Microwave Propagation in Warm, Collisional Magnetoionic Media

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***Abstract*— In this paper, we present the derivation of the magnetoionic dispersion equation and the corresponding index of refraction and propagation constant for characterizing wave propagation in warm plasma immersed in a uniform magnetic field. To demonstrate the effects of plasma temperature on wave propagation and attenuation, a numerical example of the developed theory has been given. It is well known that there are two forward propagating modes of cold plasma: one is weakly attenuated and the other is weakly amplified. By comparing the cold plasma complex propagation constant of the classical Appleton–Hartree theory with the propagation constant obtained for the warm plasma case, we observed that the attenuated mode is thermally enhanced while the amplification of the other mode decreases by increasing the temperature where it becomes damped beyond a certain electron thermal speed.**

***Index Terms*— Appleton–Hartree theory, electromagnetic waves, index of refraction, magnetized plasma, magnetoionic theory, microwave propagation, warm plasma.**

I. Introduction

The problem of the interaction of electromagnetic waves with ionized media, such as plasmas, is an important issue in physics and engineering, with a particular importance for communications [1]–[19]. In particular, electromagnetic wave propagation in low-temperature plasma has direct applications in telecommunications in the atmosphere, where the plasma can be used as an absorber or reflector of electromagnetic waves [9]–[11]. The earth ionosphere layer plays an important role in the propagation of high-frequency radio waves around the earth surface. This ionospheric layer occurs as a result of the ionization for the gases in the earth atmosphere by the sun ultraviolet radiations. The heating process for parts of the ionosphere could result from high-power radio waves launched from ground-based transmitters [17], together with other processes related to, for example, Landau damping [18].

The Appleton–Hartree magnetoionic theory was developed to describe the electromagnetic wave propagation in ionized media in the presence of static magnetic fields, for example, in [20] and [21]. Magnetoionic and optical ray theories lead to a useful and satisfactory description of wave propagation and reflection. Within the magnetoionic theory, combined with the optical ray theory, waves are assumed to be of a plane wave nature with a complex propagation constant, namely, they vary as $e^{i\omega t-Kx}$. All the dynamical effects are included in the generalized complex propagation constant $K = K_r + iK_i$, where K_r and K_i are its real and imaginary parts, respectively.

Lorentz electron and the corresponding dispersion theories constitute the basis in the derivation of the complex index for refraction in the classical magnetoionic theory of cold plasmas. Within the frame of the Maxwell's field theory, electromagnetic properties of materials are characterized by three response functions, namely, the permittivity ϵ_0, permeability μ_0, and the conductivity σ. These response functions depend generally on the wave frequency and on the physical conditions of the material under consideration. For plasma frequencies of the microwave spectrum range, motion of plasma ions is not important, and the plasma ions are treated as a neutralizing background of positive charge.

In the simplified treatment of plasma as a dielectric medium, convection currents resulting from the plasma electrons and ions are accounted for the derivation of the equivalent dielectric permittivity [22]. It is well known that electromagnetic waves cannot propagate in overdense plasma. Waves are reflected at the bulk plasma frequency and become evanescent waves [22], [23]. This may give rise to heating of the plasma and then waves do not travel further in any radial direction, but rather propagate along the plasma–vacuum or plasma–metal interfaces. The wave energy is then transferred to the plasma by the evanescent wave, which enters the plasma perpendicular to its surface and decays exponentially [24].

Although first formulated long ago [20], [21], not much development has been done on the Appleton–Hartree magnetoionic theory. Of particular interest is the work done in [25] to include the ion effect and that done in [26] to include the effect of the plasma drift. Snyder studied the effect of ion species on magnetoionic wave polarization and found possible polarization in a mixture of electrons and ions that cannot occur when only electrons are present. Unz, however, included the drifting plasma effect, where he considered homogeneous infinite plasma that is moving with a constant velocity, and derived a modified form for the complex index of refraction that accounts for the drift effect. Nevertheless, Unz's work has created lots of controversy [27], [28].

Thermal effects may be of high degree of importance in electromagnetic wave propagation in the ionosphere as well as in the emerging applications of stealth technology. A further development for the Appleton–Hartree theory is made in this paper by further studying the theory and the numerical solution of the complex dispersion equation in thermal plasma. Plasma

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temperature enters the force equation through the thermal pressure term and a modified formula for the complex index of refraction is derived. All possible solutions of the resulting system of algebraic equations are then obtained numerically with a special attention given to solutions for the temperature dependent K values that correspond to a forward wave propagation. This paper is organized as follows. In Section II, we present the derivation of the dispersion equation of the complex index of refraction of the magnetoionic theory in warm plasma. In Section III, we solve the algebraic equation of the complex index of refraction numerically for typical plasma parameters. In Section IV, we present the main comments and conclusion.

II. Magnetoionic Equation in Warm Plasma

Magnetoionic theory assumes that only motion of electrons contributes to the electromagnetic response because of their high mobility. These electrons are free to move through the material body at random without underlying the effects of restoring forces, and the medium action is considered by the motion of electrons. In a linear, homogeneous, and isotropic material medium with permittivity ϵ_0 and permeability μ_0, Maxwell's equations for the electric ($\vec{E}$) and magnetic ($\vec{H}$) fields can be written as follows:

$$\vec{\nabla} \times \vec{H} = \rho_e \vec{v}_e + \epsilon_0 \frac{\partial \vec{E}}{\partial t} \quad (1)$$

$$\vec{\nabla} \times \vec{E} = -\mu_0 \frac{\partial \vec{H}}{\partial t} \quad (2)$$

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho_e + \rho_i}{\epsilon_0}, \vec{\nabla} \cdot \vec{H} = 0 \quad (3)$$

where $\rho_e = -n_e e$ is the charge density of plasma electrons, $\rho_i = Zen_{0i}$ is the charge density of plasma ions, $\vec{v}_e$ is the velocity of electrons, Z is the ion charge state, e is the elementary charge, n_e is the total density of plasma electrons, and n_{0i} is the equilibrium density of plasma ions.

In the derivation of the magnetoionic equation, with wave propagation along the x-axis, the static magnetic field is decomposed into longitudinal H_L (along the propagation) and transverse H_T components. No generality is lost by taking H_T along the y-axis. For a plane wave propagation along the x-axis with no variations in the y- and z-directions, Maxwell's equations in component form read the following:

$$0 = -\mu_0 \frac{\partial H_x}{\partial t} \quad (4)$$

$$-\frac{\partial E_z}{\partial x} = -\mu_0 \frac{\partial H_y}{\partial t} \quad (5)$$

$$\frac{\partial E_y}{\partial x} = -\mu_0 \frac{\partial H_z}{\partial t} \quad (6)$$

$$0 = \epsilon_0 \frac{\partial E_x}{\partial t} + \rho_e v_x \quad (7)$$

$$-\frac{\partial H_z}{\partial x} = \epsilon_0 \frac{\partial E_y}{\partial t} + \rho_e v_y \quad (8)$$

$$\frac{\partial H_y}{\partial x} = \epsilon_0 \frac{\partial E_z}{\partial t} + \rho_e v_z. \quad (9)$$

Now, we find a relation between the velocity components, the electromagnetic field components, and the static magnetic field. We assume that the radiation pressure force is small so that the effect (force) of the time-varying magnetic field of the electromagnetic wave is negligible. Furthermore, we assume no initial electron drift motion and that the ions are a neutralizing background with the quasi-neutrality $n_{0i} = Zn_{0e}$ satisfied. With $n_e = n_{0e} + n_{1e}(x, t)$ and $\vec{v}_e = \vec{v}$, the components of the linearized force equation of the electron fluid become

$$m\frac{dv_x}{dt} = -eE_x - m\nu v_x - \frac{\gamma_e k_B T_e}{n_{0e}} \frac{\partial n_{1e}}{\partial x} + e\mu_0 H_T v_z \quad (10)$$

$$m\frac{dv_y}{dt} = -eE_y - m\nu v_y - \mu_0 H_L v_z \quad (11)$$

$$m\frac{dv_z}{dt} = -eE_z - n_{0e} m\nu v_z + \mu_0 H_L v_y - e\mu_0 H_T v_x \quad (12)$$

where nu represents the collisional frequency.

For a sinusoidal time variation, we assume that the field and velocity components are varying like $e^{i\omega t - Kx}$, where K is the complex propagation constant given by $K = K_r + iK_i$. Also, assume that $dK/dx \approx 0$, which is equivalent to the assumption that the medium is a homogeneous one over few wavelengths. From (3), the perturbed electron density in terms of the longitudinal electric field E_x becomes $n_{1e} = \epsilon_0 K\ E_x/e$. In addition, from (4), we see that there will be no forward wave magnetic field, namely, $H_x = 0$. Therefore, the electromagnetic mode under consideration is transverse magnetic in nature. Equations (5)–(12) form a closed system of eight equations with eight unknowns, namely, five electromagnetic field components and three velocity components.

From (7) and (10), we obtain the following wave equations for the forward electric field component E_x:

$$v_x = \frac{\epsilon_0}{en_{0e}} \frac{\partial E_x}{\partial t} \quad (13)$$

$$\left(\frac{\partial^2}{\partial t^2} + \omega_{\text{pe}}^2 + \nu\frac{\partial}{\partial t} - v_{\text{th}}^2 \frac{\partial^2}{\partial x^2}\right) E_x = \omega_{\text{pe}}^2\, \mu_0 H_T v_z \quad (14)$$

where the electron plasma frequency $\omega_{\text{pe}} = \sqrt{e^2 n_{0e}/\epsilon_0 m_e}$ and the electron thermal speed $v_{\text{th}} = \sqrt{\gamma_e k_B T_e/m_e}$ have been introduced. Substituting for v_x from (13), (12) becomes

$$m\frac{dv_z}{dt} = -eE_z - m\nu v_z + e\mu_0 H_L v_y - \frac{\mu_0\epsilon_0 H_T}{n_{0e}} \frac{\partial E_x}{\partial t}. \quad (15)$$

The wave equations for the transverse electromagnetic field components are obtained from (5), (6), (8), and (9)

$$\left(\frac{\partial^2}{\partial x^2} - \mu_0\epsilon_0 \frac{\partial^2}{\partial t^2}\right) E_y = -en_{0e}\mu_0 \frac{\partial v_y}{\partial t} \quad (16)$$

$$\left(\frac{\partial^2}{\partial x^2} - \mu_0\epsilon_0 \frac{\partial^2}{\partial t^2}\right) E_z = -en_{0e}\mu_0 \frac{\partial v_z}{\partial t} \quad (17)$$

$$\left(\frac{\partial^2}{\partial x^2} - \mu_0\epsilon_0 \frac{\partial^2}{\partial t^2}\right) H_y = -en_{0e} \frac{\partial v_z}{\partial x} \quad (18)$$

$$\left(\frac{\partial^2}{\partial x^2} - \mu_0\epsilon_0 \frac{\partial^2}{\partial t^2}\right) H_z = en_{0e} \frac{\partial v_y}{\partial x}. \quad (19)$$

Setting $\partial/\partial t \to i\omega$ and $\partial/\partial x \to -K$ in (11) and (14)–(19), eliminating the electric field components in terms of velocity components and rearranging the results yields the following algebraic system of equations:

$$\left[\omega^2 - i\nu\omega - \frac{\omega_{\rm pe}^2}{1+\frac{K^2c^2}{\omega^2}}\right]\upsilon_y - i\,\frac{\omega_{\rm pe}^2\omega H_L}{en_{0e}c^2}\,\upsilon_z = 0 \quad (20)$$

$$\Bigg[\omega^2 - i\nu\omega - \frac{\omega_{\rm pe}^2}{1+\frac{K^2c^2}{\omega^2}} + \frac{\omega_{\rm pe}^2\left(\frac{\omega H_T}{en_{0e}c^2}\right)^2}{1-\frac{\omega^2}{\omega_{\rm pe}^2}}$$
$$+ i\,\frac{\nu\omega}{\omega_{\rm pe}^2} - \lambda_{\rm De}^2K^2\Bigg]\upsilon_z + i\,\frac{\omega_{\rm pe}^2\omega H_L}{en_{0e}c^2}\,\upsilon_y = 0 \quad (21)$$

where $\lambda_{\rm De} = \upsilon_{\rm th}/\omega_{\rm pe}$ and $c = \sqrt{1/\mu_0\epsilon_0}$ have been introduced. Rewriting (20) and (21) in terms of the dimensionless parameters $n = Kc/\omega$, $A = -\omega^2/\omega_{\rm pe}^2$, $B = \omega\nu/\omega_{\rm pe}^2$, $D_T = \omega H_T/en_{0e}c^2$, $D_L = \omega H_L/en_{0e}c^2$, and noting that $\lambda_{\rm De}^2K^2 = (\upsilon_{\rm th}^2/\omega_{\rm pe}^2)\,K^2 = (\upsilon_{\rm th}^2/c^2)\,(\omega^2/\omega_{\rm pe}^2)\,(K^2c^2/\omega^2) \equiv -\beta_{\rm th}^2 A\,n^2$ with $\beta_{\rm th} = \upsilon_{\rm th}/c$ being the normalized electron thermal speed, we arrive at the following final form of the system of equations:

$$\left[A + iB + \frac{1}{1+n^2}\right]\upsilon_y + i\;D_L\;\upsilon_z = 0 \quad (22)$$

$$\left[A + iB + \frac{1}{1+n^2} - \frac{D_T^2}{1+A+iB+\beta_{\rm th}^2An^2}\right]\upsilon_z - iD_L\upsilon_y = 0. \quad (23)$$

The system of the two (22) and (23) has a nontrivial solution when the determinant of the coefficients of υ_y and υ_z vanishes identically

$$\begin{vmatrix} \alpha_1 & iD_L \\ -iD_L & \alpha_2 \end{vmatrix} = \alpha_1\alpha_2 - D_L^2 = 0 \quad (24)$$

where

$$\alpha_1 = A + iB + \frac{1}{1+n^2}$$
$$\alpha_2 = \alpha_1 - \frac{D_T^2}{1+A+iB+\beta_{\rm th}^2An^2}.$$

In the next section, (24) will be solved numerically to study the effect of the plasma temperature on the complex propagation/damping coefficient K. For cold plasma where $\upsilon_{\rm th} = 0$, the solution of (24) for the complex index of refraction is given by

$$-n^2 = -\frac{K^2}{\mu_0\epsilon_0\omega^2} = 1 + \gamma \quad (25)$$

where

$$\gamma = \frac{1}{A + iB - \frac{D_T^2}{2(1+A+iB)} \pm \sqrt{\frac{D_T^4}{4(1+A+iB)^2} + D_L^2}}.$$

Equation (25), known as the classical magnetoionic equation, was first derived in [20] and independently in [21] and [26]. This equation with plus minus sign show that the medium supports two characteristic modes, also, the propagation constant K can take two values and therefore, an incident wave will split into two wave components with different phase velocities, polarization, and absorption. These waves are usually assigned as ordinary and extraordinary waves. For propagation normal to the magnetic field, the plus sign represents the ordinary mode and the minus sign represents the extraordinary mode.

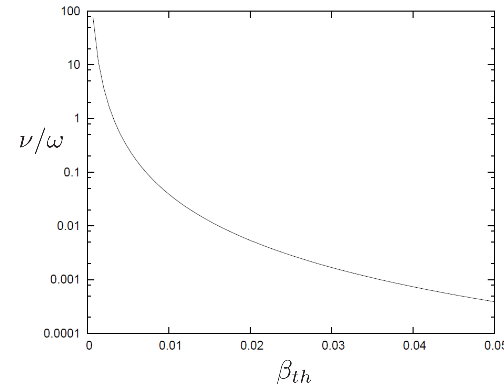

Fig. 1. Normalized collisional frequency (ν/ω) versus $\beta_{\rm th}$. Parameters are $\omega/2\pi = 4 \times 10^9$ Hz and $\omega_{\rm pe}/2\pi = 1.8 \times 10^9$ Hz.

III. Numerical Example

In this section, we solve (24) for the complex index of refraction and the corresponding complex propagation constant in warm plasma. The real and imaginary parts of K will be plotted versus $\beta_{\rm th} = \upsilon_{\rm th}/c$, the normalized electron thermal speed, and then compared with the propagation constant of cold plasma obtained from (25).

Without losing generality, and for demonstrating the importance of including the plasma thermal effect, a numerical example of the solution of (24) will be given in the following for the wave mode frequency $f_{\rm wave} = \omega/2\pi = 4 \times 10^9$ Hz, electron plasma frequency $f_{\rm plasma} = \omega_{\rm pe}/2\pi = 1.8 \times 10^9$ Hz, electron cyclotron frequency $\omega_{\rm ce} = 0.1\omega$, and a propagation angle of $\theta = \pi/2$. The effective plasma collision frequency ν is a sensitive parameter to the plasma temperature. We use the following formula to obtain the effective plasma collision frequency [29]:

$$\nu = 2.91 \times 10^{-6} n_e T_e^{-3/2} ln(\Lambda) \quad (26)$$

where the Coulomb logarithm is given by $ln(\Lambda) \approx 6.6 - 0.5ln(n_e) + 1.5ln(T_e)$. ν versus $\beta_{\rm th}$ is shown in Fig. 1, which shows the sensitivity of ν on the temperature.

From the second paragraph of Section I, positive values of K_r correspond to attenuation due to collisions, whereas negative K_r values mean amplification. In addition, positive values of K_i (with the wave phase given by $\omega t - K_i x$) correspond to outgoing (forward propagating) waves (with either attenuation or amplification depending on the sign of K_r), whereas negative K_i means incoming (backward propagating) waves. In our case, incoming waves with negative phase velocities represent unphysical solutions in a region of space of infinite extent and, hence, ignored. We will be concentrating on numerical solutions of (24) with positive K_i only.

For the parameters given in the above paragraph, in the cold plasma limit $\beta_{\rm th} = 0$, two of the four complex roots of (25) found numerically correspond to outgoing waves (have positive K_i values); $K = (K_r, K_i)$ takes the values $(1.43 \times 10^{-3}, 9.21)$ and $(-7.09 \times 10^{-3}, 9.19)$ m^{-1}. The negative of these roots are also roots of (25) (not the complex conjugates). The latter are unphysical roots for the reason mentioned earlier. The magnitudes of K_r or K_i resulting from the four numerical

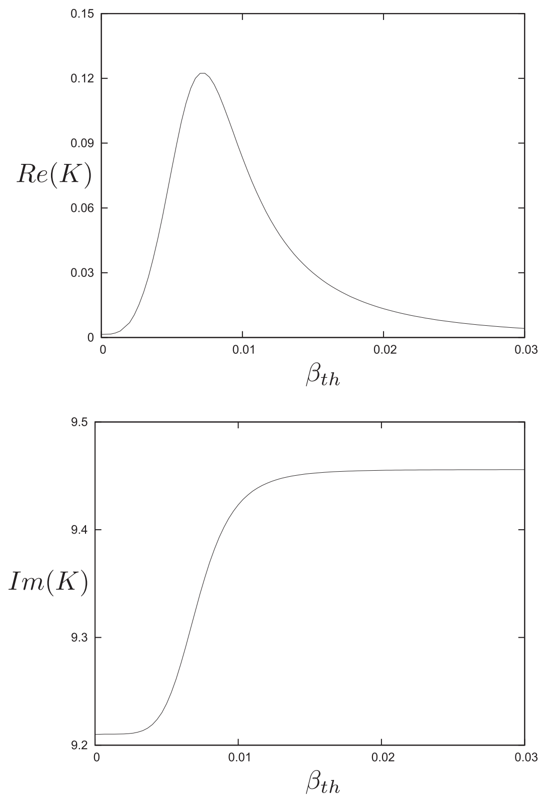

Fig. 2. Root (I): Upper and lower curves represent the real and imaginary parts of root 1 of K versus β_{th}. Parameters are $\omega/2\pi = 4 \times 10^9$ Hz, $\omega_{\text{ce}} = 0.1\omega$, $\omega_{\text{pe}}/2\pi = 1.8 \times 10^9$ Hz and $\theta = \pi/4$.

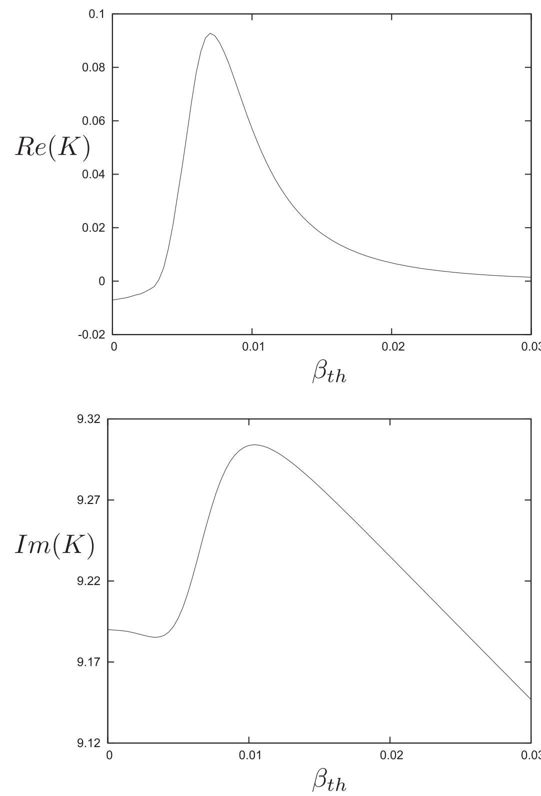

Fig. 3. Root (II): Upper and lower curves represent the real and imaginary parts of root 1 of K versus β_{th}. Parameters are $\omega/2\pi = 4 \times 10^9$ Hz, $\omega_{\text{ce}} = 0.1\omega$, $\omega_{\text{pe}}/2\pi = 1.8 \times 10^9$ Hz and $\theta = \pi/4$.

roots are nearly equal, as they should be analytically. The small values of K_r mean that these modes have weak attenuation or amplification in cold plasma. We will call the attenuated mode root (I) (with $K = (1.43 \times 10^{-3}, 9.21)$ for $\beta_{\text{th}} = 0$) and the amplified mode will be called root (II) (with $K = (-7.09 \times 10^{-3}, 9.19)$ at $\beta_{\text{th}} = 0$).

From the numerical solution of (24) for the plasma parameters mentioned earlier, we will be following up the two roots for the forward propagating mode to see the thermal impact on these two roots with positive K_i values. These two roots are shown in Figs. 2 and 3. The other two roots are the negative of these three. Fig. 1 shows the dependence of the real and imaginary parts of root (I) of K on the normalized electron thermal speed v_{th}/c. As shown in this figure, the mode attenuation is strongly enhanced by the increase in the plasma temperature within the range of $\beta_{\text{th}} \approx (0, 0.02)$ with a peak near the middle of the interval; while the mode in the cold plasma limit $\beta_{\text{th}} \to 0$ is weakly attenuated (with $K_r \to 1.42 \times 10^{-3}\ \text{m}^{-1}$), the attenuation constant reaches a maximum of $K_r \approx 0.012\ \text{m}^{-1}$ at $\beta_{\text{th}} \approx 0.0075c$. Fig. 2 shows the dependence of the real and imaginary parts of root (II) of K on the normalized electron thermal speed v_{th}/c. As shown in this figure, in the cold plasma limit, the mode amplification is negligible ($K_r \to -7.09 \times 10^{-3}\ \text{m}^{-1}$). By increasing the plasma temperature, the mode amplification dies out till we reach the stability point ($K_r \to 0$) at $\beta_{\text{th}} \approx 0.003$ beyond which the mode becomes a damped one with a peak point in the damping rate of $K_r \approx 0.09$ at around $\beta_{\text{th}} \approx 0.0075c$.

IV. Conclusion

The application of the magnetoionic theory to different phenomena, particularly to the ionosphere, was and is still an important issue for the characterization of wave propagation and attenuation in both natural and man-made phenomena. This paper represents a further development for this theory by the theoretical investigation of electromagnetic waves in warm plasma and numerical solution of the resulting dispersion relation of the complex index of refraction.

In this paper, we presented the derivation of a modified formula for the complex index of refraction and the corresponding complex propagation constant for wave propagation in warm plasma immersed in a uniform magnetic field. The impact of the thermal effect on the attenuation or amplification of the possible wave modes has been investigated through a numerical example for wave propagation in warm, collisional, and magnetized plasma for a wave mode with a frequency above the electron plasma frequency. The four complex roots equation (25) has two physical roots for a forward propagating wave with positive K_i values: one is weakly attenuated and the other is weakly amplified. The numerical solution of the warm plasma equation, namely (24), however, explains the thermal impact on wave propagation. By comparing the cold plasma wave propagation constant of the Appleton–Hartree theory with the results obtained from the case of warm plasma, we observe that the weakly attenuated mode is strongly enhanced by increasing the temperature while the amplification of the second mode is suppressed by the thermal effect. The latter mode becomes attenuated beyond a certain temperature. The real values of the propagation constant (K_r) of Figs. 2 and 3 peak around a point that may represent a minimum of the denominator of γ that is given in (25).

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