18PB-110

Control of Cylindrical Cavity Excitation for Large-Area Microwave Plasma Generation
大面積マイクロ波プラズマの円筒キャビティ励起の制御

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Feasibility of a resonant cylindrical cavity of large diameter for generation of high-density uniform microwave plasma is investigated by FDTD simulation. Among many cavity resonances, TE_{111} mode is selected owing to the most uniform radial distribution of wave amplitude. The TE_{111} mode resonance field at 2.45 GHz is azimuthally rotated in the cavity by *dual injection* through two rectangular waveguides disposed with 90° apart in azimuth, thus promising a highly uniform plasma generation.

1. Introduction

Conventionally, microwave plasmas have been generated by electromagnetic waves radiating from slots on walls of rectangular and coaxial waveguides [1]. The excitation slots on the wall are usually located at a pitch of half a free-space wavelength (λ_0~12 cm at $\omega/2\pi$ =2.45 GHz) corresponding to the node or anti-node of standing wave in waveguide. As a result, a large-area plasma exited by the conventional microwave radiation has a non-uniformity of typical scale length of $\lambda_0/2$. To avoid such inhomogeneity, we propose to use a cylindrical cavity having a highly uniform electromagnetic filed, which enables keeping homogeneity and controllability of the generated plasma.

In this paper, we report, at a first step, a FDTD simulation of TE_{111} mode resonance of a cylindrical cavity which is excited by *single* or *dual* injection of 2.45 GHz microwave coupled with rectangular waveguide system. It is demonstrated in dual injection that microwave field can be azimuthally rotated in the cylindrical cavity.

2. Model of Cylindrical Cavity Excitation

In Fig.1, a cylindrical cavity of radius *a* and height *h* is excited by microwave injection through a coupling slot between the cavity wall and a rectangular waveguide of TE_{10} mode. In case of dual injection, the second waveguide is disposed at the azimuthal angle θ=90° apart from the first waveguide. Plasma in the future study will be generated by microwaves radiated from slots made at the bottom of this cylindrical cavity. The cavity radius is fixed at *a*=190 mm while the cavity height *h* is variable for optimization.

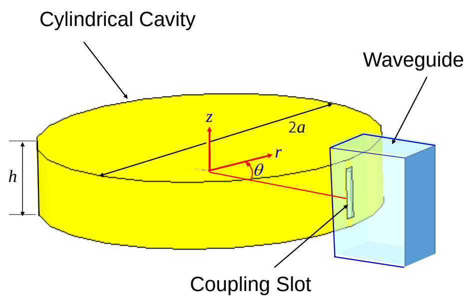

Fig. 1. Model of cylindrical cavity excitation.

3. Resonances in the Cylindrical Cavity

Figure 2 shows frequency spectrum of reflected power measured at the input port of the rectangular waveguide. It is seen in Fig. 2 that not only the

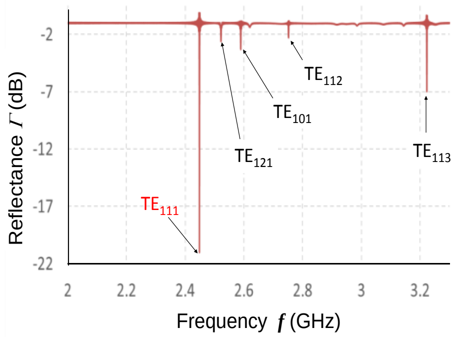

Fig. 2. Frequency spectrum of reflectance.

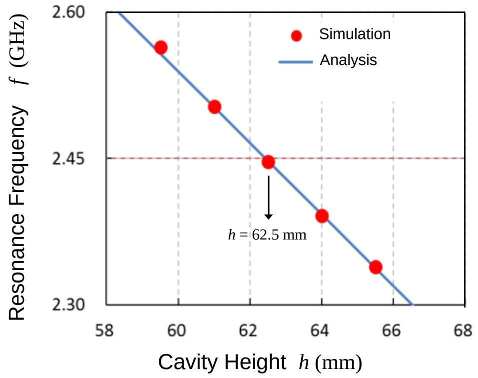

Fig. 3. Resonance frequency vs. cavity height.

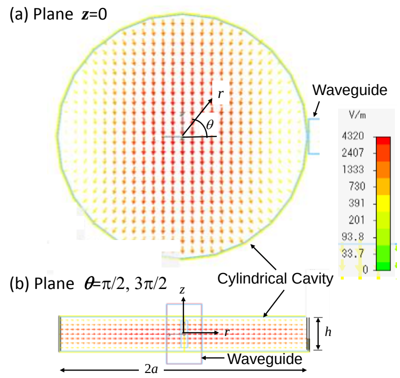

Fig. 4. Electric field vector distribution in cavity.

resonance of TE_{111} but also several other resonances are excited in the cylindrical cavity. The resonance frequency *f* of TE_{mnl} is given by

$$\left(\frac{c}{f}\right)^2 = \left(\frac{l}{2h}\right)^2 + \left(\frac{y_{mn}}{2\pi a}\right)^2 \qquad (1)$$

where *m*, *n*, and *l* respectively denote the mode number for *θ*, *r*, and *z* direction, and y_{mn} is the *n*th root for Bessel function J_m=0.

The TE_{111} mode is known to have the most uniform distribution of wave field in the transvers *r*-*θ* plane. Thus, we focus on the TE_{111} resonance whose resonance frequency is found to vary with the cavity height as shown in Fig. 3. The simulation result agrees very well with the analytical solution obtained from Eq. (1). Thus, it is concluded that the cavity height should be adjusted to be *h*=62.5 mm in order to generate the plasma at 2.45 GHz.

4. Distribution of Electromagnetic Field

Figure 4 shows the distribution of electric field vector of the TE_{111} resonance at 2.45 GHz, observed in a transvers plane *z*=0 (Fig. 4a) and a vertical plane θ=π/2, 3π/2 (Fig. 4b). The timing (wave phase) of observation is an instant of maximum amplitude. At the opposite phase, the direction of vector is reversed so that a standing wave is formed in the cavity by *single injection*. Both figures show highly uniform distributions of the electric field, promising a uniformity of a generated plasma in the future study.

As shown in Fig. 5, an anti-clockwise rotation of the electromagnetic field of TE_{111} mode at 2.45 GHz is observed in *dual injection* from two rectangular waveguides with a phase difference of π/2. Here the microwave is injected from the wave guide P at *θ*=0 and Q at *θ* = π/2, and the transvers distribution of wave amplitude at different wave phase (ωt) is shown by a color code which indicates the highest field by red and the lowest field by blue. This field rotation will provide azimuthal uniformity of the TE_{111} field distribution to guarantee a further uniformity of the generated plasma.

References

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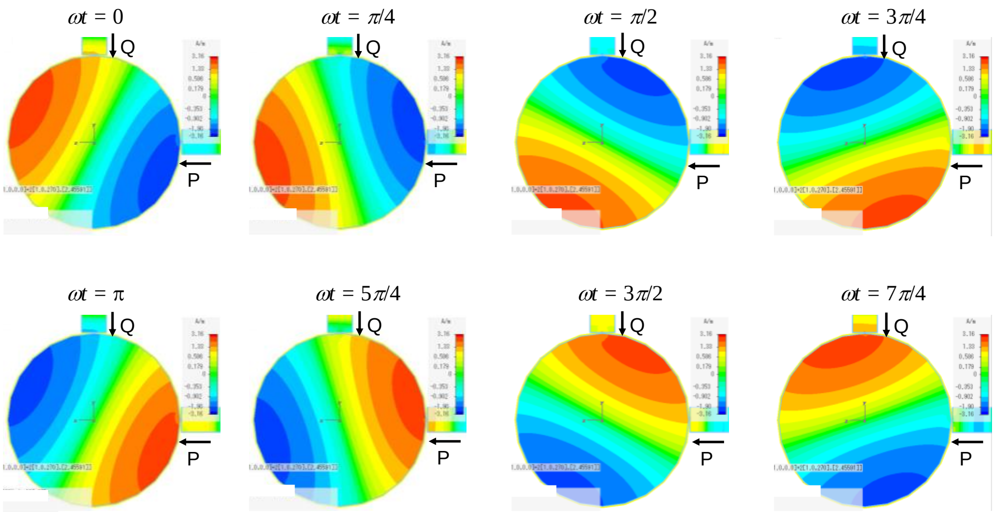

Fig. 5. Magnetic field profile on the plane *z*=0 for successive wave phase (ωt).