Dual-Frequency Microwave Plasma Source Based on Microwave Coaxial Transmission Line

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Featured Application: In various microwave plasma fields, such as Microwave Plasma Chemical Vapor Deposition (MPCVD), the dual-frequency plasma source could be used to control plasma characteristics flexibly.

Abstract: A dual-frequency plasma source has many advantages in applications. In this paper, a dual-frequency microwave plasma source is presented. This microwave plasma source is based on a coaxial transmission line without the resonator, and it can be operated in a wide band frequency region. Two microwaves are inputted from two ports into the plasma reactor: one is used firstly to excite the plasma and the other one is used to adjust plasma characteristics. Based on the COMSOL Multiphysics simulation, the experiment is carried out. In the experimental investigation, the plasma electron density and electron temperature can be controlled, respectively, by feeding in different frequencies from the second port, causing the particles at different energy levels to present different frequencies. This exploratory research improves the operation frequency of dual-frequency microwave plasma sources from RF to microwave.

Keywords: microwave plasma; dual-frequency plasma; electron temperature; electron density

1. Introduction

To control plasma characteristics flexibly, the dual-frequency plasma source has been proposed and investigated [1–8]. The dual-frequency plasma source is a hybrid source, in which one frequency is chosen to be much higher than the other in order to achieve independent control of ion bombardment and electron density [9]. Research shows that, in plasma etching, dual-frequency operating could reduce particle contamination in the plasma reactor [10], and in the plasma-enhanced chemical vapor deposition (PECVD), dual-frequency operating could improve the film stress, step coverage, chemical composition, and film stability [11–14].

In previous studies, the exciting frequency for dual-frequency plasma sources mostly were mostly radio frequency (RF), such as 13.56 MHz, 27.12 MHz, 320 MHz, 340 kHz, and 40 kHz, and the structures of the plasma reactor are mostly capacitively coupled plasma (CCP) and/or inductively coupled plasma (ICP). In recent years, more and more microwave plasma sources have been proposed and applied [15–18]. However, dual-frequency microwave plasma sources are rarely investigated. For most microwave plasma sources, the microwave is propagated through a waveguide, and the plasma is excited in a resonator. Different from CCP and ICP reactor structures [19], the size of the microwave resonator is dependent on microwave frequency, and it is difficult to resonate two non-harmonic frequencies in one resonator.

Here, a microwave coaxial transmission line is introduced as the reactor for a dual-frequency microwave plasma source. In the coaxial transmission line, the electromagnetic wave mode of the microwave is TEM mode, and ultra-wide band electromagnetic waves,
from low-frequency wave to millimeter wave, could be inputted and propagated. The 2450 and 915 MHz microwaves, which are widely used in industry, are adopted in this investigation. There are two ports to input the microwaves. The 2450 MHz microwave is inputted from one port to excite plasma, and the 915 MHz microwave is inputted from another to adjust the plasma characteristics. To investigate the characteristics of dual-frequency microwave plasma, the microwave is inputted from two ports to excite the plasma, and a comparison is conducted between single-frequency microwave plasma and dual-frequency microwave plasma in the same reactor.

2. Experiment Design

The schematic diagram for the presented dual-frequency microwave plasma source based on the microwave coaxial transmission line is shown in Figure 1.

![Figure 1. Schematic of the coaxial line plasma driven by the dual microwave sources.](image)

The plasma reactor is a coaxial line, whose outer diameter is 150 mm and the inner diameter is 8 mm. A quartz glass tube surrounds the inner conductor. Between the outer conductor and the quartz glass tube, there is a vacuum region in which the plasma is excited. There are two microwave ports at the two ends of the coaxial transmission line. One is used to input the 2450 MHz microwave, and another is used to input the 915 MHz microwave. A magnetron microwave power generator (ASTeX AX2110) is used to generate the continuous-wave 2450 MHz microwave. An isolation circulator with a water load in an isolated way is connected to the magnetron microwave power generator. In this way, the microwave feedback will be entirely absorbed by the water load. An ASTeX SmartMatch is used to match the impedance so that the maximum amount of power can be coupled with the plasma. The 2450 MHz microwave is transmitted from the generator to the plasma reactor by the waveguide. A waveguide-to-coaxial adapter is designed and installed to guide the microwave from the waveguide into the coaxial transmission line plasma reactor through Port 1 [15]. A custom-made solid-state microwave power source (Wattsine Electronic Technology Co., Ltd. Chengdu China) is used to generate a continuous-wave 915 MHz microwave. The 915 MHz microwave is transmitted by N-type coaxial cables. The incident and reflected powers are monitored by a bi-directional coaxial coupler and Keysight power meter (Narda N1914A). A coaxial-to-coaxial adapter is designed and installed to guide the microwave from the N-type coaxial cable into the coaxial transmission line plasma reactor through Port 2. A coaxial low-pass filter is installed into N-type coaxial cables to avoid the solid-state microwave power source affected by 2450 MHz.

There are several KF flanges on the outer conductor, which are used to connect a vacuum pump, gas feed mass flow meter, and diagnostic devices. A Langmuir probe and an optical emission spectrometry (OES) are used to diagnose and investigate the plasma characteristics from two KF flanges in the center of the plasma reactor.

The experimental processes are as follows: First, pump the pressure in the reactor below 10 Pa by a vacuum pump; second, adjust the argon flow rate at 15–20 sccm to stabilize the discharge pressure at 80 Pa by the mass flow meter; then, turn on the microwave source...
at Port 1 to excite plasma discharge; finally, turn on the microwave source at Port 2 to adjust plasma characteristics and measure the plasma parameters.

As shown in Figure 1, the coaxial transmission line is a non-resonant structure. Thus, ultra-wide band electromagnetic waves could be inputted into the reactor. However, it would only be discharged at the area near the input Port 1, and not at the whole reactor. To produce a dual-frequency operation, the plasma must be affected by microwaves from both ports. Therefore, the plasma excited by 2450 MHz from Port 1 should be distributed in the whole reactor. To obtain the plasma distribution in the reactor, COMSOL Multiphysics is used to simulate the plasma distribution at different microwave powers from Port 1.

In this investigation, the argon plasma considered in the simulated model contains only electrons (e), positively charged argon ions (Ar\(^+\)), metastable-state argon (Ars), and argon (Ar) atoms. For these species, the main transportation equations are provided in Table 1 [20].

| No. | Reaction | Type       | Energy Loss \(\Delta \varepsilon\) (eV) |
|-----|----------|------------|----------------------------------------|
| 1   | \(e + Ar = e + Ar\) | Elastic    |                                        |
| 2   | \(e + Ar = e + Ars\) | Excitation | 11.5                                   |
| 3   | \(e + Ars = e + Ar\) | Superelastic | -11.5                               |
| 4   | \(e + Ars = 2e + Ar^+\) | Ionization | 15.8                                   |
| 5   | \(e + Ar = 2e + Ar^+\) | Ionization | 4.24                                   |
| 6   | \(Ars + Ars = e + Ar + Ar^+\) | Penning ionization |                                      |
| 7   | \(Ars + Ar = Ar + Ar\) | Metastable quenching |                                      |

Stepwise ionization (Reaction 5 in Table 1) plays an important role in sustaining low-pressure argon discharges. Excited argon atoms are consumed via superelastic collisions with electrons, quenching with neutral argon atoms, ionization, or Penning ionization where two metastable argon atoms react to form a neutral argon atom, an argon ion, and an electron. Reaction 7 is responsible for the heating of the gas. The 11.5 eV of energy, which was consumed in creating the electronically excited argon atom, returns to the gas as thermal energy when the excited metastable-state argon atoms quenching.

In the simulation, the electron energy distribution function (EEDF) is approximately set as the Maxwellian distribution function, due to the fact that the discharge pressure 80 Pa is greater than 6.66 Pa [21,22]. Although publications show that the plasma densities in simulations as Maxwellian distribution are higher than experimental measurements, they also show that the plasma distributions in simulations present good agreement with experimental measurements [23–26]. Therefore, the Maxwellian distribution function is still useful, and the plasma distributions at different exciting powers are normalized, presented in Figure 2.

As shown in Figure 2, the plasma discharge area is spread with increasing Port 1 microwave power. When the inputted 2450 MHz microwave power is at 500 W, the electron density near Port 2 is much lower than that near Port 1. When the inputted 2450 MHz microwave power is at 600 W, the electron density near Port 2 is a little lower than that near Port 1, but the plasma distribution is still non-uniform. When the inputted 2450 MHz microwave power is at 700 W, the electron density near Port 1 is nearly the same as that near Port 2, and in the area between Port 1 and Port 2, the plasma distribution is approximately uniform. While electron density is sufficiently affected by microwave power, the electron temperature is almost unaffected by microwave power changes. Therefore, the microwave power at Port 1 was set at 700 W to excite the plasma.
The electron plasma frequency is a function of the electron number density and is given by [27],

\[ \omega_{pe} = \frac{2\pi v_{pe}}{\epsilon_0 m_e^2} \]  \hspace{1cm} (1)

where \( \omega_{pe} \) is the electron number density in Hz. The \( n_e \) is the electron density, the \( \epsilon_0 \) is the permittivity of free space, and the \( m_e \) is the mass of an electron. According to Equation (1), for \( n_e = 1.56 \times 10^{16} \text{ m}^{-3} \), the electron plasma frequency is \( v_e = 1123 \text{ MH} \), which is located between 2450 MHz and 915 MHz. Then, if the input microwave from Port 2 is 2450 or 915 MHz, the plasma would show different responding behaviors.

To compare with the influence of the 915 MHz microwave, a 2450 MHz solid-state source was used instead of the 915 MHz solid-state source and the low-pass filter for comparative experiments. In the experiment, 915 and 2450 MHz microwaves were inputted from Port 2 to investigate the plasma characteristics changes, respectively. Figure 3

![Figure 2. COMSOL simulation of the electron density and temperature distributions at a fixed pressure of 80 Pa under Port 1 2450 MHz microwave power: (a) electron density (b) electron temperature.](image-url)
shows the effect of microwave inputted from Port 2 on the electron density and electron temperature measured by the Langmuir probe.

![Figure 3](image-url)

**Figure 3.** Effect of the microwave inputted from port 2 measured by the Langmuir probe: (a) electron temperature; (b) electron density.

Figure 3a shows that, when the second microwave was inputted from Port 2, the plasma electron temperature gradually increased as the 915 MHz microwave power increased and did not change sufficiently as the 2450 MHz microwave power increased. In contrast, Figure 3b shows that, when the second microwave was inputted from Port 2, the plasma electron density did not change sufficiently as the 915 MHz microwave power increased, but it gradually increased as the 2450 MHz microwave power increased.

This means that the second incident microwaves with frequencies below the plasma electron frequency could increase the electron temperature and affect the electron density indistinctly, and the second incident microwaves with frequencies above the plasma electron frequency could increase the electron density and affect the electron temperature indistinctly.

To investigate the physical mechanism of these phenomena, the OES results at different conditions were analyzed, and the OES data were all obtained at 10-ms integral times. The spectrum at only 700 W 2450 MHz microwave that was inputted from Port 1 acquired by the OES method is presented in Figure 4.

![Figure 4](image-url)

**Figure 4.** Spectrum of the coaxial line plasma driven by the 2450 MHz microwave from Port 1 at a power of 700 W and pressure of 80 Pa.
The spectrum result presents two main particles in plasma: nitrogen molecule (N$_2$) and Ar. The N$_2$ comes from air residue. In the experiment, the intensity of the Ar I line group was much higher than the others. In the Ar I line group, the characteristic peaks at Ar I 750.3869 nm, and Ar I 811.5311 nm were quite obvious with the highest intensity.

The OES data at the 200 W–915 MHz microwave that was inputted from Port 2 and at the 200 W–2450 MHz microwave that was inputted from Port 2 are presented in Figure 5a,b, respectively.

In Figure 5, it is obviously seen that the intensity of the Ar I characteristic peaks was sufficiently improved when both 915 and 2450 MHz microwaves were inputted, and different Ar I characteristic peaks show different changes. The intensity of the two highest Ar I characteristic peaks (750.3869 and 811.5311 nm) at the 915 MHz microwave that was inputted from Port 2 were higher than that of the 2450 MHz microwave that was inputted from Port 2. Meanwhile, the intensity of other Ar I characteristic peaks (such as 696.5431 nm, 706.7218 nm, 772.3760 nm) at the 915 MHz microwave that was inputted from Port 2 are lower than that of the 2450 MHz microwave that was inputted from Port 2.

The intensity changes of several Ar I characteristic peaks versus microwave power that were inputted from Port 2 are shown in Figure 6.

**Figure 5.** Spectrum of microwave inputted from Port 2 at the power of 200 W: (a) 915 MHz microwave; (b) 2450 MHz microwave.

**Figure 6.** Intensity changes of Ar I characteristic peaks versus microwave power inputted from port 2 (a) 750.3869 and 811.5311 nm; (b) 696.5431, 706.7218 and 772.3760 nm.
The OES results show that when the intensity of the characteristic peaks is higher at only 700 W 2450 MHz that was inputted from Port 1, the intensity increase is higher at 915 MHz that was inputted from Port 2 than at 2450 MHz that was inputted from Port 2 (Table S1, Figure S1). This indicates that particles at different energy levels presented different responses to different frequencies. In addition, the particles at different energy levels contributed different ratios in plasma electron density and electron temperature, thus, different frequencies could selectively control the plasma characteristics.

4. Summary and Discussion

Based on the COMSOL Multiphysics simulation, a dual-frequency microwave plasma source is proposed and investigated. This dual-frequency microwave plasma source is based on the coaxial transmission line, and 2450 and 915 MHz microwaves are utilized in this study.

In the experiment, the plasma was excited by a 2450 MHz microwave from Port 1 first, and then a 915 MHz microwave was inputted from Port 2 to adjust the plasma characteristics. The measured experiment results by the Langmuir probe show that the electron temperature gradually increases as the 915 MHz microwave power increases, and there is little change in electron density. In contrast, if there is a 2450 MHz microwave that is inputted from Port 2, the electron density increases as the microwave power increases, and there is little change in the electron temperature. These phenomena of dual-frequency microwave plasma are similar to dual-frequency RF plasma.

The OES method is used to investigate the physical mechanism of these phenomena, and the OES results show that the particles at different energy levels presented different responses to different frequencies. Thus, different frequencies could selectively control the plasma characteristics. If a high-power wide bandwidth frequency tunable microwave source is used as the power source from Port 2, the plasma electron density and electron temperature would be controlled, respectively and precisely, in the dual-frequency microwave plasma source. This exploratory research would improve the operation frequency of dual-frequency microwave plasma sources from RF to microwave.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/app11219873/s1, Table S1: Intensity of Ar I characteristic peaks, Figure S1: Intensity of Ar I characteristic peaks versus microwave power inputted from port 2 under pressure of 80 Pa and 700 W 2450 MHz microwave at Port 1.

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