Radiophysical methods of modeling the electromagnetic waves propagation through a flat plasma layer

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Abstract. This paper presents the model variants of plasma layer creating by microwave discharges and plasma jet sources. Methods of creation a model quasi-dynamic plasma antenna on the basis of plasma jet and antenna type plasma structures of microwave range are also considered. Pulsed discharge in a capillary with ablative wall can be used as a method of creating plasma antenna. A microwave discharge is another perspective method for plasma antennas creation in centimeter-decimeter wavelengths range that allows us to apply this approach for modeling different types of plasma antennas (dipole, traveling wave antenna, spiral antenna, and others). Numerical modeling was initiated to analyze the interaction of microwave radiation with plasma layer. It is assumed that 2D consideration will allow investigating the influence of various types of regular spatial plasma structures on the characteristics of the transmission and scattering of EM waves beams. The model allows investigating also the development of MW plasma structures (it is virtually impossible to implement in the framework of 3D modeling).

This paper presents the model variants of plasma layer creating by microwave discharges [1] and plasma jet [2,3] sources. Methods of creation a model quasi-dynamic plasma antenna on the basis of plasma jet and antenna type plasma structures of microwave range are also considered.

In total, plasma sources cover a wide range of electron density $n_e \sim (10^{10}–10^{16})$ cm^{-3}. At the preliminary stage of the work our attention was focused on finding appropriate sources, to determine the optimal conditions for creation the plasma objects and performing them in test experiments. The experimental MW installation is presented in figure 1.

Surface initiated MW discharge ($\tau = 10$ μs, $W \sim 4\times10^4$ W/cm^2) is formed along a dielectric plate, where the plasma area (figure 1—photos 1, 2) is about 50×50 mm^2 and its thickness of several millimeters.

The next type of plasma layer creates by the plasma jet normally oriented to dielectric plate (figure 1—photo 4). The lifetime of the plasma layer is (3–4) ms. During this time the diameter of the plasma layer expands from ten millimeters to (40–50) mm and it thickness reaches (10–20) mm for subsonic plasma jet and increases to (50–70) mm for supersonic one. The experiments were performed at atmospheric pressure. Plasma was an object which scatters the microwave.

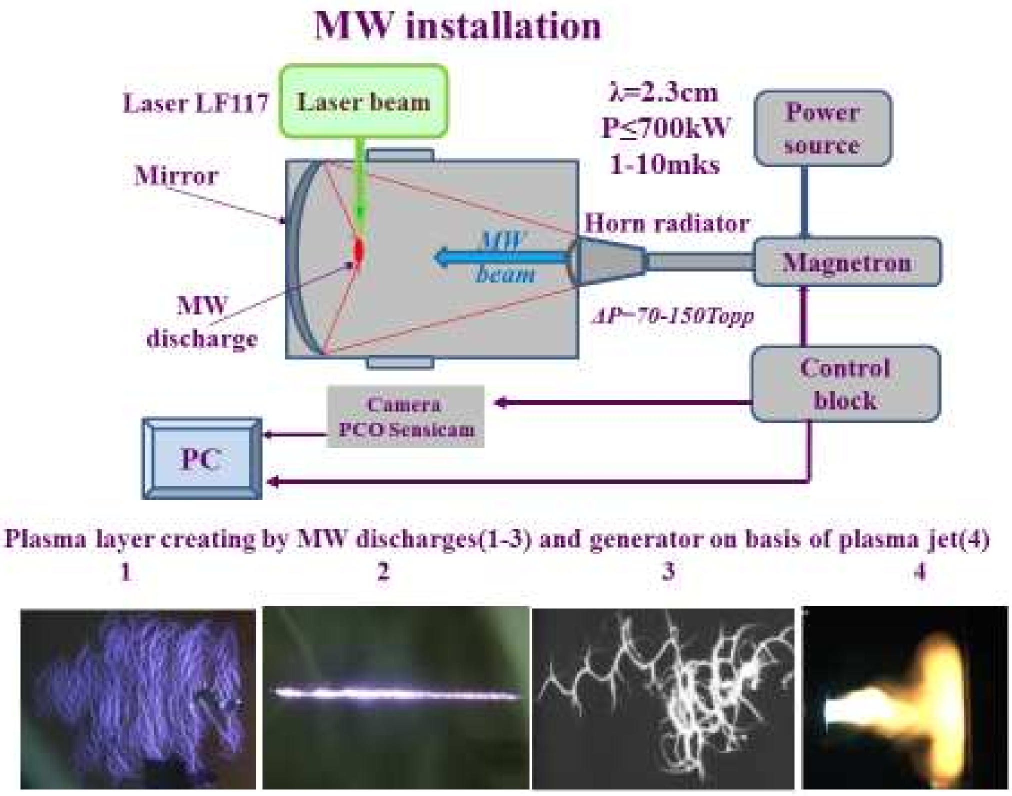


Figure 1. Microwave installation.

MW scattering method is used for plasma diagnostics. It was carried out at different stages of plasma objects development by varying the delay of the probing signal relatively to discharge pulse.

A microwave discharge [1] is another method for plasma antennas creation in centimeter-decimeter wavelengths range. A variety of plasma structures created by microwave discharge was obtained and presented in our work [1] (dipole, wave (figure 1—photo 3), disc, ball and other structures) that allows us to apply this approach for modeling different types of plasma antennas (dipole, traveling wave antenna, spiral antenna, and others).

Pulsed discharge in a capillary with ablative wall can be used as a method of creating plasma antenna, providing the formation of high enthalpy plasma jets with high specific parameters [2], in particular: high electron density (more than $n_e > 10^{17}$ cm^{-3}), high conductivity ($\sigma \sim 10^3$–$10^4 S/m$), long relaxation time of multicomponent plasma etc. In a certain range of discharge parameters the plasma jet attains a set of unusual properties, if to compare with gas jets: long propagation range in a gas atmosphere (10–20 cm at normal pressure up to 1 m in a rarefied atmosphere), weak divergence, stability in high-speed gas flow, the weak interaction and the ability to pass through the area of low-temperature plasma ($n_e \sim 10^{12}$ cm^{-3}), created by an external source. The undoubted advantages of this method are the wide operating range of ambient pressure ($p \sim$ 1–760 Torr), simplicity, reliability and compactness of the plasma generators that may be of practical importance for the application of plasma jets as onboard aircraft antennas.

The plasma jet has a certain similarity to the conductive rod that allows its application in a mode of asymmetric quarter-wave dipole. For typical plasma jet parameters (electron density $n_e \sim 10^{17}$ cm^{-3}, the plasma temperature $T_a \sim 6000$ K, pressure $p = 760$ Torr) the values of

Langmuir frequency and frequency of elastic collisions of electrons are $\omega_p \sim 1.8 \times 10^{13}$ rad/s and $\nu \sim 2 \times 10^{11}$ s^{-1}, respectively. Therefore, the condition $\omega \ll \nu \ll \omega_p$ is satisfied in the frequency range $f \sim$ 1–10 GHz (that is used in various communication systems), in which the plasma conductivity is almost entirely determined by its active component which does not depend on the field frequency. In this case the active conductivity $\sigma' \sim 14500$ S/m is noticeably higher the reactive conductivity $\sigma'' \sim$ 440–4400 S/m. Field penetration depth into the plasma jet is substantially less than the length of the electromagnetic wave $\sigma \ll \lambda \sim$ 3–30 cm. But unlike metal vibrator the plasma jet is characterized by a complex structure and a nonuniform distribution of the parameters in axial and radial directions. So, radiotechnical characteristics of the plasma jet and the metal rod may have some differences.

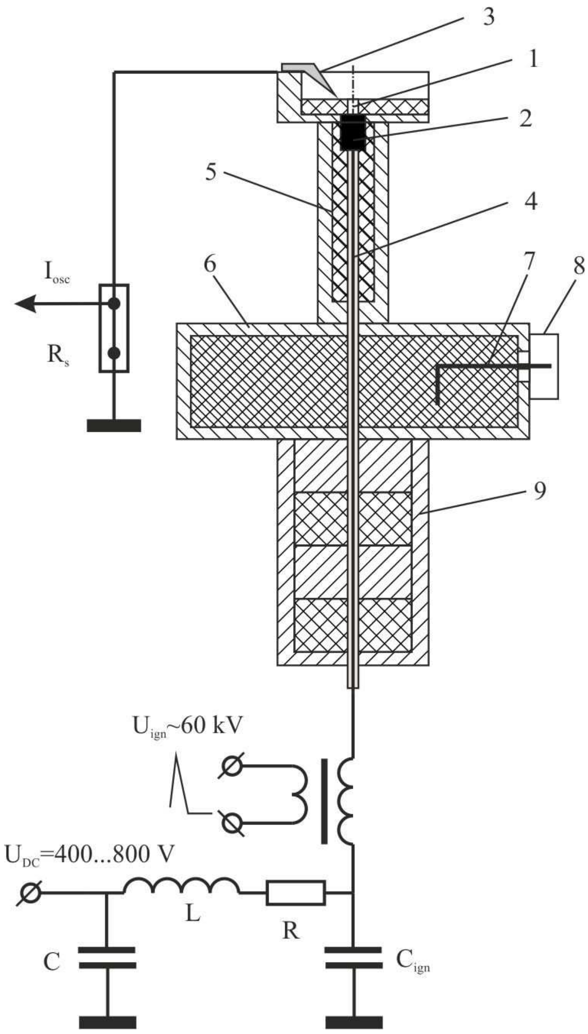
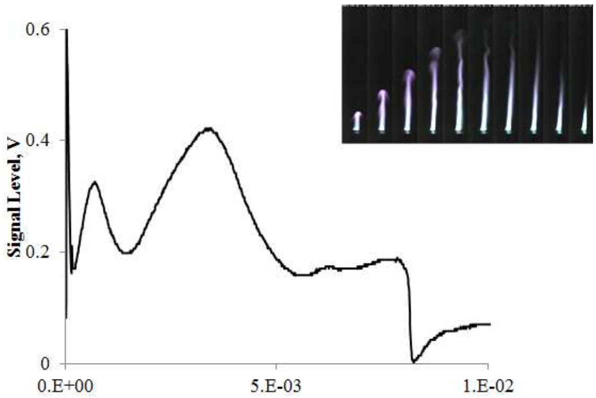


Figure 2. Principal design of plasma antenna laboratory the model: 1—capillary gap, 2—anode, 3—cathode, 4—power wire, 5—coaxial feeder, 6—cylindrical volume, 7—asymmetrical dipole, 8—microwave connector, 9—feed-through capacitor.

Laboratory model of the plasma antenna (figure 2) is used in our experiments, the detailed description of which is given in [3]. Main objectives of experiments are the study receiving and transmitting performances of plasma antenna depending on the following factors:

- influence the discharge parameters and flow regimes (subsonic and supersonic);
- influence the incident high-speed gas flow;
- influence the source of low-temperature plasma ($n_e \sim 10^{12}$ cm^{-3}, $T \sim 6000$ K).

Our experiments show the possibility of using the plasma jet as effective receiving/transmission dipole antenna (figure 3).



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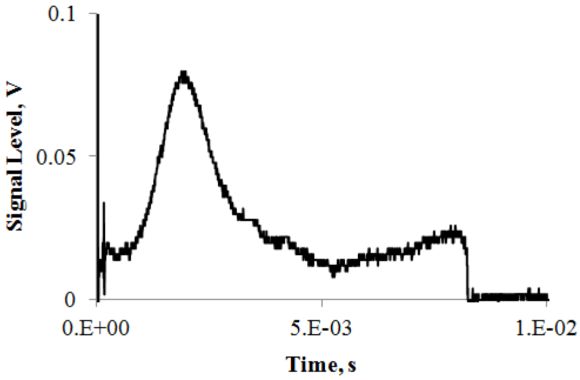

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Figure 3. Waveforms of microwave signals ($f = 1.8$ GHz) that are transmitted (a) and received (b) by plasma jet antenna.

The lower limit of the operating frequency is determined by the effective length of the plasma jet and the criterion according to which the depth of penetration of electromagnetic field into the plasma does not exceed the transverse size of the jet. It has been found that the plasma antenna efficiency in weakly perturbed atmosphere is determined mainly by absorption of electromagnetic waves in the vicinity of the plasma jet. High electron density in this domain ($n_e \sim 10^{13}$ cm^{-3}) is supported by plasma radiation in the ultraviolet spectral band, which intensity increases with discharge power. This imposes certain restrictions both on the discharge parameters and the range of operating frequency, whose upper limit is determined from the condition of radio-transparency of the plasma layer. At the same time, the increase of the electron density in the photoionization plasma domain accompanied by a decrease of field penetration depth, may lead to violation of radio-transparency condition, which imposes a limitation on the discharge power. In our experiments, the violation of radio-transparency condition was observed with increasing discharge power above 80 kW, that accompanied by a noticeable decrease of the desired signal amplitude. So the real operating frequency band of plasma jet antenna is estimated at $f \sim 0.7$–30 GHz.

The use of plasma antenna in difficult conditions of high perturbed atmosphere requires solving a number of problems. One of the main problems is to provide the stability of the plasma jet under the impact of high-speed gas flow and high temperatures. Previously the stability of plasma jet in supersonic gas flow was demonstrated in experiments conducted in rarefied atmosphere [4]. In our experiments we found that the influence of gas flow increases in the dense atmosphere. Enhancing the stability under these conditions may be achieved by increase the dynamic pressure of the plasma jet provided by the choice of appropriate discharge parameters. Obviously, the solution of this important problem requires undertaking comprehensive research.

Numerical modeling was initiated to analyze the interaction of microwave radiation with plasma layer. It is assumed that 2D consideration will allow investigating the influence of various types of regular spatial plasma structures on the characteristics of the transmission and scattering of EM waves beams. The model allows investigating also the development of MW plasma structures (it is virtually impossible to implement in the framework of 3D modeling).

Thus, plasma layers of different geometry and parameters by plasma jet and MW discharges are created experimentally. The possibility of using plasma jets as receiving and transmitting antennas of centimeter-decimeter range in a mode of asymmetric quarter-wave dipole is shown experimentally. Simulation interaction of limited microwaves beams with plasma objects is also started.

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References
[1] Brovkin V G and Kolesnichenko Y F 1994 *Zh. Tekh. Fiz.* **64** 194–196
[2] Paschina A S and Klimov A I 2014 *Chem. Phys.* **33** 78–86
[3] Pashchina A S 2014 *13th Int. Workshop on Magneto-Plasma Aerodynamics* ed Bityurin V (Moscow, Russia)
[4] Klimov A I and Mishin G I 1993 *JETP Lett.* **19** 19–24