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MODAL DISPERSION CHARACTERISTICS OF A BRAGG FIBER HAVING PLASMA IN THE CLADDING REGIONS

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Abstract—The modal dispersion relation of electromagnetic waves in a Bragg fiber having plasma in the cladding regions is investigated analytically. The proposed Bragg fiber consists of a low index central region having air surrounded by a large number of periodic cladding layers of alternating high and low refractive indices of dielectric and plasma respectively. The modal dispersion relation is obtained by solving Maxwell wave equations using a simple boundary matching method. The analysis shows that the normalized frequency parameter (also called V-number) is frequency independent. This indicates that the proposed Bragg fiber may be used for single mode operation without high frequency limitation as well as with little loss of energy compared to the conventional dielectric waveguide.

1. INTRODUCTION

It is now well established fact that in conventional lightguides, light is confined and guided by total internal reflection, which requires that the guiding region (core) has a slightly higher refractive index than the non-guiding cladding region. In the case of total internal reflection there is no loss other than intrinsic absorption and scattering losses of the materials themselves. Such losses can be reduced much in the case of a Bragg lightguide where guidance of photons takes place via Bragg reflection and central region has lower refractive index than that of surrounding periodic cladding layers of alternating high and low refractive indices [1, 2]. In this way Bragg waveguides

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are superior to conventional optical waveguides and they offer many possibilities, which are difficult to get in conventional optical fibers. One example is the possibility of guiding light in air, which attracted much recent interest [3, 4]. Similarly for Bragg fibers truly single guided mode is possible but for conventional fibers the fundamental double degenerated modes are always permitted. In this way Bragg waveguides can be used as mode filters [2]. Further the periodic cladding layers of alternating high and low refractive indices that surround the central region of the Bragg waveguide give rise to photonic band gap of recent interest [5–8]. Therefore, these waveguides may also be referred to as photonic band gap-guided Bragg waveguides [8, 9, 17].

In recent years, the Bragg waveguides have attracted serious attention of the researchers for their interesting and novel applications [9, 13]. For the first time a rigorous mathematical analysis was given by Yeh et al. [2] using optimization method. Fink et al. [3] have demonstrated the guidance of the mode in Bragg fibers. Since then considerable progress has been made in the theory and application of Bragg fibers. Recently A. Argyros [14] studied guided modes and losses in Bragg fibers. More recently Pal et al. designed Bragg fibers for transparent metro-networks and for dispersion compensation [15, 16]. Very recently Singh et al. [1] have studied the Bragg fiber using a very simple matrix method and it was shown that by using only a small number of cladding layers, a Bragg fiber is as almost as good as a conventional standard fiber under weak guidance approximation with an additional advantage that there is a very little loss in the central core region which has a low refractive index.

In the present communication we have chosen a new seven-layered Bragg fiber with a central core region filled with air and surrounding by a large number of periodic cladding layers of alternating high and low refractive indices of dielectric and plasma layer respectively shown in Fig. 1. Using a simple boundary matching technique [1, 6, 17] the modal eigen value equation known as characteristic equation is obtained. Computed results are discussed in terms of plasma frequency, plasma width and the number of layeres in cladding regions. It is seen that some high frequency confined guided modes exist in the proposed Bragg fiber. For comparing the predicted results with experimental finding the experimental investigators will be prompted and encouraged to study the actual characteristics of such Bragg fiber in future when the essential fabrication technology becomes possible. If the possibility of fabrication is not already there, it is not remote in view of the present age of advanced nano-technology when the researchers are sufficiently interested or encouraged to take up this sort of work.

The concept of proposed Bragg waveguide stems from some recent papers on optical waveguides filled with plasma [18–23]. H. M. Shen [18, 19] investigated plasma waveguide having a cylindrical vacuum core surrounded by a plasma cladding. Hojo and Mase [20] studied the dispersion relation of EM waves in one dimensional plasma photonic crystals. We thought it worthwhile to extend these concepts more rigorously to study the change in modal characteristics of a standard Bragg fiber [1] when some thin layers of plasma are introduced in its claddings. Recently Bragg waveguides, helical waveguides and fibers have been investigated with great attention and interest especially due to their novel applications in communication engineering, integrated optical electronics and sensor technology [24–27]. The study of such a proposed Bragg fiber seems very urgent because any application of the waveguide in engineering and technology pre-assumes a thorough knowledge of the properties of its eigen modes. The present study is organized in the following manner. Section 2 deals with the derivation of the characteristic equation and frequency dependence of the eigen value and other parameters. Section 3 is concerned with the solution of eigen value equation using some chosen parameters. Dispersion characteristics for the proposed Bragg fiber have been discussed with the help of figures for change in the plasma frequency, plasma width and the change in number of cladding layers. It is noted that as the plasma width as well as cladding layers decrease, the number of guided modes also decreases. Also the variation of cutoff frequency V_c for different guided modes as a function of $\frac{\omega}{\omega_p}$ has been shown graphically for five layered Bragg fiber keeping plasma width $d_2 = 0.25\,\mu\text{m}$ fixed. Finally, in Section 4 conclusions are presented.

2. THEORETICAL ANALYSIS

The dielectric Bragg waveguide filled with plasma layer in claddings alternately is an interesting structure for electromagnetic wave guiding. The cross-sectional view of the five-layered Bragg fiber filled with plasma layer in the cladding regions is shown in Fig. 1. It has low air refractive index (n_a) in central region and higher refractive indices n_1 of a dielectric and n_2 of a plasma layer in the periodic cladding regions around it. The outer cladding region is filled with air having refractive index (n_a). Plasma as a medium for propagating electromagnetic waves is characterized by permittivity ε_p, permeability μ_p and conductivity σ_p. For the case of an isotropic and low density plasma, i.e., ignoring the effect of collision, μ_p is equal to that of neutral gas, σ_p is small, and the following formula for the permittivity ε_p of the plasma is sufficiently accurate for a real propagating wave having $\omega > \omega_p$

$$\varepsilon_p = \varepsilon \left[1 - \frac{\omega_p^2}{\omega^2}\right] \tag{1}$$

Here ω_p is the angular frequency of plasma and ε is the permittivity of free space. The index profile is then written as

$$n(r) = \begin{pmatrix} n_a; & 0 < r < r_1 \\ n_1; & r_1 < r < r_2 \\ n_2 = \sqrt{1 - \frac{\omega_p^2}{\omega^2}}; & r_2 < r < r_3 \\ n_1; & r_3 < r < r_4 \\ n_2 = \sqrt{1 - \frac{\omega_p^2}{\omega^2}}; & r_4 < r < r_5 \\ n_1; & r_5 < r < r_6 \\ n_a; & r > r_6 \end{pmatrix} \tag{2}$$

where $r_1 = d_0,\ r_2 = d_0 + d_1,\ r_3 = d_0 + d_1 + d_2,\ r_4 = d_0 + 2d_1 + d_2,\ r_5 = d_0 + 2d_1 + 2d_2,\ r_6 = d_0 + 3d_1 + 2d_2$ as shown in Fig. 1.

We choose the cylindrical polar coordinate system $(r,\ \theta,\ z)$ in such a way that z-axis lies along the axis of the waveguide. We also assume that as the electromagnetic wave propagates along the z-axis, the electric and magnetic field vectors take the form

$$\psi(r, \theta, z) = \psi(r) e^{j\nu\theta} e^{i(\beta z - \omega t)} \tag{3}$$

where $\psi(r)$ can be $E_z, H_z, E_r, H_r, E_\theta, H_\theta, \omega$ is the angular frequency and β is the propagation constant. This means that fields are harmonic in the time t and the coordinate z. From the waveguide theory we know that the transverse field components can be expressed in terms of E_z and H_z as

$$E_r = \frac{i\beta}{\omega^2\mu\varepsilon - \beta^2} \left[\frac{\partial E_z}{\partial r} + \frac{\omega\mu}{\beta} \frac{1}{r} \frac{\partial H_z}{\partial \theta}\right] \tag{4}$$

$$E_\theta = \frac{i\beta}{\omega^2\mu\varepsilon - \beta^2} \left[\frac{1}{r} \frac{\partial E_z}{\partial \theta} - \frac{\omega\mu}{\beta} \frac{\partial H_z}{\partial r}\right] \tag{5}$$

$$H_r = \frac{i\beta}{\omega^2\mu\varepsilon - \beta^2} \left[\frac{\partial H_z}{\partial r} - \frac{\omega\mu}{\beta} \frac{1}{r} \frac{\partial E_z}{\partial \theta}\right] \tag{6}$$

$$H_\theta = \frac{i\beta}{\omega^2\mu\varepsilon - \beta^2} \left[\frac{1}{r} \frac{\partial H_z}{\partial \theta} + \frac{\omega\mu}{\beta} \frac{\partial E_z}{\partial r}\right] \tag{7}$$

Here $E_z(r, \theta)$ and $H_z(r, \theta)$ satisfy the wave equation

$$\left[\nabla_i^2 + \left(\omega^2\mu\varepsilon - \beta^2\right)\right] \begin{bmatrix} E_z \\ H_z \end{bmatrix} = 0 \tag{8}$$

where $\nabla_i^2 = \nabla^2 - \frac{\partial^2}{\partial z^2}$ is the transverse Laplacian operator.

The physically acceptable solutions for alternating cladding regions are

$$\left.\begin{aligned} E_z &= \left[A_1 J_\nu(u_1 r) + B_1 Y_\nu(u_1 r)\right] e^{j\nu\theta} e_e^{j(\omega t - \beta z)} \\ H_z &= \left[C_1 J_\nu(u_1 r) + D_1 Y_\nu(u_1 r)\right] e^{j\nu\theta} e_e^{j(\omega t - \beta z)} \end{aligned}\right\} \tag{9a}$$

$$\left.\begin{aligned} E_z &= \left[A_2 I_\nu(u_2 r) + B_2 K_\nu(u_2 r)\right] e^{j\nu\theta} e_e^{j(\omega t - \beta z)} \\ H_z &= \left[C_2 I_\nu(u_2 r) + D_2 K_\nu(u_2 r)\right] e^{j\nu\theta} e_e^{j(\omega t - \beta z)} \end{aligned}\right\} \tag{9b}$$

where $u_1 = \sqrt{k^2 n_1^2 - \beta^2}$, $u_2 = \sqrt{\beta^2 - k^2 n_2^2}$ corresponding to refractive indices n_1 and n_2 respectively, $k = \frac{\omega}{c}$ and c is the velocity of light in free space. Also the solutions for central region is

$$\left.\begin{aligned} E_z &= F_l I_\nu(w_l r) e^{j\nu\theta} e_e^{j(\omega t - \beta z)} \\ H_z &= L_l I_\nu(w_l r) e^{j\nu\theta} e_e^{j(\omega t - \beta z)} \end{aligned}\right\} \tag{10a}$$

and outer most cladding region is

$$\left.\begin{aligned} E_z &= G_l K_\nu(w_l r) e^{j\nu\theta} e_e^{j(\omega t - \beta z)} \\ H_z &= M_l K_\nu(w_l r) e^{j\nu\theta} e_e^{j(\omega t - \beta z)} \end{aligned}\right\} \tag{10b}$$

where $w_l = (\sqrt{\beta^2 - k^2 n_a^2}\ )$, corresponding to refractive indices n_a.

In the above equations J_ν and Y_ν are the Bessel functions of first and second kind while I_ν and K_ν are the modified Bessel functions, respectively. $A_i, B_i, C_i, D_i, F_j, G_j, L_l$ and M_l all are unknown constants.

The boundary conditions at all the boundaries are that E_z, H_z, E_θ and H_θ are continuous at the interfaces. Now for $\nu = 0$ we shall get perturbed TE and TM modes due to presence of plasma in waveguide. Thus we get a set of eight equations having eight unknown constants. The nontrivial solution will exist only when the determinant formed by the coefficients of the unknown constants is equal to zero. Calling this 8×8 determinant A_r, we have

$$A_r = 0 \tag{11}$$

known as eigen value equation. Here the matrix elements are as follows:

$$\begin{aligned} a_{11} &= I_v(w_l r_1); \quad a_{12} = -J_v(u_1 r_1); \quad a_{13} = -Y_v(u_1 r_1); \\ a_{14} &= 0; \quad a_{15} = 0; \quad a_{16} = 0; \quad a_{17} = 0; \quad a_{18} = 0; \\ a_{21} &= I_v'(w_l r_1); \quad a_{22} = -J_v'(u_1 r_1); \quad a_{23} = -Y_v'(u_1 r_1); \end{aligned}$$

$$
\begin{aligned}
a_{24} &= 0; \quad a_{25} = 0; \quad a_{26} = 0; \quad a_{27} = 0; \quad a_{28} = 0; \quad a_{31} = 0;\\
a_{32} &= J_v(u_1 r_2); \qquad a_{33} = Y_v(u_1 r_2); \qquad a_{34} = -I_v(u_2 r_2);\\
a_{35} &= -K_v(u_2 r_2); \quad a_{36} = 0; \quad a_{37} = 0; \quad a_{38} = 0; \quad a_{41} = 0;\\
a_{42} &= J'_v(u_1 r_2); \qquad a_{43} = Y'_v(u_1 r_2); \qquad a_{44} = -I'_v(u_2 r_2);\\
a_{45} &= -K'_v(u_2 r_2); \quad a_{46} = 0; \quad a_{47} = 0; \quad a_{48} = 0; \quad a_{51} = 0;\\
a_{52} &= = 0; \quad a_{53} = 0; \quad a_{54} = I_v(u_2 r_3); \quad a_{55} = K_v(u_2 r_3);\\
a_{56} &= -J_v(u_1 r_3); \quad a_{57} = -Y_v(u_1 r_3); \quad a_{58} = 0; \quad a_{61} = 0;\\
a_{62} &= 0; \quad a_{63} = 0; \quad a_{64} = I'_v(u_2 r_3); \quad a_{65} = K'_v(u_2 r_3);\\
a_{66} &= -J'_v(u_1 r_3); \quad a_{67} = -Y'_v(u_1 r_3); \quad a_{68} = 0; \quad a_{71} = 0;\\
a_{72} &= 0; \quad a_{73} = 0; \quad a_{74} = 0; \quad a_{75} = 0; \quad a_{76} = J_v(u_1 r_4);\\
a_{77} &= Y_v(u_1 r_4); \quad a_{78} = -K_v(w_l r_4); \quad a_{81} = 0; \quad a_{82} = 0;\\
a_{83} &= 0; \quad = Y_v(u_1 r_4); \qquad a_{86} = -K_v(w_l r_4);
\end{aligned}
$$

The element in the rows and columns of this determinant can be identified readily. This equation is very important equation of our analysis and is known as the characteristic or eigen value equation.

It is very easy and convenient to draw dispersion curves in terms of the normalized propagation constant b' and normalized frequency parameter V defined as:

$$V = k_0 d_1 \left(n_1^2 - n_a^2\right)^{\frac{1}{2}} \tag{12}$$

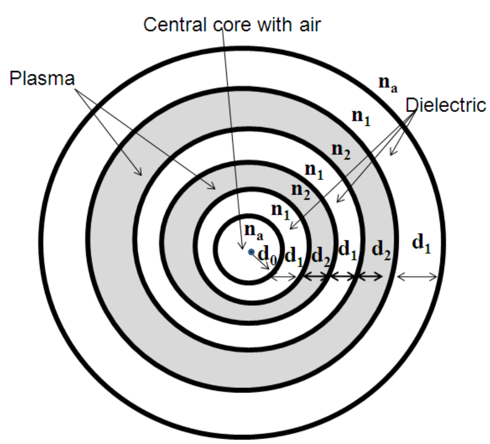

Figure 1. The cross sectional view of the five layered Bragg fiber filled with thin layer of plasma in the cladding regions.

where k_0 is vacuum wave number and d_1 is the width of first dielectric region having refractive index n_1. We define the usual normalized propagation parameter

$$b' = \frac{\beta^2 - k_0^2 n_a^2}{k_0^2 \left(n_1^2 - n_a^2\right)} \tag{13}$$

where β is the z-component of the propagation vector and k_0 is free space wavenumber. In order to get the modal profile for proposed three layered waveguide, the above set of eight equations can be written in the form:

$$A_r \psi = 0 \tag{14}$$

where $\psi = (F_1, A_1, B_1, A_2, B_2, A_3, B_3, G_1)$.

The modal profile of a waveguide mode for a proposed waveguide structure with a given width and the corresponding effective refractive index, calculated from Eq. (11) can now be calculated from Eq. (14) by assuming one of the field amplitude say $A_3 = 1$.

3. NUMERICAL RESULTS AND DISCUSSION

The eigen value Equation (11) known as characteristic equation is the most important equation of our analysis because it gives all information regarding the dispersion relation of the proposed waveguide. It is very convenient to plot normalized propagation constant b' versus V-number. In order to get dispersion relation between b' and V for the proposed Bragg fiber, we have to solve the characteristic Equation (11) numerically. For this purpose at high frequency ($\omega > \omega_p$) we have chosen the following parameters: the refractive index of air is $n_a = 1.00001$, the refractive indices of cladding layers are $n_1 = 1.5$, $n_2 = \sqrt{1 - \frac{\omega_p^2}{\omega^2}}$; which corresponds to $d_0 = 1\,\mu\text{m}$, $d_2 = 0.0625\,\mu\text{m}$, $d_2 = 0.125\,\mu\text{m}$ and $d_2 = 0.25\,\mu\text{m}$ for $\omega_p/\omega = 0.4$ fixed.

Now for obtaining dispersion curves, the left hand side (L.H.S.) of equation (11) is plotted against the admissible β values ($k_0 n_1 > \beta > k_0 n_a$) for a fixed value of d_1 and the zero crossing is noted. Each zero crossing corresponds to a particular sustained mode. Several such curves are plotted for different values of d_1 and from these graphs one can find out how β vary with d_1 for a given mode (zero crossing). From β we can calculate the normalized propagation constant b' by using equation (13) and d1 is related to V in the manner given in equation (12). Thus b' versus V curve (dispersion curve) can be plotted for each mode.

The computed results in the form of dispersion curves are shown in Figs. 2, 3 and 4 for the change in number of layers in claddings

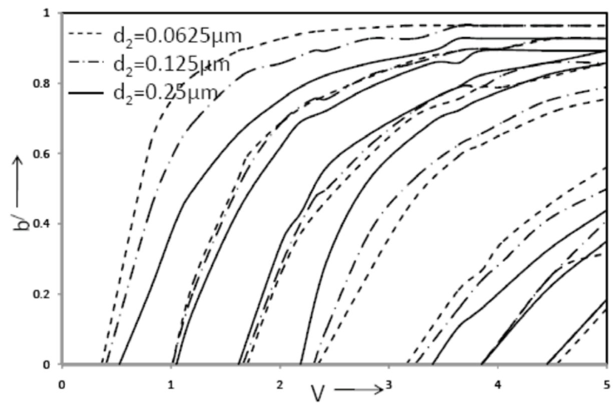

Figure 2. Dispersion characteristics curves of the proposed Bragg fiber for seven cladding layers with three different values of d_2 keeping $\frac{\omega_p}{\omega} = 0.4$ fixed.

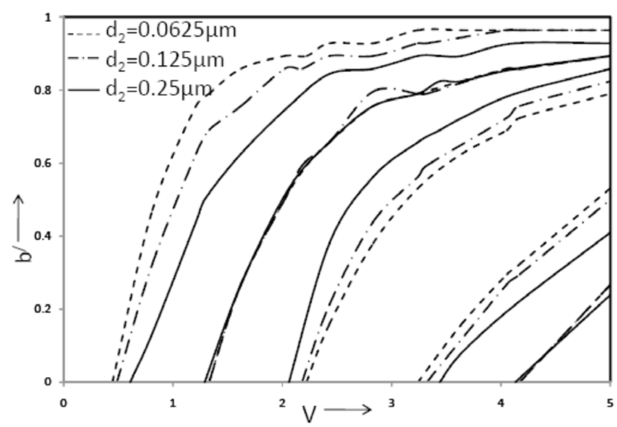

Figure 3. Dispersion characteristics curves of the proposed Bragg fiber for five cladding layers with three different values of d_2 keeping $\frac{\omega_p}{\omega} = 0.4$ fixed.

and also for the change in plasma width d_2 keeping $\omega_p/\omega = 0.4$ fixed. Several interesting features can be seen in the dispersion curves. All the curves have the standard expected shape. By examining all dispersion curves it is seen that as the number of cladding layers decreases from seven layers to three layers, the number of sustained guided modes also decreases.

Next, we want to see the effect of plasma width d_2 on the number of sustained guided modes. Considering Fig. 2, it is observed that as d_2 is increased from $d_2 = 0.0625\,\mu\text{m}$ to $d_2 = 0.25\,\mu\text{m}$, the first mode and third mode are bound to be loosely whereas second mode and fourth mode seen to be bound closely. Similarly in the case of Fig. 3, the first mode and fifth mode are found to be bound loosely whereas the third mode is observed to be closely bound. But in this case the second mode remains independent of variation of d_2. The similar type of behavior is also observed in Fig. 4. Here again the first, second, fifth and sixth mode are seen to be bound loosely while the third, fourth and seventh mode are found to be bound closely. In this way we note that the considered Bragg fiber is expected to have potential applications with d_2 as a means for controlling the modal behavior of any particular mode.

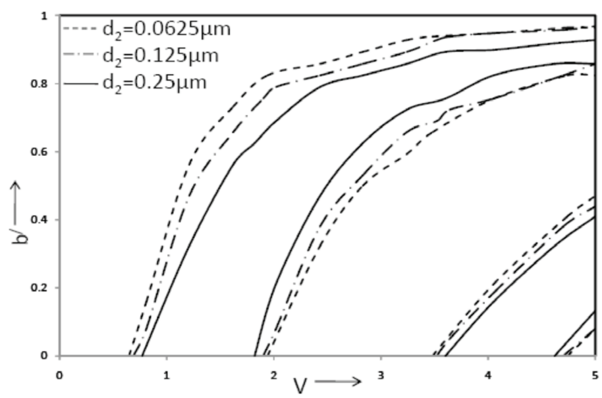

Figure 4. Dispersion characteristics curves of the proposed Bragg fiber for three cladding layers with three different values of d_2 keeping $\frac{\omega_p}{\omega} = 0.4$ fixed.

Now we consider Fig. 5 which shows the variation of ω/ω_p versus cutoff frequency V_c. It is seen that variation of LP_{11}, LP_{12}, LP_{13}, LP_{14} etc. remains constant. This indicates that if V number is chosen smaller than the $V = 0.64$, only LP_{11} mode exists in the considered Bragg fiber. Thus the proposed Bragg fiber may be used for single mode operation without high frequency limitation and at the cost of very low absorption loss. This is most interesting feature of the present study. It is to be noted that the cutoff V-number is frequency independent for the proposed waveguide, whereas for a conventional dielectric waveguide cutoff V-number is frequency dependent and there is high frequency limitation for single mode operation. We note further that such interesting features are not observed in the case of the

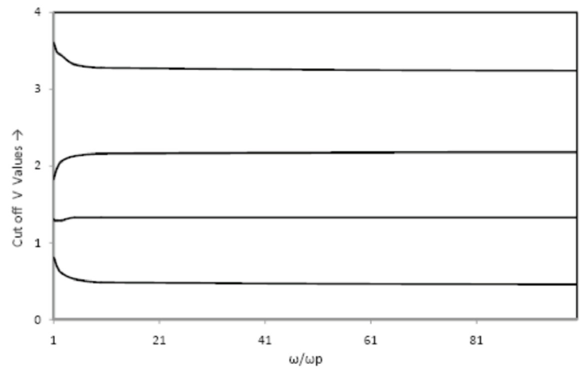

Figure 5. The variation of cutoff frequency V_c for different guided modes as a function of $\frac{\omega}{\omega_p}$ for five layered Bragg fiber at $d_2 = 0.25\,\mu\text{m}$.

standard Bragg fiber studied in our paper [1].

We come to Table 1 and Table 2. Table 1 shows the dependence of cutoff frequencies on the width of plasma layer as well as on the number of cladding layers used in the structure. This table shows that as the width of the plasma layer is increased from $d_2 = 0.0625\,\mu\text{m}$ to $d_2 = 0.25\,\mu\text{m}$ keeping the number of layers fixed, the first cutoff value for LP_{11}, LP_{12}, LP_{13}, LP_{14} etc. decreases considerably. Also when the number of layers in cladding is decreased from seven layers to three layers, the first cutoff values for LP_{11}, LP_{12}, LP_{13}, LP_{14} etc. increases in all considered cases of plasma width d_2. Next we come to Table 2, which depicts the interesting feature of the present study. Table 2 depicts that at the lower values of ω/ω_p, V_c increase very slowly and at higher $\omega/\omega_p, V_c$ become constant. That is our chosen Bragg fiber can be used for a single mode operation below $V = 0.64$.

Further, we describe the modal field distribution of the proposed Bragg fiber using a very simple approach as describe above in Section 2. The field distribution obtained by this approach is shown in Fig. 6 for proposed Bragg fiber mode with E_z component. We notice that the curve has expected standard shape. We also observe that the field decays considerably within a few pairs of cladding layers.

Basically, there are two sources that contribute to the propagation loss in Bragg waveguides, the radiation loss and the material absorption loss. The radiation loss mainly depends on the index contrast between the cladding media and the number of cladding pairs. In principle, the radiation loss can be reduced below any given number simply by using a large enough number of cladding pairs. However, using too many cladding pairs is generally undesirable or even impractical. On

Table 1. Cutoff frequencies (V_c-values) for some modes in proposed Bragg fiber for three different thicknesses of the plasma cladding strips.

Mode No.	Cut off frequencies of various modes in Bragg fiber with thickness of plasma cladding strip d_2=0.065 μm. 0<V<5			Cut off frequencies of various modes in Bragg fiber with thickness of plasma cladding strip d_2=0.125 μm. 0<V<5			Cut off frequencies of various modes in Bragg fiber with thickness of plasma cladding strip d_2=0.25 μm. 0<V<5		
LP_{1m}	Seven layered	Five layered	Three layered	Seven layered	Five layered	Three layered	Seven layered	Five layered	Three layered
LP_{11}	0.364	0.445	0.648	0.405	0.486	0.689	0.527	0.608	0.77
LP_{12}	1.013	1.33	1.94	1.013	1.33	1.90	1.05	1.29	1.82
LP_{13}	1.70	2.22	3.48	1.66	2.18	3.52	1.62	2.06	3.60
LP_{14}	2.35	3.24	4.74	2.31	3.32	4.70	2.189	3.44	4.26
LP_{15}	3.16	4.17	-	3.24	4.17	-	3.40	4.13	-
LP_{16}	3.85	-	-	3.85	-	-	3.85	-	-
LP_{17}	4.54	-	-	4.45	-	-	4.45	-	-

Table 2. Variation of Cutoff V values with ω/ω_p for five layered waveguide keeping $d_2 = 0.25\,\mu$m.

ω/ω_p	***Cutoff V values*** (V_c)			
	$\mathbf{LP}_{11}$	$\mathbf{LP}_{12}$	$\mathbf{LP}_{13}$	$\mathbf{LP}_{14}$
1	0.8107	1.309	1.824	3.608
1.25	0.77	1.29	1089	3.56
1.66	0.689	1.29	1.97	3.48
2.5	0.608	1.29	2.06	3.44
5	0.527	1.33	2.13	3.32
10	0.486	1.33	2.16	3.28
100	0.459	1.33	2.18	3.24
1000	0.459	1.33	2.18	3.24

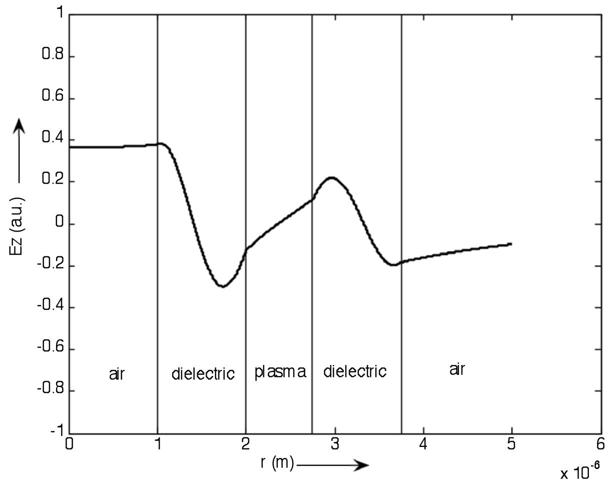

Figure 6. The E.M. field distribution of the proposed Bragg fiber mode with E_z component at $\frac{\omega_p}{\omega} = 0.4$ fixed.

the other hand, the material absorption loss depends mainly on the choice of cladding media (i.e., on plasma and dielectric) and is not considered in this paper and we hope to present this aspect in a future communication.

4. CONCLUSION

In this article an analysis of the eigen modes of a Bragg waveguide filled with plasma in the cladding regions is presented for the first time in our knowledge. This is a new idea for a new waveguide and the paper contains some new research contributions that are important in the field of plasma physics. The modal eigen value Equation (11) is obtained by solving Maxwell's wave equation using a boundary matching technique. This eigen value equation is the main result of this article that can be used for all configurations of the proposed Bragg waveguide. Our analysis shows that the introduction of thin plasma layers in Bragg fiber gives two advantages:

1) We can have single mode operation below $V = 0.64$ without high frequency limitation and at the cost of very low loss due to absorption.
2) We can control any particular mode of interest by adjusting the width of plasma layer. This is the novelty of the proposed Bragg waveguide.

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