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Microwave diagnostic complex for cold atmospheric plasma jets

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A system for microwave diagnostics of low-temperature non-stationary atmospheric plasma jets is proposed, the principle of operation of which is based on the registration of changing in the quality factor of the main mode of the electric type of a cylindrical microwave cavity resonator. The time dependences of the average volumetric conductivity of a plasma jet of a barrier discharge in a helium flow are measured. The discharge was powered from an alternating voltage source with a frequency of 9 kHz. Such a low frequency of the supply voltage made it possible to distinguish individual pulses of breakdowns of the barrier discharge.

Keywords: microwave cavity resonator, barrier discharge, plasma jet, conductivity, quality factor.

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Currently, various technologies related to the use of atmospheric plasma jets with low (approximately 300 K) gas temperature are being actively introduced and developed. For instance, low-temperature plasma jets can be used to treat the surface of heat-sensitive polymers when applying adhesives and paint coatings [1], as well as in medicine for the sterilization and disinfection of living tissues [2]. The generation of such atmospheric plasma jets is carried out by igniting discharges of various types (glow, high-frequency, barrier discharge) in a special discharge cell through which the working gas is blown. One of the important problems in the development of new types of low-temperature plasma jet sources for various applications is the need to measure and control the electron concentration of the plasma. However, most plasma diagnostic methods either have insufficient sensitivity or do not allow the study of non-stationary discharges. The most suitable methods for diagnosing cold atmospheric plasma jets are various very high frequency (VHF) methods. Thus, in works [3,4] to measure the time dependence of the electron concentration in a plasma jet of a unipolar pulsed and barrier discharge, a VHF signal with a frequency of approximately 10 GHz scattered from the plasma region under study was recorded. In the work [5], a waveguide VHF filter was used to measure the electron concentration of a plasma jet of a barrier discharge in an argon flow, which significantly increased the sensitivity of the measurements, since the probing was carried out in a closed volume and not in open space.

In this work, a system based on a cylindrical microwave cavity with a working TM010 mode is used to diagnose plasma jets. Previously [6,7], we have already tested a similar system based on a cylindrical resonant cavity with an operating TE11 mode for plasma jets of a barrier discharge in a flow of helium and argon, which were ignited from a high-voltage source with a frequency of 160 kHz. In contrast to [6,7] in this work, a high-voltage alternating voltage source with a frequency of only 9 kHz was used to ignite the barrier discharge, which allowed to distinguish individual barrier discharge breakdown pulses.

The experimental unit used (Fig. 1) is in many ways similar to that previously described in [7]. Its main element (Fig. 1, *b*) was a cylindrical microwave cavity (*1*) with a diameter of 192 mm and a length of 105 mm. Inside the resonant cavity there were two small loop antennas. One of these antennas (*2*) was an exciting one and was connected to the built-in tracking oscillator (TO) of the spectrum analyzer (*3*), the power level of which did not exceed 1 mW. Another antenna (*4*) was connected to the input (IN) of the spectrum analyzer and served as a receiver. The spectrum analyzer (Rigol 815-tg) operated in the frequency range up to 1.5 GHz. In this frequency band, only one TM010 mode can be excited in the resonator at a frequency of approximately 1.19 GHz, which has one electric field component E_z and one magnetic field component H_φ

The investigated plasma jet of the barrier discharge (*5*) was placed inside the resonant cavity through the input hole (*6*), located in the center of one of the bases of the cylindrical resonant cavity (in the vicinity of the electric field maximum). A high-voltage power source with a frequency of 9 kHz (*7*) was used with the aim of igniting the barrier discharge. The other base of the resonant cavity had a window (*8*) with a diameter of 50 mm with a thin metal mesh, which made it possible to observe and control the plasma jet inside the resonant cavity without changing the field structure of the excited mode. Since the electron concentration of the plasma jet under study is small, it changed the Q factor of the TM010 mode quite little and did not change its frequency at all. The latter circumstance is due to the fact that the effective frequency of electron collisions is several orders of magnitude higher than the frequency of the TM010 mode [8,9]. The maximum output power of the tracking oscillator is approximately three orders of magnitude lower than the discharge power,

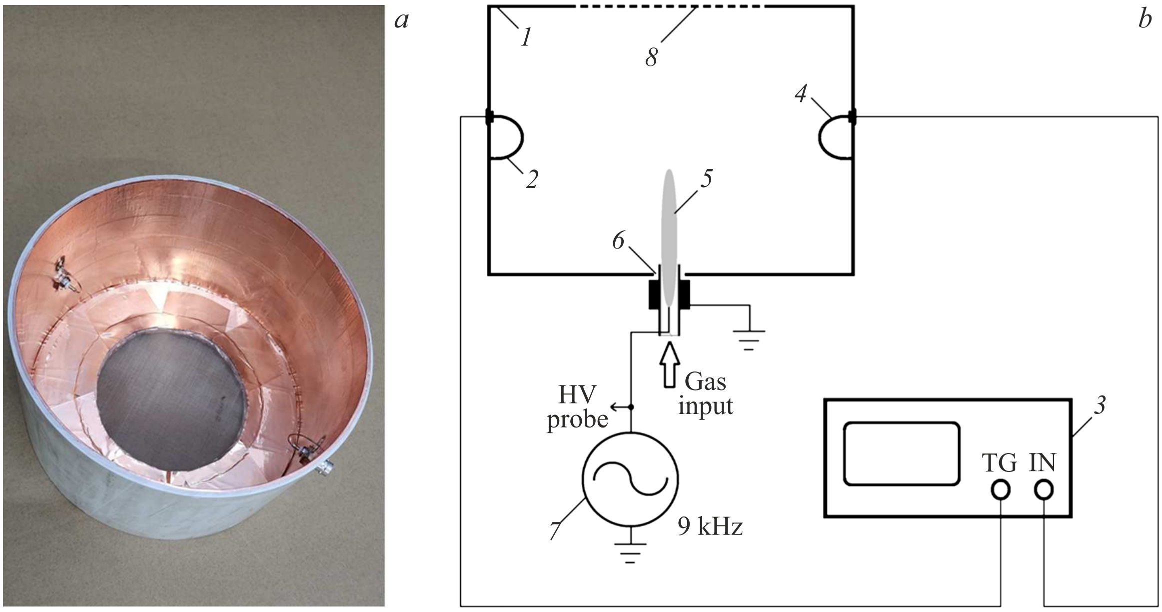

Figure 1. Image of the interior of the resonant cavity (a); diagram of the VHF diagnostics system for low-temperature plasma jets (b): *1* — microwave cavity, *2* — exciting antenna, *3* — analyzer spectrum, *4* — receiving antenna, *5* — plasma jet, *6* — inlet, *7* — power supply, *8* — window with a thin metal mesh.

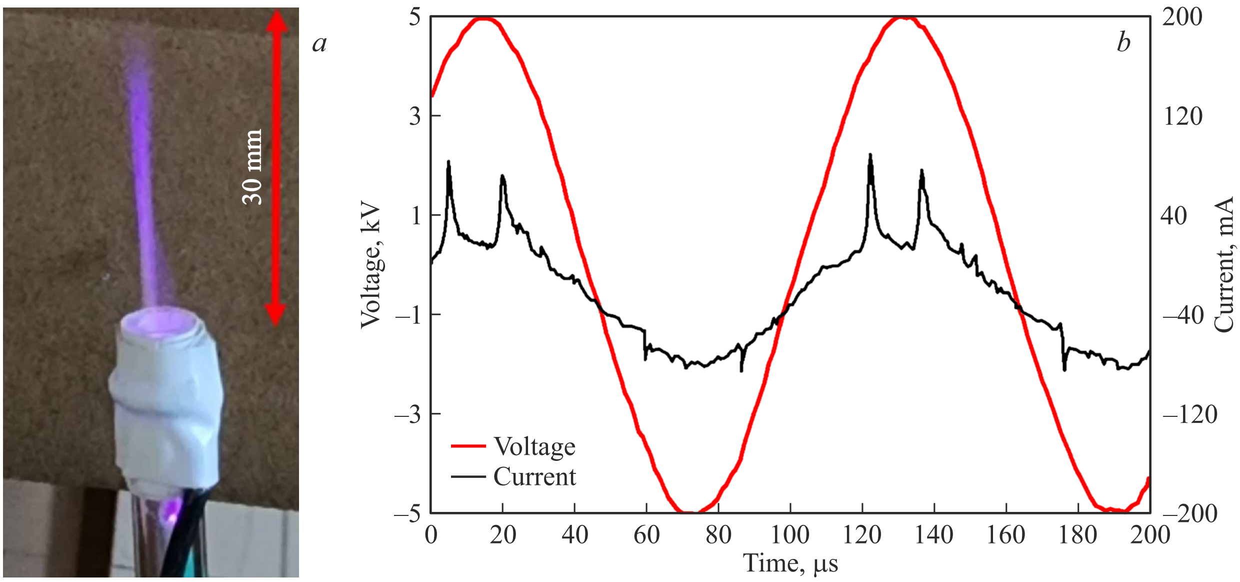

Figure 2. Image of a plasma jet of a barrier discharge in a helium flow (a); time dependences of the discharge current and voltage on the discharge cell (b).

which allows to eliminate the influence of the VHF signal on the jet and consider a linear problem.

Figures 2, a and b show the image of the plasma jet, as well as the dependences of the discharge current and voltage on the discharge cell. The dependence of the discharge current on time shows characteristic peaks of individual breakdowns of the barrier discharge.

Fig. 3, a shows the spectrum of the TM010 mode of the resonant cavity without a plasma jet, from which the value of the Q factor Q_{010} can be determined using the ratio$Q_{010} = f_{010}/\Delta f_{3db}$, where f_{010} — frequency of the TM010 mode, Δf_{3db} — the frequency bandwidth of the resonance curve at which the power is equal to half the maximum value. From the spectral characteristic in Fig. 3, a it can be determined that the frequency bandwidth of Δf_{3db} is almost 4 MHz, and the Q factor of the TM010 mode is equal to 300. When a plasma jet is ignited inside the resonant cavity, the Q factor of the resonant cavity changes

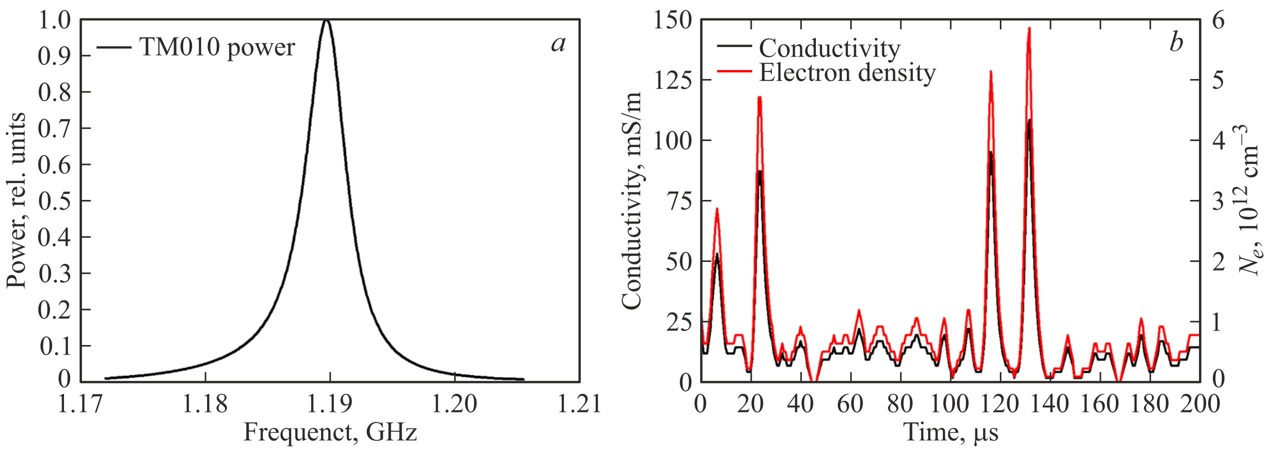

Figure 3. Spectrum of the TM010 mode of a cylindrical resonant cavity without a plasma jet (a); time dependences of the average conductivity and electron density of the plasma jet (b).

synchronously with the individual breakdowns of the barrier discharge that occur. To record such a dependence, the spectrum analyzer was switched to the zero-band measurement mode, in which the time dependence of the signal power at the selected frequency (at maximum) is measured. This time dependence is directly related to the change in the inverse value of the Q factor Q_{010} of the TM010 mode and the average conductivity of the plasma jet under study σ by the known relation [8]:

$$\Delta \frac{1}{Q_{010}} = -\frac{\int\limits_{v} \sigma |E_{010}|^2 dV}{2\pi f_{010} \varepsilon_0 \int\limits_{V} |E_{010}|^2 dV},$$

where v — volume of the plasma region under study, V — volume of the microwave cavity, ε_0 — electric constant, E_{010} — electric field of the TM010 mode of the cylindrical microwave cavity [10].

Figure 3, b shows the dependence of the average conductivity of the plasma jet on time (black curve). From Fig. 2, b and 3, b it is can be seen that the conductivity increases sharply at the moments of breakdown of the barrier discharge.

From the obtained curve for the conductivity of the plasma jet, the time dependences of the electron concentration of the plasma N_e can also be obtained using the known relation for the conductivity of the plasma [8,9]:

$$\sigma = \frac{\nu_{\text{eff}} N_e e^2}{m_e(\nu_{\text{eff}}^2 + \omega)},$$

where e — electron charge, ω — cyclic frequency, m_e — electron mass, ν_{eff} — effective electron collision frequency, which depends on the type of gas and pressure.

If we set the effective frequency of electron collisions in a helium gas-discharge plasma at atmospheric pressure to be equal to 1.5 THz [9], then from the known dependence of the average conductivity we can obtain the time dependence of the average electron concentration of the studied plasma jet of a barrier discharge in a helium flow (red curve in Fig. 3, b). However, the dependences of the electron concentration on time obtained in this way will be very approximate, since in a plasma jet the gas blown into the atmosphere is mixed with air in different proportions in different regions of the jet. Nevertheless, the obtained values correspond in order of magnitude to the known results for a plasma jet of a barrier discharge in a helium flow [3].

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Conflict of interest

The authors declare that they have no conflict of interest.

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