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# Development of Line-Shaped Microwave plasma with Rectangular Slotted Waveguide at Atmospheric Pressure

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***Abstract—***

**In this study, line-shaped plasmas are generated with slotted waveguide at 2.45GHz at Atmospheric pressure. The waveguide is designed close to the cut-off condition of $TE_{10}$ mode and thin dielectric sheets are set in the slot to get a long wavelength in waveguide. Dielectric sheets contribute to decrease ignition threshold of plasma. Permittivity dependence of ignition threshold power for plasma was measured to confirm it.**

**Then an ignition test was performed modifying experimental conditions in terms of getting long line shape plasma based on the measurement results. As the result of the improvement, 23cm of the microwave line shaped plasma using He gas was archived**

**An experiment of plasma exposure to polycarbonate (PC) was performed and it was confirmed that generated plasma is effective for surface modification based on measurement result of water contact angle.**

### Introduction

Plasma is used in material processing in manufacturing industries such as a plasma etching, a film surface modification [1-3], and plasma chemical vapour deposition. In recent year, these users require that the plasma fulfil large area, good uniformity, high electron density and low electron temperature for an improvement of the performance. In addition high pressure plasma is required to transpose the low pressure plasma process. Atmospheric pressure plasmas do not require the use of any expensive pumps and they can suitable for use in some industrial fields such as several processing described above.

Microwave-excited plasma without external magnetic fields has the advantages that the plasmas have high electron density and low electron temperature in general [4].

The large-area plasma processing can be accomplished by scanning the line-shaped plasma over the area. This line shape plasma is applied in roll-to-roll process so called.

Also microwave plasma has advantages in high pressure region including atmospheric pressure because high density plasma is possible without the use of any metal electrodes.

Although microwave line shaped plasma has been investigated [5-7], there is no report that achieves microwave line shaped plasma in atmospheric pressure as we know. The higher pressure it is, the more difficult it is to generate plasma in general.

The objective of this present study is to generate line shaped microwave plasma in atmospheric pressure.

## I. EXPERIMENTS

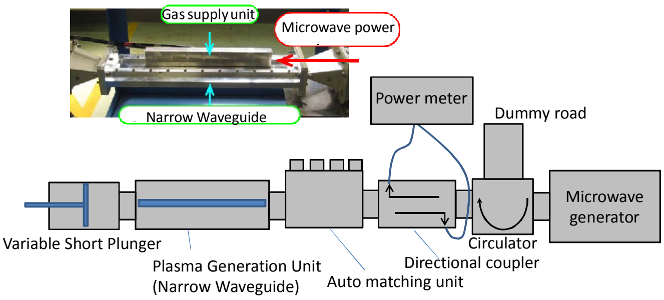


Fig. 1. Schematic illustration of experimental setup employed for generating microwave line plasma

The experimental setup which is employed for line plasma generation in atmospheric pressure is illustrated in Fig.1.The microwave power supply generates a frequency of 2.45GHz and its maximum output power is 1.0kW. Microwave power is transferred from power supply through an isolator and three-stab tuner to a slotted narrow waveguide for plasma generation and short circuit plunger. Due to short circuit plunger, standing wave arises in waveguide. Except the parts for plasma generation, waveguides are consisted of standard size. The narrow waveguide and standard size of waveguides are connected using tapered waveguides. Inner size of the waveguide is 500mm in length and 5mm in height. In order to provide a condition of long uniform line plasma generation, the widths of the waveguides are very close to the cutoff condition. In the rectangular waveguide the fundamental propagation mode is the transverse electric field $TE_{10}$. In case that there is no dielectric, magnetic material in rectangular waveguide, wavelength in wave guide is described as follows.

$$\lambda_g = \frac{\lambda}{\sqrt{1-(\lambda/2a)^2}} \quad (1)$$

In eq. (1) $\lambda_g$, $\lambda$ and $a$ are the wavelength in waveguide, wavelength in free space and width of the waveguide respectively. Calculated wavelength ($\lambda_g$) of microwave in the waveguide is shown in Fig.2.

Cross sectional diagram of narrow waveguide for plasma generation is shown in Fig.3. Dielectric plate is placed inner side of the waveguide slit as shown in Fig.3. Due to the plate, the ignition threshold of the plasmas become decrease and it avoid flowing into waveguide. If the width of the waveguide is 62mm, the wavelength is 776mm (or less because of dielectric plate). The He gas was supplied toward to outside of the dielectric plate to ignition and keep plasma.

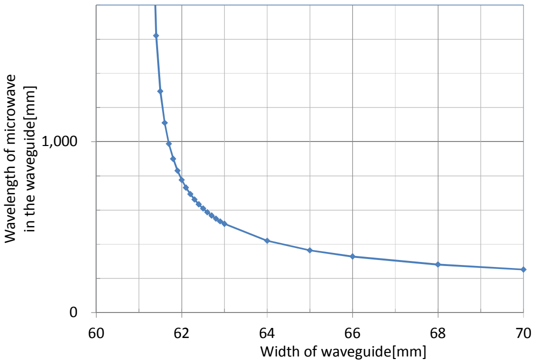


Fig. 2. Calculated of wavelength ( λ g) in the waveguide at 2.45GHz.

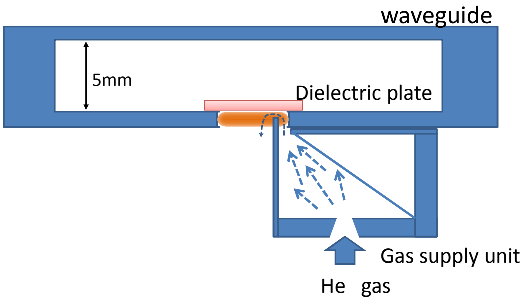


Fig. 3. Schematic illustration of cross section in waveguide

## II. RESULTS AND DISCUSSION

The experimental system established in this study contains dielectric sheets as the cover for the slot of waveguide. Dielectric sheets contribute to decrease ignition threshold of plasma. Permittivity dependence of ignition threshold power for plasma was measured to confirm it. Fig. 4 shows measurement results. Size and permittivity of dielectric sheets used for the measurement are shown in table1.When the permittivity goes up, ignition threshold power for microwave plasma goes down. In addition there is a trend that the wider waveguide is 62.8mm in width need higher ignition power.

The thinner dielectric plates in height are the better to avoid large effects on propagation mode and wavelength shortening in waveguide. For the same reason low permittivity substances have advantage for long-line plasma although higher ignition power is required. And also quarts sheet has lowest permittivity in this study can generate plasma using employed experimental setup.

An ignition test was performed changing experimental conditions in terms of getting long line shape plasma based on above discussion. A quarts sheet (400×5×t0.5mm) and waveguide is 61.8mm in width are employed. The result of the ignition test is shown in Fig.5. From the result 23cm of the microwave line shaped plasma using He gas was archived

In order to confirm generated plasma is effective for surface modification, an experiment of plasma exposure to polycarbonate (PC) was performed. With the expectation of improving of surface hydrophilicity[8], PC was exposed to microwave plasma with He / $O_2$ 1% gas mixture. Water contact angles were measured to evaluate improving of surface hydrophilicity. (Fig.6) As shown in Fig.6 the water droplet become flat and water content angle change to 29.2 degree due to plasma exposure.

Table 1. Dielectric sheets used for measurement of permittivity dependant of ignition power

| | Permitticity | Size[mm] | Manufacturer | Product ID |
|---|---|---|---|---|
| Quartz | 3.8 | 400×10×1t | – | – |
| Alumina | 10.2 | 400×10×1t | ASUZAK inc | AR-99.6 |
| Black Alumina | 16.7 | 400×10×1t | ASUZAK inc | AR(B) |
| Zirconia | 44 | 400×10×1t | ASUZAK inc | AZI |
| K-140[9] | 140 | 400×10×1t | KYOCERA | K-140 |

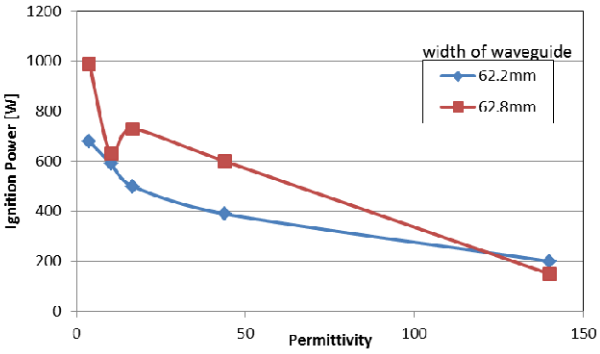


Fig. 4. Permittivity dependence of ignition threshold power for microwave plasma

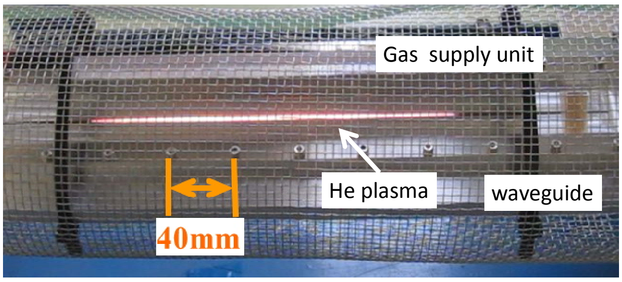
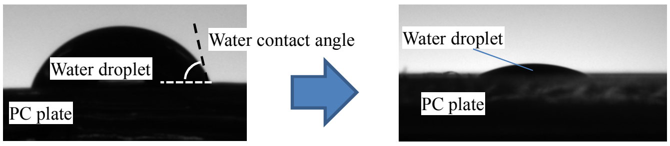


Fig. 5. Photograph of the microwave line shaped plasma in atmospheric pressure



before exposure after exposure

Fig. 6. Efficient of surface modification

## III. CONCLUSION

In this study, 23cm of the microwave line shaped plasma using He gas was archived. The waveguide was designed close to the cut-off condition of $TE_{10}$ mode and thin dielectric sheets were set in the slot to get a long wavelength in waveguide. In addition the effect of inducing hydrophilicity due to microwave plasma exposure to PC was confirmed. It is possible to extend a length of line plasma in theory as shown in Fig.2 and Eq.1. However it is expected that control of the plasma become difficult because plasma become sensitive to dimension error of waveguide. Therefore it is necessary to consider not only processing accuracy of waveguide but also heat expansion due to plasma and propagation loss of microwave.

## REFERENCES

[1] M. Nagatsu, A. Ito, N. Toyoda, and H. Sugai, “Characteristics of Ultrahigh frequency surface wave plasmas excited at 915 MHz, ” Jpn. J. Appl. Phys. Vol. 38, pp. L679-682, 1999.

[2] D. Krzec, M. Mildner, F. Hilleman, and J.Engemann, Surf. & Coat. Technol. Vol. 97, pp759, 1997 .

[3] M. Kaiser, K. M. Vaumgartner, A. Schulz, M. Walker, and E. Raushle, M. Wegmuller, J. P. von der Weid, P.Surf. & Coat. Technol. Vol.119, pp. 552, 1999.

[4] M. Umeno, et al., DSiamond and Related Materials 14(11-12), pp. 1973, 2005.

[5] T. Fukasawa, S. Fujii, and H. Shindo, “Long Line-Shaped Microwave Plasma Generation Employing a Narrow Rectangular Waveguide.” Jpn. J. Appl. Phys. 44, pp.1945-1950, 2005

[6] H. Shindo, et al. , proc. 17th Int. Conf. Gas Discharges, Cardiff, U.K. ,pp.417, 2008..

[7] Y. Kimura, H. Kawaguchi, S. Kagami, M. Furukawa, and H. Shindo, “A New Method of Line Plasma Production by Microwave in a Narrowed Rectangular Waveguide,” Jpn. J. Apply Phys. 2009

[8] J.Lai, B Sunderland, J. Xue, S. Yan, W. Zhao, M. Folkard, B. D. Michael, Y. Wang, “Study on hydrophilicity of polymersurfaces improved by plasma treatment”, App. Surface science 252, pp. 3375-3379,2006

[9] K. Fujiwara, M. Endo, Y. Ikeda, T. Suzuki, M. Ynagisawa, and H. Shindo, Vol.44,No.15,pp.457-460,2005