Progress In Electromagnetics Research M, Vol. 72, 41–47, 2018

Surface Impedance of Thin Graphite Films at Microwave Frequencies

Yuriy M. Penkin, Victor A. Katrich, Mikhail V. Nesterenko*, and Dmitry Yu. Penkin

Abstract—Surface impedance of thin graphite films with metallic properties is evaluated by a waveguide technique based on measuring reflection and transmission coefficients of thin film membranes at operating frequencies in rectangular waveguides. One- and two-layer membranes of finite thickness, completely filling the waveguide cross-section, are investigated. Formulas allowing analytical estimates of surface impedances for nonmagnetic films made of amorphous carbon are derived. Simulation results for graphite films at frequencies from 5 to 10 GHz are analyzed.

1. INTRODUCTION

The miniaturization of microwave devices stimulates new scientific and technological researches concerning microelectronic elements. One of the promising trends of such studies concerns electrophysical properties of thin and ultrathin graphite films. The ultra-thin graphite films with metallic conductivity have quite stable physicochemical characteristics over a long time, and they, in contrast to metal films, do not shield electromagnetic fields.

The carbon is of particular interest, since it is a monocomponent material, which allows to form thin films with amorphous structures [1]. The structure of thin films made of amorphous carbon was investigated in detail [2,3], where it has been shown that the films consist of carbon in diamond- and graphite-like modifications characterized by sp^3 and sp^2 hybridization of carbon atoms. The graphite-like phase consists of so-called clusters, characterized by dimensions from one to several tens of nanometers. Depending on the ratio of atoms with sp^3 and sp^2 hybridization, the electrical properties of the graphite thin films can vary from semi-metallic (graphite) to dielectric (diamond). Since resistivity of the graphite films is in range from 10^{-3} up to 10^{12} [Ohm $\times$ sm] (see, e.g., [4]), the carbon films can be used as components of functional coatings and as separate control elements for electromagnetic wave devices. The values of surface impedance of the thin graphite films thus obtained can be used for electrodynamic modeling of such devices.

At present, film resistivity can be accurately measured by various DC and low frequency AC methods. However, some applications require that the film impedance should be measured at centimeter and millimeter wavelengths. In this case, it would be desirable that dimensions of the film material were as small as possible; therefore, waveguide methods characterized by small errors have some advantage over other measuring techniques. The waveguide methods have been used earlier to estimate geometric and material parameters of dielectric inserts (see, e.g., [5–8]) and to measure conductivities of metallic films [9]. However, the authors have not found any references concerning application of waveguide techniques for estimating surface impedances of thin graphite films.

The paper is devoted to a rather simple technique to estimate the material surface impedance based on measurement (or calculation) of reflection and transmission coefficients of the film membranes completely filling cross section of a rectangular waveguide. The thin films made of the amorphous carbon with thickness from several nanometers to several micrometers are considered. The authors

Received 30 May 2018, Accepted 9 August 2018, Scheduled 17 August 2018
* Corresponding author: Mikhail V. Nesterenko (mikhail.v.nesterenko@gmail.com).
The authors are with the Department of Radiophysics, Biomedical Electronics and Computer Systems, V. N. Karazin Kharkiv National University, 4, Svobody Sq., Kharkiv 61022, Ukraine.

have not found any references concerning application of waveguide techniques for estimating surface impedances of thin graphite films. Formulas for determining the impedance of the thin films are new as it follows from the extensive bibliographic list in the review [11]. A technology of the thin film production based on ion-beam carbon deposition in argon atmosphere has already been developed to obtain graphite-like layers where the content of sp^3 hybridized carbon atoms does not exceed 7% (see, e.g., [1]). An isolated homogeneous graphite membrane and that deposited on a thin dielectric substrate are analytically investigated.

2. METHODOLOGY OF SURFACE IMPEDANCE DETERMINATION

Let us consider a device consisting of an infinite rectangular waveguide and a dielectric insert completely overlapping the waveguide cross-section (Fig. 1(a)). The internal cross section of the waveguide with perfectly conducting walls is $a \times b$, and the insert length is c. The waveguide is excited by a unit H_{10}-wave propagating in the direction $z > 0$.

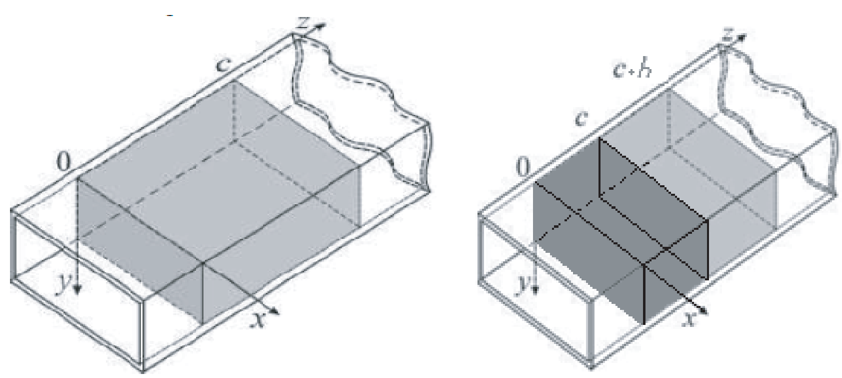


Figure 1. Geometry of the waveguide devices.

Energy characteristics, reflection and transmission coefficients, in the waveguide with insert were investigated earlier within framework of evaluating parameters of an insert material based on measurement or calculation of $S_{11(12)}$ coefficients [5–8]. The formulas defining these coefficients were obtained using the continuity conditions for tangential components of the fields E and H at the air-dielectric and dielectric-air interfaces on either side of the insert. The coefficients S_{11} and S_{12} for the insert with the relative permittivity ε and magnetic permeability μ can be written in the following form

$$\begin{aligned} S_{11} &= -\left((\gamma_{10}^{\varepsilon})^2 - \gamma_{10}^2\right) \frac{2i\sin(\gamma_{10}^{\varepsilon}c)}{(\gamma_{10}^{\varepsilon}+\gamma_{10})^2 e^{i\gamma_{10}^{\varepsilon}c} - (\gamma_{10}^{\varepsilon}-\gamma_{10})^2 e^{-i\gamma_{10}^{\varepsilon}c}}, \\ S_{12} &= \frac{4\gamma_{10}\gamma_{10}^{\varepsilon} e^{-i(\gamma_{10}^{\varepsilon}-\gamma_{10})c}}{(\gamma_{10}^{\varepsilon}+\gamma_{10})^2 - (\gamma_{10}^{\varepsilon}-\gamma_{10})^2 e^{-2i\gamma_{10}^{\varepsilon}c}}. \end{aligned} \tag{1}$$

where $\gamma_{10} = \sqrt{k^2 - (\pi/a)^2}$ are longitudinal wavenumbers of fundamental wave in the hollow waveguide and in the waveguide filled by the dielectric; $k = 2\pi/\lambda$ is the wavenumber; λ is the wavelength in free space; a is the internal dimension of the broad side of the waveguide; i is the imaginary unit. The formulas were obtained under conditions that single-mode propagation exists in the insert region. The time dependence is chosen in the form $e^{i\omega t}$ (ω is the circular frequency). The power loss factor in the film material can be easily obtained by using the power balance equation $|S_{11}|^2 + |S_{12}|^2 + |S_{los}|^2 = 1$.

Taking into account relations (1), we can represent the transverse wave components in regions $-h \le \hat{z} \le 0(I)$ and $c \le \hat{z} \le c + h(II)$, i.e., before and behind the insert, in the following form

$$\begin{aligned} &E_x^{(I)}(x,z) = 0; \quad E_y^{(I)}(x,z) = \left(e^{i\gamma_{10}z} + S_{11}e^{-i\gamma_{10}z}\right)\sin\frac{\pi x}{a}; \\ &H_x^{(I)}(x,z) = \frac{\gamma_{10}}{\omega\mu}\left(e^{i\gamma_{10}z} - S_{11}e^{-i\gamma_{10}z}\right)\sin\frac{\pi x}{a}; \quad H_y^{(I)}(x,z) = 0; \end{aligned} \tag{2a}$$

$$\begin{aligned} &E_x^{(II)}(x,z) = 0; \quad E_y^{(II)}(x,z) = S_{12} e^{-i\gamma_{10} z} \sin\frac{\pi x}{a}; \\ &H_x^{(II)}(x,z) = -\frac{\gamma_{10}}{\omega\mu} S_{12} e^{-i\gamma_{10} z} \sin\frac{\pi x}{a}; \quad H_y^{(II)}(x,z) = 0; \end{aligned} \tag{2b}$$

where (x, y, z) are the rectangular coordinates (Fig. 1).

Since formulas (1) and (2) were derived without any restrictions on the longitudinal dimension of the insert, they are valid for thin dielectric films if the inequality $\frac{c}{\lambda_{g\varepsilon}} \ll 1$ holds ($\lambda_{g\varepsilon} = \frac{2\pi}{\gamma_{10}^{\varepsilon}}$ is the wavelength in the waveguide completely filled with a dielectric). The two-sided boundary conditions of the impedance type for the thin-film membrane can be written as [10]

$$\begin{cases} Z\left(H_x^{(II)}\Big|_{z=+c} - H_x^{(I)}\Big|_{z=-0} \right) = E_y; \\ E_y^{(I)}\Big|_{z=-0} = E_y^{(II)}\Big|_{z=+c} = E_y; \end{cases} \tag{3}$$

where Z is the effective impedance distributed on the left surface of the membrane ($z = -0$). In the limit $c \to 0$, the condition (3) transforms into the one-sided boundary conditions of the impedance type. In other words, if the membrane is sufficiently thin, the two-sided and one-sided impedance boundary conditions are equivalent.

Then, using Equations (2) and (3), we can obtain the following representation

$$\bar{Z} = -\frac{k S_{12} e^{-i\gamma_{10} c}}{\gamma_{10}\left(1 - S_{11} + S_{12} e^{-i\gamma_{10} c}\right)}, \tag{4}$$

where $\bar{Z}$ is the effective impedance, normalized to the resistance of free space $Z_0 = 120\pi$ [Ohm], since $\omega\mu = 120\pi k$.

The normalized impedance of the film material can be estimate by substituting the energy coefficients $S_{11(12)}$ obtained at a fixed frequency into expression (4). The surface impedance thus obtained can be used within the impedance concept to carry out electrodynamic simulation of complex microwave devices with thin-film components [11].

Relation (4) allows us to find the module $|\bar{Z}|$ by using only the premeasured modules of energy-coefficients $|S_{11}|$ and $|S_{12}|$, without measuring their phases. Thus, we managed to avoid phase measurements and apply the two-sided impedance conditions. Moreover, if $\mathrm{Re}(\bar{Z})$ is a vanishingly small quantity, the module $|\bar{Z}|$ uniquely determines the imaginary part of the effective impedance $\mathrm{Im}(\bar{Z})$. The coefficients $|S_{11}|$ and $|S_{12}|$ can be measured experimentally using standard techniques, for example, broadband cable and antenna analyzer Site Master S810D/S820D.

Analyzing relation (3), we can unambiguously state that the surface impedance of the film depends upon the condition of waveguide propagation through the film; therefore, it can differ significantly from that of bulk sample. This technique can be used if the membrane meets the following requirements: 1) the material and thickness of the membrane should provide appropriate transparency for electromagnetic fields at an exciting wave frequency; 2) the impedance distribution across the membrane must be uniform; 3) the mutual transformation of diffraction waves of electric and magnetic types should be absent. If the membrane is made of a homogeneous non-magnetic material, we can rewrite formula (4) using relations (1) as

$$\bar{Z} = \frac{k}{\gamma_{10}\left(1 + \cos\left(\gamma_{10}^{\varepsilon} c\right)\right) + i\gamma_{10}^{\varepsilon} \sin\left(\gamma_{10}^{\varepsilon} c\right)}. \tag{5}$$

If the complex permittivity ε of the film material is known, the surface impedance can be estimated by using formula (5).

Of course, measurement of scattering coefficients $S_{11(12)}$ for ultra-thin graphite membranes by this method is a difficult task as well as the use of such membranes in microwave devices. Therefore, the graphite films can be placed on a dielectric substrate, shown in Fig. 1(b) as the region $c \le z \le c + h$. Here h is the thickness of the substrate layer with material parameters ($\varepsilon_1, \mu_1 = 1$). In this case, the scattering coefficients $S_{11(12)}$ can also be obtained in analytical form using the continuity conditions of tangential components of E and H fields at internal boundaries of the combined insert. These coefficients can be written as

$$S_{11} = \frac{(\gamma_{10}^{\varepsilon} + \gamma_{10})R - (\gamma_{10}^{\varepsilon} - \gamma_{10})}{(\gamma_{10}^{\varepsilon} + \gamma_{10}) - (\gamma_{10}^{\varepsilon} - \gamma_{10})R},$$
$$S_{12} = 2\gamma_{10}\frac{e^{-i\gamma_{10}^{\varepsilon}c} + \mathrm{R}e^{i\gamma_{10}^{\varepsilon}c}}{(\gamma_{10}^{\varepsilon} + \gamma_{10}) - (\gamma_{10}^{\varepsilon} - \gamma_{10})R} \cdot \frac{e^{-i\left(\gamma_{10}^{\varepsilon_1} - \gamma_{10}\right)(c+h)} + R_1 e^{i(\gamma_{10}^{\varepsilon_1} + \gamma_{10})(c+h)}}{e^{-i\gamma_{10}^{\varepsilon_1}c} + R_1 e^{i\gamma_{10}^{\varepsilon_1}c}}, \tag{6}$$

where

$$\gamma_{10}^{\varepsilon_1} = \sqrt{k^2\varepsilon_1 - (\pi/a)^2}; \quad R_1 = \frac{\gamma_{10}^{\varepsilon_1} - \gamma_{10}}{\gamma_{10}^{\varepsilon_1} + \gamma_{10}} e^{-2i\gamma_{10}^{\varepsilon_1}(c+h)}, \quad R = \frac{(\gamma_{10}^{\varepsilon_1} + \gamma_{10}^{\varepsilon})R_1 - (\gamma_{10}^{\varepsilon_1} - \gamma_{10}^{\varepsilon})e^{-2i\gamma_{10}^{\varepsilon}c}}{(\gamma_{10}^{\varepsilon_1} + \gamma_{10}^{\varepsilon}) - (\gamma_{10}^{\varepsilon_1} - \gamma_{10}^{\varepsilon})R_1 e^{2i\gamma_{10}^{\varepsilon}c}}.$$

If the inequality $c+h \ll \lambda$ holds, the normalized effective impedance of the film sample can be determined by substituting the scattering coefficients in Equation (6) into Equation (4). In the waveguide cross-section, the graphite layer can be located in the regions $0 \le z \le c$ or $c \le z \le c+h$, i.e., before or behind the dielectric substrate (Fig. 1(b)). If $\varepsilon = \varepsilon_1$ and $\gamma_{10}^{\varepsilon_1} = \gamma_{10}^{\varepsilon}$, Equations (6) are converted into Equations (1) after substitution $c \to (c+h)$. It is also easy to verify that relations (6) are valid for the waveguide without insert. Formulas (4)–(6) determining the film impedances are new as compared to the known ones which can be found in the review [11]. It is self-evident that the waveguide method for determining the surface impedance of thin graphite films can be realized using waveguides with various cross sections. We presented the results for the rectangular waveguide since it is the most convenient for practice and the easiest for mathematical modeling. In any case, the magnitude of the surface impedance at a particular frequency does not depend on the waveguide type.

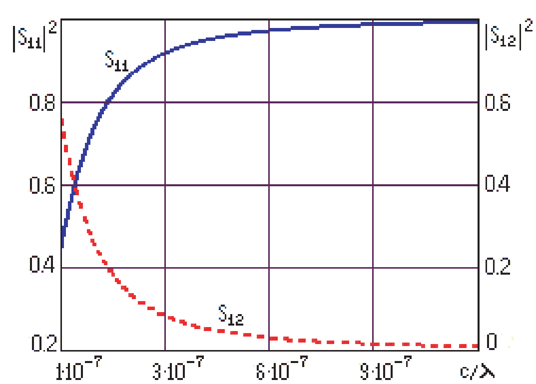
3. NUMERICAL RESULTS

For good non-ferromagnetic conductors, the imaginary part of permittivity at radio frequency wavelength is substantially larger than the real part of the permittivity; therefore, we can write [10]

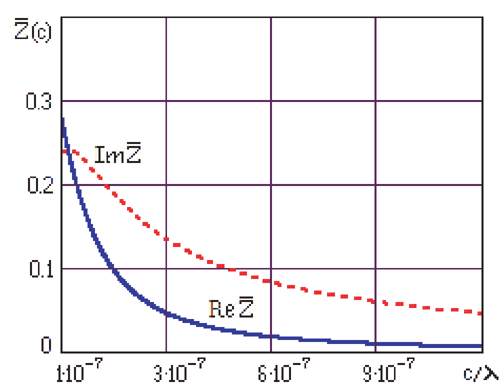
$$\varepsilon = i4\pi\sigma/(\varepsilon_0\omega), \quad \mu = 1. \tag{7}$$

Let the membrane be made of amorphous graphite with semimetal properties, characterized by the resistivity $\rho = 1/\sigma = 8 \cdot 10^{-6}\,[\mathrm{Ohm} \times \mathrm{m}]$ [12]. The simulation was carried out with the following parameters: $f = 10.0\,\mathrm{GHz}$, $a = 22.86\,\mathrm{mm}$, $b = 10.16\,\mathrm{mm}$ for variable film thickness c. The plots of modulus squared of the scattering coefficients in Equations (1) for the graphite membrane are shown in Fig. 2(a). As can be seen, the curves are exponential in nature, and the zone of rapid variation of the reflection and transmission coefficients, $|S_{11}|^2$ and $|S_{12}|^2$, lays in a relatively small interval of film thicknesses $3 \cdot 10^{-9} \le c \le 10^{-6}\,\mathrm{m}$.

In the interval $6 \cdot 10^{-7} \le c/\lambda \le 12 \cdot 10^{-7}$, $\mathrm{Re}\bar{Z}$ is a small quantity; therefore, the energy loss coefficient $|S_{los}|^2$ is practically zero. In other words, the diffraction on the membrane is determined



(a)



(b)

Figure 2. Scattering coefficients and surface impedance of the graphite membrane.

mainly by reflection of the incident wave. For amorphous graphite, the skin layer thickness determining the depth of electromagnetic field penetration into the material at the operating frequency is $d \approx 4.02 \cdot 10^{-6}$ m ($d/\lambda \approx 1.34 \cdot 10^{-4}$) [10]. Then the film thickness, corresponding to the zone of rapid variation of the membrane energy parameters, can be expressed as $c < 0.01d$.

The surface impedance of the membrane, $\bar{Z} = \mathrm{Re}\bar{Z} + i\mathrm{Im}\bar{Z}$, was calculated using Equation (5) at the interval $10^{-7} \leq c/\lambda \leq 8 \cdot 10^{-7}$. The plots of the real $\mathrm{Re}\bar{Z}$ and imaginary $\mathrm{Im}\bar{Z}$ parts of the impedance versus the ratio c/λ are shown in Fig. 2(b). As can be seen, the amorphous graphite membrane is characterized by inductive impedance. As expected, these curves are decaying functions, asymptotically approaching to zero as the film thickness is increased to the level of the skin layer. Such trend of the curves can be interpreted as the proofs of the mathematical model validity. Simulation results were also obtained for a combined film sample, consisting of a thin graphite layer on a dielectric substrate with infinitely small losses. The dielectric constant of the substrate was chosen from the range $1.0 \leq \varepsilon_1 \leq 9.0$, which corresponds to commonly used various glass types.

The simulation results, energy coefficients and surface impedance, for the two-layer film membrane at the substrate with permittivity $\varepsilon_1 = 5.0$, are shown in Fig. 3. The curves were plotted as a function of the graphite layer thickness for the substrate thickness $h = 10\,\mu\mathrm{m}$ (curve 1), $h = 400\,\mu\mathrm{m}$ (curve 2), and $h = 800\,\mu\mathrm{m}$ (curve 3). If the substrate thickness $h = 10\,\mu\mathrm{m}$ the curves practically coincide with those shown in Fig. 2.

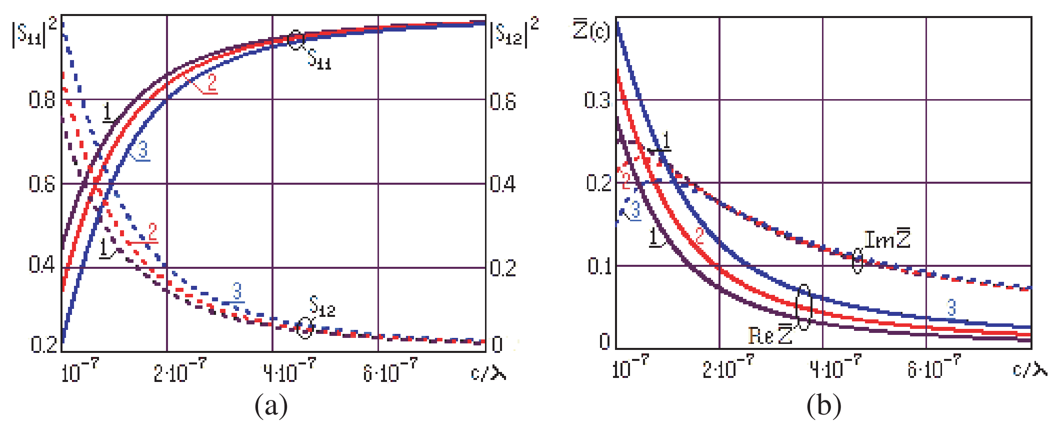


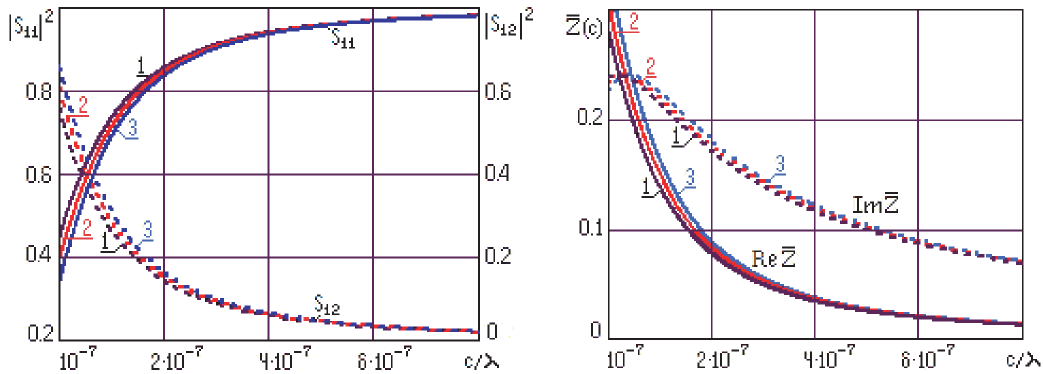
Figure 3. The scattering coefficients and the surface impedance of two-layer film for $\varepsilon_1 = 5.0$: 1 — $h = 10\,\mu\mathrm{m}$; 2 — $h = 400\,\mu\mathrm{m}$; 3 — $h = 800\,\mu\mathrm{m}$.

The plots of the energy coefficients and surface impedance, as functions of c/λ for the graphite two-layer film membrane, are shown in Fig. 4. The substrate thickness $h = 200\,\mu\mathrm{m}$, substrate permittivity $\varepsilon_1 = 1.0$ (curve 1), $\varepsilon_1 = 5.0$ (curve 2), and $\varepsilon_1 = 9.0$ (curve 3). As expected, the curves for $\varepsilon_1 = 1.0$ practically coincide with the corresponding curves shown in Fig. 2.

As can be seen, at the operating frequency $f = 10.0$ GHz, the surface impedance of the graphite films does not depend upon the substrate parameters if the permittivity and film thickness are in ranges $1.0 \leq \varepsilon_1 \leq 5.0$, $10 \leq h \leq 100\,\mu\mathrm{m}$. The simulation results have also shown that the surface impedance for the two-layer films does not depend upon the substrate orientation relative to directions of the incident wave propagation. This effect can be explained by large difference between the moduli of the permittivity for the graphite layer and substrate.

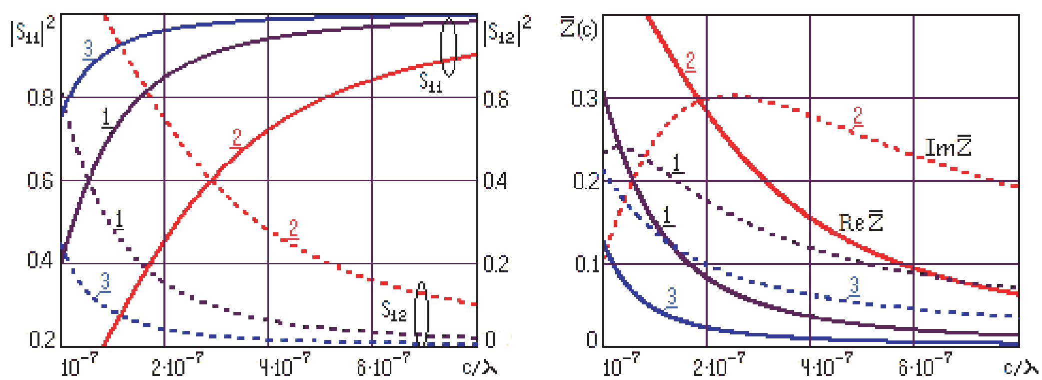
The simulation was carried out at frequencies 5, 10, and 22 GHz under conditions that dimensions of the waveguide cross-section were varied to ensure a single-mode waveguide operation. The simulation results have also shown that the surface impedance of the graphite film ($\varepsilon_1 = 5.0$ and $h = 200\,\mu\mathrm{m}$) highly depends upon the operating frequency (Fig. 5). This can be explained by the frequency dependence of the depth of field penetration into the membrane defined as the effective skin layer thickness).

We have also concluded that the operating frequency should be taken into account for simulation of microwave devices with graphite films.



(a) (b)

Figure 4. The scattering coefficients and the surface impedance of two-layer film for $h = 200\,\mu\text{m}$: 1 — $\varepsilon_1 = 1.0$; 2 — $\varepsilon_1 = 5.0$; 3 — $\varepsilon_1 = 9.0$.



(a) (b)

Figure 5. The scattering coefficients and the surface impedance of a two-layer film for $\varepsilon_1 = 5.0$ and $h = 200\,\mu\text{m}$: 1 — $f = 10.0\,\text{GHz}$; 2 — $f = 22.0\,\text{GHz}$; 3 — $f = 5.0G\,\text{Hz}$.

4. CONCLUSION

A waveguide technique for determining the surface impedance of thin membrane is proposed based on measurement (or calculation) of reflection and transmission coefficients in a rectangular waveguide in which cross section is completely overlapped by thin membrane made of amorphous graphite. The problem solution is based on using two-sided impedance boundary conditions on the film surfaces. Two types of membranes have been studied, the thin graphite film and the graphite film on the dielectric substrate. It was shown that the surface impedances of amorphous graphite layers could be estimated by calculation. This method was applied to obtain the surface impedance of the graphite films at operating frequency $f = 10.0\,\text{GHz}$. The simulation has also confirmed that the surface impedance of graphite films strongly depends upon the operating frequency. For special cases, a comparative analysis of our results and simulation results obtained by the commercial program ANSYS HFSS was carried out. Satisfactory matching of the results obtained by both methods confirms the validity of the proposed waveguide technique for determining the impedance of graphite films at microwave frequencies. The results presented in this article can be used for mathematical modeling and optimizing the electrodynamic devices with graphite thin-film elements operating at microwave frequencies.

REFERENCES

1. Kalinin, Yu. E., M. A. Kashirin, V. A. Makagonov, S. Yu. Pankov, and A. V. Sitnikov, "Properties of amorphous carbon thin films grown by ion beam sputtering," *Technical Physics*, Vol. 62, No. 11, 1724–1730, 2017 (in Russian).
2. Grill, A., "Diamond-like carbon: State of the art," *Diamond and Related Materials*, Vol. 8, 428–434, 1999.
3. Peng, X. L. and T. W. Clyne, "Mechanical stability of DLC films on metallic substrates: Part I — Film structure and residual stress levels," *Thin Solid Films*, Vol. 312, Nos. 1–2, 207–218, 1998.
4. Moustafa, S. H., M. Koos, and I. Pocsik, "DC electrical properties of amorphous carbon with different bonding hybridization," *J. Non-crystalline Solid*, Vol. 227–230, 1087–1091, 1998.
5. Onishchenko, A. A. and N. Ya. Popova, "Determination of the parameters of dielectrics through their radio engineering characteristics," *Elektronnaya Tekhnika*, Ser. Elektronika SVCH, No. 11, 21–23, 1980 (in Russian).
6. Chuprov, I. I. and A. P. Minkus, "Determination of dielectric and magnetic permeabilities with the help of microwave circuit analyzers," *Tekhnika Sredstv Svyazi*, Ser. Radioizmeritel'naya tekhnika, Vol. 6, 1–13, 1984 (in Russian).
7. Polishchuk, V .I., "Method and apparatus for measuring the electrical parameters of weakly absorbing dielectrics by a panoramic VSWR meter," *Elektronnaya Tekhnika*, Ser. Elektronika SVCH, Vol. 9, No. 413, 52–56, 1988 (in Russian).
8. Yatsuk L. P., V. V. Chukhov, and S. V Deripaska, "A simple method for estimating the dielectric constant and the loss tangent," *Visnyk Kharkivs'koho Natsional'noho Universytetu imeni V. N. Karazina*, Vol. 23, No. 1094, 66–71, 2013 (in Russian).
9. Antonets I. V., L. V. Kotov, S. V. Nekipelov, and Ye. N. Karpushov, "Conducting and reflecting properties of thin metal films," *Technical Physics*, Vol. 49, No. 11, 1496–1500, 2004 (in Russian).
10. Vainshtein, L. A., *Diffraction Theory and Factorization Method*, Golem Press in Boulder, Colo., 1969.
11. Berdnik, S. L., D. Y. Penkin, V. A. Katrich, Yu. M. Penkin, and M. V. Nesterenko, "Using the concept of surface impedance in problems of electrodynamics," *Radiofizika* & *Radioastronomiya*, Vol. 19, 57–80, 2014 (in Russian).
12. Kuchling, H., *Taschenbuch der Physik: Mit Zahlreichen Tabellen, Fachbuchverl*, Leipzig im Carl-Hanser-Verlag, 2004.