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FDTD ANALYSIS OF MICROSTRIP PATCH ANTENNA COVERED BY PLASMA SHEATH

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Abstract—In this paper, a microstrip inset-fed patch antenna covered by plasma sheath is simulated by using the $(\text{FD})^2\text{TD}$ algorithm. Expressions of calculating the coefficients in the electric field update equation for cold plasma are presented in detail. Computational examples illustrate that the resonant frequency of the patch antenna covered by plasma sheath is changed. The curves presented in this paper may be useful when introducing appropriate corrections in the design of the microstrip patch antennas in the plasma environment.

1. INTRODUCTION

Microstrip patch antennas have been extensively employed in spacecraft systems because of their low profile, reduced weight and conformal nature. However, during re-entry into the earth's atmosphere, friction between spacecraft and air will cause plasma sheath to form around the vehicle. The plasma sheath may seriously affect system performance even cause interruption of communication because of very narrow bandwidth of the microstrip patch antenna. In addition, as the most common form of matter, plasma also exists in the stars and in the tenuous space. Aerospace researches under these environments often involve the effects of plasma on the impedance and radiation of patch antennas.

On early stage it is in free space that patch antennas have been studied mainly. In 1982 Bahl [1] analyzed a microstrip antenna covered with a dielectric layer. Kashiwa [2] has simulated the near field of a patch antenna in magnetized plasma by use of the spatial network method (SNM). But few analysis of patch antennas covered by plasma sheath has been carried out because the permittivity of plasma varies significantly with frequency. Efficient numerical techniques involving the effects of plasma sheath on patch antennas are therefore desirable. In this paper, the near fields of a microstrip inset-fed patch antenna covered by plasma sheath are simulated by use of the $(\mathrm{FD})^2\mathrm{TD}$ formulation [3, 4] which allows explicit calculation of wide-band transient electromagnetic interactions with frequency dependent materials. To evaluate the discrete time convolution of the electric field and the dielectric susceptibility function, the piecewise linear recursive convolution (PLRC) scheme [5] is adopted. The critical point of this scheme is that all the electric fields are assumed to have a piecewise linear functional dependence over each time interval. The PLRC scheme greatly improves accuracy over the original RC approach but retains its speed and efficiency advantages. The effect of plasma sheath on the impedance characteristics, resonant frequency, and radiation efficiency of the microstrip patch antenna is investigated in detail.

2. FORMULATION

For this paper, we will use the cold plasma approximation and the complex permittivity $\varepsilon(\omega)$ and susceptibility $\chi(\omega)$ of plasma can be described as

$$\varepsilon(\omega) = \varepsilon_0 \left(1 + \frac{\omega_p^2}{\omega(jv_c - \omega)}\right) = \varepsilon_0(1 + \chi(\omega)) \tag{1}$$

where $\omega_p (= 2\pi f_p)$ is the inherent radian frequency of plasma, v_c is the average collision frequency of electrons. The $\exp(j\omega t)$ time convention is assumed.

To implement the FDTD analysis of the microstrip patch antenna covered by plasma sheath, it is essential to derive the field update equations for plasma media.

The Maxwell curl equations are

$$\nabla \times H = \frac{\partial D}{\partial t}, \tag{2}$$

$$\nabla \times E = -\mu_0 \frac{\partial H}{\partial t}. \tag{3}$$

Using Yee's notation, the electric flux density is related to the electric field intensity by the convolution

$$D^n = \varepsilon_0 E^n + \varepsilon_0 \int_0^{n\Delta t} E(n\Delta t - \tau)\chi(\tau) d\tau \tag{4}$$

where $\chi(t)$ is the susceptibility time-function of plasma which can be obtained by computing the inverse Fourier transform of $\chi(\omega)$. The electric field is assumed to have a piecewise linear functional dependence over Δt. That is, the continuous time electric field $E(t)$ over a given interval $[i\Delta t, (i+1)\Delta t]$ can be expressed in terms of the discrete time values E^i and E^{i+1} as

$$E(t) = E^i + \frac{(E^{i+1} - E^i)}{\Delta t}(t - i\Delta t). \tag{5}$$

Following the procedure presented in [5], we can obtain the electric field update equation for cold plasma:

$$\begin{aligned} E^{n+1} &= \left(\frac{1-\xi^0}{1-\xi^0+\chi^0}\right) E^n + \frac{\Delta t}{\varepsilon_0(1-\xi^0+\chi^0)} \nabla \times H^{n+1/2} \\ &\quad + \left(\frac{1}{1-\xi^0+\chi^0}\right)\psi^n, \\ \psi^n &= (\Delta\chi^0 - \Delta\xi^0)E^n + \Delta\xi^0 E^{n-1} + e^{-v_c\Delta t}\psi^{n-1} \end{aligned} \tag{6}$$

where

$$\begin{aligned} \chi^0 &= \left(\frac{\omega_p}{v_c}\right)^2 \left[v_c\Delta t - 1 + \exp(-v_c\Delta t)\right], \\ \xi^0 &= \left(\frac{\omega_p^2}{v_c^3 \Delta t}\right)\left[\frac{(v_c\Delta t)^2}{2} + (1 + v_c\Delta t)\exp(-v_c\Delta t) - 1\right], \end{aligned}$$

$$\Delta\chi^0 = -\left(\frac{\omega_p}{v_c}\right)^2 [1-\exp(-v_c\Delta t)]^2 ,$$
$$\Delta\xi^0 = \left(\frac{\omega_p^2}{v_c^3\Delta t}\right)[1-\exp(-v_c\Delta t)]\,[(1+v_c\Delta t)\exp(-v_c\Delta t)-1] .$$

Note that the value of ψ is zero at $n = 0$. It is evident that the magnetic field update equation will be unchanged.

3. NUMERICAL RESULTS

To investigate the accuracy of above formulations, we computed a one-dimensional example of a plane wave normally incident on a plasma slab with a thickness of 15 mm [4]. The computational domain is 60 mm long and the plasma slab is defined by the region [22.5, 37.5] mm. Parameters of the plasma are: $f_p = 28.7$ GHz, $v_c = 20$ GHz. A comparison of the (FD)^{2}TD and exact results for the magnitude of the plasma slab reflection coefficient is shown in Figure 1. The exact results were obtained using the transmission line method as done in [4]. It is observed from Figure 1 that an excellent agreement between them has been obtained.

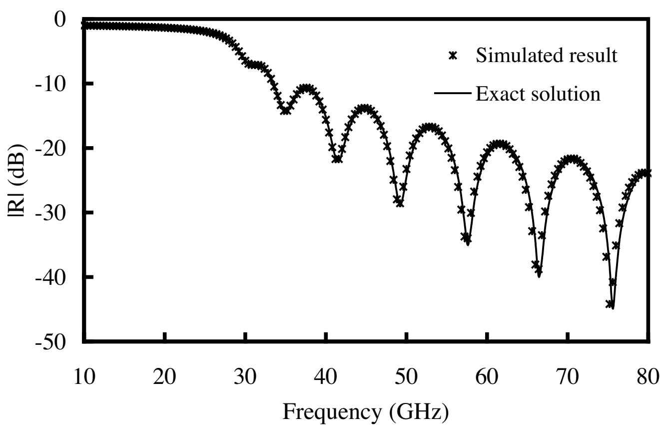


Figure 1. Comparison of reflection coefficient magnitude simulated using (FD)^{2}TD method with the analytical solution.

As shown in Figure 2, a microstrip inset-fed patch antenna covered by a plasma sheath is analyzed. The thickness of covered dielectric layer and plasma layer are h_2 and h_3, respectively. The inset-fed is applied to achieve perfect impedance matching between the microstrip

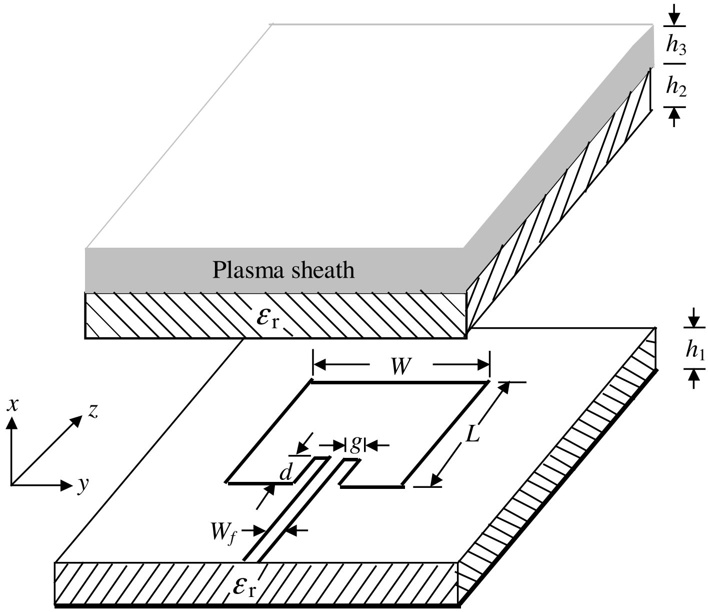


Figure 2. The structure of microstrip patch antenna covered by plasma sheath.

line and the patch antenna [6]. The RT/Duroid 5870 substrate with relative dielectric constant $\varepsilon_r = 2.33$, loss tangent $\tan\delta = 0.0012$ and thickness $h_1 = 0.787\,\text{mm}$ is used. The computational parameters used in the FDTD analysis are as follows: $\Delta x = 0.2625\,\text{mm}$, $\Delta_y = 0.762\,\text{mm}$, $\Delta z = 0.4075\,\text{mm}$, $\Delta t = \Delta x/(2c)$, $L = 16.3\,\text{mm}$, $W = 25.1$ $5\,\text{mm}$, $W_f = 2.286\,\text{mm}$, $d = 4.075\,\text{mm}$, and $g = 0.762\,\text{mm}$. It should be pointed out that the dominant mode of this antenna is TM_{001}^{x} mode.

The return loss of the typical microstrip patch antenna ($h_2 = 0\,\text{mm}$) as a function of frequency with/without the plasma layer is given in Figure 3. It can be found that the resonant frequency of the uncovered antenna ($h_3 = 0\,\text{mm}$) is about 5.75 GHz. However, the resonant frequency of the covered antenna is about 6.06 GHz with the plasma layer $h_3 = 0.525\,\text{mm}$, $f_p = 12\,\text{GHz}$ and $v_c = 10\,\text{Ghz}$. The deviation of resonant frequency relative to the uncovered case is 5.4 percent. It can also be inferred that the higher the plasma frequency f_p, the stronger the influence of plasma layer on the resonant frequency of the patch antenna. This can be reasonably explained as follows: at relatively low frequencies, the plasma layer actually becomes a metallic thin film, and at higher frequencies, it becomes transparent to electromagnetic waves. The shift of resonant frequency may seriously

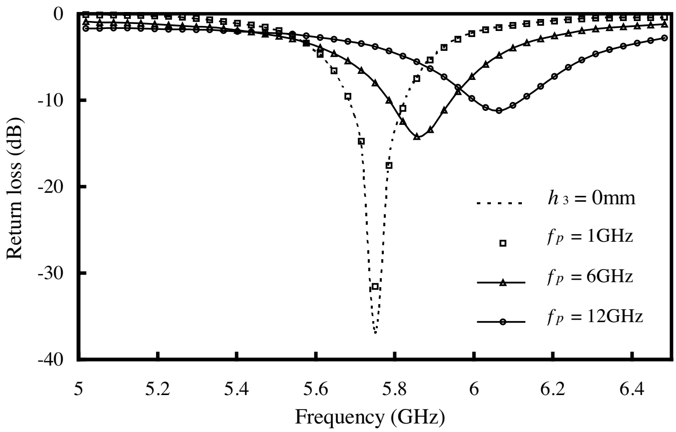
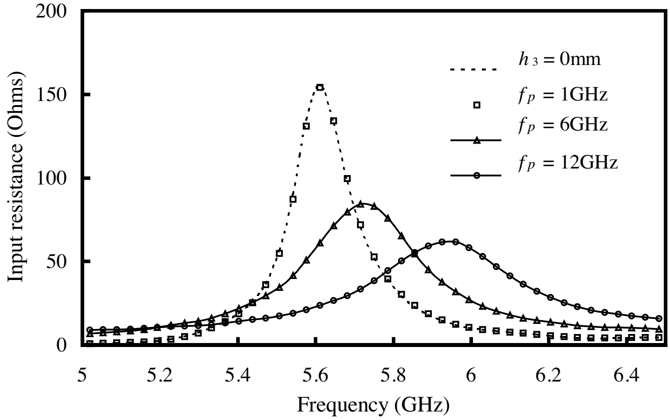


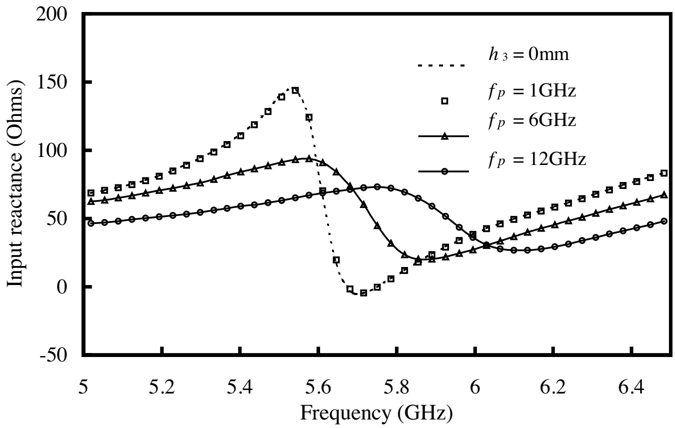
Figure 3. Return losses versus frequency with/without the plasma sheath ($h_2 = 0\,\mathrm{mm}$).

degrade the communication system performance. The input impedance of the typical microstrip patch antenna is also exhibited in Figure 4 for both covered and uncovered by plasma layers with a reference plane in the inset feeding point. In addition, numerical results demonstrate that effect of v_c on the input impedance of the patch antenna is small if f_p is kept constant. Calculated results are not presented here for brevity.

Although it is not possible to know the relative permittivity and thickness of plasma layer beforehand for the patch antenna potentially used in plasma environments, some measures can be taken to reduce the effect of plasma layer on the resonant frequency in the design of patch antenna. As shown in Figure 2, the covered dielectric layer can reduce the influence of the resonant frequency by the plasma layer. The return loss curves versus the frequency are plotted in Figure 5 for different covered cases. It can be found that the resonant frequency is 5.6 GHz for a covered dielectric layer with same permittivity and thickness as the dielectric substrate of microstrip patch antenna. Compared with Figure 3, it is found that the deviation of the resonant frequency caused by the loaded plasma layer is reduced greatly by covering the patch antenna with a thick dielectric layer. The inset depth d can be also adjusted to achieve impedance matching for the patch antenna for various values d are given in Figure 6 when the covered dielectric permittivity $\varepsilon_r = 2.33$ and thickness $h_2 = 0.787\,\mathrm{mm}$ and the plasma layer $h_3 = 0.525\,\mathrm{mm}$, f_p=12 GHz, $v_c = 10\,\mathrm{GHz}$. It can be seen from Figure 6 that the return loss reaches -28.2 dB when inset



(a)



(b)

Figure 4. Input impedances versus frequency with/without the plasma sheath ($h_2 = 0\,\mathrm{mm}$).

depth $d = 2.445\,\mathrm{mm}$.

Finally, gain of the plasma covered microstrip patch antenna is investigated. The gain of an antenna is calculated by

$$G = \eta D_0 \tag{7}$$

where η is the radiation efficiency, D_0 is the maximum directivity. They are defined as

$$D_0 = 4\pi \frac{U(\theta,\phi)|_{\max}}{P_{\mathrm{rad}}}, \tag{8}$$

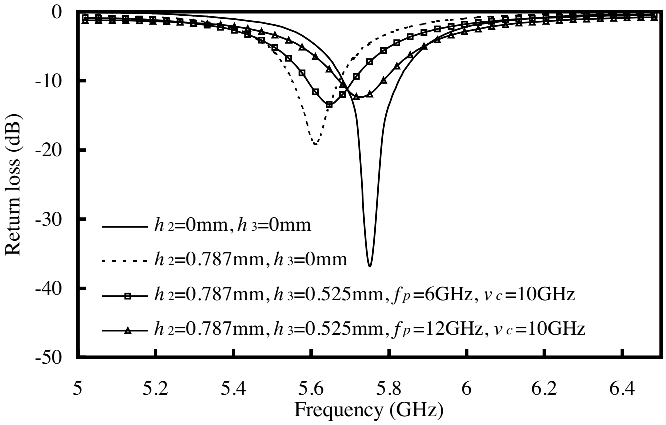


Figure 5. Effect of the covered dielectric layer on the resonant frequency of the antenna.

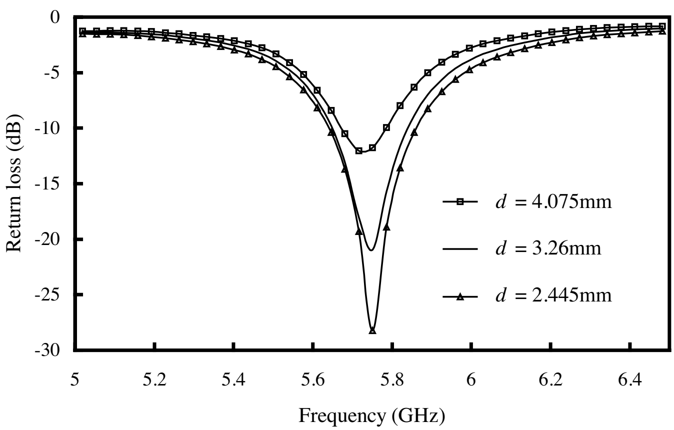


Figure 6. Return losses of the antenna for various inset depth.

$$P_{\text{rad}} = \int_0^{2\pi} \int_0^{\pi} U(\theta, \phi) \sin\theta d\theta d\phi, \tag{9}$$

$$\eta = \frac{P_{\text{rad}}}{P_{\text{in}}}. \tag{10}$$

The effect of the plasma sheath on the microstrip patch antenna is illustrated in Figure 7. It can be inferred that the plasma layer mainly degrades the radiation efficiency and hardly changes the directivity.

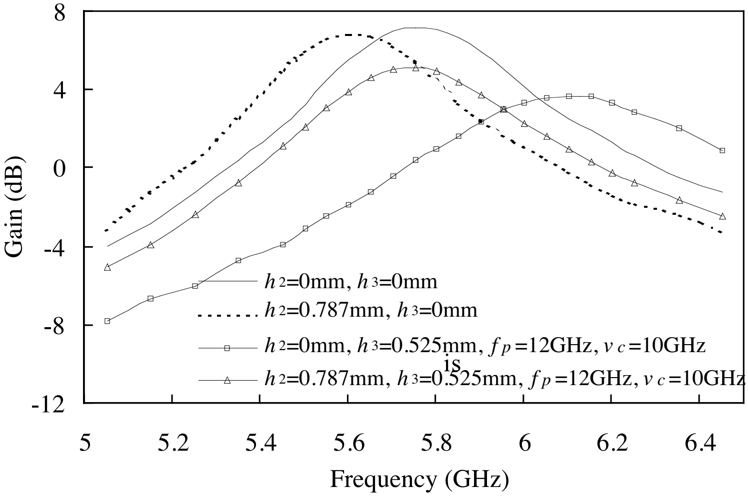


Figure 7. The gain versus the frequency for plasma covered microstrip patch antenna.

4. CONCLUSIONS

The microstrip inset-fed patch antenna covered by plasma sheath is simulated successfully by using the (FD)^{2}TD algorithm. The effect of plasma sheath on the input impedance of microstrip patch antenna is given and the shift of resonant frequency for the patch antenna is illustrated. Numerical results show that the deviation of resonant frequency can be reduced through covering the patch antenna with a thick dielectric layer and the good impedance matching of the antenna can be achieved by selecting the inset depth properly. The curves presented in this paper may be useful in the design of the microstrip patch antennas in a plasma environment.

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