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Wave Dispersion Property in Magnetized Plasma Channel Antenna*

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Abstract: In order to solve the problems existing in the current antenna for high power microwave weapon, the idea of a magnetized plasma channel used as antenna for radiating electromagnetic pulse is presented. The normal modes of Magnetized Plasma Channel Antenna (MPCA) in lossy gas are analyzed. The concrete realization method of this antenna is simply described. The geometrie model of MPCA is created based on the operating principle of this antenna. The strictest dispersion equation of MPCA is deduced by applying the boundary conditions of electromagnetic fields. Discussion is stressed on the variations of propagation constants with plasma parameters, surrounding material and external magnetic field. The analysis shows that MPCA in a finite magnetic field possesses some different properties compared with a plasma channel antenna where infinite external magnetic field exists. These results are useful for practical application of the antenna.

Key words: MPCA (Magnetized Plasma Channel Antenna); Dispersion Equation; Microwave
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1 Introduction

Plasma as the fourth form of the substance, the technology of plasma has been widely used in many fields. In military fields, it can be used in aircraft stealthy, thrust, communication and detection etc. If the wave frequency is less than the plasma frequency, the electromagnetic wave cannot propagate in the bulk plasma. The axisymmetric surface wave propagates along the cylindrical plasma column. For high density plasma, it is a perfect conductor and therefore can be used as antenna elements. Because plasma can reflect and absorb electromagnetic waves, plasma antenna has the advantage of stealth.

In recent years, with the advancement of High Power Microwave Source (HPMS) theory and technique, it has become possible to manufacture High Power Microwave Weapon (HPMW). The strongest countries in the world are actively developing the HPMW[1-2]. The antenna system has become a restricted HPMW development bottleneck[3-6]. So the research on the antenna system of HPMW stares us in the face. It is well known that the plasma channel can be induced by ultra short intense laser pulse in low-pressure gas[7]. To solve this problem, the idea of a magnetized plasma channel used as antenna for radiating electromagnetic pulse is presented. The physical base of Plasma Channel Antenna (PCA) involves electromagnetic waves propagating in plasma channel. Because knowing the characteristics of the eigen modes is the prerequisites for application in engineering[8], the deduce and analysis of the dispersion equa-

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tion is necessary and significative.

In this paper, the geometrie-model of MPCA is created. The wave equations for the longitudinal components of MPCA in cylindrical coordinate are started with. The relations between the transverse components and longitudinal ones of MPCA in circular cylindrical coordinate are given. The strictest characteristic equation of modes for MPCA is deduced by applying the boundary conditions of electromagnetic fields. The variations of propagation constants with plasma parameters, surrounding material and external magnetic field are analyzed by using numerical method. The analyses show that there are some main differences of PCA between infinite and finite magnetic field. Firstly, the PCA in a finite magnetic field could only propagate EH or HE models. Second, the phase constant of PCA in finite magnetic field is hardly related to surrounding material.

2　MPCA s Implementation

The goal of PCA is guiding and radiating electromagnetic pulse (EMP) to hit targets by using the plasma channel inducing by ultra short intense laser pulse in low-pressure gas. The schematic diagram of MPCA is shown in fig. 1. On the condition of knowing the azimuth information of the target, high power pulse laser emits ultra short intense laser pulse towards some near range target, and the plasma channel pointing to target is formed. At the same time, high power electromagnetic pulses (HPEMP) are generated by synchronous signal controlling HPEMP generator, and HPEMP are coupled to plasma channel via antenna coupling device. On the one hand, HPEMP and plasma beam is transmitting synchronously, and HPEMP head-on attack accurately target. On the other hand, the plasma channel is used as antenna for radiating HPEMP, and HPEMP being radiated from side of plasma channel destroy target.

3　Derivation of the Dispersion Relation

Based on the operating principle of the plasma channel guiding and radiating HPEMP, two factors are under consideration: one is that the plasma channel is approximately infinite plasma cylindrical for HPEMP always lagging behind ultra short intense laser pulse; the other is that the plasma channel is thought to be density uniformity plasma cylindrical along z-axis. In order to be typical, the surrounding material is dielectric or magnetic lossy gas. The plasma in channel is magnetized plasma for being the geomagnetic field. So the PCA is thought approximately to be infinite uniform magnetized plasma cylindrical in lossy material. The geometry of the problem is shown schematically in fig. 2.

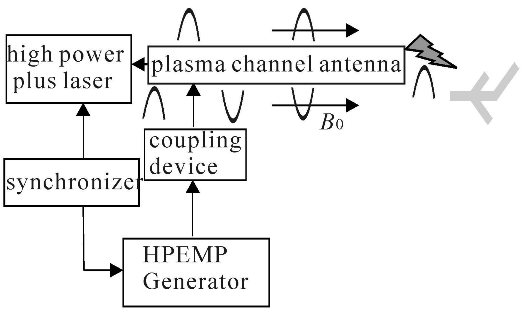

Fig. 1　Schematic Diagram of MPCA

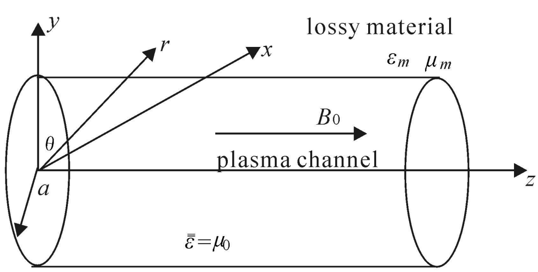

Fig. 2　Geometry of the Problem

For laser plasma channel, the plasma in channel is cold plasma. The direction of an external magnetic field B_0 is parallel to the direction of wave propagation in plasma channel. The plasma is characterized by the permeability ${}_0$ and the following permittivity tensors[9]:

$$= {}_0 \begin{pmatrix} {}_1 & - \; {}_2 & 0 \\ {}_2 & {}_1 & 0 \\ 0 & 0 & {}_3 \end{pmatrix}, \qquad (1)$$

where $_1 = 1 - \frac{^2_p/ \ ^2}{1 - \ ^2_c/ \ ^2}$, $_2 = j \frac{^2_p \ _c/ \ ^3}{1 - \ ^2_c/ \ ^2} = - j \ _g$, $_3 = 1 - \ ^2_p/ \ ^2$, $_p = \sqrt{n_0 e^2/(m_e \ _0)}$ is the electron plasma angular frequency, $_c = eB_0/m_e$ is the electron cyclotron angular frequency, n_0, e and m_e are the electron number density, the electric charge and mass of an electron, respectively, B_0 is the external magnetic field, and is the electromagnetic angular frequency.

From equation (1) and Maxwell s equation, the wave equation for longitudinal field components in plasma channel E_{pz} and H_{pz} can be obtained:

$$\begin{pmatrix} - \ ^2_t & b^m \\ b^e & - \ ^2_t \end{pmatrix} \begin{pmatrix} E_{pz} \\ H_{pz} \end{pmatrix} = \begin{pmatrix} a^e E_{pz} \\ a^m H_{pz} \end{pmatrix}, \tag{2}$$

where $^2 - \ ^2/ \ z^2 = \ ^2_t$, $(k_0^2 \ _1 - k^2) \ _3/ \ _1 = a^e$, $k_0^2(\ ^2_1 + \ ^2_2)/ \ _1 - k^2 = a^m$, $_0 \ _2 \ _3 k/ \ _1 = b^e$, $- \ _0 \ _2 k/ \ _1 = b^m$, $_0$, $_0$ and k_0 are the permittivity, permeability, and wavenumber in free space, respectively. Equations (2) are the well-known set of coupled second partical different equations and their solutions in cylindrical coordinate system are[10-12]

$$E_{pz} = A_1 J_n(p_{p1} r) + A_2 J_2(p_{p2} r), \tag{3}$$

$$H_{pz} = A_1 q_1 J_n(p_{p1} r) + A_2 q_2 J_n(p_{p2} r). \tag{4}$$

where $p^2_{p1,p2} = \frac{1}{2}[(a^e + a^m) \ \sqrt{(a^e + a^m)^2 - 4(a^e a^m - b^e b^m)}]$, $q_{1,2} = (a^e - p^2_{p1,p2})/b^m$, $J_n(\ )$ is the Bessel function, A_1, A_2 are unknown coefficients.

By the same procedure, we let $_1 = \ _3 = \ _{mr}$, $_2 = 0$ in (1) and $_0 \ _{mr}$ replace $_0$, and the wave equation for longitudinal field components in lossy gas E_{Lz} and H_{Lz} can be obtained:

$$E_{Lz} = B_1 H_n^{(2)}(p_L r), \tag{5}$$

$$H_{Lz} = B_2 H_n^{(2)}(p_L r). \tag{6}$$

where $p_L = \sqrt{k_L^2 - k^2}$, $k_L = \ \sqrt{\ _m \ _m}$, $_m = \ _0 \ _{mr}$, $_m = \ _0 \ _{mr}$ are the permittivity, permeability of surrounding gas, respectively, and B_1, B_2 are unknown coefficients. The wave factor $\exp(- jkz + jn \ )$ has been neglected in (3) ~ (6).

In order to solve the transverse field, the relations between the transverse components and longitudinal ones in circular cylindrical coordinate must be deduced. From equation (1) and Maxwell s equation, the transverse field in plasma channel $E_{pr, p}$ and $H_{pr, p}$ can be expressed in terms of E_{pz} and H_{pz} as

$$H_{pr} = \frac{1}{M}(A_1^m \frac{E_{pz}}{r} + jA_2^m \frac{1}{r} \frac{E_{pz}}{} - jA_0 \frac{H_{pz}}{r} - A_3^m \frac{1}{r} \frac{H_{pz}}{}), \tag{7}$$

$$H_p = \frac{1}{M}(- jA_2^m \frac{E_{pz}}{r} + A_1^m \frac{1}{r} \frac{E_{pz}}{} + A_3^m \frac{H_{pz}}{r} - jA_0 \frac{1}{r} \frac{H_{pz}}{}), \tag{8}$$

$$E_{pr} = \frac{1}{M}(- jA_0 \frac{E_{pz}}{r} - A_1^e \frac{1}{r} \frac{E_{pz}}{} + A_2^e \frac{H_{pz}}{r} - jA_3^e \frac{1}{r} \frac{H_{pz}}{}), \tag{9}$$

$$E_p = \frac{1}{M}(A_1^e \frac{E_{pz}}{r} - jA_0 \frac{1}{r} \frac{E_{pz}}{} + jA_3^e \frac{H_{pz}}{r} + A_2^e \frac{1}{r} \frac{H_{pz}}{}). \tag{10}$$

where $A_1^m = - \ _0 \ _g k^2$, $A_2^m = \ _0[k_0^2(\ ^2_1 - \ ^2_g) - k^2 \ _1]$, $A_3^m = kk_0^2 \ _g$, $A_1^e = kk_0^2 \ _g$, $A_2^e = \ _0 k_0^2 \ _g$, $A_3^e = \ _0(k_0^2 \ _1 - k^2)$, $A_0 = k(k_0^2 \ _1 - k^2)$, $M = [k_0^2(\ _1 - \ _g) - k^2][k_0^2(\ _1 + \ _g) - k^2]$.

By the same procedure, we let $_1 = \ _3 = \ _{mr}$, $_2 = 0$ in (1) and $_0 \ _{mr}$ replace $_0$, and the transverse field in lossy gas $E_{Lr, L}$ and $H_{Lr, L}$ can be expressed in terms of E_{Lz} and H_{Lz} as

$$\begin{pmatrix} E_{Lr} \\ E_L \\ H_{Lr} \\ H_L \end{pmatrix} = \frac{1}{p_L^2} \begin{pmatrix} - jk & 0 & 0 & - j \ _m \\ 0 & - jk & j \ _m & 0 \\ 0 & j \ _m & - jk & 0 \\ - j \ _m & 0 & 0 & - jk \end{pmatrix} \begin{pmatrix} E_{Lz}/ \ r \\ E_{Lz}/(r \ ) \\ H_{Lz}/ \ r \\ H_{Lz}/(r \ ) \end{pmatrix}. \tag{11}$$

Substituting (3) ~ (6) into (7) ~ (11), the four equations of the coefficients (A_1, A_2, B_1, B_2) are derived by matching tangential-field components at $r = a$. In order to obtain nonzero solutions to A_1, A_2, B_1, B_2 the determinant must be zero. This leads to the following dispersive equation:

$$[f_1 p_{p1}^2 J(x_{p1}) - j \quad {}_m q_1 H(x_L) + n(p_{p1}^2 g_1/x_{p1}^2 - k/x_L^2)] \quad [F_2 p_{p2}^2 J(x_{p2}) + j \quad {}_m H(x_L) + n(p_{p2}^2 G_2/x_{p2}^2 - kq_2/x_L^2)] - [F_1 p_{p1}^2 J(x_{p1}) + j \quad {}_m H(x_L) + n(p_{p1}^2 G_1/x_{p1}^2 - kq_1/x_L^2)] \quad [f_2 p_{p2}^2 J(x_{p2}) - j \quad {}_m q_2 H(x_L) + n(p_{p2}^2 g_2/x_{p2}^2 - k/x_L^2)] = 0, \quad (12)$$

where $f_{1,2} = \frac{A_1^e + jA_3^e q_{1,2}}{M}$, $g_{1,2} = \frac{A_0 + jA_2^e q_{1,2}}{M}$, $F_{1,2} = \frac{-JA_2^m + A_3^m q_{1,2}}{M}$, $G_{1,2} = \frac{jA_1^m + A_0 q_{1,2}}{M}$, $x_{p1} = p_{p1} a$, $x_{p2} = p_{p2} a$, $x_L = p_L a$, $H(x_L) = H_n^{(2)}(x_L)/[x_L H_n^{(2)}(x_L)]$, $J(x_{p1,p2}) = J_n(x_{p1,p2})/[x_{p1,p2} J_n(x_{p1,p2})]$.

4 Particular Cases

4.1 Symmetric Mode

Substitution of $n = 0$ into (12) then leads to

$$[f_1 p_{p1}^2 J(x_{p1} - j \quad {}_m q_1 H(x_L)] \quad [F_2 p_{p2}^2 J(x_{p2}) + j \quad {}_m H(x_L)] - F_1 p_{p1}^2 J(x_{p1} + j \quad {}_m H(x_L)] \quad [f_2 p_{p2}^2 J(x_{p2}) - j \quad {}_m q_2 H(x_L)] = 0. \quad (13)$$

Equation (13) indicates that hybrid modes, i. e., HE_{nm} mode and EH_{nm} mode, no longer degenerate into TE_{0m} and TM_{0m}. This result is different from that in the case of no and infinite external magnetic field.

4.2 Infinite Magnetic Field

For infinite external magnetic field, the plasma is characterized by the permeabilityand the following permittivity tensors:

$$= \quad {}_0 \quad \mathrm{diag}(1, 1, \quad). \quad (14)$$

where $= 1 - X^2$, $X = \quad {}_p / \quad$, ${}_p = \sqrt{n_0 e^2/(m_e \quad {}_0)}$ is the electron plasma angular frequency, n_0, e and m_e are the electron number density, the electric charge and mass of an electron, respectively, is the electromagnetic angular frequency. By the same procedure, the dispersive equation can be expressed as

$$[\quad {}_{mr} x_m^2 MH(x_m) - x_{p1}^2 J(x_{p1}) J(x_{p1})][\quad {}_{mr} x_m^2 MH(x_m) - x_{p2}^2 J(x_{p2})] - n^2 (\frac{k}{k_0})^2 (1 - M)^2 = 0. \quad (15)$$

where $p\,a = x_m$, $p_1 a = x_{p1}$, $p_2 a = x_{p2}$, $M = \frac{k_0^2 - k^2}{k_m^2 - k^2}$, $p_1 = (k_0^2 - k^2)$, $p_2 = k_0^2 - k^2$, $p = \sqrt{k_m^2 - k^2}$, $k_m = \quad {}_{mr} \quad {}_{mr} k_0^2$ is the wavenumber in surrounding gas.

Substitution of $n = 0$ into (15) then leads to

$$J(x_{p2}) - \quad {}_{mr} H(x_m) = 0 \text{ for } TE, \quad (16)$$

$$J(x_{p1}) - \quad {}_{mr} H(x_m) = 0 \text{ for } TM, \quad (17)$$

Equations (16), (17) shows that the TM wave is related to plasma parameters and the TE wave is independent of plasma parameters. Under conditions

$$-\mathrm{Im}(x_m) \quad 1, \mathrm{Im}(x_{p1,p2}) \quad 1.$$

The approximate solutions to Equations (16), (17) approaches to

$$k_{TE} = k_0 \sqrt{\frac{{}_{mr}^2 - \quad {}_{mr} \quad {}_{mr}}{{}_{mr}^2 - 1}} \text{ for } TE, \quad (18)$$

$$k_{TM} = k_0 \sqrt{\frac{{}_{mr}^2 - (1 - X^2) \quad {}_{mr} \quad {}_{mr}}{{}_{mr}^2 + X^2 - 1}} \text{ for } TM, \quad (19)$$

When ${}_p \quad (X \quad 1)$, $p_1 \quad p_2$. Thus the dispersive equation (15) becomes

$$[\quad {}_{mr} H(x_m) - J(x_{p1})][\quad {}_{mr} H(x_m) - J(x_{p2})] - n^2 (\frac{k}{k_0})^2 (\frac{1}{x_{p2}^2} - \frac{1}{x_m^2})^2 = 0. \quad (20)$$

5 Numerical Results and Discussion

In order to compare the difference of infinite and finite external magnetic field, fig. 3~ 6 gives the propagation constants of MPCA as a function of plasma frequency. These figures show that, for infinite or finite external magnetic field, the attenuation constant tend to increase with the increase of the order n when $_p/$ < 0.8. For infinite external magnetic field, fig. 3- a and fig. 4- a show three aspects. First, the characteristic of surrounding gas can not effect on the attenuation constant of MPCA when $_p/$ < 0.1. Second, for the same order, when 0.1< $_p/$ < 0.8, the attenuation constant of MPCA surrounding by magnetic lossy gas is always smaller than that surrounding by dielectric lossy gas, and the attenuation constant of MPCA surrounding by magnetic lossy gas reaches minimum value and that surrounding by dielectric lossy gas reaches maximum value. Third, when 0.8< $_p/$ < 1, the change of the attenuation constant of MPCA surrounding by magnetic lossy gas is always acuter than that surrounding by dielectric lossy gas. For finite external magnetic field, fig. 3- b and fig. 4- b show five aspects. First, the characteristic of surrounding lossy gas can not effect on the attenuation constant of MPCA when $_p/$ < 0.5. Second, for the same order, when 0.5< $_p$< < 0.8, the attenuation constant of MPCA surrounding by dielectric lossy gas is always smaller than that surrounding by magnetic lossy gas, and the attenuation constants of MPCA surrounding by both magnetic and dielectric lossy gas reach minimum value. Third, the numerical results show that the plasma frequency of minimum attenuation is related to the strength of external magnetic field. Forth, when 0.8< $_p/$ < 0.9, increasing $_p/$ results in the severe increasing attenuation of MPCA, and the change of attenuation constant tend to fast with the increase of the order n. Fifth, when $_p/$ 1, the attenuation of MPCA becomes infinite, and this means that the inner modes of MPCA do not exist.

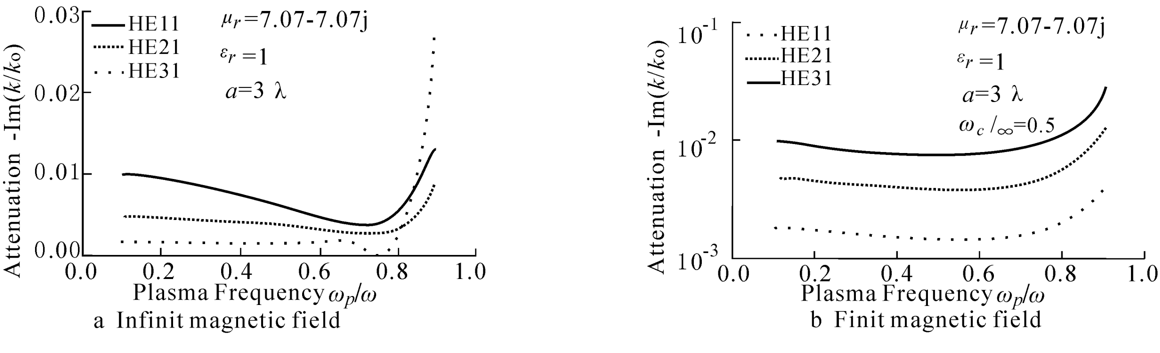

Fig. 3 Attenuation Constant of MPCA in Magnetic Lossy Gas Against Plasma Frequency for Various Hybrid Modes

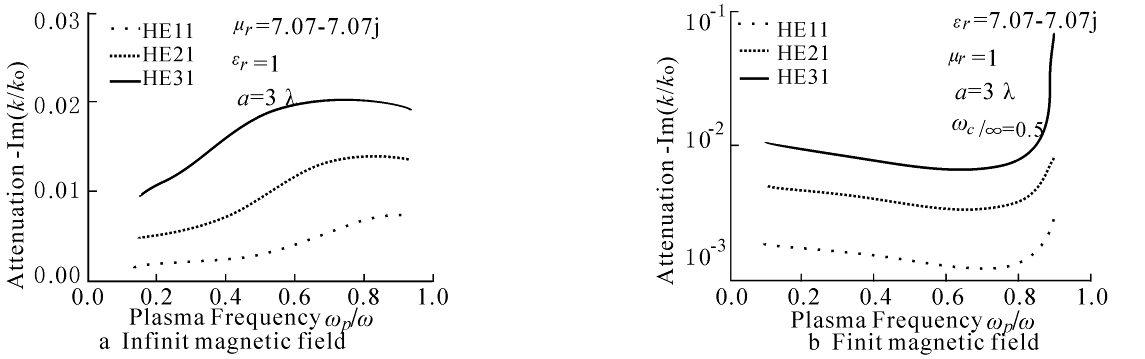

Fig. 4 Attenuation Constant of MPCA in Dielectric Lossy Gas Against Plasma Frequency for Various Hybrid modes

For infinite external magnetic field, fig. 5 shows three aspects. First, the effect of the plasma frequency on the phase constant is minute comparing with the attenuation constant. Second, when 0.1< $_p/$ < 0.8, the phase constant of MPCA in lossy dielectric lossy gas tend to increase with the increase of $_p/$, and that in lossy magnetic lossy gas tend to decrease. Third, when $_p/$ < 0.3, the phase constant of MPCA in lossy dielectric lossy gas is agreement with that in lossy magnetic lossy gas. For finite external

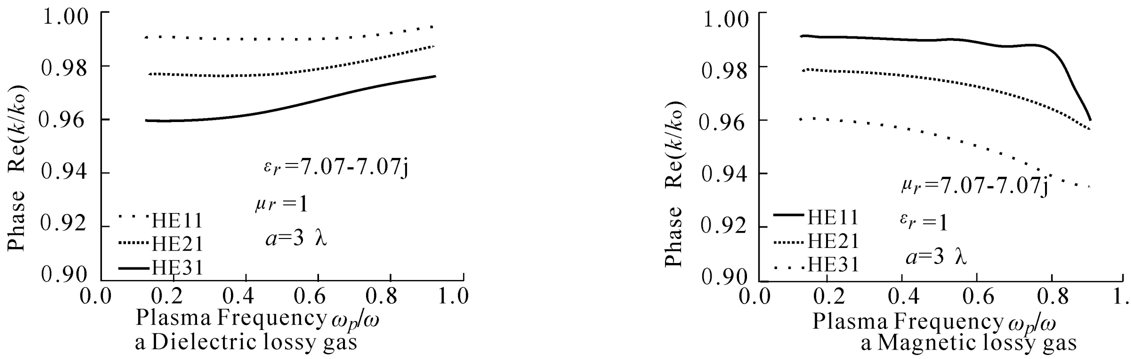

Fig. 5　Phase Constant of MPCA in Infinite External Magnetic Field Against Plasma Frequency for Various Hybrid Modes

magnetic field, fig. 6 shows that the phase constant of MPCA in dielectric lossy gas is equal to that in magnetic lossy gas and the phase constant tends to decrease with the increase of the order n.

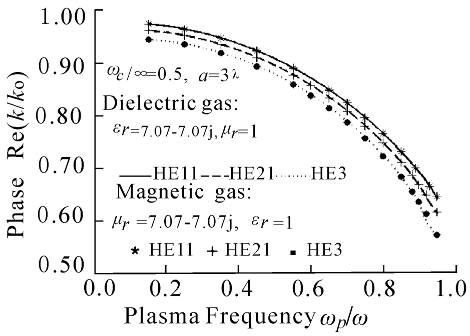

Fig. 6　Phase Constan of MPCA in Finite Exteral Magnetic Field Against Plasma Frequency for Various Hybrid Modes

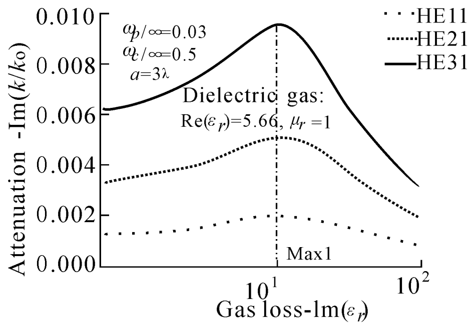

Fig. 7　Finite External Magnetic Field, Attenuation Constant of MPCA Against – Im (r　for Various Hybrid Modes

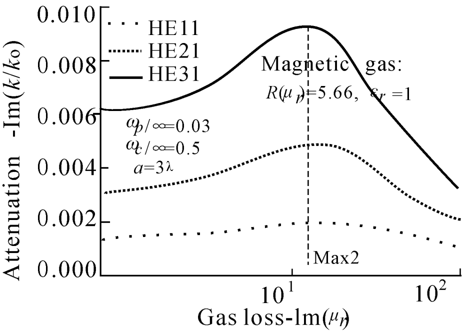

Fig. 8　Finite External Magnetic Field, Attenuation Constant of MPCA Against – Im (r　for Various Hybrid Modes

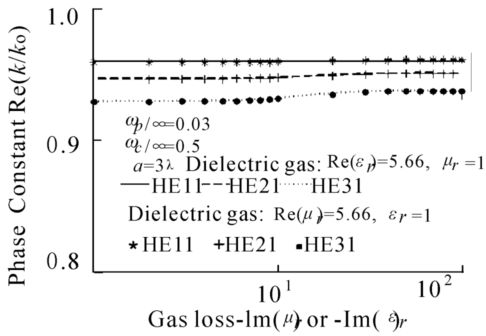

Fig. 9　Finite External Magnetic Field, Phase Constant of MPCA Against – Im (r　or – Im(r　for Various Hybrid Modes

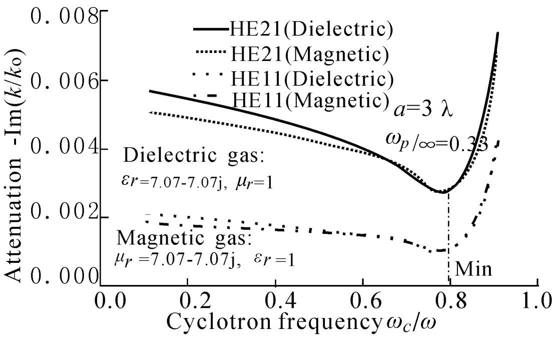

Fig. 10　Finite External Magnetic Field, Attenuation Constant of MPCA Against – Im (c/　for Various Hybrid Modes

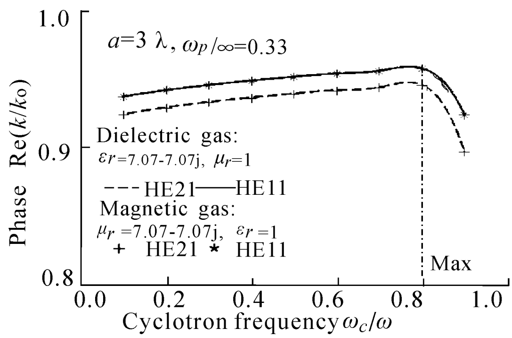

Fig. 11　Finite External Magnetic Field, Attenuation Constant of MPCA Against – Im (c/　for Various Hybrid Modes

In order to control length of this paper, propagation constants of MPCA in finite external magnetic field is only shown in fig. 7~ 11 as functions of surrounding material parameters and external magnetic intensity. Fig. 7~ 9 gives the propagation constants of MPCA as a function of surrounding gas loss. These figures show four aspects. First, the attenuation constants of MPCA reach maximum value with $-\mathrm{Im}(\varepsilon_r)$ = Max1 and $-\mathrm{Im}(\varepsilon_r)$ = Max2, and Max1< Max2. Second, increasing the order n results in the increasing attenuation of MPCA. Third, for the same order n, the attenuation constant of MPCA surrounding by dielectric lossy gas is always greater than that surrounding by magnetic lossy gas when ω_c/ω = Max2, and the result is reverse when ω_c/ω = Max2. Forth, the effect of surrounding gas loss on the phase constant is minute, and the phase constant tend to weakly decrease with the increase of the order n.

Fig. 10~ 11 gives the propagation constants of MPCA as a function of ω_c/ω. Fig. 10 shows three aspects. First, the attenuation constant of MPCA reaches minimum value with ω_c/ω = Min. Second, the attenuation constant of MPCA surrounding by dielectric lossy gas is always greater than that surrounding by magnetic lossy gas when ω_c/ω < Min, and the changes of attenuation curves are slow. Third, the attenuation constant of MPCA in lossy dielectric lossy gas is almost equal to that in lossy magnetic lossy gas when ω_c/ω > Min, and the changes of attenuation curves are very fast. Fig. 11 shows three aspects, too. First, the attenuation constant of MPCA reaches maximum value with ω_c/ω = Max. Second, the changes of phase curves are slow when ω_c/ω < Max, and the changes of phase curves are fast when ω_c/ω > Max. Third, for the same order n, the phase constant of MPCA in dielectric lossy gas is almost equal to that in magnetic lossy gas, and the phase constant tend to weakly decrease with the increase of the order n.

6 Conclusion

The efficient method for formulating the characteristic equation is developed to analyze the propagation characteristics of MPCA. The dispersion equation for the eigenvalue problem of MPCA is obtained. For infinite external magnetic field, the TE_{0m} mode and TM_{0m} mode can exist in the symmetric mode. However, for finite external magnetic field, the hybrid modes, i. e., HEnm mode and EHnm mode, no longer degenerate into TE_{0m} and TM_{0m} in the symmetric mode. The effects of the cyclotron frequency, plasma frequency and surrounding material parameters on the propagation characteristics are shown. The attenuation constant of MPCA is related to the plasma parameters. So the propagation characteristics of MPCA may be controlled by changing the external magnetic strength.

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磁化等离子体通道天线中电磁波的色散特性

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摘　要: 针对现有高功率微波武器辐射天线的不足, 提出了将磁化等离子体通道用作电磁脉冲辐射天线的思想　磁化等离子体通道天线(MPCA), 分析了 MPCA 周围为有耗气体媒质时 MPCA 所传播的一般模式. 简单阐述了 MPCA 的具体实现方法, 根据 MPCA 的工作原理, 建立了 MPCA 的几何模型, 利用边界条件导出了 MPCA 最严格的色散方程. 重点讨论了传播常数随等离子体参数、周围介质参数和外加磁场的变化. 结果表明, 有限磁场中的 MPCA 与无穷大磁场时具有一些不同的传播特性, 这些结果对于该天线的实现很有参考价值.

关键词: 磁化等离子体通道天线; 色散方程; 电磁波

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Improved K-Means Algorithm Based on a Simple Genetic Algorithm

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Abstract: K-means algorithm is sensitive to initial value, easy to fall into local minimum value. In response to these shortcomings, the idea of genetic algorithm is proposed based on genetic algorithm and k-means algorithm for hybrid clustering method. In order to test the performance of clustering algorithm, a set of experiments are conducted by using k-means algorithm and the improved algorithm, and the clustering results by the two algorithms are compared. It is showed that the clustering algorithm can effectively solve the clustering problem.

Key words: data mining; cluster analysis; genetic algorithm; k-means algorithm

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