (numerical values are indicated on Fig. 3).



(a)

(b)

Fig. 2. Dispersion diagrams of Bragg waveguide with different additional layers permittivities.

As one can see spatial distributions in the waveguide hollow core change insignificantly. The electric field intensity is reduced similar for different values of additional layers permittivity. But increase of this parameter results in more efficient field localization in the waveguide channel.

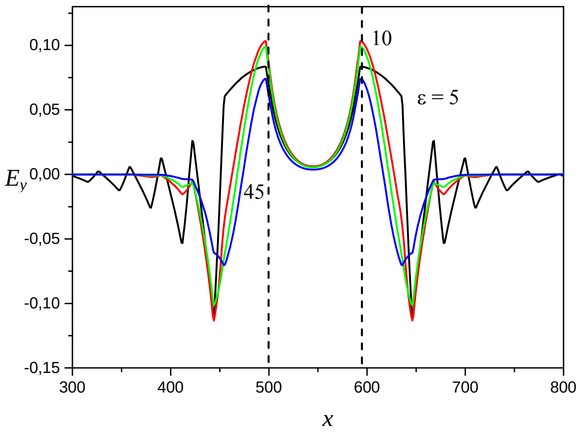


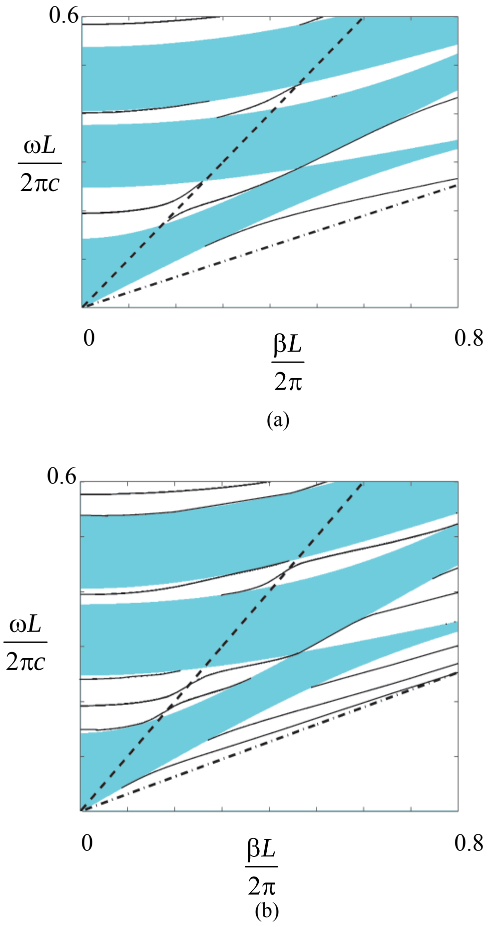
Fig. 3. The spatial field distributions of Bragg waveguide with different additional layers permittivities.

IV. ADDITIONAL LAYERS THICKNESS INFLUENCE ON MODIFIED BRAGG WAVEGUIDE CHARACTERICTICS

Let consider the effect of the additional layers thickness on modified Bragg waveguide characteristics. The Fig. 4 shows dispersion diagrams for following values: $2d = 3L$, $a = 2b$, $\varepsilon_1 = 3$, $\varepsilon_2 = 18$, $\varepsilon_g = 10$. Dispersion diagrams are calculated for different values of the additional layers thicknesses: $h = a$, $h = 2L$ (Fig. 4, a and Fig. 4, b, respectively). The “light line” in the dielectric (additional layers) is obtained for following value: $\varepsilon_g = 10$.

On the Fig. 4, a we can see one slow bulk mode in the 0-th forbidden band. This pattern is observed for cases when $h \le L$. On the Fig. 4, b we can see three modes in 0-th forbidden band. The increase of additional layer thickness h results in the appearance of more number of slow-waves modes. For any value of additional layer permittivity we can remark this trend.

The transversal spatial distributions of the longitudinal electric field intensity are shown on Fig. 5. Dashed black lines indicate the boundaries of the waveguide channel. The spatial distribution curves are obtained for different values of the additional layers thickness (numerical values are indicated on Fig. 5).



(a)

(b)

Fig. 4. Dispersion diagrams of Bragg waveguide with different additional layers thickness.

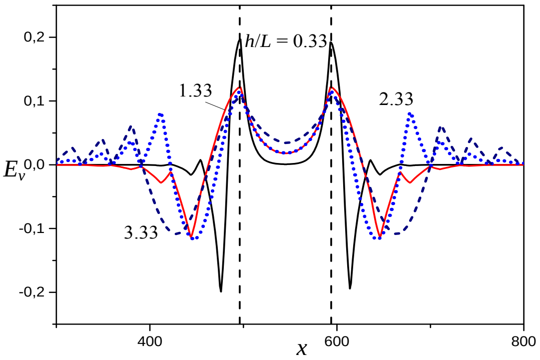


Fig. 5. The spatial field distributions of Bragg waveguide with different additional layers thickness.

Evidently in the case when additional layers are quite narrow ($h/L = 0.33$), field distribution is similar to the case of ordinary Bragg waveguide [14]. Increase of its thickness results in less intense field decay in the hollow core. But the increase of the additional layers thickness results in the decrease of the field confinement in the waveguide channel.

V. CONCLUSION

Bragg waveguide with additional layers between hollow core and periodic structure is considered. Dispersion equation in the analytical form is obtained. Dispersion diagrams and transversal spatial distributions of the electric field intensity are calculated. The effect of additional layers parameters (thickness and permittivity) on modified Bragg waveguide characteristics is considered. It is shown that increase of additional layer thickness and permittivity results in appearance of slow-wave modes in the lowest forbidden band of periodic cladding of Bragg structure. Field intensity decay in the waveguide hollow core is reduced with increase of additional layer thickness. The increase of additional layers permittivity changes spatial distribution of the electric field intensity insignificantly, but results in less efficient field localization in the modified Bragg waveguide core. So to get expected modified Bragg waveguide characteristics one can tune additional layer values. It makes this structures promising in different applications, for example, as electrodynamic system in terahertz electron-beam devices.

REFERENCES

[1] P. Yeh, A. Yariv, and C.-S. Hong, “Electromagnetic propagation in periodic stratified media. I. General theory,” J. Opt. Soc. Am., vol. 67, no. 4, pp. 423-438, 1977.

[2] P. Yeh, A. Yariv, and E. Marom, “Theory of Bragg fiber,” J. Opt. Soc. Am., vol. 68, pp. 1196–1201, 1978.

[3] Yu.N. Kulchin, Yu.A. Zinin, I.G. Nagorny, “Bragg fibers with an intermediate layer,” Quantum Electronics, vol. 42 (3), pp. 235 – 240, 2012.

[4] Y. N. Kulchin, Y. A. Zinin, and V. A. Kolchinskiy, “Bragg waveguide with an antiresonance intermediate layer,” Pacific Science Review A: Natural Science and Engineering, vol. 17, pp. 38-40, 2015.

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

[6] A. Mizrahi, L. Schächter, “Optical Bragg accelerators,” Phys. Rev. E, vol. 70, 016505, 2004

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

[8] C. Wächter, F. Lederer, L. Leine, U. Trutschel, and M. Mann, “Nonlinear Bragg reflection waveguide,” J. of Applied Physics, vol. 71, no. 8, pp. 3688-3692, 1992

[9] P. Abolghasem and A. S. Helmy, “Matching Layers in Bragg Reflection Waveguides for Enhanced Nonlinear Interaction,” IEEE J. Quantum Electron., vol. 45, no. 6, pp. 646-653, 2009.

[10] S. R. A. Dods, “Bragg reflection waveguide,” J. Opt. Soc. Am. A, vol. 6, no. 9, pp. 1465-1476, 1989.

[11] B. Nistad, M. W. Haakestad, and J. Skaar, “Dispersion properties of planar Bragg waveguides,” Optics Communications, vol. 265, pp. 153–160, 2006.

[12] E. N. Odarenko and A. A. Shmat’ko, “Photonic crystal and Bragg waveguides for THz electron devices,” Proc. IEEE 13th Int. Conf. on Laser & Fiber-Optical Networks Modeling (LFNM), September 13-15, Odessa, Ukraine, pp. 53-55, 2016.

[13] B. R. West and A. S. Helmy, “Properties of the quarter-wave Bragg reflection waveguide: theory,” J. Opt. Soc. Am. B, vol. 23, no. 6, pp. 1207-1220, 2006.

[14] E.N. Odarenko, Y.V. Sashkova, A.A. Shmat’ko. “Localized field enhancement in slow-wave modes of modified Bragg waveguide,” Proc. IEEE 5th Microwaves, Radar and Remote Sensing Symposium (MRRS), August 29 – 31, Kiev, Ukraine, pp. 147-150, 2017.