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Resonance method for measuring ionospheric plasma density onboard microsatellites

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A method has been developed for diagnostics of the ionospheric plasma density on board a microsatellite using a resonator made on a segment of a two-wire line. The measurements of plasma parameters are based on the amplitude-phase method, which permits extanding the dynamic range of measured values by three orders of magnitude without increasing the resonator length. The paper presents a measurement technique and its experimental testing on a plasma setup under conditions as close as possible to the ionospheric ones.

Keywords: micro- and nanosatellites, dielectric permittivity, resonance frequency, amplitude-phase method.

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Introduction

New methods of research of the non-stationary and heterogeneous near-Earth plasma is an urgent problem of the ionosphere physics. It is important to measure the plasma parameters both in applications ensuring stable radio communication, navigation and radiolocation and in the fundamental problems of the space plasma physics, as well. The variously-scaled space&time heterogeneities of the ionosphere cause fluctuations of the amplitude-phase characteristics of the trans-ionospheric systems GLONASS/GPS, thereby affecting the positioning accuracy [1,2]. The practical interest is focused on detailed research of a fine structure of the ionosphere heterogeneities under active impact by powerful radiophysical units, including short-wave heating benches and terrestrial communication stations [3,4]. The large interest is paid to specific features of waveguide propagation of whistle waves in plasma density ducts largely elongated along the Earth's magnetic field [5]. The detection and detailed research of the small-scaled plasma heterogeneities from several meters to dozens of kilometers in-situ provide great opportunities for organization of channels of over-the-horizon radio communication using artificial heterogeneities of the near-Earth plasma [6–8]. The direct measurements of the plasma density are required for forecast purposes in order to construct new empirical ionosphere models and improve the existing ones [9]. The search of interrelations of the plasma&wave processes and the electromagnetic ionosphere parameters will allow developing methods of forecast and monitoring natural and man-made disasters, like earthquakes [10], thunderstorms [11], volcano eruptions and sand storms [12], cosmic dust flows [13], tests of nuclear weapons and contingencies during operation of nuclear power stations.

The recent years' statistics has demonstrated an explosive growth of a number of launches of small (up to 100 kg) super-small (up to 10 kg) spacecraft designed to completely solve quite narrow scientific tasks and to promptly test new measurement technologies [14]. A small weight, small overall dimensions, low cost, tight deadlines for developing and creating scientific equipment, a possibility of concurrent launches, these are obvious advantages of micro- and nanosatellites against large spacecraft. The increased interest to the small-sized satellites stimulates development of new hardware&software diagnostics systems. Despite a variety of laboratory means for monitoring the plasma parameters, there are a few types of satellite sensors for the ionospheric plasma concentration, wherein their capabilities are quite limited. Primarily, it is related to low sensitivity of the majority of techniques as well as to rigid requirements to scientific equipment in terms of limitation of the overall dimensions, the weight, energy consumption and the cost.

The traditionally used methods of measurement of the ionosphere parameters notably include the Langmuir probe and its modifications [15]. Due to the low plasma density, the equipment operates on an electron branch of the current-voltage curve (CVC), as the electron current is much bigger than the ion one (in $\sqrt{M/m}$ times, where M and m — the masses of the ion and electron, respectively). This operation mode requires a significant area of a reference electrode (the satellite case), which must also exceed the probe area in $\sqrt{M/m}$ times. It is difficult to implement this condition on the small satellites. Moreover, the second mode of sweeping of CVC voltage also limits the space resolution of the sensor to several kilometers. Despite the simple design of the Langmuir probe, it is difficult to interpret the sensor readings due to many factors, for example, influence of the Earth's magnetic field [16].

The density and the temperature of the near-Earth plasma are determined using the method of mutual impedance of the antenna pair (MIP) [17]. The method of active resonance probing of the low-density plasma parameters has been successfully realized by French scientists by means of the Whisper instrument in the Cluster mission [18]. However, ten-meter antennas of the transceiver prevent using this diagnostics in compact satellites.

Presently, the ionosphere studies have come to the stage, which requires to create new-generation diagnostics equipment for measuring the plasma density and its space&time fluctuations. The present work is dedicated to developing and testing the technique of determination of the plasma density within the range $10^3-10^6\,\mathrm{cm}^{-3}$ using the small-sized sensor onboard the micro- and nanosatellites at the orbit height of 400–600 km. The diagnostics will allow investigating the small-scaled space heterogeneities of the plasma with the size of up to 8 m, whereas the sensor's wideband frequency range of up to 1 MHz will allow recording small relative disturbances of the plasma density of the order of 10^{-3} which are related to the wave processes in the ionosphere.

The sensor operation is based on a method of the plasma probe with the UHF resonator [19], which is successfully used in the laboratory plasma benches for simulating the electrophysical processes in the near-Earth plasma [20]. The probe is a quarter wavelength resonator at a section of the two-wire line, which is closed at one end and open at the other. Knowing a natural frequency of the resonator in the plasma f and without the plasma f_0, it is possible to determine the concentration of the electrons

$$N_e = \frac{\pi m}{e^2}\,(f^2 - f_0^2), \tag{1}$$

where m and e — the mass and the charge of electron, respectively.

The proposed method can record not only the average value of the concentration within the wide range along the motion of the satellite, but its fluctuations with the high space&time resolution. Unlike the Langmuir probes traditionally used on the satellites, the readings of resonance UHF probe do not depend on the temperature of electrons and they are determined only by the plasma density. The satellite potential is not included in the measurements, thereby making it possible to use the diagnostics onboard the micro- and nanosatellites with a limited area of the reference electrode. The UHF probe operates at the frequency exceeding all the characteristic frequencies in the ionosphere (the plasma and cyclotron frequencies, the frequency of electron-neutral collisions, etc.), thereby simplifying the analytical description of the electrodynamic model of the measurement system. The works [21–27] have further developed the method of the resonance UHF probe in terms of expanding the functional capabilities and improving the accuracy of measurement of absolute values of the density.

In research of the plasma parameters, the important characteristics of the sensor include a dynamic range, sensitivity and time resolution. In the standard method of measurements, the frequency shift must exceed a width of the resonance curve, which is determined by the quality factor of the measurement system Q [28]. At the same time, the minimum measured value of the square of the plasma frequency is: $f_{pe}^2 = 2f_0^2/Q$. For the quarter wavelength resonator of the length of 40 cm, which does not exceed typical overall dimensions of the small-sized satellite, with the natural frequency of the resonator $f_0 = 180\,\mathrm{MHz}$ and the quality factor $Q = 200$, the minimum value N_e will be $10^6\,\mathrm{cm}^{-3}$. The measurement of the lower densities of the ionosphere plasma within the range $10^3-10^6\,\mathrm{cm}^{-3}$ at the height of about 500 km would require the ten-meter probe, which is unacceptable onboard the microsatellites.

The present work offers to use the amplitude-phase method [26], which can reduce the minimum measured value of the density by the three orders from 10^6 to $10^3\,\mathrm{cm}^{-3}$ without increasing the resonator length, thereby expanding the operating range of the measurement system. Within this method, the probe operates at the fixed frequency corresponding to the natural frequency of the resonator without the plasma f_0, and the small frequency shifts within the width of the resonance curve are recorded by the amplitude-phase measurements.

The present work describes the design of the laboratory mockup of the sensor of plasma parameters (PPS) and discusses the special features of the amplitude-phase technique in order to determine the concentration of electrons and the characteristic of the electrodynamic model of the resonator. The PPS has been experimentally tested in the plasma test bench „Ionosphere" (Institute of Applied Physics of the Russian Academy of Sciences, Nizhny Novgorod) under the conditions as close as possible to the ionospheric ones.

1. Resonator of the sensor of plasma parameters

The sensor of plasma parameters consists of a resonator and an electronics unit, which are electrically connected to each other by two coaxial shielded cables. The resonator is installed on the case of the spacecraft, and the electronics unit is located inside. The most important thing in developing the sensor design is selection of its geometrical dimensions. For research of the ionosphere density within the range $10^3-10^6\,\mathrm{cm}^{-3}$ by the satellite with the orbit height of 500 km, the optimum option is a resonator with the natural frequency $f_0 = 180\,\mathrm{MHz}$ and the length 40 cm, thereby not exceeding the overall dimensions of the majority of the microsatellites. The frequency shift of the resonance $\Delta f = 300\,\mathrm{kHz}$, corresponding to the maximum density of $10^6\,\mathrm{cm}^{-3}$, will not exceed the width of the resonance curve at the quality factor of at most 300.

The PPS laboratory tests included manufacturing of the mockup of the resonator at the quarter wavelength section of the two-wire line (Fig. 1). The conductors were copper tubes *1* soldered to the metal plate *3* at the closed end. The case of the satellite *5* and the base of the resonator are galvanically coupled so that the sensor and the satellite have a common potential. The distance between the tubes is

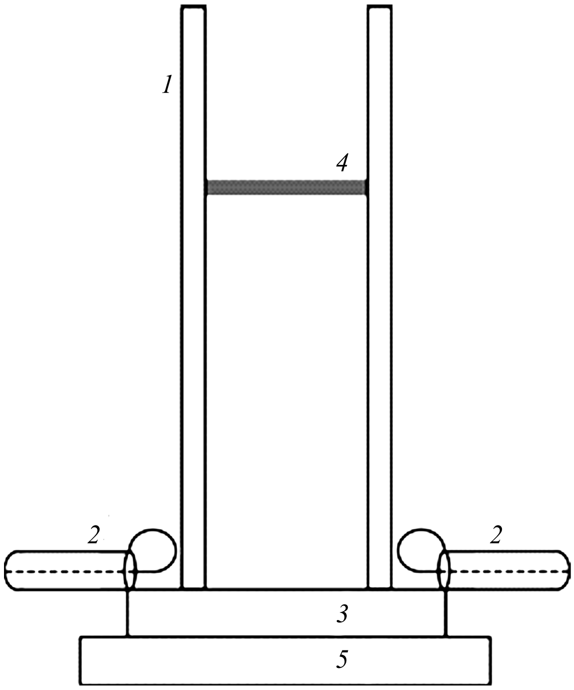

Figure 1. Scheme of the quarter wavelength resonator of the sensor of plasma parameters: *1* — the resonator tubes, *2* — the exciting and receiving lines with magnetic coupling loops, *3* — the closed end of the resonator (metal plate), *4* — the dielectric bridge, *5* — the case of the satellite.

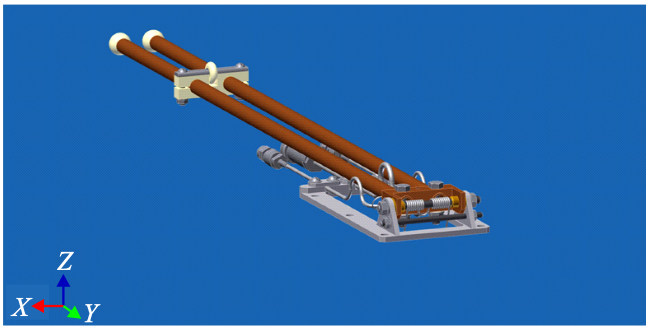

Figure 2. 3*D*-model of the laboratory mockup of the resonator.

$D = 25$ mm, the external radius is $a = 3$ mm, and the wall thickness is 1 mm.

The mechanical oscillations are compensated by rigid fixation using the dielectric bridge to each other *4*. Excitation of the high-frequency oscillations in the resonator and the reception of the resonance response are realized through the coaxial cables terminating in the magnetic coupling loops *2* of the diameter of 8 mm. The natural frequency of the resonator without plasma is $f_0 = 180$ MHz, the quality factor is 220. The 3*D*-model of the laboratory mockup of the resonator is shown on Fig. 2.

When there is plasma within the high-frequency field of the sensor, the natural frequency of the resonator is shifted upwards in relation to the „vacuum" one (without plasma). In the plasma with the density of 10^3 cm^{-3} the frequency shift Δf will be 280 Hz. It is proposed to use the amplitude-phase method to measure so small values, which can not be classically determined by the shift of the maximum resonance.

2. Amplitude-phase method for diagnostics of the small densities

The developed technique of measurement of the plasma density is optimized by assembling an experimental specimen of radioelectric equipment with the phase shift method designed therein. The method essence is measurement of phase incursion of a signal passed through the resonator with plasma (Fig. 3). The probe operates at one fixed frequency f_0. The oscillation source is a sweep generator made as a fast-operation frequency synthesizer, which is based on a phase-locked single-loop system with generatability at a fixed frequency with stability of at least 10^{-7}. The generator signal U_G is split by a resistance element into two equal signals, one of them is fed to the exciting loop of the resonator via the coaxial cable, while the another one is supplied as a reference one to the phase detector based on the ADE-R2ASKLH+ chip. The signals of the receiving coupling loop U_0 and the reference one $U_G/2$ are mixed on the phase detector. Then the signal is amplified, digitized and stored in the PC memory for further processing. The output signal from the measurement system U_{out} is expressed as follows:

$$U_{\text{out}} = kU_0 \sin(\Delta\varphi), \tag{2}$$

where $\Delta\varphi$ — the phase difference between U_G and U_0, which is determined by the length of the coaxial cables, k — the coefficient taking into account attenuation in the connecting wires and amplification of the terminal low-frequency cascade.

The cable length is selected to specify the phase shift so as to nullify U_{out} without plasma. The presence of plasma results in additional phase incursion and a non-zero level of the output signal U_{out} depending on the plasma density N_e.

It should be noted that the above-described amplitude-phase technique has been successfully applied for measurement of gas pressure within the range from 10^{-1} Torr to 1 atm [29].

The dependence $U_{\text{out}}(N_e)$ is simplified if the amplitude of the resonance curve does not change when the signal

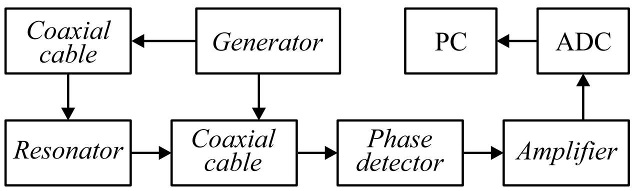

Figure 3. Block diagram of the amplitude-phase measurements of the small plasma densities.

passes through the resonator filled with plasma. It is true for the case when the total quality factor Q of the measurement system does not depend on collision losses in plasma. Generally, Q is determined by coupling with the exciting and receiving lines, ohmic losses in the resonator wires, radiation losses and collision losses in plasma. Using the formulas for each type of the quality factor [30–32], it is easy to show that Q is mainly determined by the magnetic coupling of the resonator with the lines of excitation and reception of the signal, and the collision losses in plasma are small and do not affect the total quality factor.

Using this simplification, we obtain the dependence of the output signal on the plasma density $U_{\text{out}}(N_e)$ using the electrodynamic description of the measurement system.

3. Electrodynamic model of the measurement system

The mathematical description of the sensor is based on reduction of the initial distributed system to its equivalent oscillatory circuit with the concentrated parameters (Fig. 4). For this, let us present the initial system (Fig. 4, a) as three concentrated circuits with magnetic couplings (Fig. 4, b).

The first circuit consists of the generator with the internal resistance R_G equal to the cable's wave resistance ρ, the exciting line and the magnetic coupling loop. The second circuit corresponds to a resonator as the section of the two-wire line with the wave resistance ρ_0, which is open at one end and closed at the other by the inductive coupling loop. The third circuit consists of the receiving frame, the transmitting cable and the load with the resistance R equal to ρ. The mutual load impedance between the circuits *1–2* and *2–3* is designated as $Z_M = j\omega M$ ($\omega = 2\pi f$ — the ring frequency, j — the imaginary unit). The magnetic coupling between the circuits *1* and *3* is negligibly low in comparison with *1–2* and *2–3*.

At the equalities $R = \rho$ and $R_G = \rho$ the connecting cables in the equivalent diagrams for the circuits *1* and *3* are not taken into account. The concentrated circuit *2* is produced by recalculation of the impedances of the open and closed ends of the resonator with the length $l = l_1 + l_2$ into the point $x = 0$. The small section of the short-circuited line of the length l_1 ($l_1 \ll l_2$) is equivalent to the magnetic frame.

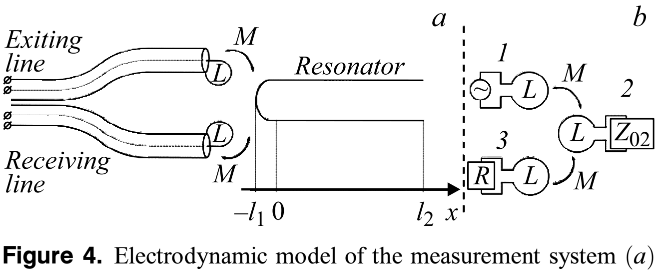

Figure 4. Electrodynamic model of the measurement system (a) and its equivalent scheme with concentrated elements (b). L — inductance of the magnetic frames, M — mutual inductance, *1–3* — the concentrated circuits; the magnetic coupling between the circuits *1* and *3* is not taken into account.

Let the length l_1 be as such that the frame inductance coincides with L:

$$\omega L = j\rho_0 \operatorname{tg}(kl_1), \tag{3}$$

where $\rho_0 = (120/\sqrt{\varepsilon})\ln(D/a)$ — the wave resistance of the line forming the resonator, $k = (\omega/c)\sqrt{\varepsilon}$ — the wave number, $\varepsilon = 1 - f_{pe}^2/f^2$ — the permittivity of plasma. The input impedance of the open end in the point $x = 0$ is equal to: $Z_{02} = -j\rho_0 \operatorname{ctg}(kl_2)$. Thus, the circuit *2* is presented by the impedance Z_{02} and the inductive resistance of the magnetic frame of the resonator $j\omega L$. The scheme of the three concentrated circuits with the magnetic couplings is shown on Fig. 4, b.

In order to determine the current in the receiving loop, we find the equivalent input resistance Z_{inp} of the measurement system by subsequently recalculating the impedance via magnetic coupling [31] from the circuit *3* to *2*, and then from *2* to *1*:

$$Z_{\text{inp}} = j\omega L - Z_M^2\big(Z_2 - Z_M^2/(j\omega L + R')\big)^{-1}, \tag{4}$$

where $Z_2 = Z_{02} + j\omega L$, $R' = -Z_M^2/(j\omega L + R)$ — the resistance R recalculate from the circuit *3* to *2*. In accordance with [30] the amplitude of the current I_1 in the excitation loop is equal to

$$I_1 = I_0(1 - G), \tag{5}$$

where I_0 — the amplitude of the incident wave, $G = (Z_{\text{inp}} - \rho)/(Z_{\text{inp}} + \rho)$ — the reflectance. Inserting G into (5), and taking into account (4) we obtain the current in the exciting loop of coupling

$$I_1 = 2I_0\big(1 + (j\omega L)/\rho - Z_M^2/(\rho Z_2 - \rho Z_M^2/Z_3)\big)^{-1}, \tag{6}$$

where $Z_3 = j\omega L + R'$. In order to find the complex amplitudes of the currents I_2, I_3, we write the Kirchhoff equations for the circuits *2* and *3*:

$$I_1 Z_M + I_2 Z_2 + I_3 Z_M = 0,$$

$$I_2 Z_M + I_3 Z_3 = 0, \tag{7}$$

where $I_1 Z_M, I_3 Z_M$ — the electromotive forces (EMF) of mutual inductance induced in the resonator by the currents I_1 and I_3, respectively, and $I_2 Z_M$ — the EMF of mutual inductance induced by the current I_2 in the receiving loop of coupling. By expressing I_3 from (7), we obtain after respective transformations

$$I_3 = I_0\left\{\left(1 + \frac{j\omega L}{\rho}\right)\left(\frac{Z_2}{2Z_M^2}(\rho + j\omega L) - 1\right)\right\}^{-1}. \tag{8}$$

The evaluations show that when changing the plasma density within the range $10^3 - 10^6\,\text{cm}^{-3}$, the permittivity variation $\Delta = -f_{pe}^2/f^2$ and the relative frequency shift $\delta = (f - f_0)/f_0$ is much less than unity: $\Delta, \delta \ll 1$. For simplification (8), let us use the method of subsequent approximations and expand I_3 into the series by the small dimensionless parameter $\alpha = \max\{\delta, \Delta, j\omega L/\rho\}$:

$I_3 = I_3^0 + I_3^1 + \ldots$, where I_3^i — the terms of the asymptotic series. In the zero order of smallness by the parameter α we obtain the equation for the current in the receiving loop:

$$I_3^0 = -I_0\left\{1 - j\,\frac{\rho\rho_0}{2(\omega_0 M)^2}\,\mathrm{ctg}(k_0 l)\right\}^{-1}. \tag{9}$$

From the condition of the maximum amplitude of the current I_3^0 we obtain the expression of the natural frequency of the quarter wavelength resonator without plasma:

$$\omega_0 = \frac{c}{l}\left(\frac{\pi}{2} + \pi n\right), \quad n = 1, 2, \ldots. \tag{10}$$

In the first order of smallness by α the resonance response of the probe is expressed as follows

$$I_3^1 = -I_0\left\{1 - 2jQ\left(\delta + \frac{\Delta}{2}\right)\right\}^{-1}, \tag{11}$$

where the quality factor of the measurement system $Q = \pi\rho\rho_0/[8(\omega M)^2]$, which determines the resonance width by the level $1/\sqrt{2}$ of the amplitude, depends on the coupling parameter ωM of the resonator with the exciting and receiving loops of coupling.

Distinguishing the absolute magnitude and the phase of the signal (11), we obtain the expressions for the amplitude U_0 and the phase $\Delta\varphi$ of the signal passed through the resonator:

$$U_0 = U_G\left(\sqrt{1 + 4Q^2\left(\delta + \frac{\Delta}{2}\right)^2}\right)^{-1}, \tag{12}$$

$$\mathrm{tg}(\Delta\varphi) = Q\left(\delta + \frac{\Delta}{2}\right). \tag{13}$$

As follows from (2), the output signal from the phase detected will be written as follows

$$U_{\mathrm{out}} = \left\{kU_G Q\left(\delta + \frac{\Delta}{2}\right)\right\}\left\{1 + 4Q^2\left(\delta + \frac{\Delta}{2}\right)^2\right\}^{-1}, \tag{14}$$

where the variation of permittivity of plasma Δ is related to the concentration of electrons $N_e = \pi m f_{pe}^2/e^2$ in the relationship

$$\Delta = -N_e\,\frac{e^2}{f^2\pi m}. \tag{15}$$

4. Characteristics of the resonator

Without plasma $\Delta = 0$, the frequency dependence $U_{\mathrm{out}}(\delta)$ takes the form

$$U_{\mathrm{out}} = \frac{kU_G Q\delta}{1 + 4Q^2\delta^2}. \tag{16}$$

Fig. 5 shows the frequency dependence of the output signal U_{out} from the phase detector, as calculated by the formula (16) (the curve *3*) and the experimental dependence (the curve *2*) obtained by frequency sweeping.

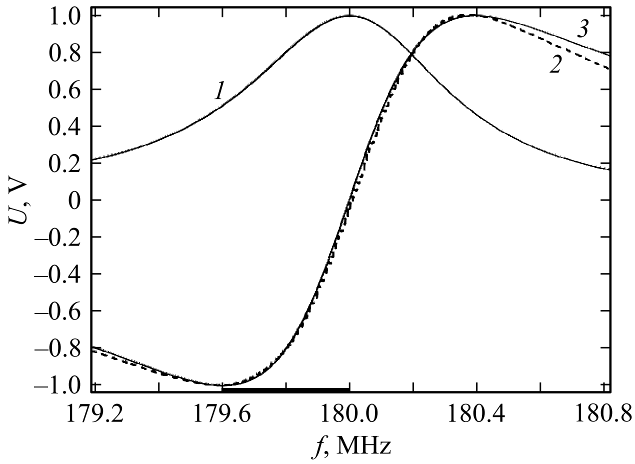

Figure 5. Characteristics of the sensor of plasma parameters: *1* — the amplitude-frequency dependence, *2* and *3* — the frequency dependence of the output signal; *2* — the experimental curve, *3* — the calculated dependence as per the formula (16). The filled rectangular shows an operating area of the sensor.

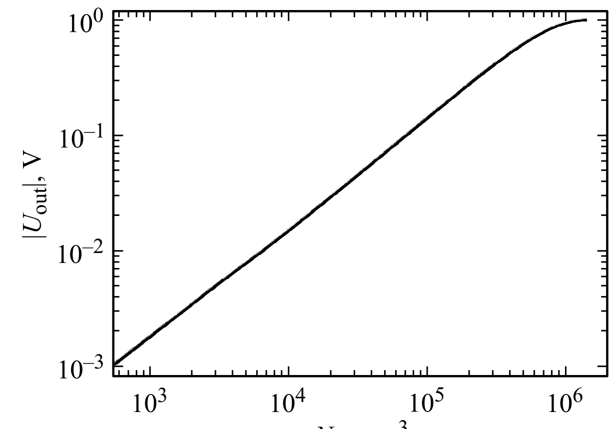

Figure 6. Calculated dependence of the output signal from the phase detector on the density of plasma.

Good coincidence of the curves within the operating area of the frequency confirms correctness of the developed electrodynamic approach, while the data discrepancy outside the resonance area is due to additional phase incursion along the length of the lead coaxial cables.

The dependence of the output signal on permittivity of plasma at the fixed frequency ($\delta = 0$) is expressed as follows:

$$U_{\mathrm{out}} = \frac{kU_G Q\Delta}{2(1 + Q^2\Delta^2)}, \tag{17}$$

where Δ and N_e are related in the relationship (15). The calculated characteristic $|U_{\mathrm{out}}(N_e)|$ in the circuit implementing the amplitude-phase method is shown on Fig. 6. When changing the density within the range $10^3 - 10^6\,\mathrm{cm}^{-3}$, the output signal varies from 2 mV to 1 V.

5. Tests of the resonator at the plasma test bench

The experiments for measurement of the density have been carried out on the plasma test bench „Ionosphere" (Institute of Applied Physics of the Russian Academy of Sciences) designed for simulating the electrophysical processes in the ionized geospheres and for testing the specimens of the space technics. The large sizes of the unit and the wide set of the diagnostics make it possible to test PPS under the conditions as close as possible to the in-situ ones. The quasi-homogeneous column of the weakly-magnetized plasma was created by an induction HF breakdown in the argon atmosphere at the pressure of $3.5 \cdot 10^{-3}$ Torr. The duration of the HF pulse is 2 ms, the generator frequency is 5 MHz. The external magnetic field was selected to be at the minimum level of 10 G and did not affect the wave dispersion in the resonator. After the discharge, the concentration of the electrons reached the maximum value of $10^{12}\,\mathrm{cm}^{-3}$ and reduced due to recombination and ambipolar diffusion of plasma to the chamber walls. The decay stage included stabilization of the quasi-stationary temperature of the electrons of about $0.2-1$ eV. The experiments were carried out in the decaying plasma after operation of the generator. The wide range of the change of the plasma parameters and good repeatability of the discharge conditions allowed carrying out the PPS tests in the most complete scope.

The sensor fixed on a rod was placed in the center of the quasi-homogeneous area of the plasma column along the chamber axis. The oscillogram of the signal from the PPS phase detector had a non-monotonic nature (Fig. 7). The extremum at the time dependence $U(t)$ at $t = 80$ ms corresponded to the minimum at the frequency characteristic of the output (Fig. 5).

The range of the measured densities of plasm restored within the time interval $t > 80$ ms, was $10^3-10^6\,\mathrm{cm}^{-3}$

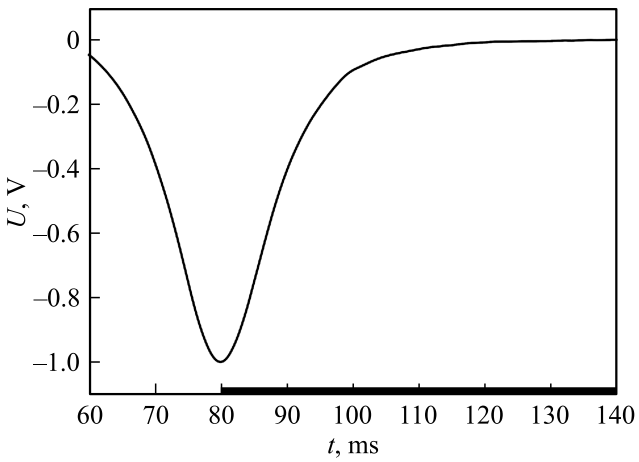

Figure 7. Typical oscillogram of the signal from the sensor in the mode of decaying plasma. The black rectangular shows the operating area corresponding to the density$10^3-10^6\,\mathrm{cm}^{-3}$.

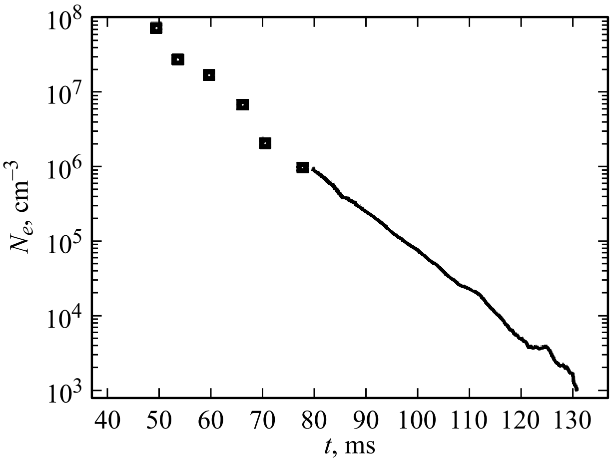

Figure 8. Dependence of the plasma density on time on the test bench „Ionosphere", as obtained by means of the resonance probe with the natural frequency of 180 MHz. The solid curve — the data are obtained by means of the amplitude-phase method, the squares – by the shift of the maximum of the resonance curve.

(Fig. 8, the solid line). The data classically obtained at $t < 80$ ms by the shift of the maximum of the resonance curve (Fig. 8, the squares) are within the range $10^6-10^8\,\mathrm{cm}^{-3}$. The total range of the measured values was five orders $10^3-10^8\,\mathrm{cm}^{-3}$. The typical time of the density fall $\tau_N \sim 8$ ms. This value well agrees with the theoretical evaluation of the decay time of the weakly-ionized plasma, which is characterized by the mode of longitudinal ambipolar diffusion with unchanged parameters within the wide time interval. The total dependence $\lg\bigl(N_e(t)\bigr)$ for all the values of the density with a good degree of accuracy obeys the linear law of decay, thereby checking the correctness of the measurements by means of the amplitude-phase method.

The technique was tested without any change of the exponential fall of the density of plasma $N_e(t)$ at the low values, as caused by influence of the double layer. Probably, it is related to the high diffusion rate in the experimental unit and presence of the weak external magnetic field.

When creating a flight model of the sensor, it is necessary to take into account the influence on the natural frequency of the resonator by surrounding items, including the satellite case, board antennas, etc. In order to determine the absolute values of ionosphere density, it is necessary to measure the natural frequency of the resonator f_0 without plasma taking into account addition electric capacitance of all the parts of the spacecraft. In doing so, the sensor is placed on the body of the flight model of the satellite, and all the board antennas are developed in the same way as in space. It should be noted that at the relatively low density of the order of $10^3\,\mathrm{cm}^{-3}$ the near-probe depletion area („sheath" in the English terminology) determined by the Debye radius exceeds the distance between the resonator wires, which can result in the measurement error. It has been concluded from the theory of the Langmuir probe, for which the recorded current is determined only by particles deposited to the surface of the conductors. However, the resonator on the section of the two-wire line is a distributed system. In this case, the phase wave speed depends on the density of plasma both inside the probe and outside it, and the permittivity is determined not only by electrons deposited to the probe surface, but reflected from this surfaces, as well as by flight electrons. The plasma volume, in which the single electromagnetic mode propagates, is of a size of an order of the wavelength, which is significantly bigger than the distance between the wires of the measurement line. The behavior of the paths of particles in a shell is a complicated problem, which can be solved only numerically by studying the orbits of the particles and considering self-consistent distribution of the potential. The linear law of density fall in the logarithmic scale within a wide time interval from 50 to 130 ms was a confirmation of the correctness of the developed method.

Conclusion

The work has proposed and tested the amplitude-phase method of measurement of the concentration of density, which is designed to reduce the minimum measured value of the electron density by the three orders without increasing the geometric dimensions of the probe, thereby making it possible to use the diagnostics onboard the microsatellites.

The measurement system was the quarter wavelength resonator at the section of the two-wired line of the length of 40 cm. The measurement were carried out at the fixed frequency of 180 MHz corresponding to the natural frequency of the resonator without plasma, and the small frequency shifts within the resonance curve were recorded by the amplitude-phase characteristics of the sensor. The application of the method is justified when the total quality factor of the resonator does not depend on the plasma losses. The quality factor of the measurement system was defined by coupling of the resonator with the receiving and exciting lines and it was 220. The work has developed the electrodynamic model of the measurement system, whose framework was used for obtaining the dependence of the output signal on the plasma density.

The technique was tested using the mockup of the sensor of plasma parameters manufactured in the scale 1 : 1. The sensor was tested for measurement of the density of the decaying plasma on the plasma test bent „Ionosphere" under the conditions as close as possible to the ionospheric ones. As a result, it has been found that the sensor recorded the values of the plasma density within the range $10^3-10^6\,cm^{-3}$, which is typical for the orbit height of the ionosphere satellite (500 km). The total dynamic range of the measured values was five orders. The linear law of density fall in the logarithmic scale was used to check the correctness of the measurements.

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Conflict of interest

The authors declare that they have no conflict of interest.

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