Optik 165 (2018) 240–247

Contents lists available at ScienceDirect

Optik

journal homepage: www.elsevier.de/ijleo

Original research article

Numerical calculation of the reflection, absorption and transmission of a nonuniform plasma slab based on FDTD

Jinzu Ji[a], Yunpeng Ma[a,*], Na Guo[b]

[a] School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, China
[b] The Institute of Disaster Prevention, Sanhe, Hebei 065201, China

ARTICLE INFO

Article history:
Received 20 February 2018
Accepted 27 March 2018

Keywords:
Finite-difference time-domain (FDTD)
Plasmas
Reflection coefficient
Transmission line theory

ABSTRACT

In this paper, reflection, absorption and transmission characteristics of nonuniform plasma layer with varying electron number density are analyzed. The plasma number density profile is parabolic. Finite-difference time-domain (FDTD) and subslabs approximation methods are utilized and the results are validated. In FDTD, we use auxiliary differential equation (ADE) to simulate the plasma dispersive characteristics. In subslabs method, the plasma layer is divided into several thin subslabs with constant electron number density in each subslab. Partial reflection coefficients at each subslab boundary with different electromagnetic parameters are calculated. The total reflected and transmitted coefficients are then deduced using transmission line method. The reflected, transmitted and absorption power ratio with respect to the incident power is acquired. Their functional dependence on the number density, collision frequency and the distribution of number density, collision frequency is studied.

1. Introduction

In recent years there has been a definite trend toward using a plasmas as absorbers or reflectors of the electromagnetic radiation depending on a specified application. It is mainly due to their tunable reflection and absorption characteristics offering some advantages [1]. Such study is very important to find out the suitable parameters of the plasma which affect the reflection, absorption and transmission of the electromagnetic energy.

Studying the electromagnetic waves interaction with a stratified layered media can be carried out using either analytical or numerical methods. Reflection, absorption and transmission of electromagnetic waves by a magnetized nonuniform plasma slab are analyzed [2]. Scattering matrix method (SMM) was used to determine nonuniform magnetized plasma characteristics [3]. They have shown an easy way to analyze propagation of an electromagnetic wave through a plasma slab by dividing it into many subslabs. By using SMM method, it is possible to determine partial absorption in each subslabs. Interaction of an electromagnetic wave with a magnetized nonuniform plasma slab having parabolic electron number density is studied [4]. SMM method was used for the analysis of electromagnetic wave propagation in planar bounded plasma region [5]. Luebbers have studied the reflection and transmission coefficients of plasma slab based on the finite-difference time-domain (FDTD) method in one-dimension [6]. In all these studies, the aim was to determine the reflection or absorption performance of the plasma layer.

* Corresponding author.
E-mail addresses: jijinzu@buaa.edu.cn (J. Ji), ma_yun_peng@126.com (Y. Ma), naguo8899@163.com (N. Guo).

https://doi.org/10.1016/j.ijleo.2018.03.118
0030-4026/

In this paper, we study the reflection, absorption and transmission of electromagnetic waves by a plasma slab. In our paper, the incident wave is assumed to be a plane wave incident at a plasma slab normally. The plasma density profile is parabolic. The plasma is cold, weakly ionized, steady state, unmagnetized, nonuniform and collisional. FDTD and subslabs method are utilized to simulate the electromagnetic wave propagation [7,8].

In subslabs method, the plasma is modeled as a series of two-dimensional subslabs with the wave being absorbed in each slab and reflected at each boundary. This model is acceptable as an approximation under the assumption that the plasma properties vary very slowly along the wave propagating path. The partial reflection coefficients at each slab boundary are computed by the method of transmission line. The total reflection coefficients at each slab boundary are then calculated by iteration. The total transmission coefficient is calculated based on the total reflection coefficients at each boundary.

In FDTD method, every wavelength with respect to the maximum frequency is divided to 40 Yee cells. Auxiliary differential equation (ADE) is used to calculate the dispersive characteristics of plasma [9]. The calculation area is truncated with perfectly matched layer (PML) to simulate infinitely large space [10,11]. The whole area is divided into total field and scattering field by the total field boundary. The fields of every time step at the two boundaries of the plasma slab are recorded and then transformed to frequency domain to obtain the reflected and transmitted coefficients.

The reflected and transmitted power ratio can be obtained by square the abstract of the reflection and transmission coefficients. Because of energy conservation, the absorption power can be calculated by subtracting incident power and the reflected and transmitted power. The dependence of the reflected, absorbed and transmitted power on the plasma number density, the collision frequency is investigated.

In this paper, the time dependence $e^{j\omega t}$ is assumed, where ω is angular frequency.

2. Formulation

2.1. Plasma model

A plane wave propagating in a lossy medium, such as plasma, obeys the following Maxwell's equations

$$\nabla \times \boldsymbol{H} = j\omega\varepsilon_{\mathrm{r}}\varepsilon_0\boldsymbol{H} \tag{1a}$$

$$\nabla \times \boldsymbol{E} = -j\omega\mu_{\mathrm{r}}\mu_0\boldsymbol{H} \tag{1b}$$

where $\boldsymbol{E}$ is electric field, $\boldsymbol{H}$ is magnetic field, ε_{r} is relative permittivity, μ_{r} is relative permeability, ε_0 is permittivity in free space, μ_0 is permeability in free space, respectively. For plasma medium, we have

$$\varepsilon_{\mathrm{r}} = 1 + \frac{\omega_{\mathrm{p}}^2}{j\omega(j\omega + \nu_{\mathrm{c}})} \tag{2a}$$

$$\mu_{\mathrm{r}} = 1 \tag{2b}$$

where ν_{c} is collision frequency, ω_{p} is plasma frequency, respectively. ω_{p} can be expressed by the plasma density N_0, which is

$$\sigma_{\mathrm{p}} = \frac{e^2 N_0}{m\varepsilon_0} \tag{3}$$

where e and m are the charge and the mass of electron, respectively.

In plasma, the complex wavenumber k is

$$k = k_0\sqrt{\varepsilon_{\mathrm{r}}\mu_{\mathrm{r}}} \tag{4}$$

where $k_0 = c/\omega$ is wavenumber in free space and c is speed of light in free space.

2.2. Subslabs method

The plasma slab can be approximated as several adjacent, homogenous two-dimensional plasma slabs. Every two slabs have a boundary at which reflection may happen because of mismatch of impedance. Total reflection coefficient can be calculated by transmission line method. To be more clear, we deduce a general solution to arbitrary layers with arbitrary dielectric media.

Assume there are N parallel boundaries and thus the space is divided to $N+1$ areas with homogeneous medium in them, which is shown in Fig. 1. The permittivity in each areas are $\varepsilon_0, \varepsilon_2, \ldots, \varepsilon_{N+1}$, respectively. The wavenumber in the areas are $k_0, k_1, \ldots, k_{N+1}$, respectively. The first and the last areas are infinitely thick and occupy half space. The thickness of the other $N-1$ layers are $d_1, d_2, \ldots, d_{N-1}$, respectively.

First, the partial reflection coefficients R_n of each n boundary are calculated by the formula

$$R_n = \frac{\sqrt{\varepsilon_{n-1}} - \sqrt{\varepsilon_n}}{\sqrt{\varepsilon_{n-1}} + \sqrt{\varepsilon_n}}, \quad n = 1, 2, \ldots, N \tag{5}$$