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Interaction between electromagnetic wave and magnetized plasma slab with linearly varying electron density with metallic substrate

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Abstract

In this article, a simple method is investigated to calculate the reflection coefficients for magnetized plasma by considering electron density profile with positive and negative slopes on the basis of the transmission matrix. Interaction between electromagnetic waves and magnetized plasmas with linearly varying electron density with metallic substrate is analyzed. In the numerical analysis, the plasma layer is divided into sufficiently thin, adjacent sub-slabs. The result shows that the structure has properties of electromagnetic absorption and frequency selective by adjusting the relative parameters.

Keywords: Absorption; electron density; EM reflection; frequency selective; magnetized plasma.

1. Introduction

The subject of interaction between electromagnetic waves and plasma, particularly numerical analysis of reflection, absorption, and transmission of electromagnetic waves in unmagnetized, magnetized, nonuniform, and uniform plasma, have taken considerable interest in literature (Ginzburg, 1970; Vidmar, 1990; Laroussi & Roth, 1993; Shi *et al.*, 2001; Laroussi, M, 1995; Haifeng *et al.*, 2003; Bin & Wang, 2005; Catarinucci *et al.*, 2006; Jin *et al.*, 2006; Soliman *et al.*, 2007; Zhang & Liu, 2007; Zobdeh *et al.*, 2008; Gurel & Oncu, 2009a; Ma *et al.*, 2010a; Ma *et al.*, 2010b). In the analysis of plasma-wave interaction in literature, scattering matrix method (Bin & Wang, 2005; Gurel & Oncu, 2009b) and direct formulation (Jin *et al.*, 2006) have been used. It has been found that inhomogenous plasma behaves as frequency selective medium and can be used as a broadband radar absorbing layer in general shielding and military stealth applications, radio communications and radio astronomy (Vidmar, 1990). In addition, the plasma which has different electron number density functions are considered such as exponential, parabolic, hyperbolic, tangent, sinusoidal, stepped and exponential with time variation.

In this paper, interaction between electromagnetic waves and magnetized plasmas with linearly varying electron density with metallic substrate is analyzed first. In order to simplify the solution, total plasma layer is first divided into very thin homogenous subslabs in each of which plasma properties are constant. Based on the transmission matrix, a simple method is proposed to describe the propagation of electromagnetic waves in the proposed plasma slab and the reflection and absorption coefficients of such plasma for right-hand circularly waves are accurately obtained by taking multiple reflections effect into account.

2. Structure of the proposed plasma slab

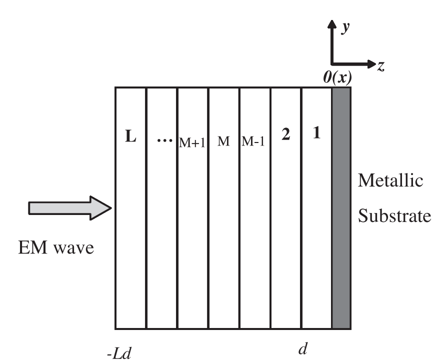

Fig. 1. Multi-layered structure of plasma

In the paper, plasma is cold, weakly ionized, steady-state, collisional and having electron density profile with a metallic substrate. The electron number density varies linearly with positive and negative slopes respectively. The wave is assumed normally incident into the plasma slab.

Background magnetic field is uniform and parallel to the propagation direction. In the analysis, inhomogeneous plasma is divided into sufficiently thin, adjacent equi-width sublayers, as shown in Figure 1. In each sublayer, plasma parameters are taken as constant. Thickness of the sublayer is *d* and *L* is the total number of sublayers.

At first, we consider plasma permittivity. As per **(**Ginzburg, (1970**)** for the magnetized plasma, in the case of normally incident electromagnetic wave propagating along the external magnetic field, plasma permittivity can be given by

$$\tilde{\varepsilon}_r = 1 - \frac{(\omega_p/\omega)^2}{1 \pm j\frac{\upsilon_{en}}{\omega} - \frac{\omega_{ce}}{\omega}} \tag{1}$$

Where ω is the microwave frequency, υ_{en} is the effective collision frequency between the electron and neutral gas, ω_p is the plasma frequency and, ω_{ce} is the electron-cyclotron frequency. The ± sign indicates the left- and right-hand polarization wave. In the study, we assume that the wave is right-hand polarization.

ω_p and ω_{ce} can be given by

$$\omega_p{}^2 = e^2\frac{N}{m\varepsilon_0} \tag{2}$$

$$\omega_{ce} = \frac{|e|B}{m} \tag{3}$$

Where *e* is the charge of an electron, the value is -1.6×10^{-19}C, *N* is electron number density, *m* is the mass of an electron, ε_0 is the permittivity in free space and *B* is the magnetic field strength.

Let us assume that the maximum electron number density value is N_m, and electron number density is linearly varying with positive or negative slopes along $+z(-Ld<z<0)$ direction, the electron number density *N* can be given by

$$N(z) = \{ \begin{matrix} N_m(-Ld+z)/(-Ld),(Positive-Slope) \\ N_m z/(-Ld),(Negetive-Slope) \end{matrix} \tag{4}$$

3. Electromagnetic wave reflectance for the multi-layered structure

The multi-layered structure with a metallic substrate is depicted in Figure 2. The angle of incidence is θ_i. The thickness of slab is *d*. Let us denote that the transverse field on the boundary with free space and first slab are E_0 and H_0 and the transverse field on the boundary with the last slab and the slab at the front of it are E_n and H_n.

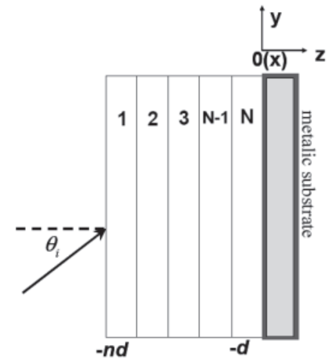

Fig. 2. The planar wave oblique incident on multilayered structure

As per Liu, (2001) and Berreman, (1972) the transmission matrix of the proposed structure, which consists of many slabs can be given by

$$\mathbf{M} = \mathbf{M_1}\times\mathbf{M_2}\times\mathbf{M_3}\cdots\times\mathbf{M_N} = \begin{pmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{pmatrix} \tag{5}$$

M_N is the transmission matrixes of slab, that can be described as,

$$\mathbf{M}_N = \begin{pmatrix} \cos(k_0 n_N d_N \cos\theta_N) & -\frac{j}{p_1}\sin(k_0 n_N d_N \cos\theta_N) \\ -jp_N\sin(k_0 n_N d_N \cos\theta_N) & \cos(k_0 n_N d_N \cos\theta_N) \end{pmatrix} \tag{6}$$

where $p_N = \sqrt{\frac{\varepsilon_N}{\mu_N}}\cos\theta_N, n_N = \sqrt{\varepsilon_N\mu_N}$

and

The E_n and H_n can be related with E_0 and H_0 by (8),

$$\begin{bmatrix} E_0 \\ H_0 \end{bmatrix} = \begin{bmatrix} m_{11} & m_{12} \\ m_{21} & m_{22} \end{bmatrix}\begin{bmatrix} E_n \\ H_n \end{bmatrix} \tag{7}$$

The incident angle and transmitted angle on the boundary with the last slab and the slab at the front of it are θ_{in} and θ_{tn},

$$\theta_{in} = \arcsin(\sin\theta_i / n_{N-1}) \tag{8}$$

$$\theta_{tn} = \arcsin(\sin\theta_i / n_N) \tag{9}$$

Where n_{N-1} and n_N are refractive index.

The transverse field in last slab can be described as

$$\begin{aligned} E_N &= E_N{}^+\exp(p) + E_N{}^-\exp(-p) \\ H_N &= (E_N{}^+\exp(p) - E_N{}^-\exp(-p))\times(-\sqrt{\frac{\varepsilon_r}{\mu_r}}) \end{aligned} \tag{10}$$

Where $p = jkz/\cos\theta_m$, $E_N{}^+$ is magnitude of incident wave and $E_N{}^-$ is magnitude of reflected wave in last slab.

at z = -d, we have

$$E_n = E_N^{+}\exp(q) + E_N^{-}\exp(-q)$$
$$H_n = (E_N^{+}\exp(q) - E_N^{-}\exp(-q)) \times \left(-\sqrt{\frac{\varepsilon_r \times \varepsilon_0}{\mu_r \times \mu_0}}\right) \tag{11}$$

Where $q = jk(-d)/\cos\theta_{tn}$

at z = 0, we have

$$E_N^{+} = -E_N^{-} \tag{12}$$

at z =-nd, we have

$$E_0 = E_0^{+} + E_0^{-}$$
$$H_0 = (E_0^{+} - E_0^{-}) \times \sqrt{\frac{\varepsilon_0}{\mu_0}} \tag{13}$$

Where E_0^+ and E_0^- are altitude of incident wave and reflected wave in free space.

We can achieve through (10), (11), (12), (13),

$$E_0^{+} + E_0^{-} = m_{11}E_n + m_{12}H_n \tag{14}$$

$$E_0^{+} - E_0^{-} = (m_{21}E_n + m_{22}H_n) \times \sqrt{\frac{\varepsilon_0}{\mu_0}} \tag{15}$$

Let us denote R is reflectance, and

$$R = \frac{\left|E_0^{-}\right|}{\left|E_0^{+}\right|} \tag{16}$$

The reflction is given by (14) and (15),

$$R = \frac{(16)-(17)}{(16)+(17)} \tag{17}$$

4. Result of numerical analysis and discussion

In this section, total plasma thickness is taken as Ld=20cm. At first, the plasma slab is assumed to have linearly increasing electron density profile and N_m=1×10^{18}/m^3 at z=0.

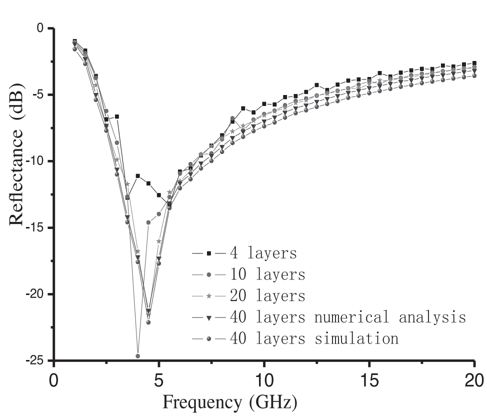

Fig. 3. The reflectance of the plasma which is divided into different layers

First, the appropriate number of layers should be determined. We denote L= 4,10,20,40 respectively, B=0.5T, υ_{en}=10GHz, N_m=1×10^{18}/m^3, the EM wave frequency is from 2 to 20 GHz. Figure 3 shows the calculated EM wave reflectance for different number of sublayers by using the proposed analytical method. From Figure 3 we can see that variation of numerical reflectance curves is having very distinct difference, when L is 4, 10 and 20 respectively. However, the numerical reflectance curves look very similar when L is 20 and 40 respectively. The result shows that variation of permittivity of plasma along +z direction should approximate to the facts, if L is bigger than 20. By using full-wave simulation based on the finite element method (HFSS), we analyze the proposed model (L=40) and validate the proposed analytical methods in respect of accuracy, as shown in Figure 3.

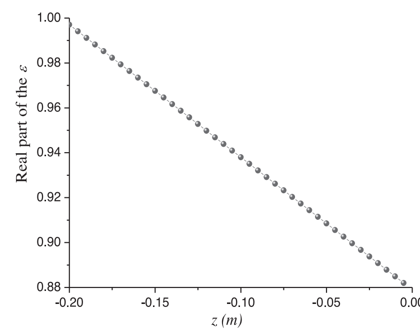

Fig. 4. The real part of ε with different thickness of plasma (f =20GHz)

In addition, we calculate the real of permittivity of each sublayer of the proposed model (L=40) at 20GHz, as shown in Figure 4. Figure 4 shows that the real of permittivity curve is linearly varying and the values are all smaller than 1. Thickness of each sublayer is smaller than the wavelength in the plasma slab at 20GHz. Another important point in Figure 4 is that, it provides good matching between the EM wave and the plasma, by means of the slowly increasing electron density value along the direction of propagation. Finally, we select L=40.

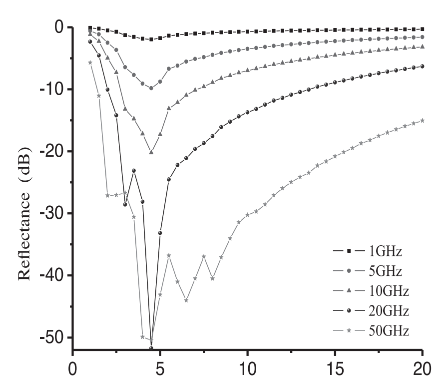

Fig. 5. The reflectance for different υ_{en}

In Figure 5, the reflectance variation for different υ_{en} is shown when B=0.5T and N_m=1×10^18/m^3. As the υ_{en} increases, the absorption capability is improved and absorption band gets wider.

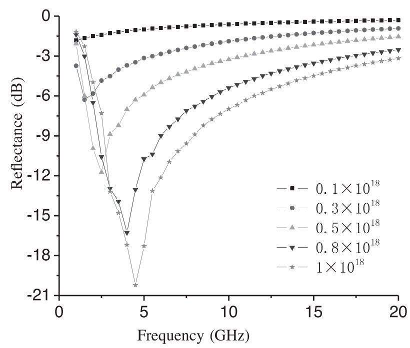

Fig. 6. The reflectance with different N_m

Then, the reflectance variation for different N_m is shown in Figure 6. N_m is from $1\times10^{17}/m^3$ to $1\times10^{18}/m^3$. Figure 7 indicates that it is required to increase electron number density along the plasma layer, while collision frequency is low value, in order to improve absorption capability.

According to Figure 5 and Figure 6, the plasma slab, which has high electron density and high collision frequency can obtain excellent absorption capability along wide frequency range. But such a case is not easy to achieve (Balanis, 1989).

Next, plasma slab is assumed to have linearly decreasing electron density profile and $N_m=1\times10^{18}/m^3$ at z=-20cm.

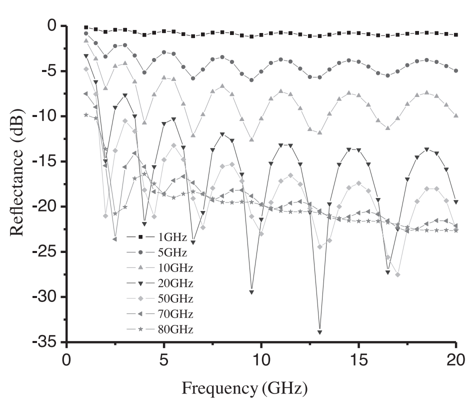

Fig. 7. The reflectance for different υ_{en}

Figure 7 shows the calculated reflectance for different υ_{en} when B=0.5T and $N_m=1\times10^{18}/m^3$ at z=-20cm. From Figure 8 we can see that absorption capability improves as collision frequency increase is accompanied with wider absorption band and many absorption peaks are observed, when υ_{en} is 20GHz especially. In this case plasma slab behaves as a reflective band-pass filter by adjusting the relative parameters, as shown in Figure 8.

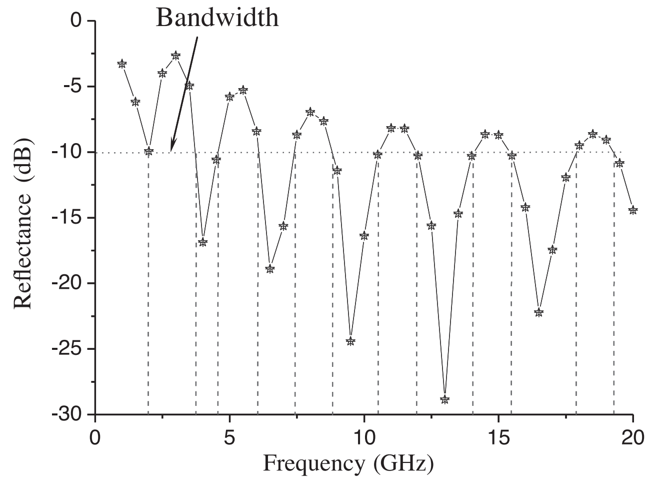

Fig. 8. The reflective band-pass filter when B=1.5T, $N_m=0.7\times10^{18}/m^3$ at z=-20cm, υ_{en}=20GHz

In Figure 8, there are many useable ranges of bandwidths for the reflective band-pass filter from 2GHz to 20GHz when B=1.5T, $N_m=0.7\times10^{18}/m^3$ at z=-20cm and υ_{en}=20GHz. According to the property, the plasma slab can be used to make frequency selective device.

In the last part of the paper, linearly increasing and decreasing profiles are compared in terms of reflection characteristics between Figure 5, 6 and Figure 7, 8. It is shown that linearly increasing profile shows better absorption capability due to good matching between the EM wave and the plasma, while linearly decreasing profile exhibit frequency selective characteristic.

5. Conclusion

Interaction between electromagnetic waves and magnetized plasmas with linearly varying electron density with a metallic substrate is first analyzed on the basis of the transmission matrix. The results of numerical analysis show that the proposed plasma has properties of electromagnetic absorption and are frequency selective when adjusting the relative parameters, such as effective collision frequency, maximum electron density, plasma frequency and external magnetic field.

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التفاعل بين الموجات الكهرومغناطيسية و الواح البلازمه مع الكثافة المتغيرة خطياً للأكترون مع مركب معدني

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خلاصة

في هذا البحث، طريقة بسيطة تحققت في حساب معامل الانعكاس للبلازما الممغنطة من خلال قياس الكثافة الإيجابية والسلبية للمنحدرات على اساس مصفوفة الانتقال. ويتم تحليل التفاعل بين الموجات الكهرومغناطيسية والبلازما الممغنطة مع اختلاف كثافة الإلكترونات مع الركيزة المعدنية خطيا. في التحليل العددي، تنقسم البلازما سوبسلابس بطبقة رقيقة كافية. والنتيجة تبين أن الهيكل له خصائص امتصاص كهرومغناطيسي وتردد انتقائي عن طريق ضبط المعايير نسبيا.