Optik 123 (2012) 371–375

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Numerical analysis of the reflection and absorption of electromagnetic wave in nonuniform magnetized plasma slab

Hong Wei Yang*, Yan Liu

Department of Physics, Nanjing Agricultural University, Nanjing 210095, People's Republic of China

ARTICLE INFO

Article history:
Received 24 October 2010
Accepted 5 April 2011

Keywords:
Electromagnetic wave
Nonuniform magnetized plasma
Reflection
Absorption

ABSTRACT

In this paper, a model for calculating the reflection and absorption powers of electromagnetic wave (EM wave) in nonuniform magnetized plasma slab is given out based on layer propagation theory. The effects of various plasma parameters and different values of magnetic field intensity on the reflected and absorbed powers are discussed. The results illustrate that the thickness of plasma seldom affects the reflection of radar wave, but it can broaden or reduce the absorption width. Meanwhile, the background magnetic field intensity has an influence upon the results, and it could change the resonance spectrum of magnetized plasma. We also find out that, with appropriate plasma density, collision frequency and magnetic field intensity, more than 90% of radar wave power can be absorbed and the resonant absorption band is about 2 GHz.

1. Introduction

In recent years, people have been interested in using plasma as absorbers or reflectors of EM wave [1,2], because plasmas can attenuate the energy of incident EM wave. There have been numerous investigations of propagation and absorption of EM wave in inhomogeneous plasma. Vidmar has already discussed that the absorption of EM wave depends on incident wave's frequency, plasma density and momentum-transfer collision rate [3]. Laroussi and Roth studied the reflection, absorption and transmission of EM wave by a magnetized nonuniform plasma slab. They give numerical results by using a subslabs model [4]. Based on scattering matrix method, Hu et al. present an analytical technique for obtaining a complete set of reflection and transmission coefficients for a stratified plasma slab, when the EM waves are vertically incident [5]. In letter [6–8], the propagation characteristic of EM wave has been studied in collisionless nonuniform plasma slabs as well as the reflection and transmission coefficients have been obtained.

In this paper, the plasma model we study is cold, steady-state, nonuniform, collisional and magnetized. The effects of the collision frequency, magnetic field intensity, plasma density and plasma slab thickness on the reflection and absorption of EM wave are discussed by using a numerical method. We find that the thickness of plasma seldom affects the reflection of radar wave, but it can broaden or shrink the absorption width. It is expected that the stealth of a broad-band radar wave can be realized by changing the plasma slab thickness. The collision frequency and the plasma density affect remarkably on absorption effect, and there exist optimum values of the collision frequency and the plasma density. However, extremely higher collision frequency and plasma density will lead to weak absorption. In addition, the different magnetic field intensity relates to the different resonant absorption peaks.

2. Formulation

A plane wave vertically propagates to the surface of the plasma (see Fig. 1).

P_i, P_r, and P_a are, respectively, the incident power, the reflected power, and the absorbed power. The direction of the background magnetic field B is parallel to z axis. The plasma density equation is given below

$$n(z) = \begin{cases} n_0 \exp[2(1-2z/L)/3] & (L/2 \le z \le L) \\ n_0 \exp[2(2z/L-1)/3] & (0 \le z < L/2) \end{cases} \tag{1}$$

where L is the plasma slab thickness, n_0 is the plasma density at $z = L/2$.

A plane wave propagating in each subslab, obeys the following Maxwell's equations

$$\nabla \times \mathbf{E} = -j\omega\mu_0 \mathbf{H}, \tag{2}$$

$$\nabla \times \mathbf{H} = (\sigma + j\omega\varepsilon_r\varepsilon_0)\mathbf{E}. \tag{3}$$

Assume a plane wave has a time dependence $\exp(j\omega t)$, Eq. (3) can be written as

$$\nabla \times \mathbf{H} = j\omega\tilde{\varepsilon}_r\varepsilon_0 \mathbf{E}, \tag{4}$$

* Corresponding author.
E-mail address: phd_hwyang@yahoo.com.cn (H.W. Yang).

0030-4026/$ – see front matter © 2011 Elsevier GmbH. All rights reserved.
doi:10.1016/j.ijleo.2011.04.015

here $\tilde{\varepsilon}_r$ is the complex dielectric constant, and $\tilde{\varepsilon}_r = \varepsilon_r - j\sigma/(\omega\varepsilon_0)$. As $\nabla \cdot \mathbf{E} = 0$, the resulting wave equation is

$$\nabla^2 \mathbf{E} = -\frac{\tilde{\varepsilon}_r \omega^2}{c^2}\mathbf{E}, \tag{5}$$

where c is the speed of light. A plane wave propagating in the z-direction with a phase dependence $\exp(j\omega t - \tilde{\gamma} z)$ is a solution to (5), we have

$$E = E_0 \exp(j\omega t - \tilde{\gamma} z) \tag{6}$$

where $\tilde{\gamma}$ is the complex propagation constant. Substituting (6) into (5), the dispersion characteristic of a plane wave in magnetized cold plasma is obtained

$$\tilde{\gamma}^2 = -\frac{\tilde{\varepsilon}_r \omega^2}{c^2} \tag{7}$$

$\tilde{\gamma}$ can be written as $\tilde{\gamma} = \alpha + j\beta$. Where α is the attenuation coefficient and β is the phase coefficient. We have

$$\alpha = -\frac{\omega}{c} I_m(\sqrt{\tilde{\varepsilon}_r}), \tag{8}$$

$$\beta = \frac{\omega}{c} R_e\left(\sqrt{\tilde{\varepsilon}_r}\right). \tag{9}$$

The plasma is modeled as 10 subslabs which are adjacent and homogeneous. We assume that the plasma density is constant in each subslab. The wave propagating in plasma subslabs is shown in Fig. 2. The wave travels from one slab to the other with a reflection at each interface. The complex dielectric function is calculated for each slab and the reflection coefficient at each interface is deduced. The total transmitted, reflected and absorbed powers are then computed. The total reflected power is computed neglecting multiple reflections between slab interfaces.

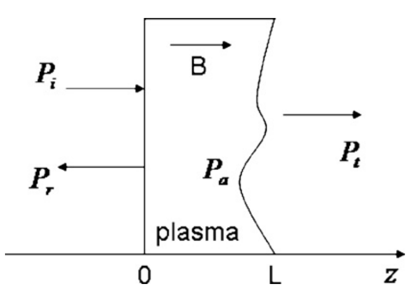

Fig. 1. Wave propagation in plasma.

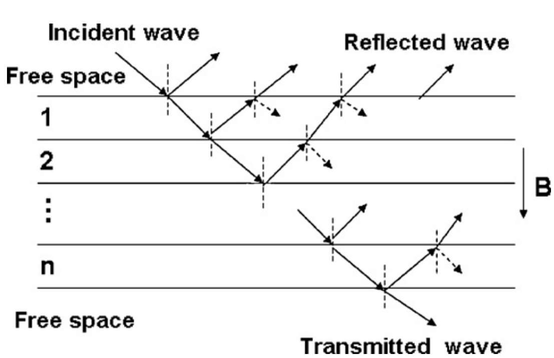

Fig. 2. Wave absorption, transmission and reflection at an arbitrary angle of incidence.

A plane wave propagating in the z-direction through a cold plasma at an arbitrary angle of incidence was derived by Appleton [9]. $\tilde{\varepsilon}_r$ is given by (10) below

$$\tilde{\varepsilon}_r = 1 - \frac{\omega_{pe}^2/\omega^2}{\left[1 - j(\nu_{en}/\omega) - ((\omega_{ce}^2 \sin^2\theta/\omega^2)/2(1 - (\omega_{pe}^2/\omega^2) - j(\nu_{en}/\omega)))\right] \pm \sqrt{((\omega_{ce}^4 \sin^4\theta/\omega^4)/(4(1 - (\omega_{pe}^2/\omega^2) - j(\nu_{en}/\omega))^2)) + (\omega_{ce}^2 \cos^2\theta/\omega^2)}} \tag{10}$$

where ω_{pe}, ω_{ce}, ω_{en}, and θ are, respectively, the plasma frequency, the cyclotron frequency, the collision frequency, and the angle of propagation with respect to the static background magnetic field. The − sign is for a right-hand polarization, and the + sign is for a left-hand polarization. In this paper, only the right-hand polarized EM wave is considered, for $\theta = 0°$ (10) becomes

$$\tilde{\varepsilon}_r = 1 - \frac{\omega_{pe}^2/\omega^2}{1 - j(\nu_{en}/\omega) - (\omega_{ce}/\omega)}. \tag{11}$$

The reflection coefficient at $z = 0$ is given by

$$R(1) = \frac{\sqrt{\tilde{\varepsilon}_r(1)} - 1}{\sqrt{\tilde{\varepsilon}_r(1)} + 1}, \tag{12}$$

$\tilde{\varepsilon}_r(1)$ denotes a complex dielectric constant of the first layer plasma.

The reflection coefficient of a wave traveling from a slab located at i with a complex dielectric constant $\tilde{\varepsilon}_r(i)$ to a slab located at $i+1$with a complex dielectric constant $\tilde{\varepsilon}_r(i+1)$ is

$$R(i+1) = \frac{\sqrt{\tilde{\varepsilon}_r(i)} - \sqrt{\tilde{\varepsilon}_r(i+1)}}{\sqrt{\tilde{\varepsilon}_r(i)} + \sqrt{\tilde{\varepsilon}_r(i+1)}}. \tag{13}$$

The total reflected power is given by the reflection coefficients at each boundary

$$P_r = P_i\left\{\left|R(1)\right|^2 + \sum_{n=2}^{10}\left[\left|R(n)\right|^2 \prod_{m=1}^{n-1}[(1 - \left|R(m)\right|^2)\exp(-4\alpha(m)d)]\right]\right\}, \tag{14}$$

where d is the each subslab thickness. The total transmitted power P_t is given by

$$P_t = P_i \prod_{m=1}^{10}[(1 - \left|R(m)\right|^2)\exp(-2\alpha(m)d)]. \tag{15}$$

The total absorbed power is thus

$$P_\alpha = P_i - P_r - P_t. \tag{16}$$

3. Numerical results

In this section, the computer simulation results are presented and discussed. We choose the radar wave frequency $f = 1$–20 GHz, the plasma density $n_0 = 1 \times 10^{15}$, 1×10^{16}, 1×10^{17}, 1×10^{18} and $5 \times 10^{18}\ \mathrm{m}^{-3}$ at $z = L/2$, the collision frequency $\nu_{en} = 0.1$, 0.5, 1.0 and 5.0 GHz, the plasma slab thickness $L = 0.1$, 0.2, 0.3 and 0.4 m, and the magnetic field intensity $B = 0.1$, 0.2, 0.3, 0.4 and 0.5 T.

3.1. The impact of the collision frequency on the reflected and absorbed powers of EM wave

Fig. 3 plots the reflected and absorbed powers fraction versus frequency for a center density of $n_0 = 1 \times 10^{17}\ \mathrm{m}^{-3}$ and for various collision frequencies. The collision frequencies ν_{en} are assumed to be 0.1, 0.5, 1.0 and 5.0 GHz, respectively. The magnetic field is assumed constant throughout the plasma with a value of $B = 0.3$ T