Simulation of propagation of the HPM in the low-pressure argon plasma

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Abstract
The propagation of the high-power microwave (HPM) with a frequency of 6 GHz in the low-pressure argon plasma was studied by the method of fluid approximation. The two-dimensional transmission model was built based on the wave equation, the electron drift-diffusion equations and the heavy species transport equations, which were solved by means of COMSOL Multiphysics software. The simulation results showed that the propagation characteristic of the HPM was closely related to the average electron density of the plasma. The attenuation of the transmitted wave increased nonlinearly with the electron density. Specifically, the growth of the attenuation slowed down as the electron density increased uniformly. In addition, the concrete transmission process of the HPM wave in the low-pressure argon plasma was given.

Keywords: low-pressure argon plasma, high-power microwave, protection application

(Some figures may appear in colour only in the online journal)

1. Introduction
High-power microwave (HPM) weapons, which are destructive to electronic systems, have developed rapidly due to the significant progress of HPM devices [1]. As a result, various protection methods against the HPM pulses appear, among which the means based on plasma is potentially effective [2].

Plasma is usually a collection of a number of charged and neutral particles, its electromagnetic propagation characteristics being closely related to the intensity of the incident wave. Typically, when the incident wave is strong enough, it can hardly propagate in the plasma due to the further ionization caused by the intense electric field. Baeva found that the ignition of the gas breakdown was characterized by the sharp drop of the electric field in an experiment of pulsed micro-wave discharge in the low-pressure oxygen [3]. Bonaventura observed that the incident microwave could be dumped by the plasma ignited in the nitrogen [4–6]. Starodubtsev noticed that the microwave would decay into the plasma due to the nonlinear interaction of the pulsed microwave with the plasma [7]. Yuan obtained that the gas breakdown would result in the enhancement of the microwave reflection and the decrease of the transmission [8]. Song explained that the plasma generated by the gas breakdown on the coupling slit of the HPM combiner would induce the absorption of the microwave energy and the rotation of microwave polarization [9].

While the above work mainly focused on the plasma generation in microwave discharge, the impact of the plasma on the HPM propagation was not deeply studied, and the relationship between the HPM attenuation and the plasma state still needed uncovering. In this paper, we first established a physical model of the HPM propagation in the low-pressure argon plasma with the fluid approximation method. Then we analyzed the HPM transmission in the plasma of different parameters, the connection between the attenuation value and the electron density being given. Finally, based on the calculation results, we discussed the concrete transmission process of the HPM with a frequency of 6 GHz.

2. Calculation method
Due to the special state of matter and the internal particle distribution, it is not easy to describe the plasma properties completely and accurately. So while calculating the attributes
of the plasma, approximate processing methods, e.g. the dielectric approximation method, the partial particle simulation method and the fluid approximation method, are widely used.

In the dielectric approximation method, the plasma is regarded as an ordinary dielectric with specific parameters, whose properties are analyzed by solving the interaction between the electromagnetic wave and the plasma. This method is relatively simple in calculation, though it only applies to weak electric fields and its computational error is relatively large. The particle simulation method [10] can describe the plasma state actually since it tracks the motions of a large number of charged particles in the plasma. However, it involves a lot of computation resources and is time consuming. In the fluid approximation method [11, 12], the plasma is taken as a conducting fluid, ignoring the existence of single particles while emphasizing the collective behavior. It is very useful to analyze the macroscopic characteristics of plasma with a fast calculating speed and small computational errors.

In this paper, we adopt the fluid approximation method to study the HPM transmission characteristics in the plasma based on the wave equation, the electron drift-diffusion equations and the heavy species transport equations.

2.1. Wave equation

The propagation of a plane electromagnetic wave in the plasma can be described by the wave equation [8] in the form of

$$\nabla \times \nabla \times \mathbf{E} - k_0^2 \varepsilon_r \cdot \mathbf{E} = 0,$$  \hspace{1cm} (1)

where $\mathbf{E}$ is the electric field of the incident wave, $k_0$ is the wave number in the free space, and $\varepsilon_r$ is the plasma’s relative dielectric coefficient given by

$$\varepsilon_r = 1 - \frac{\omega_p}{\omega (\omega - i\nu)}.$$  \hspace{1cm} (2)

Here $i$ is the complex unity, $\omega$ is the incident wave’s angular frequency, $\omega_p$ is the plasma frequency and $\nu$ is the electron collision frequency.

2.2. Electron drift-diffusion equation

The rate of change of the electron density can be calculated by the electron drift-diffusion equation [11, 12]

$$\frac{\partial}{\partial \tau}(n_e) + \nabla \cdot \mathbf{\Gamma}_e = R_e,$$  \hspace{1cm} (3)

$$\mathbf{\Gamma}_e = - (\mu_e \cdot \mathbf{E}) n_e - D_e \cdot \nabla n_e,$$  \hspace{1cm} (4)

where $n_e$ is the electron density, $\mu_e$ is the electron mobility, $D_e$ is the electron diffusivity, and $R_e$ is the electron rate expression, reflecting the electron generation and quenching caused by collision reactions. Supposing there are $M$ reactions contributing to the growth or decay of the electron density, $R_e$ can be computed by

$$R_e = \sum_{j=1}^{M} x_j k_j N_0 n_e,$$  \hspace{1cm} (5)

where $x_j$ is the mole fraction of the target species for reaction $j$, $k_j$ is the rate coefficient of reaction $j$ and $N_0$ is the total neutral number density.

2.3. Heavy species transport equation

Supposing a reaction flow consists of $k = 1, \ldots, Q$ species, the mass fraction of each species can be solved using [13]

$$\frac{\partial}{\partial \tau} (\omega_k) + \rho (\mathbf{u} \cdot \nabla) \omega_k = \nabla \cdot \mathbf{j}_k + R_k,$$  \hspace{1cm} (6)

where $\omega_k$ is the mass fraction of the $k$th species, $\rho$ is the density of the mixture and $\mathbf{u}$ is the mass averaged fluid velocity vector. $\mathbf{j}_k$ is the diffusive flux vector defined as

$$\mathbf{j}_k = \rho \omega_k \mathbf{V}_k,$$  \hspace{1cm} (7)

$$\mathbf{V}_k = D_{k,m} \frac{\nabla \omega_k}{\omega_k} + M_n \frac{\nabla M_n}{M_n} + \frac{D_k^T}{\rho \omega_k} \nabla T - z_k \mu_{k,m} \mathbf{E}.$$  \hspace{1cm} (8)

Here $D_{k,m}$ is the averaged diffusion coefficient of the mixture, $M_n$ is the mean molar mass of the mixture, $T$ is the gas temperature, $D_k^T$ is the thermal diffusion coefficient of species $k$, $z_k$ is the charge number of species $k$, and $\mu_{k,m}$ is the mixture averaged mobility of species $k$.

3. Calculation model

The main calculation work of this paper is completed with the simulation software COMSOL Multiphysics [14], especially in building the two-dimensional model of the HPM propagation in the plasma as shown in figure 1. The propagation direction of the HPM, whose intensity is characterized by the electric field, is chosen to be parallel to the $y$ axis. Argon, as the reaction gas, is filled inside the glass tubes with involved
species and reactions listed in table 1. Moreover, the perfectly matched layer and periodic structures are set to eliminate numerical reflection and diffraction, respectively.

In the calculation, we set the HPM frequency to be 6 GHz with the initial electric field intensity being 2.0 × 10^4 V m^{-1}. The electrons are assumed to be uniformly distributed in the plasma region and the initial electric field density is 1.0 × 10^{17} m^{-3}. The initial temperature and pressure of the plasma gas are given as 293 K and 3 Torr, and the inner and external diameters of the glass tube are respectively 2.5 cm and 2.6 cm.

### 4. Results and discussions

As mentioned above, the HPM would be interfered while it is incident on plasma. In order to show the phenomenon intuitively, we solve the distribution of the instantaneous electric field in the transmission model. The result is given in figure 2, where different colors represent different levels of the electric field. As can be seen from figure 2, the color of the air area below the plasma region gradually darkens as the time increases from 1.0 × 10^{-7} to 4.0 × 10^{-5} s, which reflects the decrease of the electric field due to the attenuation with the irradiation time going. Meanwhile, a standing wave field appears above the plasma region, indicating the existence of the reflected wave. At the moment of 2.0 × 10^{-6} s, the electric field becomes nearly zero and the standing wave pattern becomes much clearer. It can be inferred that at this moment the incident wave cannot transmit through the plasma region with most energy reflected.

The time dependence of the averaged energy density (including the forward and backward energy) at the incident boundary and the outgoing boundary is shown in figure 3. As can be seen in the figure, we divide each curve into three parts according to the trend. In period I (0–1.0 × 10^{-7} s), the two curves remain relatively stable, from which it can be inferred that at this time the HPM can propagate in the plasma with a small energy loss. In period II (1.0 × 10^{-7}–1.0 × 10^{-5} s), we can see that the two curves change dramatically, reflecting that the effect of plasma becomes more and more severe. During this time, while the HPM transmits through the plasma region, most of the energy is lost. In period III (1.0 × 10^{-5}–1.0 × 10^{-2} s), the energy density at the outgoing boundary approaches zero while the value at the incident boundary becomes nearly twice the initial one. Obviously, at this time most energy has been reflected and the HPM can hardly propagate in the plasma region.

The time dependence of the averaged electron density is shown in figure 4. In this figure, the mean value is plotted because the distribution of electrons in the plasma becomes inhomogeneous during the HPM excitation time. It can be seen from the figure that in period I, the averaged electron density roughly stays at 1.0 × 10^{17} m^{-3}, and increases rapidly from 1.0 × 10^{17} to 1.0 × 10^{20} m^{-3} in period II and III. We can infer that the internal collision reactions, especially the inelastic collision reactions which result in the electron generating, are rather small at the initial time, and become more and more severe with the accumulation of absorbed energy of the HPM. Besides, by examining figures 3 and 4, it can be concluded that the attenuation of transmitted wave is relevant to the plasma electron density.

The correlation between the transmitted wave attenuation and the plasma electron density is shown in figure 5. It can be seen from the figure that the attenuation caused by the absorption and reflection in the plasma becomes large while the electron density increases, with the changing being nonlinear. Specifically, the attenuation value increases rapidly when the electron density is relatively small (1.0 × 10^{17}–5.0 × 10^{19} m^{-3}), and then the growth of the attenuation slows down as the electron density increases.

Accordingly, we can obtain the concrete transmission process of the 6 GHz HPM in the low-pressure argon plasma, which is described as follows.

1. In period I (0–1.0 × 10^{-7} s), the internal collision reactions stay at a low level, and the plasma electron density remains about 1.0 × 10^{17} m^{-3}. The energy absorption of about 1 dB plays a primary role in the attenuation of the transmitted wave, indicating that the HPM propagates in the plasma with little energy loss.

2. In period II (1.0 × 10^{-7}–1.0 × 10^{-5} s), the collisions (especially the inelastic collisions) in the plasma become severe, which leads to the rapid growth of the electron density from 1.0 × 10^{17} to 5.0 × 10^{19} m^{-3}. In this phase, the averaged electron density becomes larger than the critical one (which can be calculated by \( N_e = 1.24 \times 10^{-2} \rho^2 \), and is 4.464 × 10^{17} m^{-3} for the 6 GHz microwave). Meanwhile, the energy absorption in the plasma further increases due to the ionization. As a consequence, the reflection appears and rapidly grows, resulting in that the attenuation value of the transmitted wave increases sharply from 2 to 35 dB. At this moment, while the HPM is projected on the plasma, a notable part of its energy would be reflected back.

3. In period III (1.0 × 10^{-5}–1.0 × 10^{-2} s), the ongoing collisions cause the electron density to increase consistently from 5.0 × 10^{19} to 1.0 × 10^{20} m^{-3}. The reflection of the incident energy becomes dominant with a small part absorbed. As a result, the transmitted wave continues to decrease with most energy reflected.

### Table 1. Formula and type of collision reactions inside the argon plasma.

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Formula</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>e + Ar ( \Rightarrow ) e + Ar</td>
<td>Elastic</td>
</tr>
<tr>
<td>2</td>
<td>e + Ar ( \Rightarrow ) e + Ars</td>
<td>Excitation</td>
</tr>
<tr>
<td>3</td>
<td>e + Ars ( \Rightarrow ) 2 e + Ar^+</td>
<td>Ionization</td>
</tr>
<tr>
<td>4</td>
<td>e + Ar ( \Rightarrow ) 2 e + Ar^+</td>
<td>Ionization</td>
</tr>
<tr>
<td>5</td>
<td>Ars + Ars ( \Rightarrow ) e + Ar + Ar^+</td>
<td>Penning ionization</td>
</tr>
<tr>
<td>6</td>
<td>e + Ar^+ ( \Rightarrow ) Ar</td>
<td>Recombination</td>
</tr>
<tr>
<td>7</td>
<td>Ars ( \Rightarrow ) Ar</td>
<td>Surface reaction</td>
</tr>
<tr>
<td>8</td>
<td>Ar^+ ( \Rightarrow ) Ar</td>
<td>Surface reaction</td>
</tr>
</tbody>
</table>
and the HPM can hardly transmit through the plasma region.

5. Conclusions

In this paper, we studied the propagation of the HPM in the low-pressure argon plasma based on the fluid approximation method. With the help of the software COMSOL Multiphysics, we established the two-dimensional model of HPM propagation in the plasma and investigated the transmission characteristics.

We found that the electron density increased fleetly during the HPM irradiation period, which led to the sharp change of the plasma state. Moreover, it was given that the incident wave would be decayed in the propagation, and the attenuation was closely relevant with the plasma state. In detail, the attenuation would become large with the increase of the electron density. While the electron density was about $1.0 \times 10^{17} \text{ m}^{-3}$, the attenuation value was quite small (about 1 dB), and the 6 GHz
HPM could propagate in the plasma with little loss. While the electron density varied from $1.0 \times 10^{17}$ to $5.0 \times 10^{18} \text{m}^{-3}$, the attenuation value increased from 2 to 35 dB, and the 6 GHz HPM would transmit with a considerable part of energy reflected. While the electron density continued to increase, most energy of the incident wave would be reflected and the 6 GHz HPM nearly could not pass through the plasma.

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References