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Application of gas-discharge plasma at reduced pressure as a radiating body of an asymmetrical dipole antenna

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A plasma asymmetrical dipole antenna was investigated in the frequency range 1–3 GHz, the radiating body of which was a glow discharge positive column in neon at reduced pressure. It was shown that the antenna has a circular azimuthal radiation pattern with one main lobe directed at an angle of 60° to the horizon, with a width of about 30° in elevation. The influence of the electron density in the plasma column on the S parameters and gain of the plasma antenna was experimentally investigated. It was shown that at an electron density of more than $10^{14}\,\mathrm{cm}^{-3}$ the maximum gain is more than -6 dBi. The importance of simultaneous measurements of S_{11} and S_{21} parameters of a plasma antenna is noted. The possibility of using atmospheric pressure discharges as a plasma dipole antenna is considered. The obtained results are important for the development of high-speed adaptive radioelectronic systems.

Keywords: gas discharge, asymmetrical dipole, antenna, radiation pattern, gain, electron density.

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Introduction

Currently the adaptive („smart") system of wireless data transmission of various purpose are actively developed, such as software-defined radio systems, 6G communication systems, radar, navigation and electronic warfare systems [1,2]. For these systems antennas with possibility of programmable electronic control of the parameters and characteristics are necessary. There are different types of such antennas and antenna systems: linear and aperture antennas, phased arrays, MIMO antennas, etc. The electronic control is implemented using semiconductor elements or integrated circuits, using „smart" materials etc. [2–4]. One of the development directions of antennas and antenna systems with controlled characteristics is plasma antennas. The plasma antennas can be conditionally divided to two classes: first — plasma is part of radiating element of antenna (dipole, loop antennas) [5–8], and second — plasma is used to control passage and shielding of radio waves (for example, drum type antenna) [9–12]. By design, antennas can be dipole, loop, mirror, lens, horn and other types. The gas-discharge plasma is created by various methods, these can be HF or microwave discharges, LF discharges, DC discharges [13,14]. The plasma antennas distinctive feature is the possibility of electrical adjustment of its characteristics by change of plasma electron density n_e [15–17]. In antennas, which use a plasma column as a radiating element, a change in plasma parameters leads mainly to a change in backscattering S_{11} and the antenna gain with insignificant changes in the radiation pattern [18,19]. In antennas, which use plasma as a control element, a change in plasma parameters can lead to changes in the shape of the radiation pattern [12] and its direction (electronical scanning and changes of the transmitted power level) [20].

The main characteristics of the gas-discharge plasma, which determine its interaction with external electromagnetic waves, are dielectric permittivity ε_p and conductivity σ. Generally, they are functions of $\omega_p^2 = \frac{4\pi e^2 n_e}{m_e}$ — electron plasma frequency, ν — frequency of electron collisions with the neutral particles and $f_0 = \omega_0/2\pi$ — electromagnetic wave frequency [21]:

$$\varepsilon_p = 1 - \frac{\omega_p^2}{\omega^2\left(1 - i\frac{\nu}{\omega_0}\right)} = \varepsilon_{re} + i\varepsilon_{im}$$

$$= 1 + \frac{\omega_p^2}{\omega_0^2 + \nu^2} - i\frac{\omega_p^2 \nu}{\omega_0(\omega_0^2 + \nu^2)}, \tag{1}$$

$$\sigma = \sigma_{re} + i\sigma_{im}, \quad \sigma_{re} = \frac{e^2 n_e}{m_e} \cdot \frac{\nu}{\omega_0^2 + \nu^2},$$

$$\sigma_{im} = -\frac{e^2 n_e}{m_e} \cdot \frac{\omega_0}{\omega_0^2 + \nu^2}, \tag{2}$$

where e — electron charge, ε_0 — dielectric constant of vacuum and m_e — electron mass.

The main task of any antenna is transmission or reception of electromagnetic wave energy through the space surrounding it. For the successful execution of this objective the antenna shall be well matched with the

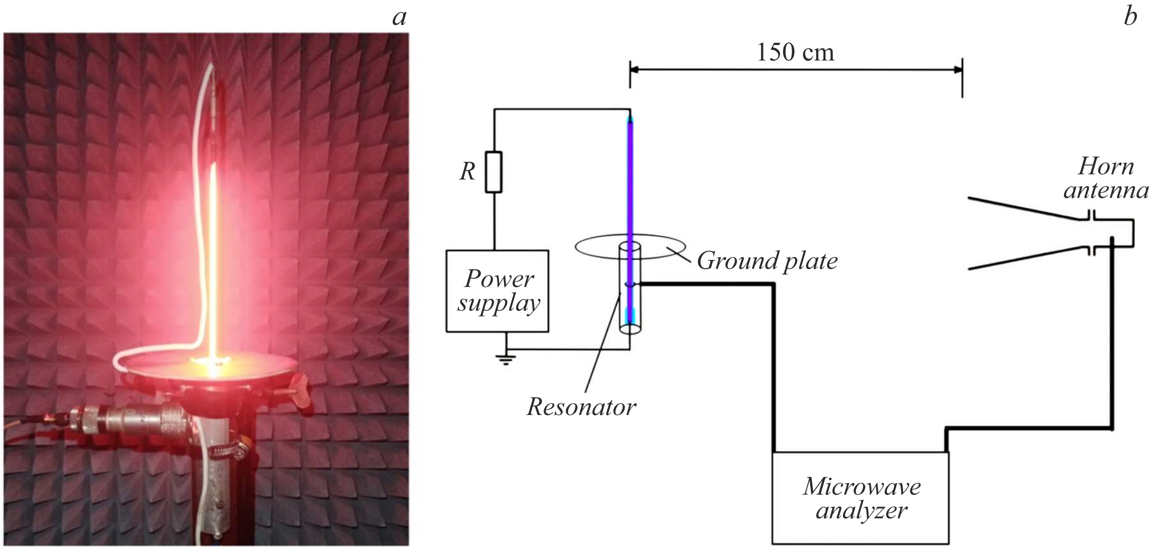

Figure 1. *a* — Photo of plasma asymmetric dipole antenna, *b* — scheme of S parameters registration.

feeder line, i.e. have low backscattering (low values of the parameter S_{11}) in working frequency range. The vast majority of plasma antennas studies come down to identification of a significant decreasing of the reflected signal at antenna input ($S_{11} < -10\,\mathrm{dB}$) depending on electron density in plasma column and further modeling of radiation pattern of the implemented antennas [13,22]. In our opinion, this approach is limited, since a sharp decrease of the coefficient S_{11} can be due to various factors of waves interaction with plasma of the gas-discharge column, accordingly simultaneous registration of radiation level in the surrounding space is required. Most literary sources mainly present the studies on use of discharges at low pressure of the order of several Torr [5–19], which is often motivated by the simplicity of experimental implementation and analysis of the radio waves interaction with plasma, since $\nu < \omega_p$ and $\nu < \omega_0$, while the use of gas discharges at reduced and atmospheric pressures for the implementation of plasma antennas are not known to the authors of this paper. In papers [16,17] it is shown that in order for the plasma dipole antenna to achieve radiation characteristics similar to the characteristics of the metal antenna (linear mode) it is necessary to form along its plasma column the surface electromagnetic wave with dispersion characteristic, which linear part is close to line kc in working frequency range (k — wave number, c — light speed in vacuum). To form such surface wave the plasma frequency must exceed the electromagnetic wave frequency by more than an order of magnitude $\omega_p > 10 \cdot \omega_0$. At fixed plasma frequency (electron density) this ratio determines the upper limit of the operating frequency range of the plasma antenna. Thus, the electron density increasing in the plasma column served as radiating element of antenna, (ω_p increasing) due to the transition from the use of low pressure discharges to reduced and atmospheric pressure discharges can make it possible to increase the upper limit of the working frequency range of plasma antennas. Besides, use of atmospheric pressure discharges will prevents occurrence of unwanted microwave discharge in the working gas when the power level of the transmitted signal increases. At the same time, papers [23,24] showed that gas-discharge plasma at reduced and atmospheric pressure can act as an effective control element of high-speed microwave devices operating at high power levels.

In present paper the possibility to implement the plasma antenna using reduced pressure gas-discharge plasma (about 70 Torr) is experimentally demonstrated, the main characteristics of the implemented antenna are determined depending on the plasma parameters, and the prospects of using such discharges at reduced and atmospheric pressures as part of antenna devices are estimated.

1. Experimental setup and study methods

The plasma asymmetric dipole is a plasma column of gas-discharge lamp GSh-5. In microwave technology lamp GSh-5 is known as gas-discharge noise generator in centimeter wavelength range, it is a sealed quartz tube filled with neon (Ne) at pressure of about 70 Torr. Microwave power was fed to the lamp using coaxial resonator connected to a disk grounded plate (Fig. 1). The plate diameter is 10 cm, resonator central hole diameter is 20 mm, distance from plate to anode of lamp GSh-5 is 12.5 cm, inner diameter of quartz tube of lamp GSh-5 is 3 mm. Distance from grounded plate surface to central core of microwave connector of type IV, used to feeding microwave signal, was 3.5 cm. Lamp GSh-5 was powered by a constant voltage source $U = 0{-}600\,\mathrm{V}$, ballast resistor varied from 1 to 15 kΩ. S parameters were measured using portable

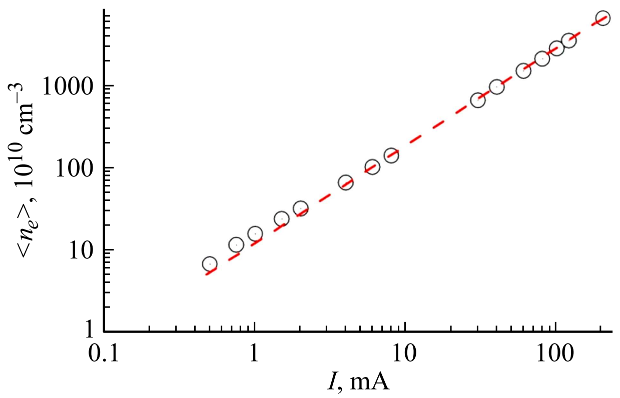

Figure 2. The electron density dependence on discharge current in the GSh-5 lamp. [25].

Vector Network Analyzer N9918A (Keysight Technologies) in frequency range $1-3$ GHz. The microwave output power level of the analyzer was -15 dBm. Preliminary calibration of the analyzer was performed using set of calibration standards NKMM-11 „Micran“. The receiving measuring pyramidal horn antenna P6-20 (effective area 125 cm^2 at frequency 1.8 GHz, working frequency range 1.4–3 GHz) was positioned at distance of 1.5 m from the plasma antenna, which corresponds to the fulfillment of the far-field conditions. To reduce the waves reflection from the nearby objects in room an absorbing coating TORA-9 with reflectance -20 dB at frequency 3 GHz was used.

Estimates of the electron density and collision frequency in the gas-discharge plasma of the lamp GSh-5 were carried out in the paper [25] and are presented in Fig. 2. The collision frequency of electrons with neutral atoms is $4 \cdot 10^{10}\,\mathrm{s}^{-1}$.

The radiation patterns (D) of the plasma antenna were measured using network analyzer N9918A and horn antenna P6-20. Receiving antenna P6-20 was fixed and directed to center of grounded plate of plasma antenna. In this case, the azimuthal and elevation angles were changed by the plasma antenna rotation around the center of the grounded plate. If the shape of the radiation pattern is determined, then for antenna gain determination it is enough to measure its value in maximum, since antenna gain (G) is directly related to its radiation pattern and efficiency (η):

$$G(\varphi, \theta) = \eta D(\varphi, \theta).$$

In this work, to determine the maximum gain, the method of three antennas was used, according to which a series of measurements of transmitted power from each antenna to another two antennas was performed, and its relationship with the antenna gain was determined [26]:

$$G_1 G_2 = \frac{P_{12}}{P_0}\left(\frac{4\pi R}{\lambda}\right)^2,$$

$$G_1 G_3 = \frac{P_{13}}{P_0}\left(\frac{4\pi R}{\lambda}\right)^2,$$

$$G_2 G_3 = \frac{P_{23}}{P_0}\left(\frac{4\pi R}{\lambda}\right)^2,$$

where G_1, G_2, G_3 — realized gains of each of the three antennas, P_{12}, P_{13}, P_{23} — power received by antennas during three measurements, P_0 — power level of signal transmitted to feeder of radiating antenna, R — distance between antennas, λ — wavelength of microwave radiation.

Let's $P'_{12} = P_{12}/P_0$, $P'_{13} = P_{13}/P_0$, $P'_{23} = P_{23}/P_0$ — normalized values of received power level, then gain of the studied antenna (let it be antenna 1):

$$G_1 = \sqrt{\frac{P'_{12}P'_{13}}{P'_{23}}}\frac{4\pi R}{\lambda}.$$

As can be easily seen, the attractiveness of this method is that the gains for all three antennas may not be known before starting measurements. Under experimental conditions antennas P6-20 ($G_2 = 5.1$ or in relative units 7.1 dBi), rod probe ($G_3 = 1.6$ or in relative units 2.0 dBi) and studied plasma antenna were used. Gain was also measured for antenna that is geometrically similar to the plasma antenna, in which the plasma column was replaced by copper rod.

2. Numerical model

The experimental radiation patterns and gains were compared with results of modeling performed by finite element method (FEM) in program COMSOL Multiphysics [27]. In this program a three-dimensional model of antenna and antenna-feeder path used in experiment was made. Permittivity ε_p and conductivity σ of plasma column were set in accordance with (1) and (2), and its diameter was assumed to be equal to inner diameter of quartz tube. Electron density distribution in column was assumed to be uniform over the volume. Antenna was excited by TEM mode of coaxial waveguide. Antenna was surrounded by space with open boundary conditions required to calculate the antenna far field. View of model and example of calculated radiation pattern of plasma antenna are presented in Fig. 3.

3. Results and discussion

Measurement results of coefficient S_{11} of plasma antenna and coefficient S_{21} of signal transmission from plasma antenna to measuring antenna at different discharge currents in lamp GSh-5 are presented in Fig. 4. Coefficient S_{11} of plasma antenna in the studied frequency range upon discharge current absence has value about $-(3-6)$ dB. When discharge occurs, local minima appear in the spectrum of S_{11}, which, with discharge current increasing, change their depth and shift to the low-frequency region (Fig. 4, a). For example, at discharge current 1.75 mA ($n_e \approx 3 \cdot 10^{11}\,\mathrm{cm}^{-3}$) the coefficient S_{11} has minimum at frequency about 1.8 GHz ($\omega_0 = 1.13 \cdot 10^{10}$ rad/s,

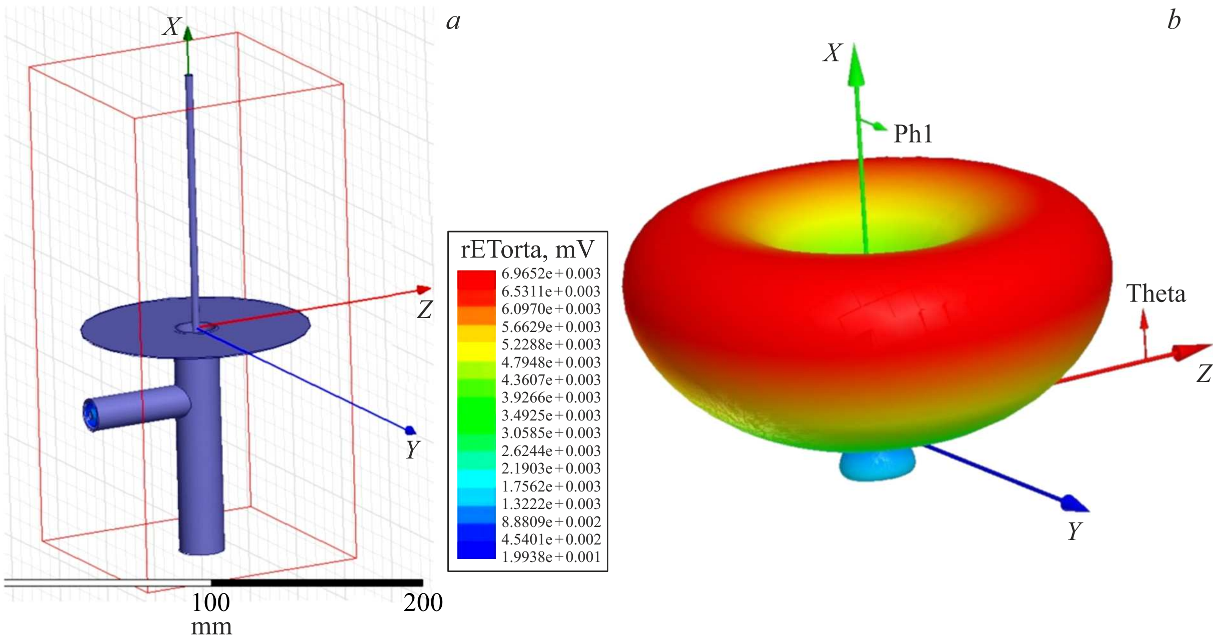

Figure 3. View of plasma antenna model (a) and (b) example of its calculated radiation pattern.

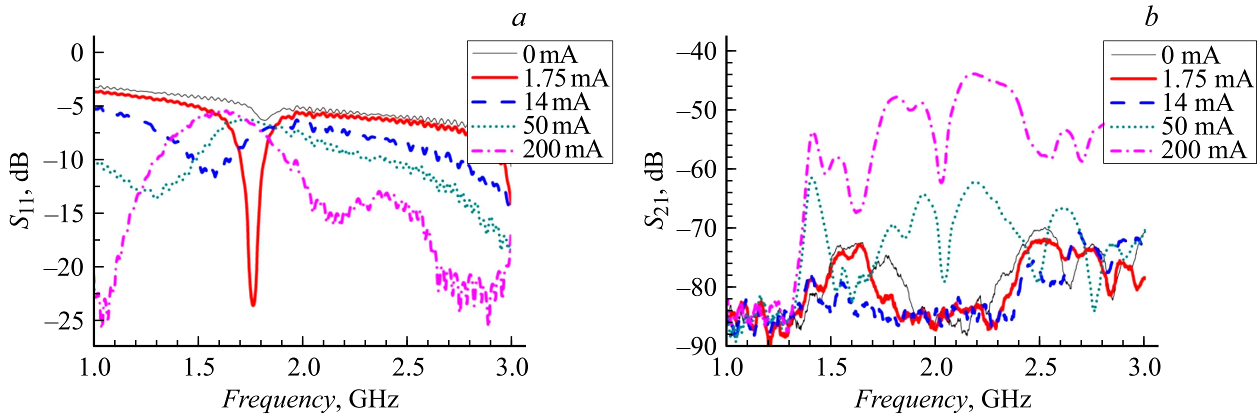

Figure 4. S_{11} and S_{21} ($\theta = 45^\circ$) spectra of asymmetric plasma dipole antenna.

$n_c = 4 \cdot 10^{10}\,\mathrm{cm}^{-3}$ — „critical" electron density) with value below -20 dB. Further increasing of the discharge current up to 200 mA and electron density (plasma frequency) up to $n_e = 7 \cdot 10^{13}\,\mathrm{cm}^{-3}$ ($\omega_p = 476.9 \cdot 10^9$ rad/s) in lamp GSh-5 leads to the frequency characteristic minimum of S_{11} shift from 1.8 GHz to region of 1.05 GHz, and from region above 3 GHz to range 2.1–2.4 GHz. Minimum of coefficient S_{11} in low frequency region of spectrum changes from -12 to -25 dB at changing of discharge current from 14 to 200 mA. At that at frequencies over 2 GHz the value of parameter S_{11} also decreases up to $-(15-25)$ dB. The presence of a sharp minimum of the coefficient S_{11} and its position in spectrum at low discharge currents is associated, probably, with matching of the coupling loop of the coaxial resonator of antenna with the plasma column, since they change when the geometry of the coupling loop changes.

The spectrum of coefficient S_{21} (Fig. 4, b) demonstrates absence of radiation at discharge current increases up to 14 mA. At further it increasing the level of transmitted signal increases, and noticeable increase of coefficient S_{21} is observed at currents about 50 mA and more. At the discharge current 200 mA maximum of transmission coefficient is in frequency range of 1.7 to 2.4 GHz and is $-(50-45)$ dB. Changes absence in frequency range 1.0–1.3 GHz is associated with limited working spectral range of receiving antenna. Note also peculiarities of behaviour of S_{11} and S_{21} spectra in low frequency range about 1.3–1.5 GHz: at discharge current change from 50 to 200 mA the antenna radiation increasing is observed, although the coefficient S_{11} increases.

Thus, the observed absence of plasma antenna radiation at return loss decreasing in some frequency ranges at low

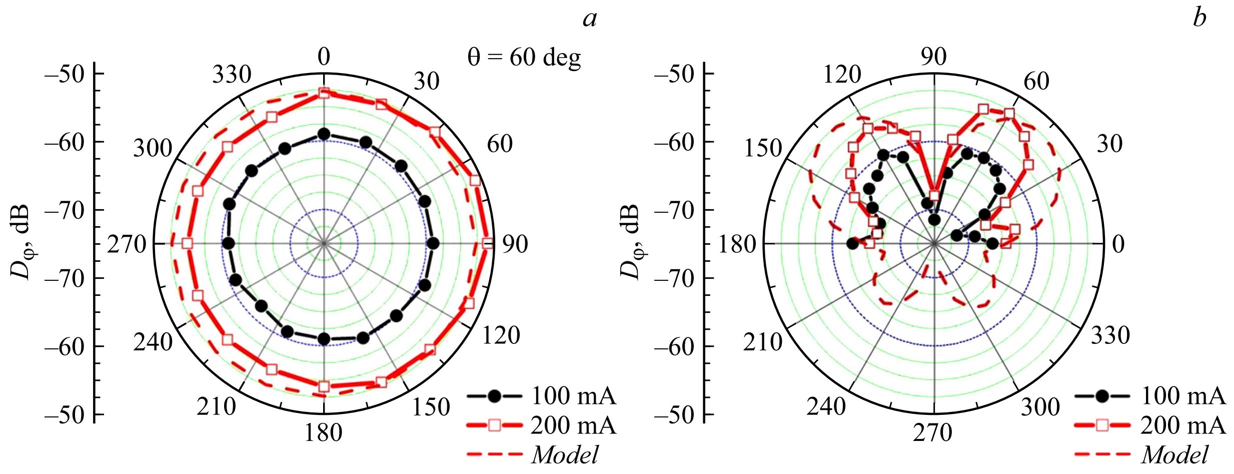

Figure 5. Radiation patterns of plasma antenna in azimuthal (H) (a) and elevation (E) (b) planes.

discharge currents, and, on the contrary, the transmitted radiation level increasing at increase of return loss indicate the importance of simultaneous measurements of its S_{11} and S_{21} parameters.

In accordance with [17] for the studied plasma antenna we estimated ratio between plasma frequency and microwave signal frequency required for antenna operation in linear mode. In experimental conditions the collision frequency of electrons with neutral atoms exceeds frequency of microwave signal $\omega_0 < \nu$ within entire investigated frequency range. At current 50 mA the minimum threshold value of plasma density is overcome for the antenna switching to radiation mode — $\omega_p \geq 10\omega_0$. To switch the antenna to linear operating mode, it is required that $\omega_p \geq 42\omega_0$ [17]. This ratio, for example, for one of the characteristic frequencies $f_0 = 1.8$ GHz, should be satisfied at an electron density of more than $7 \cdot 10^{13}$ cm^{-3}, which for lamp GSh-5 corresponds to a discharge current of about 200 mA. As it will be shown below, entering of plasma antenna to the linear operating mode corresponds to achieving its gain to constant level.

The characteristic radiation patterns of the realized antenna obtained at frequency 1.8 GHz at different discharge currents are presented in Fig. 5.

The azimuthal radiation pattern has practically circular shape. Insignificant asymmetry is associated with nonperfect position of the lamp GSh-5. The discharge current increasing leads to signal increasing without change in pattern shape. During measurements the angle is metered from the grounded plate plane towards the antenna axis. Maximum of the radiation pattern is observed at angle 60° to the grounded plate plane, and width of the beam was about 30°. The obtained data are well agreed with the results of modelling of antenna RF properties made in program COMSOL Multiphysics. Appropriate radiation patterns calculated for the plasma density $n_e = 7 \cdot 10^{13}$ cm^{-3}, are marked in Fig. 5 by dashed curves. The maximum of calculated elevation radiation pattern is at angle 40° to the grounded plate, and beam width is about 50°. The modelling showed that presence of the anode wire does not provide noticeable distortions in the radiation pattern of the antenna at case that it is positioned along the gas-discharge tube.

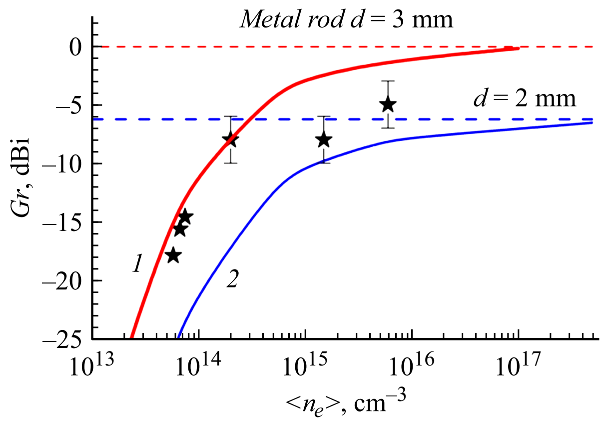

Figure 6. Dependence of the realized gain of plasma asymmetric dipole antenna on the electron density. Plasma column diameter: *1* — 3 mm, *2* — 2 mm. Dashed lines — copper rods.

The realized gain of plasma antenna was determined in the direction of maximum of elevation radiation pattern at angle $\theta = 60°$ using method of three antennas. The obtained values are marked with asterisks in Fig. 6. The electron density increasing leads to the gain increasing, and at density over $2 \cdot 10^{14}$ cm^{-3} it achieves constant level $-(8-5)$ dBi. The experimentally obtained data were compared with the results of modelling made in program COMSOL Multiphysics (solid curves — dependence of the plasma antenna gain on the electron density in plasma column and dashed lines — the gain of similar antenna with copper rod as radiating element). The calculated values of the gain of the antenna with copper rods with diameter of 3 and 2 mm correspond to the experimental data.

The experimentally obtained constant value of the plasma antenna gain is somewhat lower than calculated values (curve *1*, Fig. 6) and does not reach limit value of the gain $= -0.1$ dBi, corresponding to similar antenna with copper rod with diameter 3 mm. It is close to the gain value of antenna with copper rod with diameter 2 mm (-6.5 dBi) and to the calculated gain values of plasma antenna with plasma column diameter 2 mm (curve *2*, Fig. 6) at electron densities over $10^{16}\,\mathrm{cm}^{-3}$. Apparently, the observed difference in experimental and calculated gain values of the plasma antenna on side of high electron densities is due to discharge contraction at high currents, which is equivalent to decrease in the effective radius of the plasma column. In accordance with paper [28] for characteristics of lamp GSh-5 (70 Torr, inner radius 1.5 mm) the discharge contraction starts at currents over 100 mA, and radius of plasma column decreases by about two times. But the discharge contraction in neon was not specifically discussed in present paper.

The created model of plasma antenna allowed us to estimate the possibility of using the atmospheric pressure discharges as plasma dipole antenna in terms of the required plasma parameters. In setting of model parameters the transition from reduced pressure (70 Torr, $\nu = 4 \cdot 10^{10}\,\mathrm{s}^{-1}$, plasma column diameter 3 mm) to atmospheric pressure is represented as change of the collision frequency of electrons with neutral particles by order of magnitude, i.e. ν set equal to $4 \cdot 10^{11}\,\mathrm{s}^{-1}$, at that $\nu > \omega$ in studied frequency range and $\nu > \omega_p$ for electron density up to $5 \cdot 10^{13}\,\mathrm{cm}^{-3}$. Appropriate dependence of the maximum realized gain of the plasma antenna on electron density is shown in curve *2* in Fig. 7. The gain of plasma antenna will approach values of the gain of geometrical similar metal antenna (dashed line) at electron densities over $10^{16}\,\mathrm{cm}^{-3}$, which about by one order of magnitude exceeds the required electron density ($n_e > 10^{15}\,\mathrm{cm}^{-3}$) in reduced pressure discharges (curve *1*).

To estimate the influence of the electron collision frequency on the gain of plasma antenna, calculations were

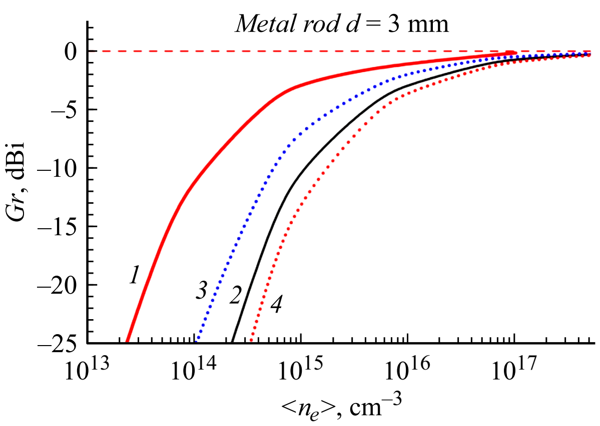

Figure 7. Dependence of the realized gain of plasma asymmetric dipole antenna on the electron density. The electron collision frequency: *1* — $4 \cdot 10^{10}$, *2* — $4 \cdot 10^{11}$, *3* — $2 \cdot 10^{11}$, *4* — $6 \cdot 10^{11}\,\mathrm{s}^{-1}$. Dashed line — copper rod.

also performed at collision frequencies $2 \cdot 10^{11}\,\mathrm{s}^{-1}$ (curve *3*) and $6 \cdot 10^{11}\,\mathrm{s}^{-1}$ (curve *4*). For example, to form a plasma antenna gain above — 3 dBi at given collision frequencies, the electron density must exceed $5 \cdot 10^{15}\,\mathrm{cm}^{-3}$ and $1.5 \cdot 10^{16}\,\mathrm{cm}^{-3}$, respectively, i.e. to obtain the desired gain of a plasma antenna the electron density must change proportionally to the change in the collision frequency, which is explained by the need to ensure equal conductivity in the plasma column. Actually, as it follows from (2), at $\nu > \omega$ conductivity is $\sigma \approx \frac{e^2 n_e}{m_e} \cdot \frac{1}{\nu}$. Thus, to create plasma antennas, the main plasma characteristic is its conductivity. In this case, the conductivity of the plasma column must be more than 1000 S/m. Electron densities of the order of $10^{16}\,\mathrm{cm}^{-3}$ at atmospheric pressure can be obtained in pulse discharges [23].

Conclusion

In this paper the asymmetrical dipole plasma antenna was studied, the radiating element of which was a positive column of a glow discharge in neon at reduced pressure. The maximum gain of the antenna, its azimuthal and elevation radiation patterns were determined experimentally. The dependences of the antenna characteristics on the electron density in plasma column of the gas-discharge lamp were determined. The obtained results were compared to the results of modelling made in program COMSOL Multiphysics.

It was shown that the plasma antenna has a circular azimuthal radiation pattern with one main lobe directed at an angle 60° to grounded plate with width about 30° in elevation. It was shown that at the electron density over $10^{14}\,\mathrm{cm}^{-3}$ the maximal gain of plasma antenna is more than -6 dBi, which is close to the gain of geometrically similar metal antenna with a metal rod diameter smaller than the inner diameter of the gas-discharge lamp tube. This difference, probably, is due to the phenomenon of discharge contraction in neon, which should be taken into account during design of the plasma antennas utilizing of atmospheric and reduced pressures discharges.

The influence of the electron density in the plasma column on S parameters of the plasma antenna was experimentally studied. The importance of simultaneous measurements of its S_{11} and S_{21} parameters was noted. It was shown that the fulfillment of the conditions for the plasma antenna to reach linear operating mode at increase of the electron density in the plasma column corresponds to its gain reaching a constant (maximum) level.

The comparative analysis of the results of gain modeling for antennas implemented using discharges at different pressures showed that the main criterion for ensuring a gain value close to that of the antenna with metal radiating element is the creation of a conductivity in the plasma volume of more than 1000 S/m .

The obtained results are important for the development of high-speed adaptive radio electronics systems.

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Conflict of interest

The authors declare that they have no conflict of interest.

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