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Microwave discharge in a finite length vessel

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Abstract. A microwave surface-wave discharge at low pressure in a finite length vessel is experimentally investigated. Argon plasma is created in a dielectric capillary with length of 15 mm, the tube being an extension of an open-ended coaxial structure. Microwave power at frequency 2.45 GHz is coupled into the source applicator at power levels 6-15 W. The plasma column increases with the power applied and standing wave mode is realized when its length is equal to the capillary length. The electron temperature and plasma density are obtained simultaneously by passive optical emission spectroscopy using the line-ratio method. The surface waves phase-diagram shows that their wavelengths are much lower than the free-space wavelength. The input impedance of the plasma column - modelled as a lossy transmission line - has resonance behaviour when its length is equal to \( \lambda_g/2 \) or \( \lambda_g \) (\( \lambda_g \) being the surface waves wavelength). The results obtained for the plasma parameters, the surface waves wavelength and the vessel length show correlation to the power reflected, absorbed and radiated from the plasma column. The radiation pattern of the column shows that the main lobe is nearly perpendicular to the capillary axis.

1. Introduction
Microwave discharges operated at low and atmospheric pressure, especially surface-wave (sw) sustained discharges, have been lately intensively investigated. Recent studies on sw discharges pointed out the role of the plasma boundaries on the wave-plasma power coupling and on the distribution of the plasma parameters [1]. The propagation of surface waves in a finite length vessel with insulated closed ends can be modelled as a propagation of EM waves in a lossy transmission line coupled at the microwave launcher. The results obtained [2] show that if the tube is \( \frac{1}{4} \) or \( \frac{1}{2} \) wavelength long, the input impedance of the line is low or very high, respectively.

In this study, a microwave discharge was investigated in argon gas (0.026 Torr) in a finite length vessel (quartz capillary with insulated closed ends). Signal with frequency \( f = 2.45 \) GHz from a microwave generator was fed to the surface-wave coaxial exciter [3]. In our source, the plasma column was a complex load [4]. Its value varied depending on the power applied and the discharge conditions. In this case, the reflected power also varied and part of the applied power was radiated in the free space surrounding the source. A line-ratio spectroscopy method was used for rapid simultaneous measurement of the two main plasma parameters in our source – the electron temperature and the plasma density. The collisional-radiative model for low pressure argon plasma [5, 6] was used for the calculation of these parameters. The axial wave number and attenuation

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coefficient of the surface waves were obtained from the dispersion relation. The results obtained for the input impedance and radiation pattern of the plasma column showed a correlation between the sw wavelength, discharge tube length and the values of the reflected and radiated power.

2. Experimental set-up and diagnostics

Microwave signal at frequency $f = 2.45$ GHz from a generator was fed to the source through a Pasternack-PE2219-30 double directional coupler and a triple stub (figure 1). The exciter of the surface waves was the end of an open coaxial line [3] with length of $l \approx \lambda_0/4\sqrt{\varepsilon_d}$ ($\lambda_0$ - wavelength in the free space, $\varepsilon_d$ - dielectric constant of line filling). The discharge tube was a quartz capillary ($\varepsilon_d=3.8$) with inner radius of $r = 1$ mm, outer radius of 1.5 mm and length of 15 mm. The capillary had two insulated ends and was filled with argon gas at pressure $p = 0.026$ Torr.

The initial precise tuning of the source at frequency 2.45 GHz by the triple stub resulted in good matching with the microwave generator. The forward and reflected power were measured by a HP 437B power meter. The radial component of the surface waves electric field was registered by one radial microwave probe positioned outside the tube and connected to the spectrum analyzer HP 8594E. The radiated microwave power from the plasma column was measured in the far-field region at distance 2.7 m by a HF-analyzer HF 38B. The equipment for optical emission spectroscopy included a collimating lens, an optical fibre, an Ocean Optics HR4000 spectrometer and an infrared thermometer. High-sensitivity measurements were performed by an infrared thermometer to determine the wall temperature of the quartz capillary. The gas temperature in the plasma column was obtained by theoretical estimation [3] from the wall temperature and the microwave power applied.

3. Results and discussion

The plasma column in the capillary increased with the increase of the absorbed power until reaching the end of the tube. At power levels above 10 W, the discharge was in a standing-wave mode. The reflected power could be reduced to 0.1 W at forward power of 12 W. The calculated average gas
temperature in the plasma column was $T_e = 600$ K. At these conditions, spectra of microwave discharge were recorded in the wavelength range 650–830 nm (figure 2a). They were mainly composed of neutrals lines in the spectral region 690-830 nm, belonging to transitions from the 3p$^5$4p to 3p$^5$4s configuration.

The spectral diagnostic method applied in the study was proposed initially in [5] and extended further in [6]. It combines measurements of certain argon line-intensities with collisional-radiative modeling (CRM) of the excitation kinetics at low pressures. The model includes kinetic processing determination of the population densities of the first fourteen excited levels. In the simulation, the gas pressure, the discharge tube radius and the gas temperature are fixed input parameters. The results generated by the model are the excited level population densities, the line-intensities and the line-intensity ratios as a function of the electron density $n_e$ and the temperature $T_e$. The line-intensity ratios are imposed on application of cross-point method for simultaneous determination of $n_e$ and $T_e$, described in detail in [5, 6]. The plasma parameters, $n_e = 2.6 \times 10^{12}$ cm$^{-3}$ and $T_e = 3.1$ eV, in a continuous mode of discharge operation, were obtained by averaging the results of 5 line-intensity ratio combinations (I$_{794.8}$/I$_{826.5}$, I$_{706.7}$/I$_{727.3}$, I$_{738.4}$/I$_{696.5}$, I$_{738.4}$/I$_{727.3}$, I$_{751.5}$/I$_{727.3}$ each one of them with I$_{811.5}$/I$_{826.5}$). The lines were selected so as to be close in wavelength, which ensures the same spectral response of the optical detecting system and sensitivity to temperature and electron density variations. Figure 2b illustrates the grid of isolines for line-intensity ratio $r_1 = I_{738.4}$/I$_{727.3}$ (grey isolines) and $r_2 = I_{811.5}$/I$_{826.5}$ (black isolines). The dashed isolines correspond to the values of the experimentally measured line intensity ratios $r_1 = 6$ and $r_2 = 5.3$.

The dispersion relation of sw waves in a symmetrical cylindrical system plasma-dielectric-vacuum [7] was used for calculating the space damping rate $\alpha$ and axial wave number $\beta$ (phase constant).

In the calculations, $k=\beta+j.\alpha$ is the complex wave number, $r=1$ mm is the discharge tube inner radius and $d=0.5$ mm is the tube wall thickness. The media are characterized by the dielectric constants $\varepsilon$, $\varepsilon_d$, $\varepsilon_v$ for plasma, dielectric and vacuum, respectively. The dispersion behavior of the waves was investigated in the region of plasma density close to the experimentally obtained $n_e=(1-10) \times 10^{12}$ cm$^{-3}$. The theoretical results (figure 3) show that the surface waves in the plasma column are weakly damped waves with wavelengths much shorter ($\lambda_s \sim 1.2-6.5$ cm) than the wavelength in the free space ($\lambda \sim 12.24$ cm). The column length $l$ of 15 mm is approximately $1/2$ of the wavelength of surface waves at plasma density $n_e = 2.6 \times 10^{12}$ cm$^{-3}$. According to [2], the input impedance of the plasma column in a finite length vessel with insulated end plates can be calculated as the impedance of an open-ended lossy transmission line $Z_{in}=\eta/\tanh(\gamma l)$, where $\eta$ is the characteristic impedance of the line, $\gamma=\alpha+j.\beta$ is the propagation constant and $l$ is the vessel length. The calculated value of the characteristic impedance of this line is $\eta=45$ $\Omega$ at our experimental conditions. The dependence of the input impedance of the plasma column ($Z_{in}=R_a+jX_a=\text{Re}[Z]+j.\text{Im}[Z]$) on the values of $\alpha$ and $\beta$ is presented in figure 4. The results show that the input impedance of the plasma column in a finite length vessel has resonance behavior when its length is equal to $\lambda_s/2$ or $\lambda_s$. The real part has a maximum while the imaginary part is equal to zero. The reactive resistance changes its sign in these regions from negative (capacitance) to positive (inductance) and vice versa. In this mode, the plasma column can be considered as an antenna with real part of the impedance $R_a=R_l+R_r$, i.e., the sum of the antenna losses and the radiation resistance, respectively. The microwave power radiated from the plasma column with a small ground plate increases up to 1.5 W in the standing-wave mode and works as a monopole plasma antenna. This result is confirmed by radiation pattern measurements and simulations of the electric field of the real column (vertical capillary) in the far-field region by EM simulator HFSS (figure 5).
Conclusions
The input impedance of the plasma column in a standing-wave mode in a finite-length dielectric vessel with insulated ends shows resonant behavior when the column length is equal to $\lambda_g/2$ or $\lambda_g$ of the surface waves sustaining the discharge. The real part of the impedance has a maximum and the imaginary part is equal to zero. The plasma column with a ground plate radiates microwaves as a monopole plasma antenna and the main lobe in the radiation pattern is close to being perpendicular to the capillary axis.

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