Filamentation of 2.45-GHz microwave discharge plasmas in sub-atmospheric pressure

Zentarou Sasaki[1], Tsubasa Saito[1], Takaharu Kamada[2], Katsuyuki Takahashi[1], Koichi Takaki[1] and Seiji Mukaigawa[1]

[1] *Iwate University, Ueda 4- 3-5, Morioka, Iwate 020-8551, Japan.*
[2] *National Institute of Technology Hachinohe College, Tamonoki Uwanotai 16-1, Hachinohe, Aomori 039-1192, Japan*

Abstract: Filamentary discharge plasmas were generated by 2.45-GHz microwave in a sub-atmospheric pressure. The filament length and thickness were measured. The results show that the maximum length, which is about half of the wavelength in the tube of a vacuum vessel considered a waveguide, is determined by a change in power balance due to circuit losses independent of pressure. Increasing pressure decreases the plasma volume but does not change the power consumption because the plasma density also increases.

Keywords: Microwave plasma, photonic crystals

1. Introduction

Plasma photonic crystals (PPCs), which are periodically arranged plasmas, have potential engineering applications for electromagnetic wave control devices. In this study, we generate filamentary structures using 2.45-GHz microwave discharge plasmas, which can generate high-density plasma, and study their plasma characteristics, bearing in mind the construction of PPCs designed to control electromagnetic waves near 10 GHz.

The radial contraction of plasmas at atmospheric pressure is often observed in microwave plasmas [1,2]. To obtain stable plasma filaments, filamentary discharges on electrode rods are generated using a method in which copper electrode rods are placed inside a cylindrical metal container as a cavity resonator under sub-atmospheric pressure with zero flow velocity. To control the filamentary structures, changes in microwave power balance and plasma filament length and thickness were measured in the pressure range of 200–900 hPa and microwave incident power range of 150–900 W. Plasma densities were also determined from emission spectroscopy.

2. Experimental set-up

Figure 1 shows a schematic of our experimental set-up. The microwave power supply comprises a control unit (JHF MKN-102-3S2-PS), a generator (JHF MKN-102-3S2-0SC), an isolator (JHF WUG-22M1), a directional coupler (JHF WDK-C-0295), a 3-stub matching device (JHF WMS-021XH2B) and a mode changer (WTM-TE10-TM01). Microwaves are introduced into a cylindrical vacuum vessel (as a cavity resonator). The microwave power is measured by a directional coupler, and the input power P is obtained by the difference between the incident power P_{inc} and the reflected power P_{ref} ($P = P_{inc} - P_{ref}$). He gas is introduced from the vacuum vessel's side and evacuated from its bottom by a rotary pump (ALCATEL Pascal 10).

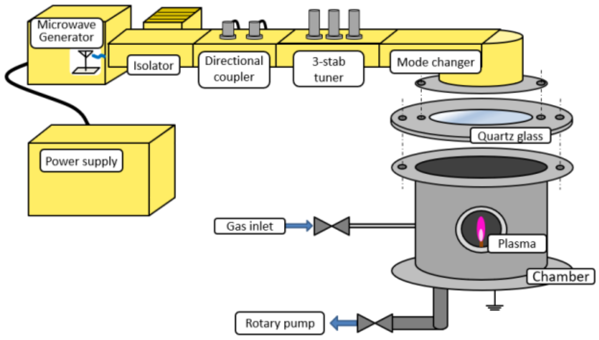

Fig. 1. Experimental set-up.

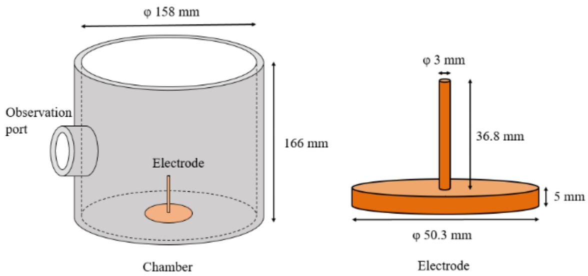

Fig. 2. Vacuum chamber (as a cavity resonator) and electrode.

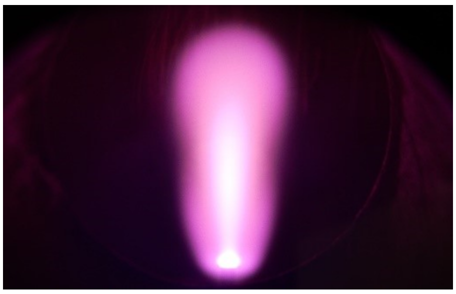

Fig. 3. Typical image of the microwave plasma filament.

Figure 2 shows the copper electrodes and their arrangement in the vacuum vessel. The vacuum vessel has an inner diameter and height of 158 and 166 mm, respectively, and is made of Type 304 stainless steel. It

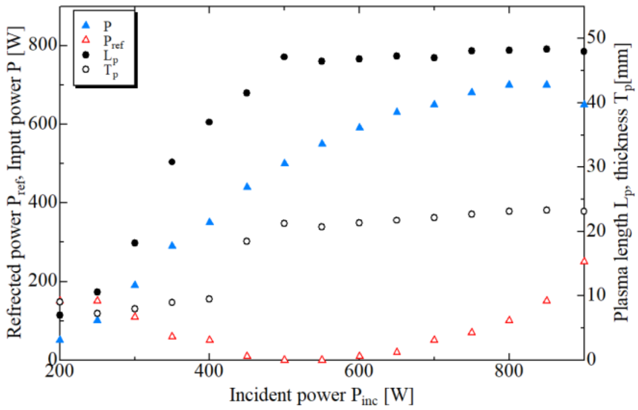

Fig. 4. Filament length L_p and filament thickness T_p.

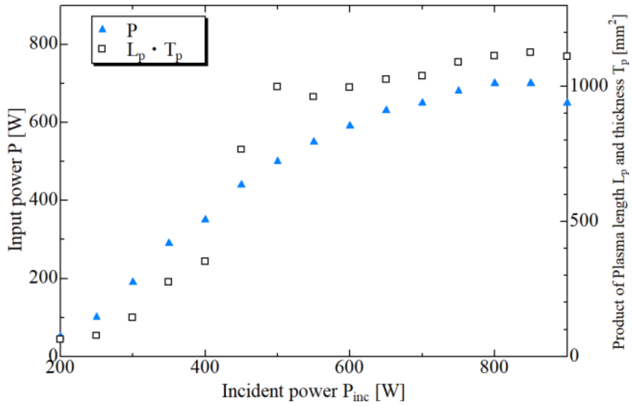

Fig. 5. Product of Filament length L_p and thickness T_p versus P_{inc} at 500 hPa.

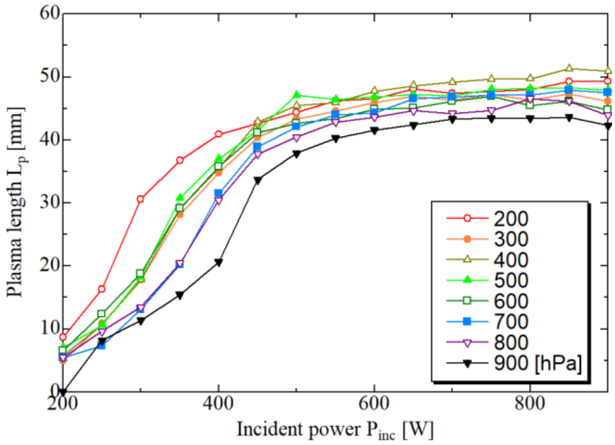

Fig. 6. Plasma length L_p at several sub-atmospheric pressures.

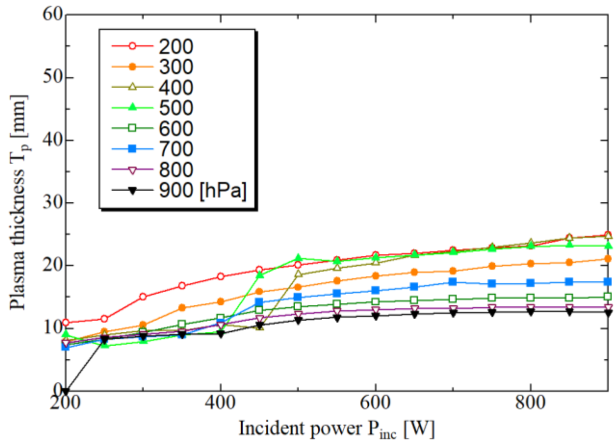

Fig. 7. Plasma thickness T_p at several sub-atmospheric pressures.

has two observation windows, which are used for digital imaging and spectroscopy. The copper electrodes comprise a supporting disc and a rod. The diameter and thickness of the disc are 50.3 and 5.0 mm, respectively, and the length and thickness of the rod are 3.0 and 36.8 mm, respectively. The electrode rod is placed at the centre of the lower part of the vacuum vessel and is electrically grounded.

Figure 3 shows a typical image of the generated microwave plasma filament at a 1,000-hPa pressure and a 450-W input power (500-W incident power and 50-W reflected power).

When microwaves are injected into the vacuum vessel, plasma filaments are generated on the electrode rods. The gas flow rate is zero. The filament length and thickness are obtained from images captured by a digital camera (NIKON Coolpix S9900), which are converted to 16-bit grayscale and binarised to separate the discharge region. Emission spectra are measured using a spectrometer (HAMAMATSU PHOTONICS C10027-01, 200–950 nm, FWHM < 2 nm). Excitation temperatures and electron densities are determined from the emission spectra. Excitation temperatures were determined by the two-line intensity ratio method using He 706 nm lines (20.96–22.72 eV, $1.83 \times 10^7\ \mathrm{s}^{-1}$) and He 587 nm lines (20.96–23.07 eV, $7.07 \times 10^7\ \mathrm{s}^{-1}$) [3]. Electron densities are derived by measuring the Stark width of the 706 nm He lines. The instrumental width and gas temperature are assumed to be 3.59 nm and 10,000 K, respectively.

3. Results

Figure 4 shows the reflected power P_{ref}, input power P, plasma length L_p and plasma thickness T_p versus the incident power P_{inc} at a 500-hPa vessel pressure. The power input increases gradually with increasing incident power, approaching 700 W. The reflected power is the same as that of the matching plasma at 500 W (vessel pressure: 500 hPa). The reflected power is 0 W at an incident power of 500 W (matching point) and increases as one moves away from the matching point. The plasma length is nearly constant in the incident power range of 500–900-W (saturation region), about 40–50 mm, whereas it decreases as the incident power decreases from about 450 to 200 W (transition region), and the plasma turns off when the incident power falls below

200 W. The plasma thickness remains thin in the transition region, whereas it becomes one step thicker at about 20 mm in the saturation region.

Figure 5 shows the curves of the product of filament length L_p and filament thickness T_p against the input power P, indicating a strong correlation. In the saturated region, the $L_p \cdot T_p$ product increases with power input P, but the curve is relatively flat.

Figures 6 and 7 show the plots of L_p and T_p at 200–900 hPa. Most of the plots are correlated with the input power P, and the values of L_p and T_p generally decrease with increasing pressure. At a 100-hPa pressure, a filament is formed, and a uniform discharge occurs; meanwhile, at 900 hPa and 200 W, the plasma turns off.

Figure 8 is a plot of the values of the $L_p \cdot T_p$ product at 200–900 hPa. The values are highly pressure dependent, and the value of the $L_p \cdot T_p$ product tends to decrease with increasing pressure, attributable to the increase in the mean free path and the change in the breakdown electric field due to the reduced pressure affecting the filament cross-sectional area.

Figure 9 shows the excitation temperature and electron density values obtained from the emission spectra. The excitation temperature is around 6,000 K and varies slightly. The electron density varies in the range of $4.81 \times 10^9 - 4.02 \times 10^{10}$ cm^{-3}, with mild increasing trend with increasing pressure. The pressure variation range, as well as the electron density variation range, is approximately one order of magnitude, suggesting that the electron density variation is due to the pressure-induced plasma contraction.

The electron density is low because the spectrometer system’s measurement range includes areas outside the filament region and a spatially averaged electron density is calculated. Because there is no significant change in the plasma density, the filament core is homogeneous, and the increase in filament length is attributable to the increase in core volume. The $L_p \cdot T_p$ product correlates well with the power input P, responding to pressure increase/decrease, and there is no pressure dependence of the incident and reflected power. The power consumption in the plasma is determined by the change in power balance due to circuit losses. In filament propagation, pressure also affects the length and thickness (and hence the volume) of the plasma. Meanwhile, the filament length takes a maximum value of about 50 mm to form a saturated region. When the vacuum vessel is considered a waveguide, the wavelength of 2.45-GHz microwaves in the tube, λ_g, is approximately 133 mm. The maximum value of about 50 mm is about half the wavelength in the tube (66.5 mm).

4. Conclusion

Filamentary discharge plasmas were generated by 2.45-GHz microwave irradiation in a sub-atmospheric pressure range of 200–500 hPa. The filament length L_p, the filament thickness T_p and the $L_p \cdot T_p$ product were investigated at 200–900 W incident power. The filament length is divided into two regions: transition and saturation. The filament length is proportional to the power in the former, whereas the filament length is stable at about 40–50 mm in the latter. The plasma filament size is determined by the change in power balance due to circuit losses independent of pressure. Increasing the pressure decreases the plasma volume but does not change the power consumption because the plasma density also increases.

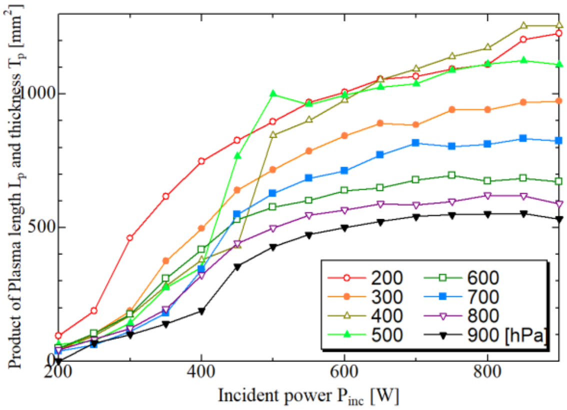

Fig. 8. Product of Plasma length L_p and thickness T_p in several sub-atmospheric pressures.

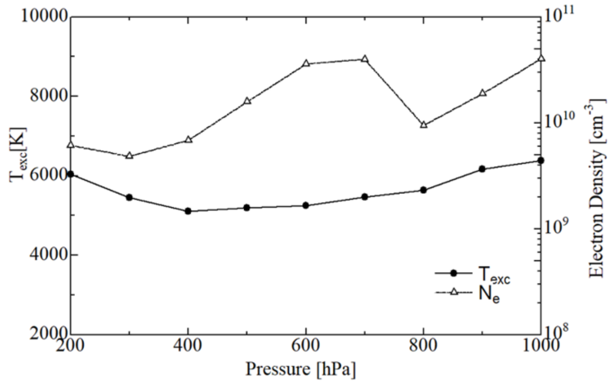

Fig. 9. Excitation temperature T_{exc} and electron density N_e as a function of pressure (P_{inc} = 500 W).

5.References

[1] M. Snirer *et al.*, Plasma Sources Sci. Technol., **30**, 095009 (2021).

[2] J. Hnilica *et al.*, J. Phys. D: Appl. Phys., **45**, 055201 (2012).

[3] https://www.nist.gov/ He I lines and spectrum

Acknowledgements

This work was supported by JSPS KAKENHI Grant Numbers 21K03519.