1. Vladimir Niriforovich LAVRUSHEV[1], 2. Osman Shakirovich DAUTOV[1],
3. Mohammad Sadon AL-ABADI[2], 4. Ali Nadhim Jbarah ALMAKKI[2]

Department of Radio-Engineering and Telecommunications Systems, Kazan National Research Technical University named after A. N. Tupolev - KAI, Kazan, Russia (1), College of Engineering, University of Diyala, Iraq (2)

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Scattering of electromagnetic waves by plasma layer sandwiched between two layers of thin glass

***Abstract**. A technique for monitoring plasma parameters for antenna measurements using a model of low-pressure fluorescent lamps is studied. The physical parameters of the plasma in the layout were obtained using microwave interferometry measurements. Using an accurate analytical model, it is shown that, this layer absorbs almost half the incident power. The noticeable dissipation of electromagnetic waves in the frequency band makes it possible to consider a thin layer of plasma as a plasma absorber.*

***Streszczenie.** Badana jest technika monitorowania parametrów plazmy do pomiarów antenowych przy użyciu modelu niskociśnieniowych lamp fluorescencyjnych. Parametry fizyczne plazmy w układzie uzyskano za pomocą pomiarów interferometrii mikrofalowej. Korzystając z dokładnego modelu analitycznego, wykazano,że warstwa ta pochłania prawie połowę mocy padającej. Zauważalne rozpraszanie fal elektromagnetycznych w paśmie częstotliwości pozwala uznać cienką warstwę plazmy za absorber plazmy. (**Rozpraszanie fal elektromagnetycznych przez warstwę plazmy umieszczoną między dwiema warstwami cienkiego szkła**)*

Keywords: Plasma layer, reflection coefficient, transmission coefficient, fluorescent lamp.
Słowa kluczowe: Warstwa plazmy, współczynnik odbicia, współczynnik transmisji, lampa fluorescencyjna.

Introduction

As it is known, radar absorbers are structures that cover an object and minimize the reflection of incident electromagnetic waves. In other word, for minimize the reflection and reducing the effective scattering area (RCS) accordingly, are based on covering the object with absorbing materials and changing the geometry of the object to redirect scattered waves away from the direction of backscattering. The main problems of these absorbers are their susceptibility to damage, large size [2], sensitivity to the angle of incidence [3], narrow bandwidth [4] and special design [5].

On the other hand, plasma reflects, absorbs and transmits electromagnetic waves depending on three different situations of interaction of waves with a plasma medium. These situations of interaction include the plasma electron frequency, the frequency of collisions of plasma electrons with neutrons, and the angular frequency of an incident wave [6]. Therefore, using plasma in radar protection is an urgent problem requiring control of the plasma parameters according to operation frequency in general.

Atmospheric (high) pressure plasma gas has an optimal ability to absorb waves. The interaction of microwaves with atmospheric plasma gas was studied in [7]. There are studies on the physical and numerical analysis of plasma, for example, on the interaction of waves in inhomogeneous [8], anisotropic [9], and spherical structures [10]. The decrease in RCS with the help of a cold inhomogeneous plasma was studied numerically in [11]. Optimization of a broadband absorber of electromagnetic waves was carried out using plasma layers at atmospheric pressure [12]. Optimal plasma with atmospheric parameters absorbs electromagnetic waves in a wide frequency band and in a wide sector of incidence angles. These improvements are achieved with a thin plasma coating layer, are characterized by high absorption of waves in a wide frequency band and a wide sector of incidence angles, fast switching between switching on and off, and controllability [13]. Plasma is a better absorber than traditional radio absorbing materials and has a number of advantages [14].

As experiment, the direct implementation for such work is impossible, so, in [15] had been proposed a very interesting method for controlling plasma parameters by probing a flat thin layer of plasma with a plane wave. I.e., simulate a plasma layer as a set of fluorescent lamps. Where in [15], the work was carried out in the range of plasma frequency variation from 25 to 75 deg/s by using the CST application. The discrepancy turned out to be large (30% on average), except for a single point with a frequency of 43 deg/s, where it was 10%. So, this large discrepancy led us to improve the accuracy of the method under consideration. To achieve it, the following tasks are supposed to be solved:

- Apply a more modern mathematical model that takes into account not only the plasma itself, but also the effect of glass on the walls of fluorescent lamps, and consider a three-layer model equivalent in terms of plasma and glass volume to a real lamp model,
- Replace the matrix model with an accurate analytical one, free from errors that arise when multiplying matrices with a large number of layers [21],
- To conduct additional experiments in the off-plasma mode to assess the influence of the mock-up structural elements on the measurement results.

Plasma physical parameters

Traditionally, approaches to calculating the transmission and reflection coefficients and fields of an electromagnetic wave in a magnetized plasma layer can be divided into two types. One approach is to integrate a system of ordinary differential equations from one side of the layer to the other (Pittway [15]; Miller and Smith [16]). The second approach consists in dividing the layer into many thin layers and calculating the passage of the wave field through the layer using the boundary conditions at all adjacent layer boundaries. In 1991, a new method was presented [17] based on solving a system of ordinary differential equations as a two-point boundary value problem. The peculiarity of this new method is to impose restrictions on the amplitude and phase relationships that satisfy the boundary conditions at both boundaries of the layer.

Lontano and Lunin in 1991, proposed a new analytical procedure for determining the reflection and transmission coefficients in a plasma based on the application of the Magnus approximation (the Magnus approximation was originally introduced to study the evolution of quantum systems described in the time domain).

It was noted in [18] that a change in the plasma frequency shows that, at a low plasma frequency, the transmission and absorption coefficients are minimal, while the reflection coefficient is maximum.

A confirmation of the validity of the theoretical approach and, at the same time, a study of the limits of its applicability is presented in [19] based on a comparison of analytical predictions obtained using the Magnus approximation with the exact solution of the obtained wave equation, as well as numerically using the Berreman matrix method. The comparison made it possible to determine the range of physical parameters in which a different order of approximation can be considered justified. Moreover, even when an analytical approach cannot be used, it is still possible to obtain the reflection and transmission coefficients of the electromagnetic field through the plasma sheet using the Berreman matrix method for direct integration of the wave propagation equation.

When microwaves interact with plasma generated at atmospheric pressure [20], there are two frequency ranges that characterize this type of plasma. The first is the frequency range in which the phase velocity and damping of the wave increase with frequency. The second is the range in which the phase velocity and attenuation of the wave remain constant. It was also found that for a small penetration depth is observed at a plasma density close to 10^{13} *cm*$^{-3}$.

In 2020, the new proposed spherical slotted antenna covered by two layers of dielectric material and plasma was analysed by utilizing the Integra-functional equations method [22]. The authors suggested that, the thickness of dielectric layer must not be less or more than λ/6, otherwise, it will be attenuation in the level of radiation pattern, furthermore, they proposed manipulating the operation frequency to enable antenna to work in most circumstances.

As it is known, there are two main internal physical parameters of plasma. the first one is the electron frequency, measured in radians per second, and the second one is the electron-neutron collision frequency, measured in hertz. There are several methods for determining these parameters. For example, the Langmuir probe method for obtaining the parameters of an ionized medium [23, 24] and microwave interferometry [25]. In the present work, the method of microwave interferometry is chosen.

The results of calculations using the electrodynamic model described below, which takes into account the electro physical parameters of the plasma, the reflection and transmission coefficients, are compared with their measured values on the mock-up fluorescent lamps to establish the plasma parameters in. The properties of a plasma are characterized by the frequency v (frequency of collisions of electrons with neutrons) and ωp (frequency of electrons in plasma). According to the Drude model [26], the plasma has a relative permittivity $\varepsilon_r = (1-\omega_p^2/\omega^2+v^2)-i(v/\omega*\omega_p^2/\omega^2+v^2)$ as a dielectric material with dispersion and losses [6], where ω is the angular frequency of incidence, and $\omega_p = \sqrt{e^2 n_e/\mathrm{m}_e\,\varepsilon_o}$ is the plasma electron frequency (both measured in radians/sec), where n_e is the electron density *(cm*$^{-3}$*)* and e, m_e, and ε_o are constant values of elementary charge, electron mass and vacuum permittivity, respectively. Since the mass of the ion is greater than the mass of the electron (the frequency of the ion is lower than the frequency of the electron), the low frequency of the ion does not interfere with the incident wave. In addition, it is assumed that these elements have a pressure of 2 Torr (266.6 Pa) [26]. Based on low pressure argon direct current glow discharge technology, the collision frequency is approximately $v = 6.5 * P(Torr) * 109 = 11.2\mathrm{GHz}$.

Electrodynamic model

As noted above, for higher simulation accuracy, it is advisable to use an accurate analytical model to represent the field in a layered medium [21]. As applied to the case of normal incidence of a plane wave polarized parallel to fluorescent lamps and propagating along the z coordinate, the field components can be represented as:

$$E(z) = E(0)\exp(-i\int_0^z k(z)\frac{1-R(z)}{1+R(z)}dz), \tag{1}$$

$$\mathrm{H}(z) = \frac{1-R(z)}{\mathrm{W}(z)(1+R(z))}\mathrm{E}(z), \tag{2}$$

where $E(0) = E_{0t}(0)(1+R(0)) -$ is the total field (the sum of the incident and reflected waves) in front of the inhomogeneous medium, and the reflection coefficient $R(z)$ satisfies the Riccati equation:

$$R' - 2ik(z)R + \frac{W'(z)}{2W(z)}(1-R^2) = 0. \tag{3}$$

The equivalent of Maxwell's equations in this case is the differential equation for the electric field with variable coefficients $\mu(z)$, $\mathrm{k}(z)$, for the electric field:

$$\frac{d^2E}{dz^2} - \frac{1}{\mu}\frac{d\mu}{dz}\frac{dE}{dz} + k^2E = 0 \tag{4}$$

In contrast to the well-known WKB approximation, relations (1), (2) are exact and take into account reflections in an inhomogeneous medium. With their help, it is possible to calculate the power density $S_p(z)$ which absorbed by the plasma, which is defined as the derivative of the average power flux density over the period (half of the real part of the complex Poynting vector P):

$$S_p(z) = -\frac{dp}{dz} \tag{5}$$

$$P = \frac{|E(z)|^2\,\mathrm{Re}(\frac{1-R(z)}{W(z)(1+R(z)})}{240\pi} \tag{6}$$

For a magnetically homogeneous medium with a linear dependence of the normalized wave resistance W(z)in the range 0<z<D:

$$W(z) = (W(D)-W(0))\,\mathrm{z}/\,\mathrm{D} + \mathrm{W}(0) \tag{7}$$

The Riccati equation has an exact solution and, accordingly, the field can be calculated using the above formulas (1), (2).

Accordingly, the reflection coefficient can be represented as:

$$R(\mathrm{z}) = \left(C\frac{1+B\left(\frac{W(\mathrm{z})}{W(D)}\right)^C}{1-B\left(\frac{W(\mathrm{z})}{W(D)}\right)^C} - A \right) \tag{8}$$

Where

$$A = i2k_o\frac{DW_o}{W(D)-W(0)},\ C = \sqrt{1+A^2}$$

$$B=-\frac{R(D)+A-C}{R(D)+A+C},\; W_0=\sqrt{\frac{\mu_0}{\varepsilon_0}}$$

k - free space propagation coefficient, and W(D), W(0) *- boundary values of the characteristic impedance normalized to the characteristic impedance of free space* W_0.

Description of the experimental setup

Figure 1 shows the experimental setup, which includes the model under study and the transmit/receive and receive horns. The layout is made in the form of a row of 13 small luminescent tubes located parallel to the electric field of the incident wave of the transmitting horn in the plane of the simulated plasma layer. The plasma tubes are ionized by high energy sources in one adjacent unit. The ionization source has peak voltage and current values of 1 kV and 20 mA for each element, respectively. Each plasma tube is 2.5 cm in diameter and 60 cm long and is filled with argon gas

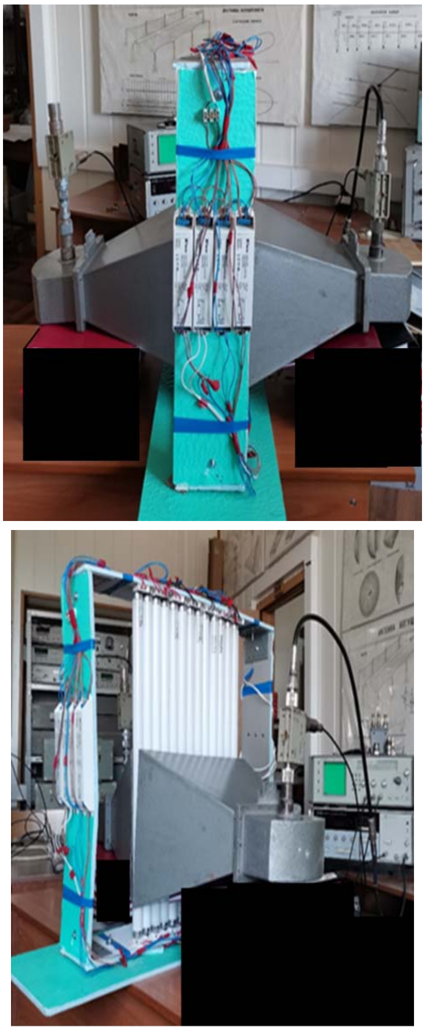

Fig.1. Experimental setup for measuring reflection and transmission coefficients

Comparison of the experiment with the model

To make it possible to apply the analytical model, taking into account the small thickness of the plasma and lamp walls compared to the wavelength, we replace the real system of plasma tubes with a glass shell with an equivalent system of three flat layers of material with the same total volume of plasma and glass located in free space. This can be justified by the fact that for a small total layer thickness, the electric field, since it is polarized parallel to the tubes, changes little within the plasma and glass region due to the boundary conditions for the continuity of the tangential components. and the reflected and transmitted fields are measured at distances much greater than the distance between adjacent lamps. Under these conditions, the secondary field induced by the polarization currents depends on the total volume of the plasma and glass and, to a lesser extent, on their distribution within the grating spacing. The three-layer planar structure with the preservation of the sequence of glass and plasma layers is the closest to the actual layout structure. These three layers are a plasma layer sandwiched between two layers of thin glass with the following dimensions:

- Equivalent thickness of the first layer of glass 0.77 mm;
- Equivalent thickness of the plasma layer 1.81 cm;
- Equivalent thickness of the second layer of glass 0.77mm.

Taking into account, the dielectric constant of glass according to reference data provided by Phillips is 7.

It is necessary to select the plasma frequency based on the results of measurements of the reflection and transmission coefficients. The values of the plasma frequency are selected using the MATHCAD application according to the proximity of their calculated and experimental values with respect to the results of measurements in two plasma modes ON and OFF shown in Figures 2 and 3.

The results of measurements of the wave reflection and transmission coefficients for the plasma frequency $22*10^9$ rad are closest to the simulation results. The real part of the plasma permittivity is 0.95 and the imaginary part is -0.5. In the figures, the orange lines show the experimental measurements, and the blue lines show the simulation results. According to fig. 2a, 2b, (plasma is switch off), the measured reflection and transmission coefficients are close to the calculated ones.

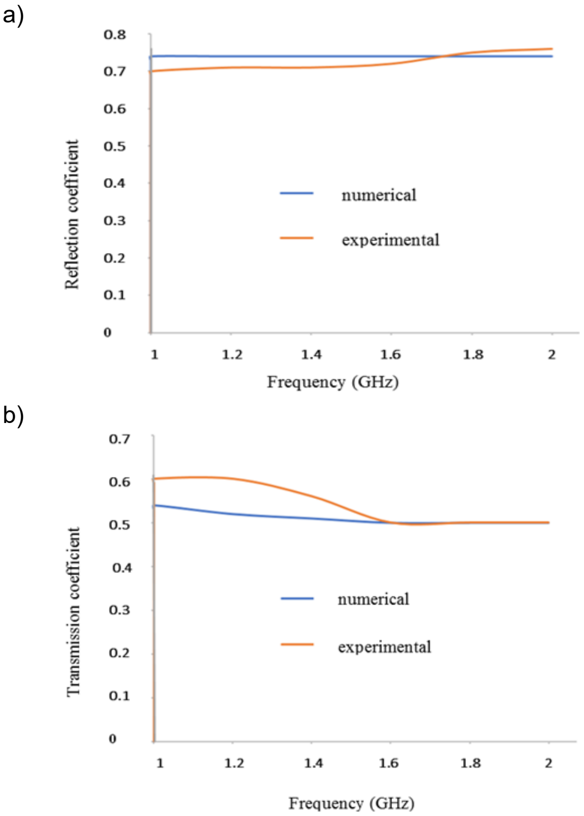

Fig.2. Numerical and experimental coefficient of a-reflection, b-transmission when plasma is switched off.

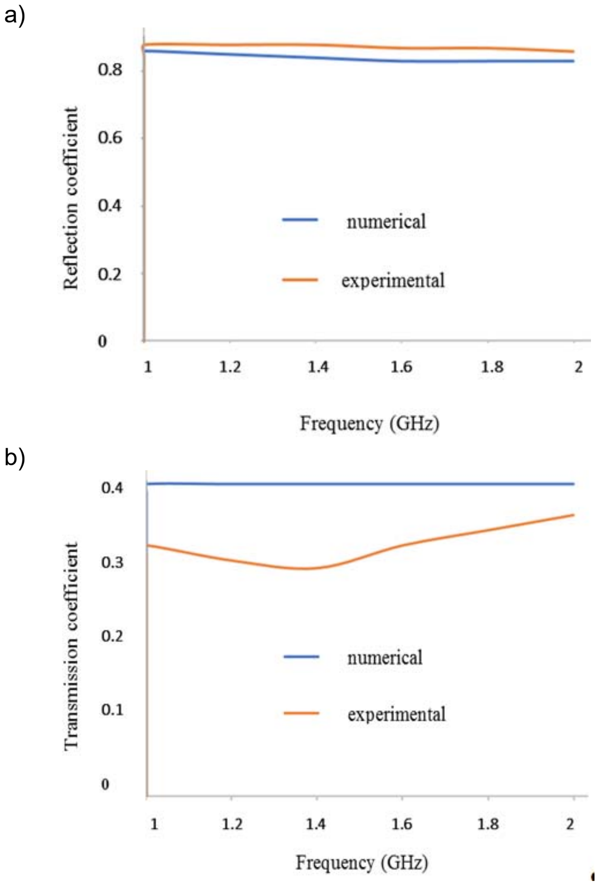

Fig.3. Numerical and experimental coefficient of a-reflection, b-transmission when the plasma is turned on.

According to fig. 3a for the included plasma, we see that the reflection coefficient demonstrates good agreement between the calculated and experimental values for the entire frequency band. At the same time, the transmission coefficient in Fig. 3b has a smaller value than for the switched off plasma, since absorption in the plasma is added. As well as for the switched off plasma, there is a good agreement between the calculated and experimental values.

Finally, the experimental results have the following features:

1. The model and experiment were performed not only for the switched-on plasma, but also for the switched off one. This made it possible to take into account the influence of the lamp walls on the results of probing the glass, the share of which is 8.5% of the plasma volume, which is confirmed by the presence of significant reflection when the plasma is turned off.
2. The discrepancy between the results of measurements and calculations of the reflection coefficients does not exceed 4%. The same results are observed with the plasma turned off.
3. For the transmission coefficients, the difference between the measured and calculated values turned out to be expectedly somewhat larger due to the lower absolute value of the transmitted power (about 2 times) and the same detector sensitivity in both cases.

Conclusion

Assessing the results of the research as a whole, it is possible to formulate the main conclusions on the work. It can be stated that the goal has been achieved. The closeness of the numerical and experimental results has increased by at least six times compared to those known in the literature, and the achieved accuracy makes it possible to use this technique to control plasma parameters for various problems. The good agreement between the experimental and calculated results in two probing modes for switched on and switched off plasma indirectly confirms with a high probability the adequacy of the applied analytical model. It also has a certain scientific value. And the practical value is determined by the possibility of controlling the plasma parameters by relatively simple means.

***Authors**: prof. dr Vladimir Niriforovich Lavrushev. Department of Radio-Engineering and Telecommunications Systems, Kazan National Research Technical University named after A. N. Tupolev - KAI, Kazan, Russia,*
E-mail: Lavrushev@bk.ru;
prof. dr Osman Shakirovich Dautov. Department of Radio-Engineering and Telecommunications Systems, Kazan National Research Technical University named after A. N. Tupolev - KAI, Kazan, Russia, E-mail: dautov_kstu@mail.ru;
Dr Mohammad Sadon Al-Abadi. College of Engineering, University of Diyala, Iraq, E-mail: msmhhjk@yahoo.com;
Dr Ali Nadhim Jbarah Almakki. College of Engineering, University of Diyala, Iraq, E-mail: alinadhimj@gmail.com;

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