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Resonant transmission of electromagnetic waves in one-dimensional multilayer plasmas having graded optical thickness

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ABSTRACT

Electromagnetic wave transmission through one dimensional multilayer plasmas, consisting of air and plasma, and having graded optical thickness is analyzed for under dense plasma ($\omega > \omega_p$) and over-dense plasma ($\omega < \omega_p$). Transmittivity of such a structure is found by solving wave equations and matching the electric field and its derivatives at the boundaries. It is observed that gradation in the thickness of either air or plasma or both simultaneously; leads to increase in the number of resonant frequency for under dense and over dense plasma. Respective resonant frequency is found to be shifted towards higher and lower frequency for over dense and under dense plasma for the gradation in the thickness of constituent materials. It is also found that by proper choice of gradation parameters, transmission of electromagnetic waves through such multilayer structure can be controlled and tuned to a particular frequency regime.

1. Introduction

Interaction of electromagnetic (EM) waves with plasma is important subject matter in the realm of plasma physics and it has been explored for years in numerous fields; such as fusion plasma, laser produced plasma, ionospheres, and plasma materials processing reactors, etc. When EM waves are incident onto the plasma slab, depending upon its angular frequency in free space, it is attenuated or gets transmitted through plasma slab. EM waves with angular frequency smaller than plasma frequency are attenuated while EM waves having higher frequency than plasma frequency get transmitted. However, it is also possible to have reflection less transmission, which is also known as resonant transmission, under when certain conditions are satisfied. This is known as Fabry–Perot resonance [1]. This It can be realized in a single under dense plasma slab whereas for over dense or critical plasma slab; it is not possible to have reflection less transmission. However, it is shown by Hojo et al. [2] that reflection less transmission of EM waves can occur from multilayer of plasmas even for over dense or critical case.

Recently, some researchers have shown that there is enhancement in the reflection [3–5], transmission [6,7] and band width [8] due to chirping of structures or by gradation in geometrical thickness of constituent materials of multilayer. Some researcher has used chirped structure for optical communication [9], dispersion control [10]. Liu et al. has studied the effect of gradation in geometrical thickness on phase shift defect modes [11].

The above mentioned studies show that properties of one dimensional multilayer structure can be controlled by gradation in geometrical thickness of constituent materials of multilayer. The optical thickness is a multiplication of geometrical thickness with refractive index, therefore any gradation in geometrical thickness can be considered as gradation in optical thickness. Hence, in present study, we have investigated the effect of gradation in optical thickness on the resonant transmission of EM waves in multilayer structure. The paper is organized as follow: in Section 2, the expression of transmittivity of the proposed structure is given. Section 3 is devoted to results and discussion. A conclusion is drawn in Section 4.

2. Theoretical formulation

The proposed one dimensional multilayer plasma consists of three layers of plasma and two layers of air with different thickness, as shown in Fig. 1. An EM wave of angular frequency ω is incident normally onto multilayer plasma. Each plasma layer has plasma frequency ω_p with different geometrical thickness. We solve one dimensional Maxwell wave equation in each constituent layer of this multilayer. We can write one dimensional Maxwell wave equation assuming exp $(-i\omega t)$, as follow for under dense plasma $(\omega > \omega_p)$:

$$\left(\frac{d^2}{dz^2} + \frac{\omega^2 - \omega_p^2}{c^2}\right) E(z) = 0 \quad (1)$$

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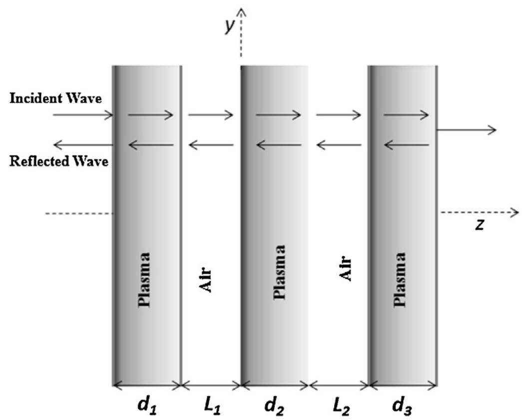

Fig. 1. Schematic diagram of one dimensional multilayer plasmas consisting of plasma and air.

ω_p is the plasma frequency and is given by $\omega_p = \sqrt{e^2 n_p/\varepsilon_0 m}$, n_p is density of plasma. Similarly, we can write wave equation in air region also.

The plasma density is given in each region of multilayer is as follows:

$$n_p(z) = \begin{cases} 0 & z < 0 \\ n & 0 < z < d_1 \\ 0 & d_1 < z < d_1 + L_1 \\ n & d_1 + L_1 < z < d_1 + d_2 + L_1 \\ 0 & d_1 + d_2 + L_1 < z < d_1 + d_2 + L_1 + L_2 \\ n & d_1 + d_2 + L_1 + L_2 < z < d_1 + d_2 + d_3 + L_1 + L_2 \\ 0 & z > d_1 + d_2 + d_3 + L_1 + L_2 \end{cases} \quad (2)$$

The obtain solution of above equation in plasma as well air region are as follows:

$$E = \begin{cases} A_1 e^{ik_1 z} + B_1 e^{-ik_1 z}, z < 0 \\ A_2 e^{ik_{p1} z} + B_2 e^{-ik_{p1} z}, 0 < z < d_1 \\ A_3 e^{ik_2 z} + B_3 e^{-ik_2 z}, d_1 < z < d_1 + L_1 \\ A_4 e^{ik_{p2} z} + B_4 e^{-ik_{p2} z}, d_1 + L_1 < z < d_1 + d_2 + L_1 \\ A_5 e^{ik_3 z} + B_5 e^{-ik_3 z}, d_1 + d_2 + L_1 < z < d_1 + d_2 + L_1 + L_2 \\ A_6 e^{ik_{p3} z} + B_6 e^{-ik_{p3} z}, d_1 + d_2 + L_1 + L_2 < z < d_1 + d_2 + d_3 + L_1 + L_2 \\ A_7 e^{ik_4 z}, z > d_1 + d_2 + d_3 + L_1 + L_2 \end{cases} \quad (3)$$

where $k_i = \omega/c$, $i = 1, 2, 3, \ldots$ and $k_{pi} = \sqrt{\left(\omega^2 - {\omega_{pi}}^2\right)/c^2}$ Here A_1 is incident wave amplitude and A_7 is transmitted wave amplitude. Other coefficient $A_2, B_2 \ldots A_6, B_6$ is determined by using continuity condition of E and its derivative, $\left(\mathrm{d}E/\mathrm{d}z\right)$ transmittivity of the considered multilayered structure is given by:

$$T = \left|\frac{A_7}{A_1}\right|^2 \quad (4)$$

Similar exercise can also be done to obtain the transmittivity of the present multilayered structure for over dense plasma.

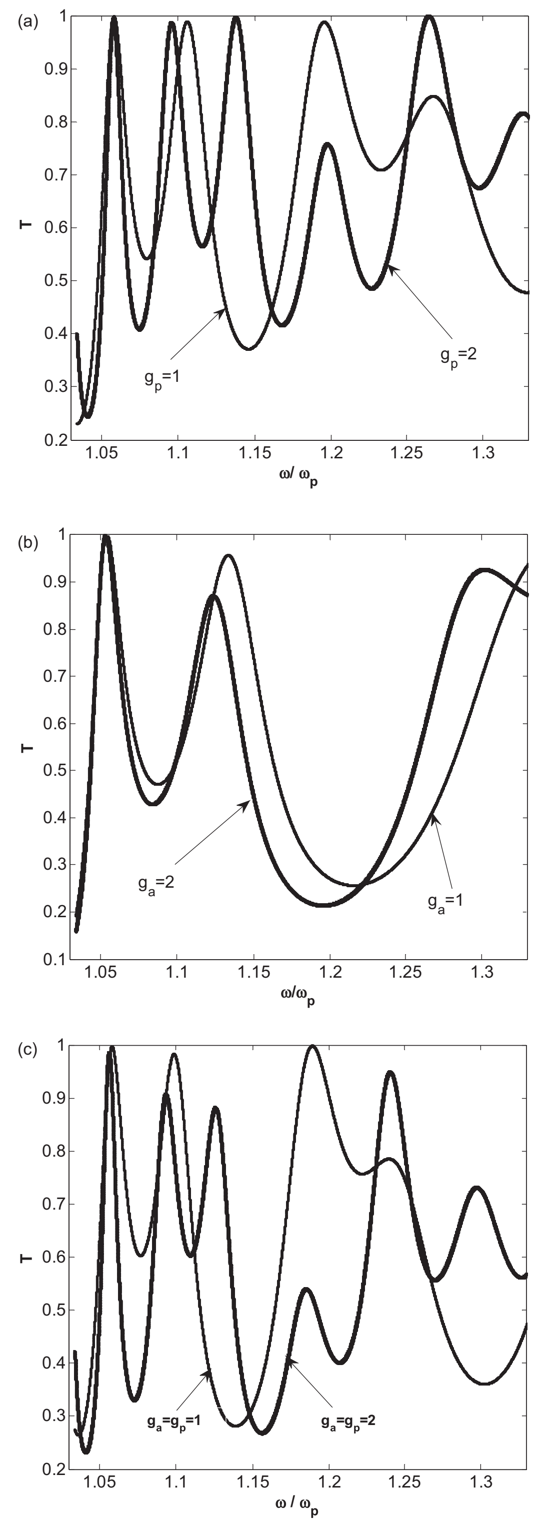

Fig. 2. (a) Transmittivity of multilayer plasma when there is gradation in the thickness of plasma for under dense case. (b) Transmittivity of multilayer plasma when there is gradation in the thickness of air for under dense case. (c) Transmittivity of multilayer plasma when there is gradation in the thickness of plasma and air for under dense case.

3. Results and discussion

We have computed the transmittivity of one dimensional multilayer plasmas having plasma and air with graded optical thickness for underdense and overdense plasma. Here, we have taken multilayer structure consisting of three layers of plasma and two layers of air and this multilayer structure is kept in air. The chosen thickness of each plasma layer (d_0) and air (L_0) without gradation is $d_0 = L_0 = 1000\ \mu$m and plasma frequency is 9.0×10^{11} Hz. It is assumed that plasma is nonmagnetic and homogeneous.