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 has not 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 $\tau_i=15$ ns and the carrier frequency $f_0=1.7$ GHz ($\omega_{0}=1.07\times10^{10}$ rad\cdot 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).](image-url)

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3. Simulation results and discussion

In this chapter I will discuss the spectra of the electromagnetic fields components $E_z$ 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 $f_p = 2 \cdot f_0 = 3.4 \text{ GHz}$ ($\omega_p = 2\omega_{\text{e}0} = 2.14 \cdot 10^{10} \text{ rad/s}$) and the plasma density $n_e = 1.4 \cdot 10^{11} \text{ cm}^{-3}$. 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 $E_z$ 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.

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 $f_p = 5 \cdot f_0 = 8.5 \text{ GHz}$ ($\omega_p = 5\omega_{\text{e}0} = 5.35 \cdot 10^{10} \text{ rad/s}$), the plasma density $n_e = 9.1 \cdot 10^{11} \text{ cm}^{-3}$. 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 $E_z$. 

![Figure 2](image2.png)

**Figure 2.** Electromagnetic wave spectra in non-radiative 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 $f_p = 10 \cdot f_0 = 17 \text{ GHz}$ ($\omega_p = 10\omega_{\text{sw}} = 10.7 \cdot 10^{10} \text{ rad/s}$) and the plasma density $n_e = 3.6 \cdot 10^{12} \text{ cm}^{-3}$. The Langmuir 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 $2f_0$, 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 $E_r \big|_{r=\infty} = 0$.

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

**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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