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Simulation of a plasma antenna by PIC method

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Abstract. The numerical model of a plasma asymmetric dipole antenna is studied in this paper. This antenna consists of a dielectric tube with discharge plasma and a metal screen. The plasma in the tube is simulated by Particle-in-cell (PIC) method. The spectra of the electromagnetic field components were studied in the plasma and the near antenna field for various antenna operating modes. The operating modes depend on a ratio of a plasma frequency and a frequency of radiated electromagnetic wave. Langmuir frequency component was found in spectra within plasma for all antenna operating modes. The amplitude of this spectral component is greater than the amplitude of the component at the carrier frequency for non-radiative and non-linear modes. The biggest amplitude of the radiated signal spectrum is at the carrier frequency in the linear mode.

1. Introduction

Plasma antennas with discharge plasma in dielectric tubes are researched by many scientific groups [1-10]. These antennas are very perspective, because they have some advantages such as low radar cross section and fast reconfigurable parameters (a frequency, a radiation pattern, a radiation resistance and etc). However, when we change the antenna parameters, we should use receiving and transmitting modes in which a signal hasn't noticeable non-linear distortions and high noises. Nowadays the researches of the plasma antenna noises and the non-linear distortions of a signal are key trends.

One of the most convenient plasma antenna types is a Plasma Assymetrical Dipole antenna (PAD or "monopole"). The plasma assymetrical dipole antenna consists of a dielectric discharge tube with plasma and a metal screen (see figure 1). A control of PAD parameters can be made by changing a plasma concentration or the length of the plasma column.

A dispersion equation of a surface electromagnetic wave on a plasma cylinder was solved for a cylinder radius r_0=0.5 cm and plasma density values $n_e=10^{10}$-10^{12} cm^{-3} and the plasma assymetrical dipole was simulated by a Drude model in KARAT code in work [10]. In this work three operation modes of a plasma antenna were found: *non-radiative*, *non-linear* and *linear*. These operation modes depend on a ratio of an electromagnetic frequency f_0 (or $\omega_0=2\pi f_0$) and a plasma frequency f_p (or $\omega_p=2\pi f_p$) and relate with propagation conditions of the surface wave [11-13]. Only a potential surface wave exists along the plasma cylinder and PAD's parameters differ a lot from parameters of the same metal antenna on the frequency f_0 into the non-radiative mode. In the non-linear mode a velocity of surface wave is less than the velocity of light c on the frequency f_0 and the PAD's parameters differ from the metal antenna parameters. In the linear mode the surface wave velocity is close to the velocity of light *c* on the same frequency and the plasma antenna parameters are almost coincide with the metal antenna parameters. However, the Drude model considers only dielectric properties of the plasma, which are determined by a plasma density and an electron collision frequency.

But an interaction of a propagation electromagnetic wave and plasma can bring non-linear distortions and noises on a transmitting and receiving signal in the different operation modes. A selection of the operating modes with the minimal distortions demands the study of signal spectra of the plasma dipole antenna. In this task the plasma should be studied as a collection of particles. The Particle-in-Cell (PIC) method allows studying plasma as the collection of the particles.

A propagation in plasma antenna and radiation of a Gaussian form pulse is researched in this paper. The plasma asymmetrical dipole antenna parameters are: the length l=4 cm and the inner radius of the discharge tube r= 0.5 cm and the Gaussian form pulse parameters are: the duration τ_i = 15 ns and the carrier frequency f_0=1.7 GHz (ω_{ew0}=1.07·10^{10} rad·s^{-1}). This consideration will allow progress in solving two major problems: understanding of the process of plasma antenna signal radiation in different modes and the effect of plasma particles in the emitted signal.

2. Numerical model

A PIC model of the plasma asymmetric quarter wave dipole antenna have been done in KARAT code [14]. KARAT code is a program for electromagnetic numerical simulation, it uses the Final Differences in Time Domain (FDTD) method for solving Maxwell's equations. A scheme of plasma antenna model is shown in figure 2. From the coaxial cable 1 the electromagnetic wave passes to the plasma in dielectric tube 2, which together with the metal screen 3 forms an asymmetric dipole antenna. Perfect Matching Layer (PML) 4 is located on the borders of the modeling area. The spectra of electromagnetic field components E_r and E_z were recorded inside the plasma at a point number 1 (z = 7 cm, r = 0.5 cm) and in the near antenna field zone at a point number 2 (z = 8 cm, r = 5.8 cm). The point number 2 is located in the near zone, because the size increase of the simulated area endangering a stability of the PIC model. PIC plasma consists of two particle sorts, they are electrons and argon ions.

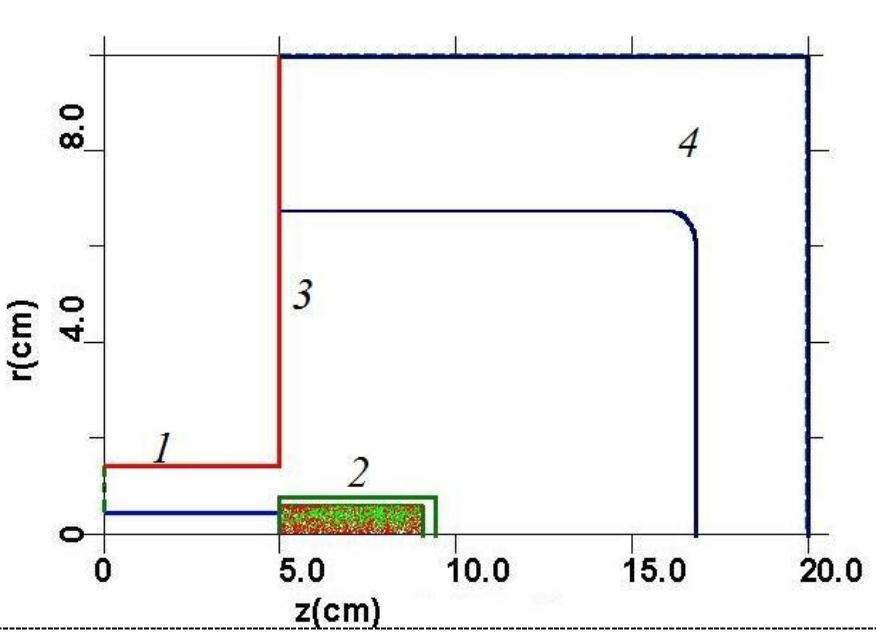
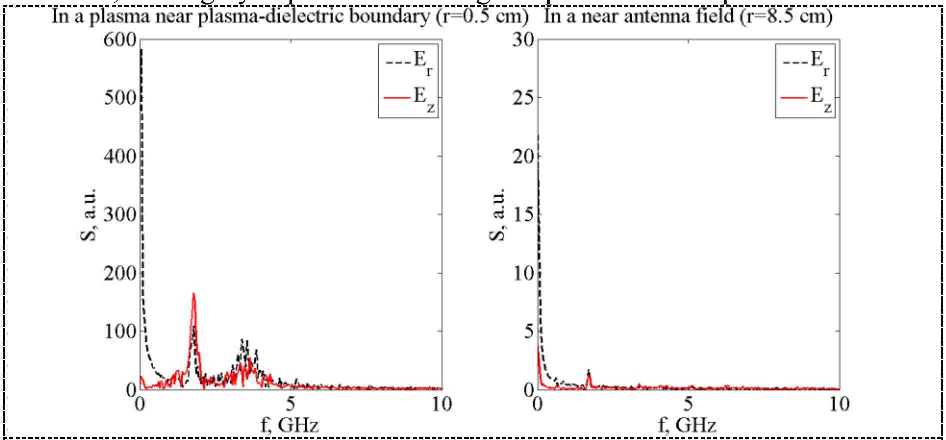


Figure 1. Plasma antenna model in KARAT code: 1 — coaxial cable, 2 — dielectric discharge tube with PIC plasma, 3 — metal screen, 4 – perfect matching layer (PML).

3. Simulation results and discussion

In this chapter I will discuss the spectra of the electromagnetic fields components $E_я$ and E_r, which were obtained by simulation of the plasma asymmetric dipole antenna.

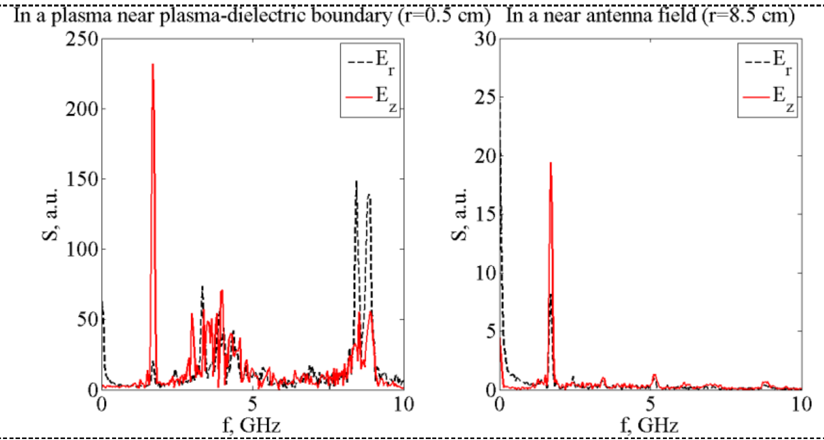
The spectra are shown in figure 2 in the non-radiative mode. Parameters of plasma in this mode are the plasma frequency $f_p = 2 \cdot f_0 = 3.4$ GHz ($\omega_p = 2\omega_{ew0} = 2.14 \cdot 10^{10}$ rad/s) and the plasma density $n_e = 1.4 \cdot 10^{11}$ cm^{-3}. Amplitudes of E_z and E_r components at the frequency 1.7 GHz are more than the ones at the frequency 3.4 GHz inside plasma (figure 2a). The amplitude of E_r components at low frequencies is more than the one at the frequency f_0. In point number 2 (Figure 3b) there are a low-frequency noise component, the carrier frequency f_0 and Langmuir frequency f_p in the spectra of E_z and E_r. This antenna operating mode is a *non-radiative,* since the amplitude of the signal in the near field of the antenna is much smaller than in plasma. The amplitude of the low-frequency noise component in the signal is more than the amplitude of the carrier signal frequency f_0. Langmuir frequency f_p coincides with the double harmonic of the carrier frequency $2f_0$, it is resonant for this type of antenna. Therefore, it is highly expressed in the signal spectrum in the points 1 and 2.



(a) (b)

Figure 2. Electromagnetic wave spectra in non-radiative mode in: (a) point 1, (b) point 2.

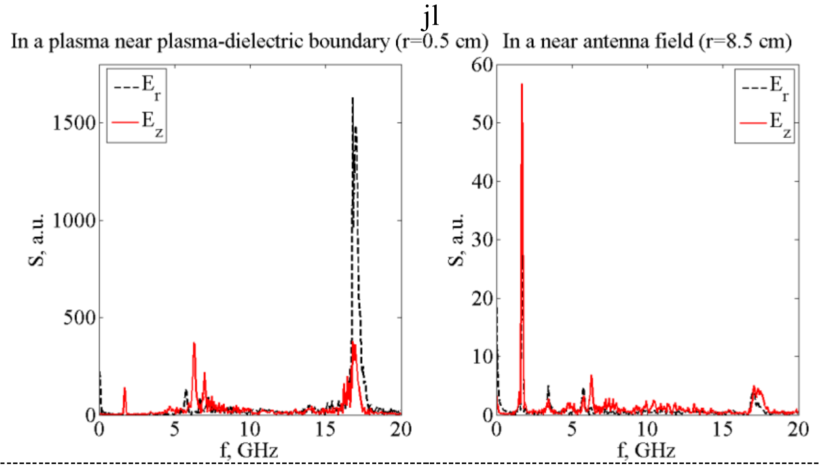
The spectra of the signal are presented in figure 3 in the non-linear mode. The parameters of plasma in this mode are the plasma frequency $f_p = 5 \cdot f_0 = 8.5$ GHz ($\omega_p = 5\omega_{ew0} = 5.35 \cdot 10^{10}$ rad/s), the plasma density $n_e = 9{,}1 \cdot 10^{11}$ cm^{-3}.The spectra of E_z and E_r have noises components between the frequencies f_0 and f_p and the high amplitude double components near the frequency f_p inside plasma (figure 3a). In point number 2 (Figure 3b) the amplitude at the signal frequency f_0 is best visible in spectrum of E_z, but the low-frequency components, the harmonics $2f_0$, $3f_0$ and noises with small amplitude is visible from f_0 till f_p. The amplitude of the low-frequency noise component is the biggest in the spectrum of E_r as for the rest spectrum of E_r is near the same the spectrum of E_z.



(a) (b)

Figure 3. Electromagnetic wave spectra in non-linear mode in: (a) point 1, (b) point 2.

The signal spectra of the linear plasma antenna operation mode are presented in figure 4. The plasma parameters in this mode are the plasma frequency $f_p = 10 \cdot f_0 = 17$ GHz ($\omega_p = 10\omega_{ew0} = 10.7 \cdot 10^{10}$ rad/s) and the plasma density $n_e = 3.6 \cdot 10^{12}$ cm^{-3}. The Langmur frequency component f_p has the biggest amplitude in E_r spectrum inside plasma (Figure 5a), other components have smaller amplitudes than the f_p component. The components of the 6.1 GHz, f_p and f_0 are the best visible in the E_z spectrum, they amplitude are smaller than the amplitude E_r at f_p. This antenna operating mode is a linear because the f_0 spectrum component is the biggest for E_z and E_r signal spectra in the near antenna field (figure 4b). The spectrum component at the frequency f_0 is bigger than 2 f_0, 6.1 GHz, f_p components in figure 4b and f_0 components in figure 3b. Let us note, that the field of the quarter wave dipole antenna has structure of a TM-mode and in the radiation direction of the dipole antenna $E_r|_{r=\infty} = 0$.



(a) (b)

Figure 4. Electromagnetic wave spectra in linear mode in: (a) point 1, (b) point 2.

4. Conclusions

PIC antenna model confirmed the relationship obtained in the Drude model of three plasma antenna operating modes to the terms of propagation of a surface wave [8,9]. It also allowed to study the effect of plasma oscillations in the radiated signal. It was showed in the present work that inside the plasma Langmuir oscillations with the frequency f_p and high-frequency harmonics of the input signal are excited in all antenna operating modes. The field components amplitude at the plasma frequency exceeds the amplitude at the frequency f_0 inside plasma in the non-radiative and non-linear modes. The biggest amplitude of the radiated signal spectrum is at the carrier frequency f_0 in the linear mode, but there is high-frequency noises in the band from f_0 to f_p. Parameters of the plasma antenna are changed in a wide range in linear mode. Energy losses of the input signal are due to the excitation of Langmuir oscillations in the plasma.

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