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A Model for Antenna-Plasma Wave Coupling towards Control of Uniformity in Slot-Excited Microwave Discharges

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A surface wave plasma device using the slot plate with a few slots sometimes exhibits a jump or hysteresis behavior of plasma profiles when the input power is changed. On the other hand, a multi-slot excited plasma device, in which the slot plate has slot openings of more than 1000, has produced uniform plasmas with smooth change in densities for a wide range of the input power and gas pressure. It is important to control the spatial profile of the radiated waves for uniform and stable plasma production in slot-excited microwave discharge devices. The radiated wave profile can be calculated by several numerical methods. However, the calculation cost is high. The purpose of this study is to establish a simple analysis model. In this model, the mode spectrum of the radiated wave field is obtained by convolving the mode spectra of the incident waves formed in the antenna cavity and the aperture function of the slot plate. The calculation results are compared with experimentally measured values and full-wave calculations. These trends have a good agreement in the viewpoint of the mode spectra.

Keywords: microwave discharges, surface wave eigenmode, multi-slotted planar antenna, mode spectrum

1. Introduction

It has been known that slot-excited microwave discharges can produce plasmas suitable for plasma-aided manufacturing that requires large area, low damage and high speed processing. In the slot-excited device, the microwave propagates through a waveguide, a cavity space, a slot plate and a dielectric window and is supplied to the plasma. Surface wave plasma (SWP) device often uses the slot plate with a few slots resulting in the jump or the hysteresis behavior of plasma profile when the input power is changed [1]. On the other hand, multi-slot excited plasma (MSP) device, in which the slot plate has slot openings of more than 1000, has produced uniform plasmas with smooth change in the densities for a wide range of the input power and gas pressure [2].

We consider the reason for the difference between the SWP and the MSP in the plasma production. In both plasmas, the plasma is mainly produced by the surface waves and/or enhanced microwave fields due to the resonant absorption arisen just under the dielectric window [3]. When the plasma is produced in the chamber with the cylindrical structure, the plasma profile is determined by the spatial structure of the waves characterized by the azimuthal mode number m and the radial mode number n. If the multiple modes of (m, n) are excited by the slot antenna, the plasma selects one mode for one value of the densities. As a result, the modes of the waves change as the input power is changed. This is the case of the SWP. In the case of the MSP, it is expected that these problems can be prevented by controlling the spatial structure of the waves.

The wave profile can be calculated by several numerical methods, for example, three-dimensional finite-difference time-domain (FDTD) scheme with proper model of the antenna cavity, the slot plate, the plasma and so on. It is, however, time-consuming and not suitable for the analytical consideration. The purpose of this study is to establish a simple analysis model that relates the incident wave formed in the antenna cavity to the wave profile radiated to the plasma. The calculation results by the model are compared the mode spectra observed in the experiments. These trends have a good agreement in the viewpoint of the mode spectra.

2. Experimental equipments

Figure 1 shows the experimental equipment schematically. A discharge chamber has the radius of R = 250 mm and the depth of 380 mm and a quartz window with the same diameter and the thickness of 30 mm is set on the top. The multi-slotted planar (MSP) antenna is set above the quartz window and it is used to radiate the microwave driven at $\omega/2\pi$ = 2.45 GHz. The antenna system consists of some components connected to the microwave source, the slot plate with the concentric array of the slots and a back plate. We use the cylindrical waveguide with a polarizer for the rotating TE_{11} mode excitation [4]. A quadruple three stub tuner is set between the polarizer and the slot antenna to prevent the power reflected from the antenna or the plasma from going back

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into the polarizer. The slots are 23 - 26 mm in length, 2 mm in width and 4 mm in slot interval in the radial direction and about 1000 slots on the MSP antenna are distributed on the whole region except the central part. Ar gas pressure p_{Ar} is controlled in the range of 10 - 300 mTorr and the flow rate is set at 100 sccm. The plasma parameters are measured by a radially fast-scanning Langmuir probe. The two-dimensional distribution of the light emission from the plasma is monitored using the charge-coupled device (CCD) camera located beneath a substrate stage.

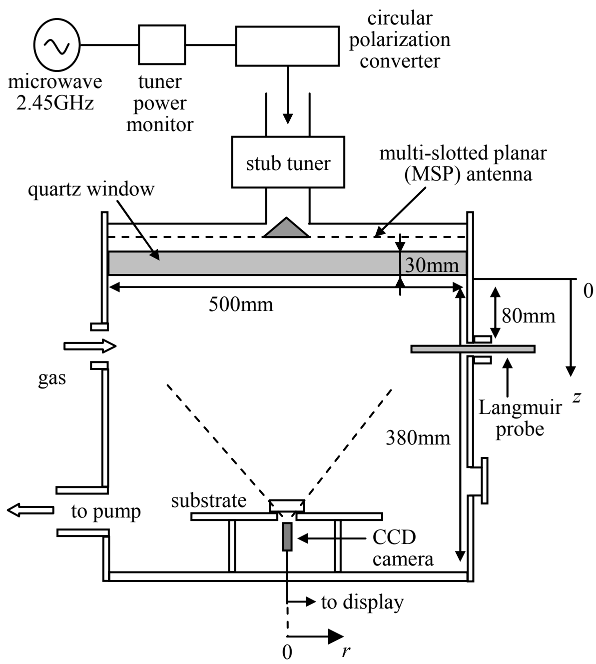

Fig. 1. An experimental equipment.

3. The mode spectrum

In the cylindrical geometry, the wave distribution on the $r\theta$ -plane for the transverse magnetic (TM) waves is given by

$$E_z(r,\theta)=\sum_{m=0}^{\infty}\sum_{n=1}^{\infty}\left(A\cos m\theta+B\sin m\theta\right)\mathrm{J}_m(j_{mn}\frac{r}{R}), \qquad (1)$$

where A and B are constants, R is inner radius of the plasma chamber, r is the radial position, θ is the azimuthal angle and j_{mn} is n-th zero point of the Bessel function J_m [3]. The dispersion relation of the surface wave eigenmodes for TM waves in the cylindrical plasma approximated by a simple 2-layer model which consists of the dielectric window and the plasma layer is given by

$$\frac{p_1}{\varepsilon_1}\tanh(p_1 h)+\frac{p_2}{\varepsilon_p}=0 \quad \text{and} \qquad (2)$$

$$\frac{q_1}{\varepsilon_1}\tan(q_1 h)-\frac{p_2}{\varepsilon_p}=0, \qquad (3)$$

where $p_1=\sqrt{\lambda^2-k_0^2\varepsilon_1}$, $p_2=\sqrt{\lambda^2-k_0^2\varepsilon_{\mathrm{p}}}$, $q_1=\sqrt{k_0^2\varepsilon_1-\lambda^2}$, $\varepsilon_1=4.0$, $\varepsilon_{\mathrm{p}}=1-(\omega_{\mathrm{pe}}/\omega)^2$, $k_0=\omega/c$, $\lambda=j_{mn}/R$, $h=0.03$, ε_1 is a dielectric constant of the quartz window, ω_{pe} is plasma angular frequency, c is the velocity of light, h is the thickness of the quartz window [3]. Equations (2) and (3) represent dispersion equations of pure and hybrid modes, respectively. It is reported that the plasma produced by a few slots antenna device has various surface wave eigenmodes [1]. Therefore, it is expected that the plasma produced by the few slot antenna will take place jumps at specific densities. On the other hand, in case of the plasma produced by the MSP device, the main component of the radial mode number measured by the analysis of the brightness pattern is 4 - 6 [4].

4. Electromagnetic field calculations

The electromagnetic fields can be calculated by several numerical methods. We use two-dimensional FDTD scheme for the cylindrical geometry. Figure 2 shows the device geometry used in the calculation. The device consists of the antenna cavity, the slot plate, the quartz window and the plasma chamber. In Fig.2, d_{a} and d_{air} show the distance between the top surface of the antenna cavity and the top surface of the quartz window and the distance between the bottom surface of the slot plate and the top surface of the quartz window, respectively. In this model, the slot plate has 10 slots with the ring structure and the width of the slot and the interval of the adjacent slots are 10 and 10 mm, respectively. This method solves the Maxwell equations, the equation of the current density for the electrons and the equation of motion for the electrons given by

$$\nabla\times\boldsymbol{H}=\boldsymbol{J}+\varepsilon_0\varepsilon\frac{d\boldsymbol{E}}{dt}, \qquad (4)$$

$$\nabla\times\boldsymbol{E}=-\mu_0\frac{d\boldsymbol{H}}{dt}, \qquad (5)$$

$$\boldsymbol{J}=-en_{\mathrm{e}}\boldsymbol{v}_{\mathrm{e}} \quad \text{and} \qquad (6)$$

$$m_{\mathrm{e}}\frac{d\boldsymbol{v}_{\mathrm{e}}}{dt}=-e\boldsymbol{E}-m_{\mathrm{e}}\nu_{\mathrm{m}}\boldsymbol{v}_{\mathrm{e}}, \qquad (7)$$

where $\boldsymbol{H}$, $\boldsymbol{E}$, $\boldsymbol{J}$, $\boldsymbol{v}_{\mathrm{e}}$, ε_0, ε, μ_0, e, n_{e}, m_{e} and ν_{m} represent the magnetic fields, the electric fields, the current density, the velocity of the electrons, the permittivity in the vacuum, the relative permittivity of the medium, the permeability in the vacuum, the electron charge, the electron density, the mass of the electron and the momentum transfer collision frequency, respectively. The calculation is performed by assuming m = 1 because m is fixed to be 1 by the waveguide in the experiments. The microwave source for TE_{11} mode excitation is set on the top face of the waveguide. The electron density in the plasma has the density gradient in the z-direction and the plane of $\omega=\omega_{\mathrm{pe}}$

is set at z = 15 mm, where ω_{pe} represents the electron plasma angular frequency. Figure 3 shows the distribution of the electric fields E_z on $\omega = \omega_{pe}$ plane in case of d_{air}= 3 mm.

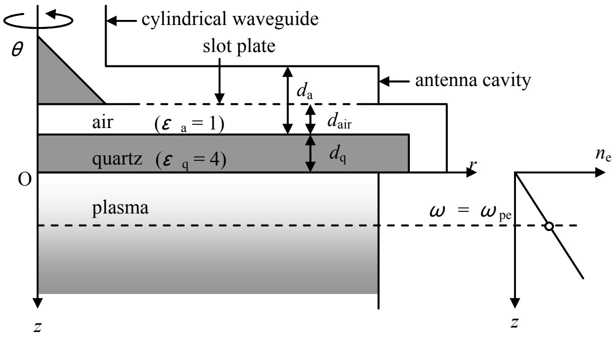

Fig. 2. The device geometry used in the calculation.

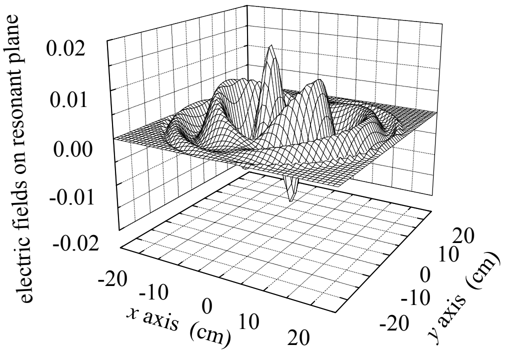

Fig. 3. The electric field distribution on the resonant plane in case of d_{air} = 3 mm.

Figure 4 shows the relation between d_{air} and the radial mode number n of E_z on $\omega = \omega_{pe}$ plane, where d_{air} is varied from 0 to 39 mm. The mode spectra for the n are calculated from $E_z(r)$ by the Fourier-Bessel transform in case of m = 1. In general, the results show the main spectra and a few sub spectra. In this study, the arithmetic weighted mean is used to evaluate the shift of the peak position in the n-direction. In Fig.4, the squares show the arithmetic weight mean calculated from the n and the spectrum and the dashed line is the linear approximation line for the squares. The result shows that the n slightly decreases when the d_{air} increases. If the d_{air} increases, ε in the space becomes small. In general, the wavelength is inversely proportional to the square root of ε. Therefore, this phenomenon is explained that the decrease of n results from the increase of relative ε corresponding to d_{air}. However this calculation cost is high and it is somewhat hard to interpret the results because of the complexity of the device geometry. Therefore it is not suitable for the analytical consideration.

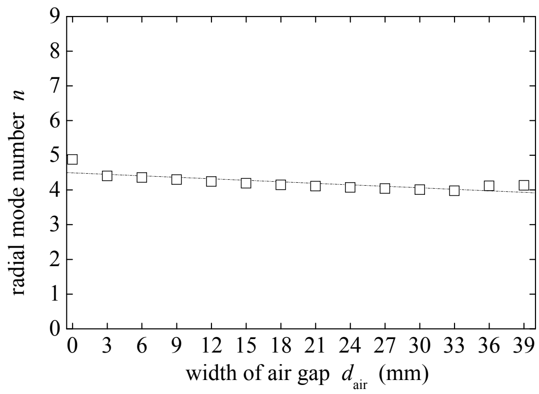

Fig. 4. The relation between the d_{air} and n.

5. Simple analysis model

The spatial structure of the waves is characterized by the mode numbers (m, n). We propose the simple analysis model. This model can immediately calculate the mode spectra of the radiated waves. First of all, the incident waves $a(r, \theta)$ formed just above the slot plate are calculated by using the FDTD scheme. In this calculation, the analysis space consists of the waveguide and the antenna cavity with a relative dielectric constant which is given as the average value of those of mediums forming the cavity space, the dielectric window and the space between them. The slot geometry is represented by the aperture function $g(r,\theta)$, where g is equal to 1 for the opening part and 0 for the other. In this study, the slot plate has 260 slots except the central part. The radiated waves in the real space $w(r, \theta)$ is defined by multiplying $a(r, \theta)$ by $g(r, \theta)$. Here we define the mode spectra for a, g and w as $A(m, n)$, $G(m, n)$ and $W(m, n)$, respectively. These mode spectra are calculated by the Fourier-Bessel transform

$$F(m,n) = \frac{1}{\pi R^2 J_{m+1}^2(j_{mn})} \times \int_0^R \int_{-\pi}^{\pi} f(r,\theta) \mathrm{J}_m\left(j_{mn}\frac{r}{R}\right) \exp(-im\theta)\, r dr d\theta, \quad (8)$$

where F and f represent the function in the wavenumber space and the function in the real space, respectively. In addition, the mode spectra of the radiated waves W are also obtained by the convolution of A and G;

$$W = A * G = \iint A(a,b)\, G(m-a, n-b)\, da db\,. \quad (9)$$

The n depends on a relative permittivity because the wavelength is inversely proportional to the square root of the relative permittivity in general. In this study, we define the relative permittivity as

$$\langle \varepsilon \rangle = \frac{d_a \varepsilon_a + d_q \varepsilon_q}{d_a + d_q} \tag{10}$$

where d_a, d_q, ε_a and ε_q represent the distance between the top surface of the antenna cavity and the top surface of the quartz window, the thickness of the quartz window, the relative permittivity of the air and the relative permittivity of the quartz window, respectively, as shown in Fig. 2. In the electromagnetic field calculation, the cavity space is filled with the dielectric material of $\langle \varepsilon \rangle$ to add the effect of $d_{air.}$ It is understood that $\langle \varepsilon \rangle$ depends on d_a in Eq. (10).

6. Comparison between experiments and calculations

Figure 5 shows the brightness pattern observed by the CCD camera and the plasma production condition is the rotating mode excitation, P_{in} = 1.51 kW and p_{Ar} = 200 mTorr, where P_{in} represents the input power of the microwave. We measured the n by the spectrum analysis. It is calculated by

$$P(r) = \sum_n A_n \mathrm{J}_1^2\left(\frac{j_{1n}}{R} r\right) + A_0 \quad \text{and} \tag{11}$$

$$Q = \sum_j \left\{ P(r_j) - E(r_j) \right\}^2, \tag{12}$$

where A_n is the mode spectra and $E(r)$ is the experimental value. The mode spectra A_n is defined by the least-square technique as Q becomes minimum The n is obtained the arithmetic weighted mean of the three major components of the spectrum. Figure 6 shows the relation between the average relative permittivity and the radial mode number. In Fig. 6, the squares are the arithmetic weighted mean, the continuous line is the linear approximation line of them, the dashed line is that of the simple calculation and the dotted line is that of 2D-FDTD as shown in Fig.4. Figure 6 shows that all results have same trends that the n increases when the average relative permittivity increases. In Fig. 6, the difference between the lines for the experimental results and the simple analysis model is smaller than 1. Therefore, the both results have a good agreement in the viewpoint of the n. On the other hand, the results of 2D-FDTD calculation including the plasma region are smaller than the experimental results. In general, it is known that the wavelength becomes short by the perturbative effect when the slots exist. In this calculation, many slots on the MSP antenna used in fact are approximately given by some slots with the ring structure. As a result, the relative permittivity of the space in the 2D-FDTD calculation including the plasma region may be smaller than the other. In Fig. 6, the difference between the result for the experiments and the 2D-FDTD calculation including the plasma region nearly equals to 1. Therefore, the simple model is effective to evaluate the antenna system although the calculation cost is lower than that of the general methods.

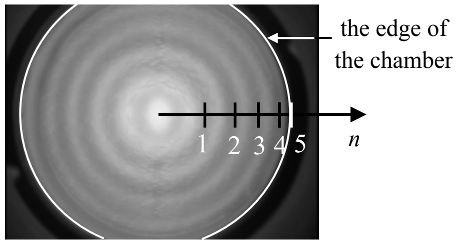

Fig. 5. The brightness pattern observed by the CCD camera.

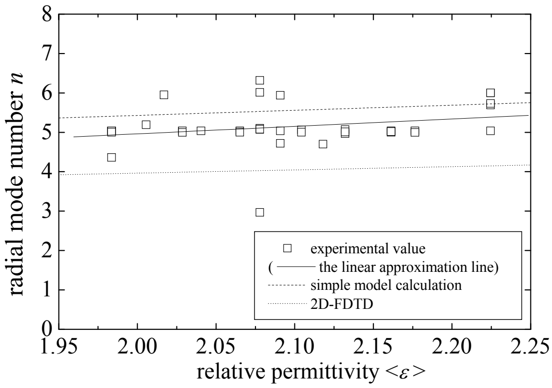

Fig. 6. The relation between the average relative permittivity and the radial mode number.

7. Summary

The spatial structure of the waves in the microwave discharges using the MSP antenna is investigated by the experimental measurements and the calculations. In the calculation, we have established the simple analysis model to compare with the full-wave model. On the other hand, the experiments show that the n is controlled by the relative permittivity which is the average value of the relative permittivity of the mediums forming the cavity space, the dielectric window and the space between them. The simple analysis model is applied to the analysis of the antenna system and the result is compared with the mode spectra observed in the experiments. These trends have a good agreement in the viewpoint of the n. The results of the experiments and the calculations have the same trend that the n increases when the $\langle \varepsilon \rangle$ increases. Therefore, the newly-proposed model is effective to evaluate the antenna system although the calculation cost is lower than that of the general methods.

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