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Phase-Sensitive Microwave Reflectometer for Plasma Diagnostics Part II-Application to Electron Density Measurements in Gas Discharge Plasmas

1. Introduction

In the first part of this paper [1] a phase-sensitive waveguide reflectometer system has been described. The application of the reflectometer to the diagnostics of low pressure gas discharge plasmas is discussed below. A description of direct measurements of electron density in a positive column of glow discharge plasma in noble gases is presented. The measurements were performed in steady state conditions, as well as in presence of density oscillations.

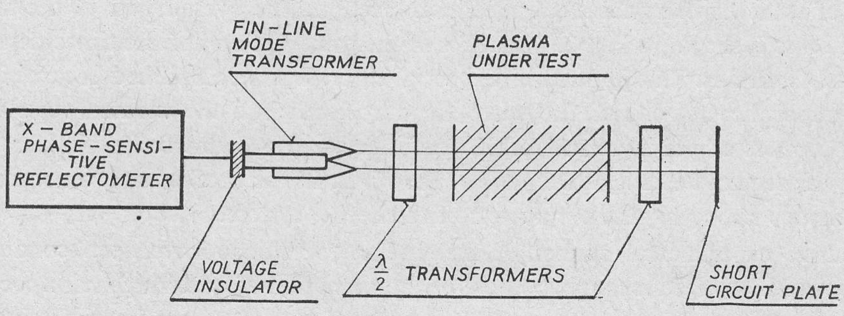

Fig. 1. Simplified diagram of microwave measuring arrangement

The microwave measuring arrangement is presented in Fig. 1. It consists of the waveguide reflectometer and the Lecher wire system terminating the main path of the reflectometer.

The Lecher wire system and the method of coupling the electromagnetic field in waveguide circuit with that in plasma will be described first, followed by a typical example of application and of experimental results.

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2. Lecher wire system and measured phase shift

The Lecher wire system in the experiment in question consisted of a transmission line terminated with a short circuit plate, vacuum sealed $\lambda/2$ transformers and fin-line transition (electromagnetic field mode transformer) from the X-band waveguide to the Lecher wires. The whole system is galvanically decoupled with the rest of reflectometer circuit to enable measurements in discharge plasmas.

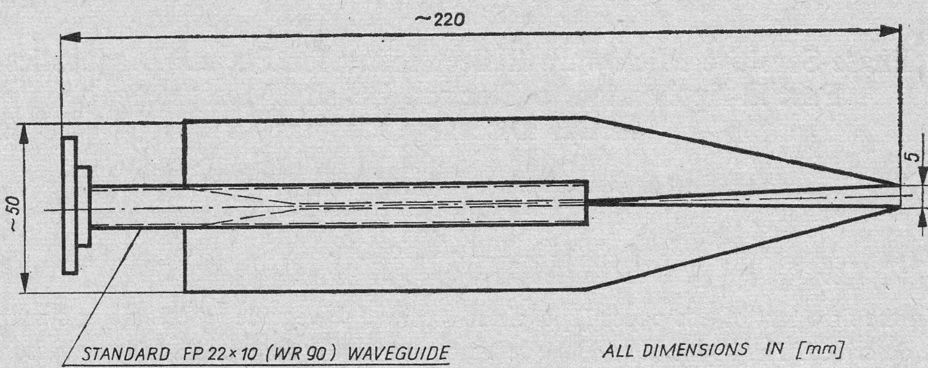

Fig. 2. Overall view of the fin-line transition

Our fin-line transition is similar to that described by Makios [2], except that it is shorter and of somewhat simpler mechanical construction. The overall view of the transition made of brass is shown in Fig. 2. The wires of the transmission line are tin-soldered to the nibs of the both fins. This joint requires special care when accomplished because it is vital for the impedance matching. The wires are introduced into the vacuum vessel through $\lambda/2$ transformers of polystyrene. These transformers are vacuum sealed with a beeswax assuring the required elastic attachment of the wires. It was checked that the transformers do not change noticeably the parameters of the Lecher system.

Extensive experimental studies of the fin-line transitions have been conducted [3] using the well known, Deschamps method for determination of scattering matrix coefficients. The absolute values of scattering coefficients M_{11}, M_{12}, M_{22} have been obtained. Here the indices 1 and 2 refer to the waveguide and transmission line side of the transition, respectively.

The final design of the fin-line transitions has been chosen by a successive tests method. The reproducibility of parameters of the chosen variant was very good. The achieved values of scattering coefficients were:

$$|M_{11}| \lesssim 0.05, \quad |M_{22}| \lesssim 0.1 \text{ and } |M_{12}| \approx 0.7.$$

For the transition selected in the described experiment these values were

$$|M_{11}| \cong 0.02, \quad |M_{22}| \cong 0.06 \text{ and } |M_{12}| \cong 0.7.$$

The phase shift of a wave propagating along the Lecher wires immersed in plasma is such as that of a wave propagating in free space. In case that there are no reflections at the plasma boundary and the electron density is low ($n_0 \gtrsim 0.3\ n_c$) this phase shift during the two-way transmission through plasma becomes

$$\theta \cong \frac{8\pi}{3} \frac{R}{\lambda} \cdot \frac{n_0}{n_c}, \tag{2.1}$$

where R – radius of cylindrical discharge tube, λ – wavelength, n_0 – electron density at the tube axis, n_c – cirtical density. The parabolic radial distribution of the density has been assumed to obtain (2.1).

The phase shift θ is measured through the transition. An error caused by the imperfection of the transition can, for a lossless plasma, be estimated as follows. Let $\Gamma_n = \Gamma_p / \Gamma_0$ be a normalized reflection coefficient in the load plane of the reflectometer with Γ_p and Γ_0 being the reflection coefficients in presence and in absence of plasma, respectively. The coefficients are expressed as

$$\Gamma_p = M_{11} + \frac{M_{12}^2 \exp j\phi}{1 - M_{22} \exp j\phi} \tag{2.2}$$

and

$$\Gamma_0 = M_{11} + \frac{M_{12}^2 \exp j\phi_0}{1 - M_{22} \exp j\phi_0}, \tag{2.3}$$

where ϕ and ϕ_0 denote the phase shift of the wave in the Lecher line with and without plasma, respectively, and $\theta = \phi - \phi_0$. For small phase shifts:

$$\Gamma_n = \frac{\Gamma_p}{\Gamma_0} \cong e^{j\theta} \left[1 - j\theta \left(\frac{M_{11}}{M_{12}^2} + M_{22} \right) \right]. \tag{2.4}$$

The phase shift measured by the reflectometer after introducing the plasma is $\theta_M = \text{Arg}\,\Gamma_n$ From (2.4) it follows directly that the relative error caused by the measurement of phase shift θ through transition is less than

$$\left| \frac{\theta_M - \theta}{\theta} \right|_{\max} = |M_{22}| + \frac{|M_{11}|}{|M_{12}|^2}. \tag{2.5}$$

Then, the error caused by imperfect transition should not exceed 10% in the described case.

3. Experiments and results

The reflectometer has been used for measuring the electron density in a positive column of glow discharge in noble gases. A schematic diagram of the experimental arrangement is shown in Fig. 3. The internal diameter of the heated cathode discharge tube was 55 mm, the total length about 2000 mm. The base pressure in the tube was of the order of 10^{-6} Torr; the tube having been filled with working gas of spectral purity.

The procedure of the reflectometer initial adjustment and of the phase shift measurement has already been described in [1]. The difference of detector output voltages $(U_A - U_B)$ can be directly measured or displayed on the oscilloscope screen. For small phase shifts, not exceeding 30°, this difference is proportional to the measured electron density

$$n_0 \cong \frac{3}{8\pi} \cdot \frac{\lambda}{R} \cdot \frac{U_A - U_B}{2U_0} \cdot n_c \tag{3.1}$$

as follows from (2.1). Here U_A, U_B and U_0 have the same meaning as in [1].

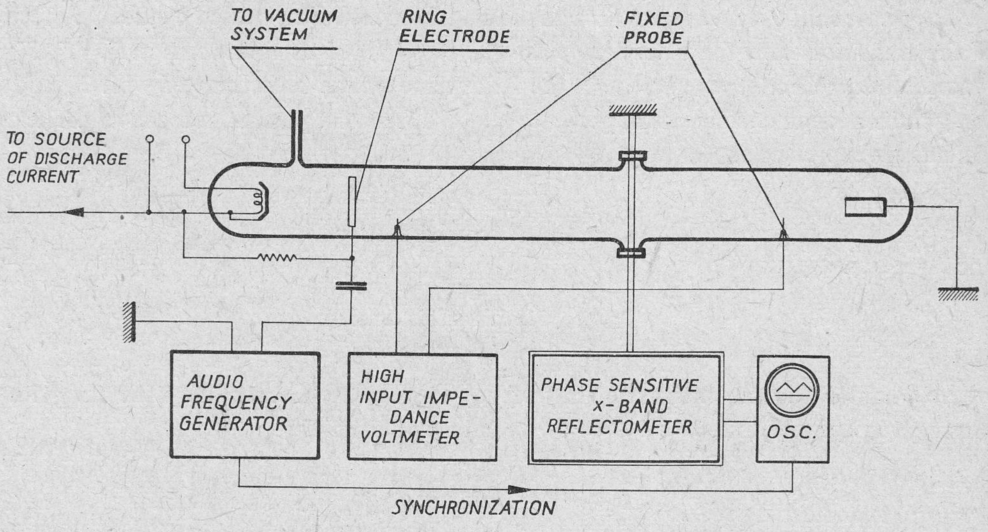

Fig. 3. Schematic diagram of experimental arrangement

All the described measurements were carried out at the center frequency of the microwave X-band ($f = 9375$ MHz, $\lambda = 32$ mm, $n_c = 1.1 \cdot 10^{12} \text{cm}^{-3}$). It has been estimated that the total error of measurement does not exceed 15% for the phase shifts within the range 1° - 30° in the experimental conditions described.

The time resolution of the reflectometer has been estimated [1] to be better than 1 μs. Also the spatial resolution of the Lecher system was checked by bringing metal objects in the vicinity of the transmission line wires. In agreement with Makios [2] we found the spatial resolution to be about 10 mm in the plane of the wires and at least two times better in the direction of discharge tube axis. The phase angle resolution of the X-band reflectometer [1] enables the measurement of electron density as low as 10^{-9} cm^{-3} in typical experimental conditions.

Fig. 4 shows typical results of electron density measurements in a homogeneous positive column of a helium discharge. The phase shift measurement yields directly the value of density averaged along the transmission line path. It was recalculated using (3.1) in order to obtain the value of density at the tube axis, as presented in Fig. 4. These results have been compared with the absolute value of electron density calculated from the relation expressing the dependence of total discharge current I_D on the electron mobility μ_e and axial electric field E_z

$$I_D = 2\pi n_0\, e\mu_e E_z \int_0^R r f(r)\, dr\,, \tag{3.2}$$

where e denotes electron charge and $f(r) = 1-(r/R)^2$ is the assumed radial distribution of electron density.

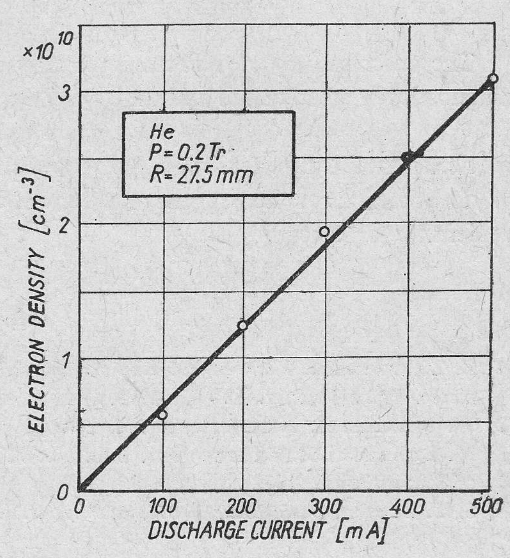

Fig. 4. Electron density on the axis of a homogeneous positive column of helium discharge vs. discharge current

The electric field was measured with two fixed probes placed in the region of the positive column. Using the results of these measurements and the values of electron mobility after Brown [4] an approximate expression for the electron density at the tube axis for the conditions of this experiment has been obtained from (3.2) in the form:

$$n_0 \cong 8 \cdot 10^7 I_D \ [\mathrm{cm}^{-3}], \tag{3.3}$$

where I_D in [mA].

A comparison of (3.3) with Fig. 4 shows that the both results do not differ by more than 25%. This can be considered as a fairly good coincidence.

The results of dynamic measurement of electron density are presented in Fig. 5, showing the local value of the density in a positive column of a neon discharge. The large amplitude self excited ionization waves were present in the plasma. In order to obtain a long time stability of the oscillation parameters their frequency was externally synchronized. For this purpose a sinusoidal voltage was applied to a ring shaped auxilliary electrode placed in the region of cathode end of the positive column. The frequency of the synchronizing signal was selected to be nearly equal to the natural frequency of self excited ionization waves present in the plasma.

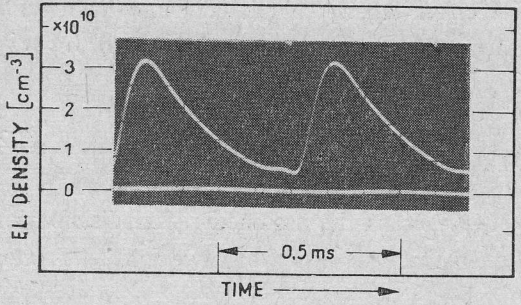

Fig. 5. Measured electron density variation in presence of large amplitude ionization waves. Neon, pressure $p=1$ Torr, discharge current $I_D=200$ mA

The described above reflectometer may constitute an useful and convenient tool for diagnostics of steady state and time -varying, low-pressure plasmas.

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Fazoczuły reflektometr mikrofalowy dla potrzeb diagnostyki plazmy Część II — Zastosowanie do pomiaru koncentracji elektronów w plazmie wyładowania

Streszczenie

Opisany w pierwszej części artykułu mikrofalowy reflektometr pracujący w pasmie X został wykorzystany do diagnostyki niskociśnieniowej plazmy.

Dzięki zastosowaniu linii Lechera uzyskano zmniejszenie przestrzennego obszaru oddziaływania plazmy z polem elektromagnetycznym. Przedstawiono opis i wyniki pomiarów lokalnej wartości koncentracji elektronów w kolumnie dodatniej wyładowania jarzeniowego w helu i neonie. Pomiary wykonano zarówno w warunkach statycznych jak i dynamicznych.

Phasenempfindliches Mikrowellenreflektometer zur Plasmadiagnostik Teil II — Anwendung zur Messung der Elektronenkonzentration im Entladungsplasma

Zusammenfassung

Das in der Bandbreite X arbeitende Mikrowellenreflektometer, welches in Teil I dieser Arbeit beschrieben worden ist, wurde zur Diagnostik des Niederdruckplasmas verwendet.

Durch Anwendung der LecherLinie wurde eine Verminderung des Gebietes von Gegenwirkung zwischen Plasma und dem magnetischen Feld erreicht. Es wird der Meßvorgang beschrieben und die Meßergebnisse der lokalen Elektronendichte in der positiven Plasma-Glimentladungssäule in He und Ne dargestellt. Die Messungen erfolgten sowohl in statischen als auch in dynamischen Bedingungen.

Фазочувствительный микроволновой рефлектометр для диагностики плазмы
Часть II — Применение для замера концентрации электронов в плазме разряда

Резюме

Описанный в первой части работы микроволновой рефлектометр, работающий в полосе *X*, был использован для диагностики плазмы низкого давления.

Благодаря применению линии Лехера достигнуто уменьшение пространственной зоны воздействия плазмы с электромагнитным полем. Представлено описание и результаты замеров местного значения концентрации электронов в положительной колонне тлеющего разряда в гелии и неоне. Замеры проводились как в статических, так и в динамических условиях.