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Theory of electromagnetic wave propagation in a plasma-filled corrugate waveguide immersed in a finite magnetized field

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The linear theory of electromagnetic radiation from a high-power backward-wave-oscillator (BWO), travelling-wave-tube (TWT) with plasma-filled, sinusoidally corrugate waveguide driven by an intense relativistic electron beam (IREB) has been derived and analysed numerically. A general dispersion relation is presented for analysing a plasma-filled corrugate waveguide immersed in magnetized plasma in this paper. It is shown that the linear theory developed here is in good agreement with the previous work.

Keywords: corrugate waveguide, magnetized plasma, "hot" dispersion relation
PACC: 5000, 5200, 5240D

1. Introduction

Many experiments have reported an improved efficiency in high power microwave generation by using plasma filling in backward-wave-oscillator (BWO), travelling-wave-tube (TWT) and other microwave devices.[1−4] The study of beam–wave interactions in the plasma-filled microwave devices has formed a new field of science and technology, namely plasma microwave electronics.[2,5] Although a large number of papers have been published recently, there still remains much work to be done. The mechanisms of beam–wave interactions in plasma-filled devices are not yet completely understood. For example, a magnetized plasma fill couples the TE and TM modes in waveguides and resonators. This coupling generates the hybrid HE and EH modes.[5−7] Furthermore, the magnetized plasma fill gives rise to a variety of propagating waves which could not exist in the vacuum case or even in the case of a plasma fill without a magnetic field.[8]

A combined scheme of plasma filling in a non-uniform slow wave structure (SWS) is investigated to further increase microwave output power. The linear dispersion relations of quasi-TE mode or quasi-TM mode[5,6] for a sinusoidally corrugated, metal-wall SWS are extended and analysed for the case of an IREB. The results of numerical analysis are compared with the experimental results and previous work.

2. Basic physics equations

The model we used is schematically shown in Fig.1. It consists of an interaction chamber made of an infinitely long axisymmetric corrugated-wall. This waveguide is immersed in an electromagnetic field with a plasma-fill. After a solid IREB injection along the axis into the waveguide an ion-channel is formed.

The metal wall is assumed to be perfectly conducting. The wall radius $R(z)$ varies according to the relation $R(z) = a + b\cos(k_0 z)$, where a is the average radius, b is the corrugation amplitude, $k_0 = 2\pi/L$, and L is the axial length of the corrugation period. There are infinite space modes in the corrugated waveguide and its phasic constant can be given by

$$k_{z,n} = k_z + \frac{2\pi n}{L} \qquad (n = 0, \pm 1, \pm 2, \ldots).$$

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A solid IREB of density n_b and radius r_b propagates through the waveguide, which is loaded completely with a cold magnetic collisionless plasma column of uniform density $n_{\rm p}$. The plasma is assumed as the first region I ($r_i \le r \le R(z)$), the ion-channel is assumed as region II ($r_b \le r \le r_i$), and the solid IREB is assumed as region III ($r \le r_b$).

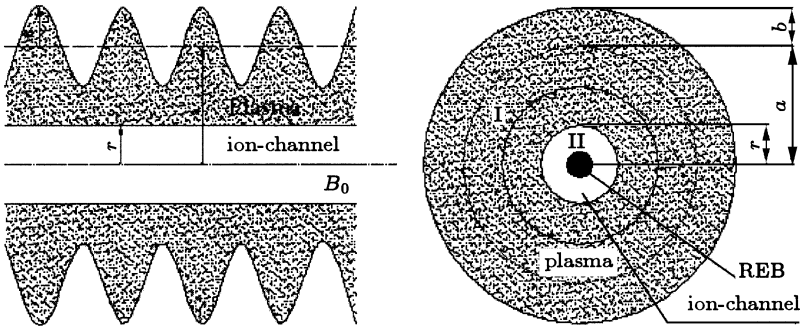


Fig.1. The uniform magnetized plasma-filled sinusoidally corrugated slow-wave structure with a perfectly conducting wall. The ion-channel effect is taken into account.

During the solid IREB head propagation through the plasma, it continuously expels the plasma electrons from the beam volume, leaving the relatively immobile ions fixed to provide focusing for the remainder of the beam. These un-neutralized ions occupy a cylindrical volume of radius $r_i = r_b\sqrt{\dfrac{n_b}{n_p}}$, which forms the so-called 'ion-channel'.[5,6] So the radius of ion-channel is related to the radius, electron density of the IREB and electron density of plasma.

2.1. The field components in each region can be obtained as follows

For region I (plasma region, $r_i \le r \le R(z)$), we have

$$\begin{cases} E_{z,n} = A_{7,n}J_0(p_1 r) + A_{8,n}N_0(p_1 r) \\ \qquad +A_{9,n}J_0(p_2 r) + A_{10,n}N_0(p_2 r), \\ H_{z,n} = A_{7,n}h_1 J_0(p_1 r) + A_{8,n}h_1 N_0(p_1 r) \\ \qquad +A_{9,n}h_2 J_0(p_2 r) + A_{10,n}h_2 N_0(p_2 r). \end{cases} \tag{1}$$

For region II (ion-channel region, $r_b \le r \le r_i$), all electrons are expelled from this region, so we have

$$\begin{cases} E_{z,n} = A_{3,n}J_0(k_c r) + A_{4,n}N_0(k_c r), \\ H_{z,n} = A_{5,n}J_0(k_c r) + A_{6,n}N_0(k_c r). \end{cases} \tag{2}$$

For region III (IREB region, $r \le r_b$), we also have

$$\begin{cases} E_{z,n} = A_{1,n}J_0(x_n r), \\ H_{z,n} = A_{2,n}J_0(x_n r), \end{cases} \tag{3}$$

where

$$x_n^2 = (k^2 - k_{z,n}^2)\left[1 - \frac{\omega_b^2}{\gamma_0^3(\omega - k_{z,n}v_0)}\right], \tag{4}$$

$$k_c^2 = k^2 - k_{z,n}^2. \tag{5}$$

For symmetric modes (m=0), the corner part of the field is $E_{\theta,n}$, $H_{\theta,n}$ and the radial part can be expressed as

$$E_{r,n} = \frac{1}{D}\left[-\mathrm{j}k_{z,n}K^2\frac{\partial E_{z,n}}{\partial r} + \omega\mu_0 k_g^2\frac{\partial H_{z,n}}{\partial r}\right], \tag{6}$$

$$E_{\theta,n} = \frac{1}{D}\left[k_{z,n}k_g^2\frac{\partial E_{z,n}}{\partial r} + \mathrm{j}\omega\mu_0 K^2\frac{\partial H_{z,n}}{\partial r}\right], \tag{7}$$

$$H_{\theta,n} = \frac{1}{D}\left[-\mathrm{j}\omega\varepsilon_0(\varepsilon_1 K^2 - \varepsilon_g k_g^2)\frac{\partial E_{z,n}}{\partial r} + k_{z,n}k_g^2\frac{\partial H_{z,n}}{\partial r}\right], \tag{8}$$

$$H_{r,n} = \frac{1}{D}\left[-\omega\varepsilon_0\varepsilon_g k_{z,n}^2\frac{\partial E_{z,n}}{\partial r} - \mathrm{j}k_{z,n}K^2\frac{\partial H_{z,n}}{\partial r}\right], \tag{9}$$

where

$$\begin{aligned} D &= K^4 - k_g^4, \\ K^2 &= \gamma^2 + k^2\varepsilon_1, \\ \gamma &= \mathrm{j}k_z, \\ k_g^2 &= \omega^2\mu_0\varepsilon_0\varepsilon_g = k^2\varepsilon_g, \\ \varepsilon_g &= |\varepsilon_2|, \\ \varepsilon_2 &= -\mathrm{j}\varepsilon_g, \\ h_{1,2} &= \frac{(\gamma^2 + k^2\varepsilon_1)\dfrac{\varepsilon_3}{\varepsilon_1} - P_{1,2}^2}{\mathrm{j}\omega\mu_0\gamma\dfrac{\varepsilon_2}{\varepsilon_1}}, \end{aligned}$$

$$P_{1,2}^2 = \frac{1}{2\varepsilon_1}[\gamma^2(\varepsilon_1+\varepsilon_3)+k^2(\varepsilon_1\varepsilon_3+\varepsilon_1^2+\varepsilon_2^2)] \pm \frac{1}{2\varepsilon_1}\{[\gamma^2(\varepsilon_3-\varepsilon_1)+k^2(\varepsilon_1\varepsilon_3-\varepsilon_1^2-\varepsilon_2^2)]^2 + 4k^2\gamma^2\varepsilon_2^2\varepsilon_3\}^{1/2};$$

$$\varepsilon_1 = 1-\frac{\xi^2(1-\mathrm{j}\delta)}{(1-\mathrm{j}\delta)^2-\tau^2},$$
$$\varepsilon_2 = \frac{\mathrm{j}\tau\xi^2}{(1-\mathrm{j}\delta)^2-\tau^2},$$
$$\varepsilon_3 = 1-\frac{\xi^2}{1-\mathrm{j}\delta},$$
$$\xi = \frac{\omega_p}{\omega}, \quad \tau = \frac{\omega_c}{\omega}, \quad \delta = \frac{\gamma_{\mathrm{eff}}}{\omega},$$
$$B_0 = B_0\boldsymbol{e}_z, \quad \omega_p = \left(\frac{n_e e^2}{m\varepsilon_0}\right)^{1/2}, \quad \omega_c = \frac{eB_0}{m}.$$

2.2. The field must satisfy the following continuity and boundary conditions

For $|r| = r_i$, we have

$$E_{z,n}^{\mathrm{I}} = E_{z,n}^{\mathrm{II}}, \quad E_{\theta,n}^{\mathrm{I}} = E_{\theta,n}^{\mathrm{II}},$$
$$H_{z,n}^{\mathrm{I}} = H_{z,n}^{\mathrm{II}}, \quad H_{\theta,n}^{\mathrm{I}} = H_{\theta,n}^{\mathrm{II}}. \tag{10}$$

For $|r| = r_b$, we have

$$E_{z,n}^{\mathrm{III}} = E_{z,n}^{\mathrm{II}}, \quad E_{\theta,n}^{\mathrm{III}} = E_{\theta,n}^{\mathrm{II}},$$
$$H_{z,n}^{\mathrm{III}} = H_{z,n}^{\mathrm{II}}, \quad H_{\theta,n}^{\mathrm{III}} = H_{\theta,n}^{\mathrm{II}}. \tag{11}$$

For $|r| = R(z)$, we have

$$E_{z,n}^{\mathrm{I}} + E_{r,n}^{\mathrm{I}}\frac{\mathrm{d}R}{\mathrm{d}z} = 0,$$
$$H_{r,n}^{\mathrm{I}} + H_{z,n}^{\mathrm{I}}\frac{\mathrm{d}R}{\mathrm{d}z} = 0. \tag{12}$$

Substituting Eqs.(1)–(9) into Eqs.(10)–(12), we obtain the following matrix expressions:

$$D\cdot A = \sum_{n,s=-\infty}^{\infty} D_{n,s}A_n = \sum_{n,s=-\infty}^{\infty}\begin{bmatrix}(F_{0,1})_{n,s} & (F_{0,2})_{n,s}\\ (G_{0,1})_{n,s} & (G_{0,2})_{n,s}\end{bmatrix} \times \begin{bmatrix}A_{1,n}\\ A_{2,n}\end{bmatrix} = 0. \tag{13}$$

To ensure that the equations can be solved, the value of their coefficient matrix must be zero. So the 'hot' dispersion relation for the magnetized plasma-filled BWO or TWT is expressed by the determinant equation

$$D = \det[D_{n,s}] = 0, \tag{14}$$

where

$$(F_{0,1})_{n,s} = C_1\cdot[1+(n-s)Q_1]\cdot C_{ns1}^J + C_2\cdot[1+(n-s)Q_1]\cdot C_{ns1}^N + C_3\cdot[1+(n-s)Q_2]\cdot C_{ns2}^J + C_4\cdot[1+(n-s)Q_2]\cdot C_{ns2}^N, \tag{15}$$

$$(F_{0,2})_{n,s} = B_1\cdot[1+(n-s)Q_1]\cdot C_{ns1}^J + B_2\cdot[1+(n-s)Q_1]\cdot C_{ns1}^N + B_3\cdot[1+(n-s)Q_2]\cdot C_{ns2}^J + B_4\cdot[1+(n-s)Q_2]\cdot C_{ns2}^N, \tag{16}$$

$$(G_{0,1})_{n,s} = C_1\cdot\left[P_{n1}\cdot S_{ns1}^J + (n-s)\frac{\mathrm{j}k_0h_1}{p_1}\cdot T_{ns1}^J\right] + C_2\cdot\left[P_{n1}\cdot S_{ns1}^N + (n-s)\frac{\mathrm{j}k_0h_1}{p_1}\cdot T_{ns1}^N\right] + C_3\cdot\left[P_{n2}\cdot S_{ns2}^J + (n-s)\frac{\mathrm{j}k_0h_2}{p_2}\cdot T_{ns2}^J\right] + C_4\cdot\left[P_{n2}\cdot S_{ns2}^N + (n-s)\frac{\mathrm{j}k_0h_2}{p_2}\cdot T_{ns2}^N\right], \tag{17}$$

$$(G_{0,2})_{n,s} = B_1\cdot\left[P_{n1}\cdot S_{ns1}^J + (n-s)\frac{\mathrm{j}k_0h_1}{p_1}\cdot T_{ns1}^J\right] + B_2\cdot\left[P_{n1}\cdot S_{ns1}^N + (n-s)\frac{\mathrm{j}k_0h_1}{p_1}\cdot T_{ns1}^N\right] + B_3\cdot\left[P_{n2}\cdot S_{ns2}^J + (n-s)\frac{\mathrm{j}k_0h_2}{p_2}\cdot T_{ns2}^J\right] + B_4\cdot\left[P_{n2}\cdot S_{ns2}^N + (n-s)\frac{\mathrm{j}k_0h_2}{p_2}\cdot T_{ns2}^N\right], \tag{18}$$

in which

$$P_{n1} = \frac{p_1(\omega\varepsilon_0\varepsilon_g k_z^2 + K^2\mathrm{j}k_zh_1)}{D}, \tag{19}$$

$$P_{n2} = \frac{p_2(\omega\varepsilon_0\varepsilon_g k_z^2 + K^2\mathrm{j}k_zh_2)}{D}, \tag{20}$$

$$Q_1 = \frac{k_0(k_zK^2 + \mathrm{j}\omega\mu_0h_1k_g^2)}{D}, \tag{21}$$

$$Q_2 = \frac{k_0(k_zK^2 + \mathrm{j}\omega\mu_0h_2k_g^2)}{D}. \tag{22}$$

Here, C_{ns1}^J, C_{ns1}^N, C_{ns2}^J, C_{ns2}^N; S_{ns1}^J, S_{ns1}^N, S_{ns2}^J, S_{ns2}^N; T_{ns1}^J, T_{ns1}^N, T_{ns2}^J, T_{ns2}^N are obtained in our previous paper Ref.[9]. Thus,

$$C_1 = -\frac{\mathrm{j}\omega\varepsilon_0}{\varepsilon_1k^2k_c}(k_{z,n}k_g^2 + \mathrm{j}\omega\mu_0K^2h_2)N_0(p_1r_i) \times[U_nJ_1(k_cr_i) + V_nN_1(k_cr_i)] - p_1h_2N_1(p_1r_i) \times[U_nJ_0(k_cr_i) + V_nN_0(k_cr_i)], \tag{23}$$

$$C_2 = \frac{\mathrm{j}\omega\varepsilon_0}{\varepsilon_1 k^2 k_c}(k_{z,n}k_g^2 + \mathrm{j}\omega\mu_0 K^2 h_2)J_0(p_1 r_i) \times [U_n J_1(k_c r_i) + V_n N_1(k_c r_i)] - p_1 h_2 J_1(p_1 r_i) \times [U_n J_0(k_c r_i) + V_n N_0(k_c r_i)], \quad (24)$$

$$C_3 = -\frac{\mathrm{j}\omega\varepsilon_0}{\varepsilon_1 k^2 k_c}(k_{z,n}k_g^2 + \mathrm{j}\omega\mu_0 K^2 h_1)N_0(p_2 r_i) \times [U_n J_1(k_c r_i) + V_n N_1(k_c r_i)] - p_2 h_1 N_1(p_2 r_i) \times [U_n J_0(k_c r_i) + V_n N_0(k_c r_i)], \quad (25)$$

$$C_4 = \frac{\mathrm{j}\omega\varepsilon_0}{\varepsilon_1 k^2 k_c}(k_{z,n}k_g^2 + \mathrm{j}\omega\mu_0 K^2 h_1)J_0(p_2 r_i) \times [U_n J_1(k_c r_i) + V_n N_1(k_c r_i)] - p_2 h_1 J_1(p_2 r_i) \times [U_n J_0(k_c r_i) + V_n N_0(k_c r_i)], \quad (26)$$

$$B_1 = -\frac{\mathrm{j}\omega\mu_0}{\varepsilon_1 k^2 k_c}[k_{z,n}k_g^2 h_2 + \mathrm{j}\omega\varepsilon_0(\varepsilon_1 K^2 - \varepsilon_g k_g^2)] \times N_0(p_1 r_i) \cdot [U_n J_1(k_c r_i) + V_n N_1(k_c r_i)] + p_1 N_1(p_1 r_i) \times [U_n J_0(k_c r_i) + V_n N_0(k_c r_i)], \quad (27)$$

$$B_2 = \frac{\mathrm{j}\omega\mu_0}{\varepsilon_1 k^2 k_c}[k_{z,n}k_g^2 h_2 + \mathrm{j}\omega\varepsilon_0(\varepsilon_1 K^2 - \varepsilon_g k_g^2)] \times J_0(p_1 r_i) \cdot [U_n J_1(k_c r_i) + V_n N_1(k_c r_i)] + p_1 J_1(p_1 r_i) \times [U_n J_0(k_c r_i) + V_n N_0(k_c r_i)], \quad (28)$$

$$B_3 = -\frac{\mathrm{j}\omega\mu_0}{\varepsilon_1 k^2 k_c}[k_{z,n}k_g^2 h_1 + \mathrm{j}\omega\varepsilon_0(\varepsilon_1 K^2 - \varepsilon_g k_g^2)] \times N_0(p_2 r_i) \cdot [U_n J_1(k_c r_i) + V_n N_1(k_c r_i)] + p_2 N_1(p_2 r_i) \times [U_n J_0(k_c r_i) + V_n N_0(k_c r_i)], \quad (29)$$

$$B_4 = \frac{\mathrm{j}\omega\mu_0}{\varepsilon_1 k^2 k_c}[k_{z,n}k_g^2 h_1 + \mathrm{j}\omega\varepsilon_0(\varepsilon_1 K^2 - \varepsilon_g k_g^2)] \times J_0(p_2 r_i) \cdot [U_n J_1(k_c r_i) + V_n N_1(k_c r_i)] + p_2 J_1(p_2 r_i) \times [U_n J_0(k_c r_i) + V_n N_0(k_c r_i)]; \quad (30)$$

$$\begin{cases} U_n = k_c J_0(x_n r_b)N_1(k_c r_b) - x_n J_1(x_n r_b)N_0(k_c r_b), \\ V_n = x_n J_1(x_n r_b)J_0(k_c r_b) - k_c J_0(x_n r_b)J_1(k_c r_b). \end{cases} \quad (31)$$

3. Discussion and conclusions

The ion-channel being formed, it will focus the IREB, so the additional induct field can be cancelled. We first discuss the case that the induct field is absent, B_0=0. This case is significant, and the dispersion equation can be reduced into TM and TE modes independently, and then we have

$$p_1^2 = p_2^2 = y_n^2 = k^2(1 - \omega_p^2/\omega^2) - k_{z,n}^2,$$

making h_1=0 and $\varepsilon_m = y_n^2/k_c^2$. For the TM mode, its dispersion equation can be predigested

$$|(F_{0,1})_{n,s}| = \left| C_1 \cdot \left[1 + (n-s)\frac{k_0 k_{z,n}}{K^2}\right] \cdot C_{ns1}^J + C_2 \cdot \left[1 + (n-s)\frac{k_0 k_{z,n}}{K^2}\right] \cdot C_{ns1}^N \right| = 0, \quad (32)$$

where

$$C_1 = y_n[U_n J_0(k_c r_i) + V_n N_0(k_c r_i)]N_1(y_n r_i) - \frac{\varepsilon_m}{\varepsilon_1} k_c[U_n J_1(k_c r_i) + V_n N_1(k_c r_i)]N_0(y_n r_i), \quad (33)$$

$$C_2 = -y_n[U_n J_0(k_c r_i) + V_n N_0(k_c r_i)]J_1(y_n r_i) + \frac{\varepsilon_m}{\varepsilon_1} k_c[U_n J_1(k_c r_i) + V_n N_1(k_c r_i)]J_0(y_n r_i). \quad (34)$$

For the TE modes, the dispersion equation is predigested as

$$|(G_{0,2})_{n,s}| = |B_3 \cdot [k_{z,n}S_{ns2}^J + (n-s)k_0 \cdot T_{ns2}^J] + B_4 \cdot [k_{z,n}S_{ns2}^N + (n-s)k_0 \cdot T_{ns2}^N]| = 0, \quad (35)$$

where

$$B_3 = y_n[U_n J_0(k_c r_i) + V_n N_0(k_c r_i)]N_1(y_n r_i) - \varepsilon_m k_c[U_n J_1(k_c r_i) + V_n N_1(k_c r_i)]N_0(y_n r_i), \quad (36)$$

$$B_4 = -y_n[U_n J_0(k_c r_i) + V_n N_0(k_c r_i)]J_1(y_n r_i) + \varepsilon_m k_c[U_n J_1(k_c r_i) + V_n N_1(k_c r_i)]J_0(y_n r_i). \quad (37)$$

The following parameters were used for our calculation and analysis. The average radius is a=14.45mm, the corrugation amplitude is b=1.45mm, the axial length of the corrugation period is L=16.7mm, the plasma electron density is $n_p = 2\times10^{11}(\mathrm{cm}^{-3})$, and the radius of ion-channel is r_i=4.45mm. From formula (32) a dispersion curve was obtained as shown in Fig.2. Figure 3 was obtained from the following formula (38) which was given in our previous work released in Ref.[9]:

$$
\begin{aligned}
(F_{0,1})_{n,s} = & \left[1+(n-s)\frac{k_{z,n}k_0}{K^2}\right]C^J_{ns1} + \frac{\pi r_i}{2p(\varepsilon_1 K^2-1)J_0(pr_i)J_1(pr_i)} \\
& \times [J_1(pr_i)J_0(p_2r_i) - K^2\varepsilon_1 pp_2 J_0(pr_i)J_1(p_2r_i)][K^2 J_1(pr_i)N_0(p_2r_i) - pp_2 J_0(pr_i)N_1(p_2r_i)] \\
& \times \left[1+(n-s)\frac{k_{z,n}k_0}{K^2}\right]C^J_{ns2} + \frac{\pi r_i}{2p(\varepsilon_1 K^2-1)J_0(pr_i)J_1(pr_i)} \\
& \times [K^2 J_1(pr_i)J_0(p_2r_i) - pp_2 J_0(pr_i)J_1(p_2r_i)][-J_1(pr_i)J_0(p_2r_i) + K^2\varepsilon_1 pp_2 J_0(pr_i)J_1(p_2r_i)] \\
& \times \left[1+(n-s)\frac{k_{z,n}k_0}{K^2}\right]C^N_{ns2}. \qquad (38)
\end{aligned}
$$

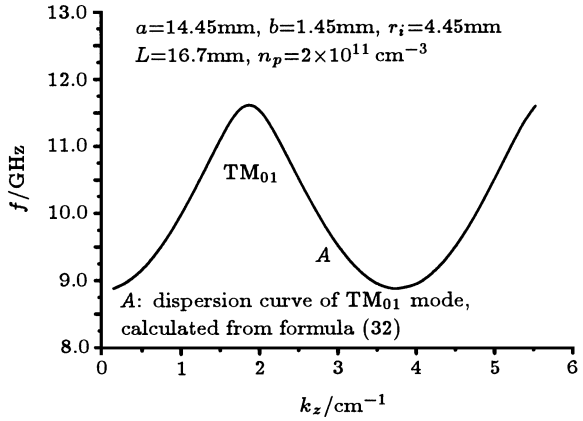


Fig.2. The dispersion curve obtained from formula (32) (TM_{01} mode).

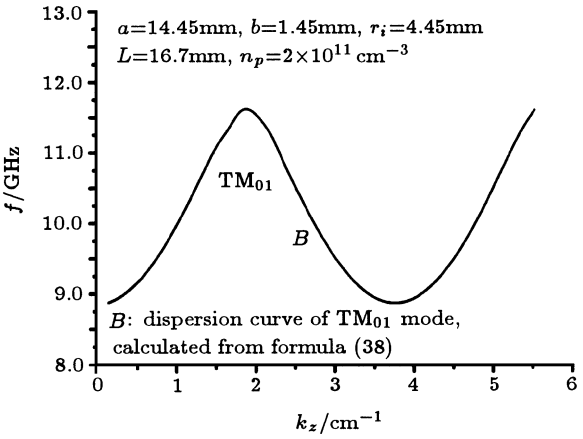


Fig.3. The dispersion curve obtained from formula (37) (TM_{01} mode).

In Figs.2 and 3 two methods are compared and we find a good agreement, showing the validity of the theory. Figure 4 was obtained from formula (32) using different beam densities, for which B is lower than C, the other parameters being the same as Fig.3. The 'cold' dispersion curve of Fig.3 is also reproduced in Fig.4 for comparison. For the media dispersion properties of electronic beam in the lower k_z range, the 'hot' dispersion curves (B and C) show weaker dispersion property, which is closer to the real conditions. The higher beam density would make a more broadened frequency band of curve C than curve B. If there is no electronic-beam, the 'hot' dispersion curves B and C will coincide with A.

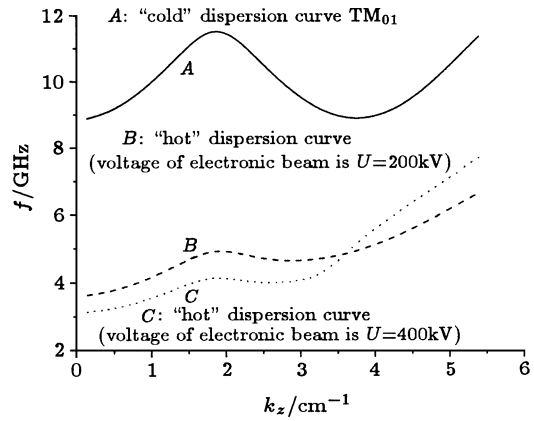


Fig.4. The 'hot' dispersion curves obtained from formula (32).

In conclusion, a general 'hot' dispersion equation of corrugated waveguide immersed in a finite magnetized field with ion-channel being taken into account is obtained. The 'cold' dispersion equation can also be deduced from the 'hot' dispersion equation. Many forms and results have been obtained and discussed in some special cases: e.g., dispersion relations with ion-channel taken into account were obtained in the case of the magnetic field being infinite or zero. If the ion-channel is ignored, the dispersion equation will degenerate to the same form as given in the literature,[9−17] showing that the above theory is correct.

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