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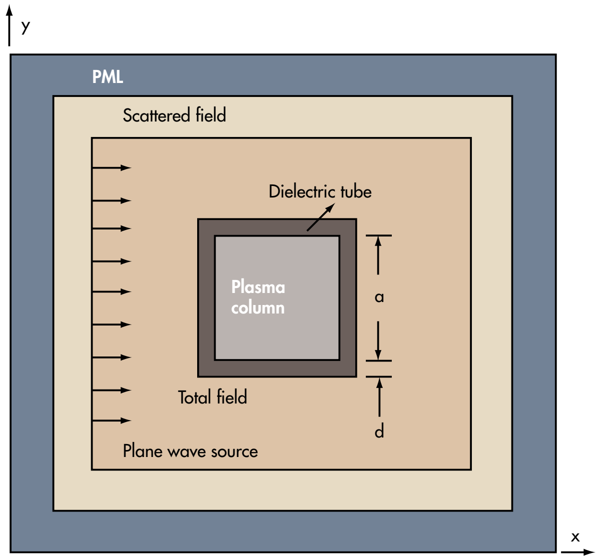
Analyze The RCS Of A PLASMA ANTENNA

Plasma antennas offer some advantages over metal antennas for stealth applications, although they still exhibit an RCS when operating for transmission or reception in a system.

Plasma antennas offer some special qualities that make them attractive for electronic-warfare (EW), radar, and other applications that may require stealth operation. The plasma in these antennas is essentially a blend of electrons, ions, and neutrons. When the density of the plasma is high enough, an electromagnetic (EM) wave will travel on its surface rather than deep into it. The plasma will exhibit the properties of a conductor, serving as an antenna for transmitting and receiving signals.

Consequently, a plasma column can be used as a radiative element in place of a metallic conductor. The plasma becomes conductive when energized by an RF source, and nonconductive once the source is removed. As a result, it can be made to have a radar cross section (RCS) that virtually disappears to an enemy radar once the RF source is removed.[1] Another advantage of a plasma antenna compared with its metal counterpart is that it can be reconfigured; its radiation characteristics can be changed conveniently by electrical rather than mechanical control.[2]



1. A plasma antenna can be modeled by surrounding the plasma with a dielectric tube and using FDTD analysis.

Much study has focused on plasma antennas—mainly to understand their radiation characteristics, including the input impedance, the radiation pattern, and the loss of the plasma column by means of analytical solutions or numerical simulations.[3-5] Because a plasma antenna has little or no RCS when it is turned off, it has had great appeal for defense applications. But when it is on, whether transmitting or receiving, it does have an RCS and can be detected by an enemy radar. Understanding its RCS characteristics when it is powered on is important for applying these antennas to stealth applications.

Unfortunately, of the studies performed so far on plasma antennas, none has addressed the RCS characteristics of these

> “Because a plasma antenna has little or no RCS when it is turned off, it has had great appeal for defense applications. But when it is on, it does have an RCS and can be detected by enemy radar.”

antennas. As is known, plasma is a dispersive media for which the relative permittivity is dependent upon frequency. Various approaches can be used to simulate the interaction of EM waves with a plasma antenna. The two main methods based on finite-difference-time-domain (FDTD) analysis are the direct integration and the recursive convolution methods. Yoonjae Lee[6] and Fan Luo[7] studied the radiation characteristics of plasma antennas using the former method. Xue-Shi Li[8] investigated the input impedance and radiation patterns of plasma antennas with nonuniform distribution of the plasma using the latter method. But neither addressed scattering fields from plasma antennas.

In the present study, FDTD analysis using the Z-transform will be applied for simulating the interaction of EM waves and an unmagnetized plasma antenna. Considering a plasma antenna as an infinite square column with a dielectric tube, it can be simulated by means of iterative formulas. The simulations can be applied to analyze the antenna's RCS characteristics in terms of inhomogeneous plasma density, different EM incident frequencies, different plasma collision frequencies, and different relative dielectric constants for the tube containing the plasma.

Unmagnetized cold plasma is a dispersive material, with an effective relative dielectric constant, ε_r, given by Eqs. 1 and 2[9]:

$$\varepsilon_r = \mathbf{1} - \omega_{pe}^2 / \omega(\omega - i v_c) \quad (1)$$

$$\omega_{pe}^2 = n_e e^2 / m_e \varepsilon_{\mathbf{0}} \quad (2)$$

where:

v_c = the electron-neutral collision frequency;

w_{pe} = the plasma angle frequency;

w = the angle frequency of the incident EM wave;

n_e = the plasma density;

e = the electron charge; and

m_e = the mass of the electron.

The complete set of Maxwell's equations for unmagnetized cold plasma is given by Eqs. 3-6:

$$\frac{\partial \vec{D}}{\partial t} = \nabla \times \vec{H} \quad (3)$$

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E} \quad (4)$$

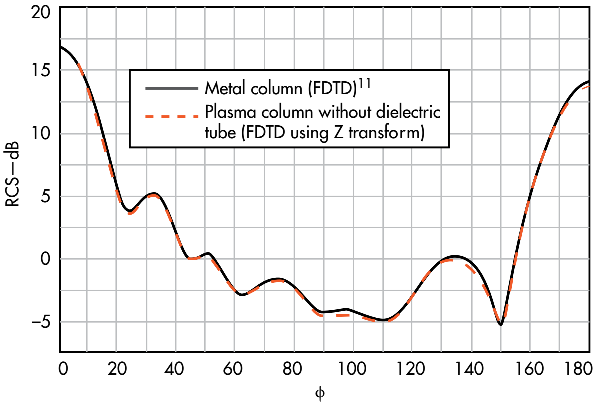
$$\vec{D}(\omega) = \varepsilon_0 \varepsilon_r^*(\omega) \vec{E}(\omega) \quad (5)$$

$$\vec{B} = \mu \vec{H} \quad (6)$$

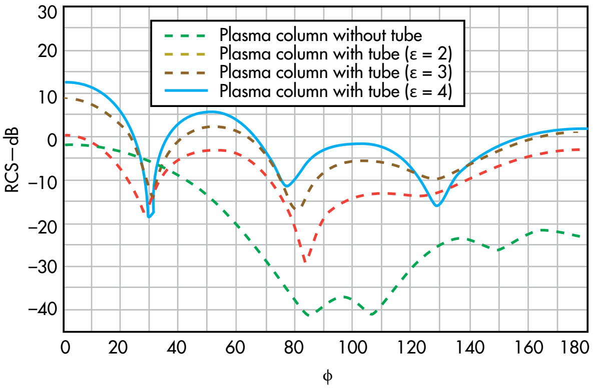
Note that Eq. 3 is written in the frequency domain and must be translated into the time domain for implementation into FDTD analysis. Substituting Eq. 1 into Eq. 5 yields Eq. 7:

$$\vec{D}(\omega) = \varepsilon_0 \left(1 - \frac{\omega_{pe}^2}{\omega(\omega - i v_c)}\right) \vec{E}(\omega) \quad (7)$$

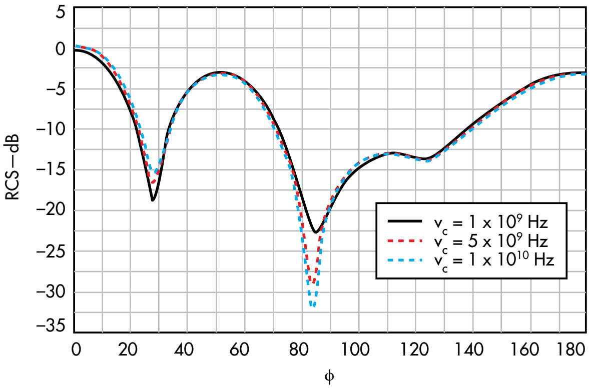
By the convention theorem,[10] the Z transform of Eq. 5 becomes Eq. 8:



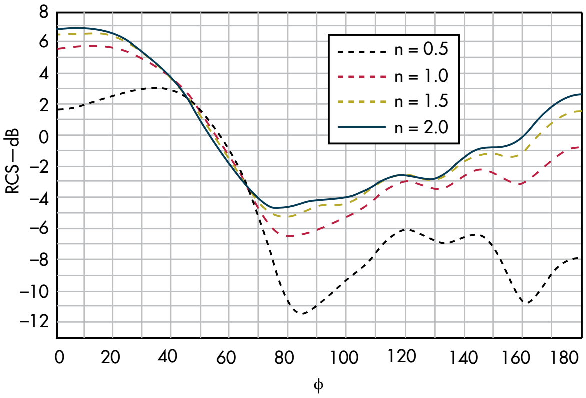
2. These curves represent RCSs for a metal column and a plasma column without a dielectric tube.



3. These curves show RCSs for a plasma column without surrounding dielectric and for plasma columns with a number of different relative dielectric constants.



4. The RCSs of a plasma column with a dielectric tube are shown for various plasma collision frequencies.



5. The RCSs of a plasma column with inhomogeneous plasma in a dielectric tube are shown for different electron densities.

$$D(z) = E(z) + \frac{\omega_{pe}^2 \Delta t}{v_c}\left(\frac{\left(1-e^{-v_c\Delta t}\right)z^{-1}}{1-\left(1+e^{-v_c\Delta t}\right)z^{-1}+e^{-v_c\Delta t}z^{-2}}\right)E(z) \quad (8)$$

Introducing an auxiliary term:

$$I(z) = \frac{\omega_{pe}^2 \Delta t}{v_c}\left(\frac{\left(1-e^{-v_c\Delta t}\right)}{1-\left(1+e^{-v_c\Delta t}\right)z^{-1}+e^{-v_c\Delta t}z^{-2}}\right)E(z) \quad (9)$$

E(z) can be solved as shown in Eqs. 10 and 11:

$$E(z) = D(z) - I(z)z^{-1} \quad (10)$$

$$I(z) = \left(1+e^{-v_c\Delta t}\right)z^{-1}I(z) - e^{-v_c\Delta t}z^{-2}I(z) + \frac{\left(1-e^{-v_c\Delta t}\right)\omega_{pe}^2\Delta t}{v_c}E(z) \quad (11)$$

As a result, the iterative formulas for FDTD are shown in Eqs. 12 and 13:

$$E^n = D^n - I^{n-1} \quad (12)$$

$$I^n = \left(1+e^{-v_c\Delta t}\right)I^{n-1} - e^{-v_c\Delta t}I^{n-2} + \frac{\left(1-e^{-v_c\Delta t}\right)\omega_{pe}^2\Delta t}{v_c}E^n \quad (13)$$

Equations 12 and 13 apply to one-dimensional space. They can be extended to two-dimensional use by means of Eqs. 14 and 15:

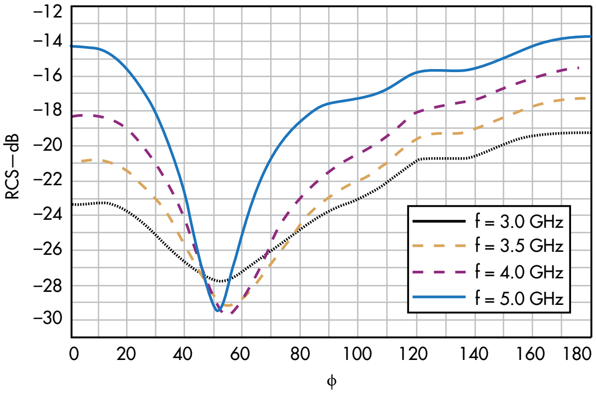
$$E^n(i,j) = D^n(i,j) - I^{n-1}(i,j) \quad (14)$$

$$I^n(i,j) = \left(1+e^{-v_c\Delta t}\right)I^{n-1}(i,j) - e^{-v_c\Delta t}I^{n-2}(i,j) + \frac{\left(1-e^{-v_c\Delta t}\right)\omega_{pe}^2\Delta t}{v_c}E^n(i,j) \quad (15)$$

Achieving a stealth state is an important capability of a plasma antenna that sets it apart from traditional antennas. When the RF source is off, a plasma antenna will revert to a dielectric tube with a small RCS, and EM scattering from the tube can be neglected. But when the RF source is active, a plasma antenna is much like a metal antenna—transmitting and receiving signals—and it will have an RCS that is visible to detection. *Figure 1* shows an infinite unmagnetized cold plasma column with a dielectric tube for a plane incident wave in the direction of the positive x axis.

To demonstrate the use of the iterative formulas for FDTD based on the Z-transform, the RCS of a plasma column can be computed without the dielectric tube, when the frequency of the incident EM wave is much less than the operating frequency of the plasma. In such a case, the incident EM waves will interact with the plasma column, with the column behaving like a perfect conductor. Using a simplified two-dimensional (2D) model, the plasma column is simulated with an incident wave having a wavelength, λ, of 0.03 m, the side of the square column being equal to 2λ, the plasma density, n_e, equal to 7.5 x $10^{18}/m^3$, and the electron-neutral collision frequency, v_c, equal to 5 x 10^9 Hz. *Figure 2* shows that the RCS of a plasma column with high plasma density complies with the results for a perfecting conducting column.

Since plasma is a kind of ionized gas, a plasma antenna is typically molded with the help of a dielectric tube. Of course, the permittivity of a dielectric tube will have an impact and reduce the RCS of a plasma antenna. For a model of a plasma antenna with a dielectric tube, the key parameters are: the frequency of the incident wave, f_{in} = 1 x 10^{10} Hz, the plasma density, n_e = 1.3 x $10^{17}/m^3$, the electron-neutral collision fre-



6. The RCSs of a plasma column with inhomogeneous plasma in a dielectric tube are shown for different incident EM frequencies.

quency, $v_c = 5 \times 10^9$ Hz, the side of the square plasma column, a =1.5 cm, and the thickness of the dielectric tube, d = 0.15 cm. Since the dielectric tube is part of the plasma antenna, impedance matching between the air and plasma is further deteriorated.

As *Fig. 3* shows, when the dielectric tube is absent, the backscattering cross section of the plasma column decreases; the backscattering cross section for the plasma column with the dielectric tube present increases with decreasing permittivity. For a case where $f_{in} = 1 \times 10^{10}$ Hz, $n_e = 1.3 \times 10^{17}/m^3$, a = 1.5 cm, d = 0.15 cm, and the relative dielectric constant of the dielectric tube is ε = 2.0, *Fig. 4* shows that the collision frequency has only a minor impact on the backscattering cross section for a plasma column with dielectric tube.

As *Fig. 2* indicates, a plasma column acts as a perfect conductor if the frequency of an impacting EM wave (such as from an outside radar system) is much greater than the operating frequency of the plasma antenna, resulting in a large RCS from the antenna. If the plasma density is reduced by controlling the excitation source, the RCS of the plasma antenna will decrease significantly (as in *Figs. 3 and 4*). This is because the plasma antenna may be functional in a low-frequency range when the plasma density is smaller, and the plasma will act as a lossy medium, absorbing and scattering EM waves, and the RCS of the plasma antenna will be reduced.

Even while it achieves a low density, a plasma antenna can normally transmit and receive high-frequency signals. The characteristic plasma density is that required at a certain value to maintain a plasma column working as an antenna, To reduce the antenna's RCS, it is necessary to understand the electrical characteristics of the plasma density, and this can be done by modeling the distribution function of the plasma density with reasonable accuracy. That density can be computed with the aid of Eq. 16[12]:

$$n_e(x) = n_m + (n_c - n_m) \times |x - x_0|^{\mathrm{n}} / (a/2)^{\mathrm{n}} \quad (x_0 - a/2 \leqslant x \leqslant x_0 + a/2) \tag{16}$$

where:

n_e = the electron density;
$n_c = 5 \times 15\ \mathrm{m}^{-3}$ is the characteristic plasma density for the plasma antenna; and
$n_m = 1.3 \times 10^{18}\ \mathrm{m}^{-3}$ to maximize the electron density of the plasma antenna.

Assuming $f_{in} = 1 \times 10^{10}$ Hz, $v_c = 5 \times 10^9$ Hz, ε = 2, a = 1.5 cm, and d = 0.15 cm, *Fig. 5* shows the RCS of a plasma column with inhomogeneous plasma having different electron densities (n = 0.5, 1, 1.5, and 2). Figure 5 indicates that as n decreases, it has greater impact on reducing the antenna's RCS. For a case where $n_c = 5 \times 10^{15}$, $n_m = 1.12 \times 10^{17}$ (a plasma frequency, f_{pe}, of 3 GHz), $v_c = 5 \times 10^9$ Hz, ε = 2, a = 1.5 cm, and d = 0.15 cm. *Figure 6* shows the RCS for a plasma column for different EM wave frequencies (f_{in} = 3.0, 3.5, 4.0, and 5.0 GHz).

As *Fig. 6* shows, different EM wave frequencies have different capabilities of absorption for a distribution of inhomogeneous plasma density. When the frequency of the incident EM waves approaches the upper limit of the plasma frequency, attenuation of the incident EM waves increases due to the absorption of EM waves by the plasma resonance. **mw**

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