A novel non-invasive diagnostic technique for parameters of glow discharge plasma

Meng Ge

1Beijing Aerospace Institute for Metrology and Measurement Technology, Beijing, China

Email: gemeng08@mails.ucas.ac.cn

Abstract. A new diagnostic technique using a quasi-optical cavity resonant system to detect parameters of glow discharge plasma is presented in this paper. In this approach, electron density was calculated from resonant parameters of the quasi-optical cavity. The reliability and repeatability of this new diagnostic technique was well approved. The key feature of the proposed method is that the experimental implementation was in real time with high stability and sensitivity.

1. Introduction

In order to study the propagation characteristics of electromagnetic wave in plasma, the basic physical parameters of plasma need to be characterized and diagnosed. In particular, the density parameters of plasma need to be diagnosed. There are many approaches to diagnose plasma which are classified as contact and non-contact diagnostics [1-3]. Among them, the Langmuir probe method need to be implemented at low pressure condition, which is only suitable for high vacuum conditions plasma [4-5]. Microwave cavity method is a non-contact diagnosis, which is always used to diagnose plasma with high temperature. Unlike microwave closed resonator, quasi-optical resonator can work in microwave wavelength range, which is much smaller than its cavity size. It also has the advantages of high quality factor, simple structure, and good stability [6].

These advantages make the quasi-optical method a promising diagnostic method for plasma. The purpose of this paper is demonstrating a quasi-optical cavity diagnostic system. A brief description of the diagnostic method is given Section 2. The experimental set-up of the glow discharge plasma sources and the analysis of present results are showed in section 3.

2. Diagnostic principle and method

The quasi-optical resonator consists of two symmetrical spherical mirrors. A specific frequency of electromagnetic waves can be reflected back and forth between the left and right walls to form resonance. With presence of plasma in the cavity, the resonant frequency and quality factor will change. A schematic diagram of experiment set up is showed in Fig. 1.

![Block diagram of experiment set up](image-url)
The resonance system loaded with plasma is showed in Fig. 2. D represents the height of the resonator, \( R_0 \) is curvature radius of spherical mirror, \( d \) is surface radius of spherical mirror, and \( t \) is thickness of plasma.

![Fig.2 Schematic of quasi-optical resonant cavity loaded with plasma](image)

After the cavity is loaded with plasma of which relative complex permittivity is defined as \( \varepsilon_r = \varepsilon_r' - j\varepsilon_r'' \), and TEM\(_{001}\) is selected as resonant mode, we can get the characteristic equation by field distribution and boundary conditions:

\[
\frac{1}{\sqrt{|\varepsilon_r'|}} \tan \left( \sqrt{\varepsilon_r'} \cdot k \cdot t \cdot \phi_t \right) + \tan \left( k \cdot (D - t) - \phi_{D-1} \right) = 0
\]  

(1)

Where \( k \) is propagation constant, \( \phi_t \) and \( \phi_{D-1} \) is the resulting additional phase when Gaussian beam propagates in material and free space.

Besides, the loss tangent of the plasma is calculated from the following equations:

\[
\tan \delta = \frac{\varepsilon_r'}{\varepsilon_r} = \frac{2\sqrt{\varepsilon_r'} \cdot k \cdot t \cdot (d + t \cdot \Delta)}{Q_s \left(2\sqrt{\varepsilon_r'} \cdot k \cdot t \cdot \Delta - \Delta \cdot \sin(\sqrt{\varepsilon_r'} \cdot k \cdot t - \phi_t)\right)}
\]  

(2)

and

\[
\Delta = \frac{\varepsilon_r'}{\varepsilon_r' \cdot \cos^2 \left( \sqrt{\varepsilon_r'} \cdot k \cdot t - \phi_t \right) + \sin^2 \left( \sqrt{\varepsilon_r'} \cdot k \cdot t - \phi_t \right)}
\]  

(3)

\[
\frac{1}{Q_s} = \frac{1}{Q_{0s}} - \frac{1}{Q_i}
\]  

(4)

\[
Q_i = Q_{0i} \cdot \frac{2 \cdot (t \cdot \Delta + d)}{D \cdot (\Delta + 1)}
\]  

(5)

\( Q_{0s} \) and \( Q_{0i} \) are the quality factors of the cavity with and without plasma, respectively. Both of them can be obtained with VNA.

The real part and imaginary part of complex permittivity are derived from equation (1) and equation (2). After \( \varepsilon_r' \) is obtained, angular frequency \( \omega_p \) and collision frequency \( \nu \) of plasma are
calculated according to the following equation:

\[ \varepsilon_r = \varepsilon'_r - j\varepsilon''_r = 1 - \frac{\omega_p^2}{\omega^2 \times (1 - \frac{f \times V}{\omega})} \]  \hspace{1cm} (6)

then

\[ N_e = \frac{\omega_p^2 \varepsilon_e m_e}{q_e^2} \]  \hspace{1cm} (7)

Where \( N_e \) is plasma density, \( q_e \) and \( m_e \) is quantity of electricity and mass of electron. From equation (1) to (5), we can see that electron density of plasma can be obtained by measuring the shift of resonant frequency and the change of quality factor after the plasma is loaded into the cavity.

3. Experimental results

The experiment set up of glow discharge plasma source is showed in Fig. 3.

![Fig.3 Set up of glow discharge plasma source](image)

The main part of discharge plasma reactor was a closed cavity and the AC voltage was exerted between the two cylindrical electrodes inside the cavity. Due to high voltage, the plasma was generated by the strong electric field which ionizes the air, and plasma density can be adjusted by adjusting the discharge current from 0 to 10A. During experiment, the plasma reactor was placed in the middle of quasi-cavity which was connected to coaxial cable for VNA measurements.

The density of plasma measured by the quasi-cavity system when the discharge current was 8A is showed in Fig. 4.

![Fig.4 Experimental results of plasma density when current is 8A](image)
As can be seen, the overall trend of change was relatively flat and the law of fluctuation was obvious during the measurement. The main reason of the jagged fluctuations was that the pressure in the cavity changes with time which cause the fluctuation of plasma density. Also, the measured average plasma density was about $2.16 \times 10^{16}$ m$^{-3}$, which was consistent with the theoretical simulation results.

The measured curve of plasma density reflects the real state of the plasma fluctuations which was caused by the changing of pressure. The measured results were well agreed with the theoretical results. Several repeatable results when the current was 8A are showed in Fig. 5. The amplitude and trend of these several curves roughly matched with each other which mean these measurements were stable and repeatable. The reliability and feasibility of using quasi-optical cavity resonant system to diagnose glow discharge plasma were verified.

![Fig.5 Several reproducible experimental results when current is 8A](image)

4. Conclusion

This letter presents a method of using quasi-optical cavity resonant system to diagnose the plasma density. The plasma density was obtained by measuring the shift of frequency and quality factor before and after the plasma was loaded into cavity. The resonant system was applied to the measurement of glow discharge plasma density, and the measured results were consistent with the theoretical simulation results. Besides, the method was implemented in real time and showed good sensitivity and stability. A novel and effective non-invasive diagnostic method was demonstrated.

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