Investigation on continuous and modulated microwave plasma filaments at atmospheric pressure

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ABSTRACT Microwave atmospheric pressure plasma jets continue to evolve with the growth of atmospheric plasma’s applications in sterilization, material modification, and cancer treatment. In this article, continuous and modulated microwave plasma filaments were produced by a hand-held microwave plasma jet, and then they were compared in plasma length, electron temperature, and emission spectrum. The electron temperature was measured by the emission spectroscopy diagnostic method, and the regularities of the compared parameters’ change were studied by varying duty cycles and periods of the modulating signal. The results prove that the modulated microwave can generate stable plasma filaments directly in the air without protective tubes, and it is different from the continuous microwave plasma in all compared parameters. Besides, stable dendritic tearing of plasma filaments was observed. These results imply that modulated microwave and continuous microwave plasma filaments cannot be regarded as the same, the changing manner and the reaction on the surface of the medium may be completely different even if they are the same to the naked eye in most cases. These results are helpful for the controlling and understanding of microwave plasma, and the stable tearing could be used to expand the treated area of a single plasma jet.

INDEX TERMS Microwave devices, Plasma sources, Atmospheric-pressure plasmas, Plasma stability, Plasma diagnostics, Plasma jet.

I. INTRODUCTION

The atmospheric pressure plasma jet (APPJs) have gained a lot of attention over the last few years since they are often applied in plasma photonic crystal filters [1-3], material surface modification [4-6], cancer treatment [7-8], wound treatment [9], and sterilization [10-13]. APPJs are usually powered by high voltage DC or radio-frequency and microwave AC power sources. Among them, microwave APPJs are increasingly used due to high efficiency via impedance matching and high safety given by the absence of high voltage. Microwave power sources used by APPJs are increasingly used due to high efficiency via impedance matching and high safety given by the absence of high voltage. Microwave power sources used by APPJs are categorized into two types: magnetron and solid-state microwave sources. As a vacuum device, magnetron has been widely used for its high power capability, efficiency, and affordable cost, while when it is used to power small APPJs, the microwave power normally needed is just a few watts to tens of watts, so the output power of the magnetron needs to be reduced. Lowering the voltage of the magnetron cathode can reduce the output power, however, magnetron can’t work if the voltage is lower than the emission threshold, thus the lower limit of magnetron’s power is limited, the pulsed power supply needs to be used to modulate microwave, then changing average power through pulse width modulation (PWM) without changing the magnetron’s peak power. Solid-state microwave power sources have low-power output capacity; Nevertheless, expensive microwave power meters are necessary for closed-loop control if high precision power management is required. PWM can be used to achieve high-resolution power control for the solid-state microwave power source with digital circuits such as the single-chip microcomputer, especially when the digital circuit for PWM is mature and low in cost nowadays.

PWM is widely used to control the microwave power level of both magnetron and solid-state microwave power sources, however, the microwave plasma filaments produced by PWM microwave cannot simply be treated as the continuous-wave plasma with different power levels. A study by Zhao-Quan Chen et al. on the pulsed microwave plasma jet showed that the continuous wave APPJs’ filaments had exotic plume patterns [14]. The previous study by Jaroslav Hnilica et al. showed that modulated microwave plasma would tear at atmospheric pressure [15]. According to R. P. Cardoso's
research, modulated microwave plasma filaments were torn under atmospheric pressure, resulting in the formation of multiple plasma filaments, and this tearing got more strong as the power was raised [16]. Therefore, it is worthy of investigation and comparison on continuous microwave plasma and modulated microwave plasma.

A high-efficiency, hand-held microwave APPJ had been developed in our previous work [17]. Stable plasma filament was produced with continuous microwave power in the air. It remains to be explored if the PWM microwave will also excite stable plasma filament and if its rule shifts differently. In this paper, plasma filaments were produced by a double-coaxial line plasma jet and powered by a solid-state microwave power source with a PWM function. Images and spectra were recorded using a digital camera and fiber optic spectrometer, respectively. By images with a scale and emission spectrum applied with optical emission spectroscopy diagnostic (OES) method respectively, the length and electron temperature were determined. The observed results show that the length, electron temperature, and shape of the two plasmas are different, which are not only important for a better understanding of atmospheric-pressure microwave plasma but also demonstrate a novel control method of microwave APPJs.

II. EXPERIMENTAL SETUP AND THEORY

A lab-made solid-state microwave source with a maximum output power of 200 W, and a fixed frequency of 2.45 GHz, whose PWM parameters including duty cycle and the modulation frequency are controlled by a laptop is used to power the microwave APPJ. The microwave power source is connected to the N-type head on the APPJ by a coaxial line, as is shown in figure 1. The plasma jet has a double coaxial composite structure proposed in our previous work, whose detailed structure can be found in reference [17]. Argon gas of 99.999% purity supplied by a cylinder is divided into two separate channels through a T-joint. Then argon gas arrives at the microwave APPJ by two pneumatic push-in connectors, which are installed on the side and bottom of the APPJ, respectively. The gas at the bottom enters the inter coaxial line to provide ionizing gas, while the gas on the side enters the outer coaxial line to provide protection. The flow rate of both streams is controlled by rotor flowmeters. Plasma filament is excited at the electrode's tip with proper power and argon gas flow.

With the extremely high particle number density at atmospheric pressure, plasmas produced by APPJs usually have a high electron density and are commonly considered to be in local thermodynamic equilibrium (LTE) or partial local thermodynamic equilibrium (PLTE), so the plasma electron temperature can be calculated by Boltzmann fitting of the spectral lines measured by fiber-optic spectrometer [19-21]. The electron excitation temperature $T_e$ can be applied with Max-Boltzmann statistics:

$$\frac{N_m}{N_n} = \frac{g_m}{g_n} \exp\left(-\frac{E_m - E_n}{k_B T_e}\right)$$

(1)

where the $N$ is the density of the particles at a specific level, the subscripts $m$ and $n$ denote the upper level and the lower energy level of the particles, respectively. $g$ is the statistical weight of the level, $E$ is the energy of the level, $k_B$ is the Boltzmann constant factor. The radiation energy density can be expressed as:

$$\varepsilon_{mn} = \frac{1}{4\pi} N_m A_{mn} h\nu_{mn}$$

(2)

FIGURE 1. Schematic diagram of microwave APPJ’s configuration. The red arrow represents the microwave power, and the blue arrow represents the argon channel. The emission light is focused by a collimator, then coupled into the fiber spectrometer (AvaSpec-ULS2048).
where $\varepsilon_{mn}$ is the emission coefficients and $A_{mn}$ is the transition probability. Keeping the angle and the instrument unchanged during the measurement, the ratio of two spectral lines’ intensities at different energy levels $I$ is proportional to the particle density, this leads immediately to

$$\frac{I_1}{I_2} = \frac{\lambda_2 A_1 g_1}{\lambda_1 A_2 g_2} \exp\left(\frac{E_2 - E_1}{k_B T_e}\right)$$

(3)

where $\lambda$ is the wavelength of the emission light. Taking the natural logarithm of both sides of the equation, then equation 3 can be rewritten as:

$$\ln\left(\frac{\lambda I_1}{A_1 g_1}\right) = -\frac{1}{k_B T_e} E_i + C$$

(4)

where $C$ is a constant, the electron excitation temperature can be calculated through sloped of the fitting line and multiple spectral lines can be applied with equation 4 to improve accuracy. In this paper, the selected Ar I lines at 706.72 nm, 727.3 nm, 738.398 nm, 750.39 nm, 763.51 nm, 826.45 nm, 842.46 nm, 852.14 nm, 866.8 nm, 912.07 nm, 922.45 nm, 965.779 nm, and 978.45 nm. The A and g of those lines can be found in the NIST atomic spectra database.

### III. RESULTS AND DISCUSSIONS

To prevent the plasma from discharging inside the coaxial line due to inadequate argon flow or from swirling and sparking in turbulent flow due to excessive argon flow, the flow rates of two channels were fixed at 2 L/min [18]. Figure 2 shows the typical spectral of microwave APPJ produced by the continuous microwave and the PWM microwave. The continuous microwave power is 20 W and the PWM microwave average power is 20 W, which is obtained by a PWM wave with a 50% duty cycle at 40 W peak power. As can be seen, owing to the gas shielding, only two spectra lines occurred, namely Ar I (4p-4s) and OH lines. The wavelength distributions of the continuous and PWM microwave plasma are similar, but the spectrum intensities of Ar I and OH lines from the continuous microwave plasma are respectively higher and lower compared with the PWM one. Since the production of OH line is mainly produced by the ionization of water vapor distributed in the air, this implies that the reaction between the modulated plasma and the external environment is enhanced, but the ionization of the internal argon atoms is reduced.

Figure 3 shows the photos and calculated length of the plasma filament at varying peak power and PWM duty cycles while maintaining the argon gas flow rate at 2 L/min, PWM period 10 ms. It can be seen that as the PWM duty cycle increases, so does the plasma filament length. Interestingly, the length of the modulated plasma filament changes almost linearly with the duty cycle, but the length of the continuous microwave plasma filament changes with the microwave power has been proved to be proportion to the microwave power in dBm [17], namely it is proportional to the logarithm of the power. This change is also reflected in figure 3(b), that is, the continuous wave represented by the 100% duty cycle is not at the same interval between the different peak power curves, but gets closer as the power increases.

**FIGURE 2.** Emission spectra of plasma filaments. Continuous microwave plasma at 20 W, and the PWM plasma powered with 40 W peak power, 50% PWM duty cycle, and 50 ms period. Both argon flow rates are 2 L/min.

**FIGURE 3.** Length changes as a function of the PWM duty cycle. (a) Photos of PWM microwave plasma under various duty cycles, the peak power was fixed at 20 W, (b) Length of plasma filaments under different peak power levels as well as duty cycles. Both argon flow rates are 2 L/min, PWM period 10 ms.
The electron temperature of both PWM microwave and continuous microwave plasma is determined by the OES method, as is illustrated in figure 4 (a) and (b), respectively. It can be seen that the electron temperature of continuous microwave plasma decreases as the power increases, but the situation is reversed for the PWM microwave plasma. Moreover, the adjustment of the PWM duty cycle can obtain a larger electronic temperature variation range than changing the power of the continuous wave, which could be of benefit to applications in material processing where the electron temperature needs to be controlled. Interestingly, the change manners of the two plasmas are just opposite, although the average power of the PWM microwave is the peak power multiplied by the duty cycle, hence the average power for both plasmas is increased. This is inextricably linked with spectrum changes in figure 2, implying the discharge of PWM microwave plasma and continuous microwave is different inside the filaments.

For most PWM microwave applications, power control can be achieved only by changing the duty cycle without changing the PWM period, because it does not affect the average power level. However, this is different in plasma applications. The length and electron of the PWM microwave with different PWM periods as a function of the PWM duty cycle are depicted in figure 5. The growth of plasma length with duty cycle is predictable, however, the length does not remain constant at different PWM periods, despite having the same average power at the same duty cycle. The length of the plasma was decreasing when the PWM period was increased. This might be due to the plasma's increasing energy dissipation during PWM intervals without the microwave. In addition, the plasma cannot be excited at a low duty cycle, especially when the PWM period lengthens. This indicates that the modulated microwave plasma may have a process of repetitive discharge in each pulse, and exist a threshold period, that is related to the peak power of the microwave.

The influence of the PWM period on plasma electron temperature also exists as is shown in figure 6. When the period of PWM is increased further, the electron temperature...
of the plasma will vary differently from the 10 ms period of PWM microwave plasma in figure 4. The electron temperature varies slightly with the PWM duty cycle rather than rises. This implies that when the PWM microwave plasma has a long microwave off time in each period, the change of electron temperature during the reionization process is more determined by the peak power.

The difference between continuous and PWM microwave plasma is not only in length and electron temperature but also in filamentation. At certain PWM parameters, the plasma can be bent and be torn. Figure 7. (a) shows a photograph of a surge-like plasma filament structure with a periodical change in diameter, while figure 7. (b) depicts a dendritic tearing plasma filament with several sub-filaments growing from the parent plasma filament. The shutter time of the camera is 1/640 s, being much less than the period of the PWM. Such short imaging results are almost indistinguishable from those observed with the naked eye, implying a very stable tearing pattern of the plasma is formed. Unlike the previous study, which reveals a snapshot of tearing plasma that varies in turbulence [15-16], this tearing plasma is steady in this unique form without twinkling.

Furthermore, even though some continuous and PWM microwave plasmas seem to have the same single filament to the naked eye, they take on a different structure as they spraying on the surface of an object. Figure 8 shows the plasma excited by continuous and PWM microwave with the same average power in contact with the same mica sheet surface. The PWM microwave is a single filament when there is no contact as is illustrated in figure 3(a), but the PWM microwave plasma filament is torn when spraying on the mica, while continuous microwave plasma is just bent as is shown in figure 8(a). The dendritic tearing plasma looks like a parent plasma filament with several sub-plasma filaments, that continue to split and gradually cover an area rather than behaving like a straight line. This means that using the same average power, PWM microwave plasma with tearing expands the treated surface.

VI. CONCLUSIONS

In summary, the plasma excited by continuous and PWM microwave were studied by a microwave APPJ with a dual coaxial composite structure, including changes in length, electron temperature, spectra, and geometry. Results show that PWM microwave plasma can control the length and electron temperature by PWM duty cycle and period, and the plasma filament would tear at specific PWM parameters. The dendritic tearing found when PWM microwave plasma is being sprayed on an object can be used to expand the plasma-treated area to replace traditional plasma torch arrays, minimizing the APPJs needed. These results also imply that the PWM microwave plasma and continuous microwave plasma cannot be treated as the same, there may be different physical mechanisms behind them. PWM microwave may cause a re-breakdown in the pulse which may be due to the microwave power fluctuations with the modulating signal; As a result, the electron temperature, length, and spectrum are different, and thus the inhomogeneity is enhanced, leading to the occurrence of tearing.

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