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大気圧下でのメートル級マイクロ波プラズマの生成と応用
Production and Application of Meter-Scale Microwave Plasma at Atmospheric Pressure

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1. Introduction

In recent years, application of non-thermal equilibrium atmospheric-pressure plasma to large surface treatment have been given much attention due to the expansion of demand for electronic products. For such purpose, uniform, high-density and large-scale plasma sources are required and atmospheric-pressure microwave plasma (APMP) sources are considered as one of promising candidates because they can produce high-density plasma easily. However, spatial uniformity of the APMP strongly depends on nonuniform electromagnetic field due to standing wave inside waveguide. To solve this issue, we developed a microwave plasma source where the propagating electromagnetic waves is realized in the waveguide suppressing the standing wave. Based on this concept, we have succeeded in producing atmospheric pressure plasma in the meter-scale slot. In addition, by modifying the cross-sectional structure of the waveguide from the symmetric rectangular to the asymmetric one, the electric field in the slot is enhanced, resulting in the molecular gas plasma production in a meter-scale [1]. So far, however, the optimization of the cross-sectional waveguide structure is still an issue, and optimization procedure is not clarified yet. Moreover, a power difference between the upstream and the downstream of the propagating wave along the slot is presumably induced by the plasma production. Such nonuniformity influences the plasma density uniformity along the slot, although such phenomena was not confirmed in our previous space-resolved measurements of the plasma density and the emission intensity [2].

In this study, the optimization procedure of the waveguide structure is explored by using three-dimensional electromagnetic field simulation. In the experiment, not only the microscopic measurement of the plasma in the slot but also its spatial distribution in the longitudinal direction of the slot is investigated by operating the microscope parallel to the slot.

2. Simulation for Waveguide Optimization

In the case of conventional rectangular waveguide with the symmetric cross-sectional structure and TE_{10} mode, the conduction current on the inner wall is also completely symmetric with respect to the center plane of the waveguide in parallel to the E-face. When a slot is cut along the longitudinal direction on one side wall of the waveguide, utilization of the transmitting microwave power is insufficient because only a half part of the symmetric surface current is utilized and opposite side of the surface current with respect to the plane of symmetry does not contribute to the plasma production. One of ideas to solve the above issue is to modify the configuration of the waveguide cross section from symmetric to asymmetric one. Asymmetric cross section can vary the ratio of two surface currents flowing in opposite sides and can enhance the surface current of one side for the better plasma sustainment. Based on this concept, microwave distribution in the waveguide is explored using an electromagnetic simulation.

In the simulation, three-dimensional electromagnetic simulation software (CST-STUDIO®) is used and the cross-sectional configuration of simulation model geometry of is shown in Fig. 1. To simplify the calculation, the slot is not included in the model. Instead, x component of the surface current density at x=0 mm (J_x) on E plane is evaluated. Our previous investigation, the optimum value a and b of the narrow part to enhance the surface current was explored when the waveguide width A=96 mm and the height B=27 mm. The calculated current

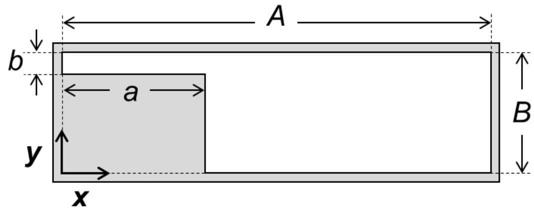

Fig. 1. Simulation model.

densities J_x were always their maximum at a = 32 mm in any value of b at a microwave frequency was 2.45 GHz.

Figure 2 shows the amplitude of the current density J_x as a function of b. The J_x increases monotonically, because the waveguide impedance of the narrow waveguide area becomes lower by decreasing the cross-sectional area of the waveguide. Figure 3 shows the optimum width a at which the current density J_x becomes its maximum as a function of the waveguide width A at a microwave frequency of 2.45 GHz. The optimum value of a does not depend on the wavelength of the microwave but depends only on the waveguide width A, and when the narrow part width a is about 1/3 of the waveguide width A (dashed line in Fig. 3), the current density J_x which contributes the electric field intensity inside the slot becomes the maximum.

3. Microscopic investigation of the plasma

3.1 Experimental Setup

In the experiment, the asymmetrical waveguide (width A: 96 mm, height B: 27 mm, width a: 32 mm, height b: 22 mm) with a narrow-gap long slot (width: 0.15 mm) and a waveguide length of 1.2 m is used. Argon gas is introduced into the waveguide from small holes on the side face of the waveguide. Both ends of the waveguide are gas-sealed by airtight windows. A microwave power at a frequency of 2.45 GHz is applied to the waveguide to generate the plasma inside the slot.

An optical bench is installed parallel to the waveguide, along which a microscope with a digital camera is movable. The magnification of the objective lens is 20 times. In the range of ±30 cm from the slot center, the structure of the plasma in the slot is investigated.

3.2 Results and Discussion

Firstly, the accuracy of the slot width along the longitudinal direction was confirmed to be 0.15 mm ±less than 5% by using the microscope. In this slot configuration, meter-length plasma was successfully produced at an Ar flow rate of 1.4 slm and a microwave power of 900 W. Plasma structure in the slot was evaluated using the optical microscope at slot positions from the upstream side to the downstream side. Figures 4 (a), (b) and (c) show the observed images at microwave power upstream side, at slot center, and at downstream side, respectively, at an exposure time of 1/40 s. The spatial emission profiles across the slot width direction show that the emission intensity is slightly increased near the edge, irrespective of the position along the long slot. Furthermore, the emission intensity along longitudinal direction was confirmed to be almost uniform with an intensity fluctuation less than ±5%.

In the presentation, surface treatment of organic matter removal as an example of applications of the slot plasma will be reported.

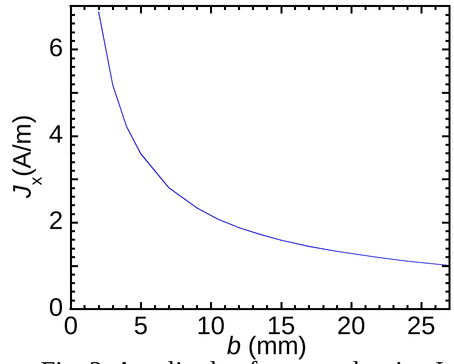

Fig. 2. Amplitude of current density J_x as a function of b at a=32 mm.

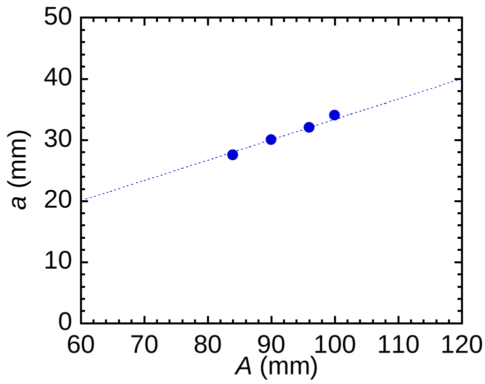

Fig. 3. Optimum width of a as a function of waveguide width A.

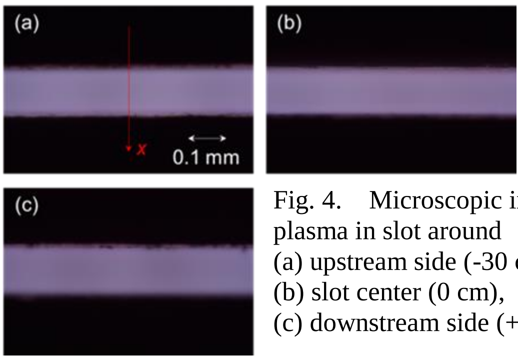

Fig. 4. Microscopic image of plasma in slot around
(a) upstream side (-30 cm),
(b) slot center (0 cm),
(c) downstream side (+30 cm).

Acknowledgement

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References

[1] H. Suzuki et al.: 69th Annual Gaseous Electronics Conf. NW3.7. (Bochum, 2016).

[2] Y. Tamura et al.: The 64th JSAP Spring Meeting (2017), 14p-P1-2.