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FRACTAL GEOMETRY-BASED MODEL OF ELECTROMAGNETIC RADIATION INTERACTION WITH ROUGH SURFACES FOR MICROELECTRONICS AND RADIOPHOTONICS APPLICATIONS

Abstract. The article presents the results of substantiation and approbation of the model of electromagnetic radiation interaction with rough surfaces. This model differs from analogues in the following: 1) surface roughness profiles are described using fractal geometry; 2) it is taken into account that the distribution of the electric field over the surfaces is characterized by the presence of strong discontinuities. The second of the indicated differences led to the use of Maxwell's equations reduced to wave equations in the framework of the developed model. The developed model is recommended for use in the design of thin-film electromagnetic shields for microelectronics products protection from external and internal interference impact, as well as in the design of such products, in the design of radiophotonics products and theoretical evaluation of the optical and thermal properties of materials.

Keywords: fractal geometry, rough surface, electromagnetic radiation

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МОДЕЛЬ ВЗАИМОДЕЙСТВИЯ ЭЛЕКТРОМАГНИТНОГО ИЗЛУЧЕНИЯ С ШЕРОХОВАТЫМИ ПОВЕРХНОСТЯМИ, ОСНОВАННАЯ НА ФРАКТАЛЬНОЙ ГЕОМЕТРИИ, ДЛЯ МИКРОЭЛЕКТРОНИКИ И РАДИОФОТОНИКИ

Аннотация. Представлены результаты обоснования и апробации модели взаимодействия электромагнитного излучения с шероховатыми поверхностями. Данная модель отличается от аналогов следующим: 1) профили шероховатости поверхности описываются с помощью фрактальной геометрии; 2) учитывается, что распределение электрического поля по поверхностям характеризуется наличием сильных разрывов. Второе из указанных отличий привело к применению в рамках разработанной модели уравнений Максвелла, сведенных к волновым уравнениям. Полученная модель рекомендуется к использованию при проектировании тонкопленочных электромагнитных экранов для защиты изделий микроэлектроники от воздействия внешних и внутренних помех, при проектировании таких изделий и изделий радиофотоники, а также при теоретической оценке оптических и температурных свойств материалов.

Ключевые слова: фрактальная геометрия, шероховатая поверхность, электромагнитное излучение

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Introduction. The development of microelectronics products is associated with the solution of problems related to their protection from the electromagnetic interference impact, as well as to ensure their electromagnetic compatibility. The need to solve such problems is due to the fact that electromagnetic radiation impact on these products causes a decrease in the mean time between failures typical for such products [1, 2]. The solution of problems related to the microelectronics products protection from the external and internal electromagnetic interference impact, as well as to ensure their electromagnetic compatibility, is usually based on the use of thin-film electromagnetic shields. Such shields are included in the structure of the product housings and / or in the structure of PCB shielding elements [3, 4].

The process of developing thin-film electromagnetic shields, as a rule, includes a modeling stage. At this stage, the optimal values of the thickness and composition parameters of these shields are determined, i. e. such values that correspond to the greatest efficiency of these shields. It should be noted that the surfaces of the substrates on which thin-film electromagnetic shields are applied are usually not ideal, i. e. they are characterized by the presence of roughness. The specified substrates can be either the housings of microelectronics products and PCB shielding elements, or plates intended for fastening to such housings or elements [5]. The roughness of the electromagnetic shields surfaces affects the nature of the electromagnetic field distribution near them, which affects such shields efficiency. This fact is theoretically substantiated in [6, 7] and experimentally confirmed in [8].

It should be noted that the approaches currently used in electromagnetic shields modeling can be conditionally divided into two groups:

1) approaches based on the assumption that the surface of the shields is ideally smooth [9–11];

2) approaches based on the description of the roughness of the surfaces of the shields using discrete models, the parameters of which are determined by measuring the thickness of the material profiles at several points [12, 13].

The advantage of using these approaches is the speed of solving the modeling problem. The disadvantage of such approaches is the low degree of correspondence between the simulation results and the experimental results. The indicated disadvantage of the approaches of the first of these groups is due to the complete neglect of the surface roughness of electromagnetic shields, within the framework of the models on which these approaches are based. The indicated disadvantage of the approaches of the second of these groups is due to the lack of consideration of the nature of the distribution of roughness over surfaces materials, ~~with~~in the framework of the models on which these approaches are based.

It was shown in [14] that the topology of rough surfaces can be most accurately described using fractal geometry. To date, models of the interaction of electromagnetic radiation with rough surfaces based on the indicated feature have not been developed. In this regard, the authors set the development of such a model as the aim of the study presented in this article.

The developed model justification. To eliminate these limitations, the authors proposed to describe rough surfaces in the framework of models of these surfaces interaction with electromagnetic radiation using the following equation:

$$z(x,y)=L\left(\frac{G}{L}\right)^{FD_s-2}(\ln\gamma)^{\frac{1}{2}}\sum_{n=1}^{n_{\max}}\gamma^{(FD_s-3)n}\times$$
$$\times\left[\cos\varphi_n-\cos\left(\frac{2\pi\gamma^n(x^2+y^2)^{\frac{1}{2}}}{L}\cos\left(\arctan\left(\frac{y}{x}\right)-\pi m\right)+\varphi_n\right)\right], \tag{1}$$

where L is the sample length, G is the sample length scale, $FDs = FD + 1$, FD is the fractal dimension, γ^n is the frequency spectrum of a rough surface, n is the frequency index, φ_n is the random phase $n_{\max}$ is the maximum value of the frequency index, calculated by the equation $n_{\max}=\mathrm{int}\left[\frac{\ln(L/L_m)}{\ln\gamma}\right]$, where L_m is the sample length limit [14].

It should be noted that, as a rule, when calculating with formula (1), the value of γ is taken to be equal to 1.5 [14]. The limit of the sample length must be taken into account in formula (1) in order to ensure the dimensionlessness of the sublogarithmic expression.

Rough surfaces are a combination of nano-, micro- and macro-sized adjacent homogeneous media. In this regard, when electromagnetic radiation interacts with such surfaces, phenomena arise that are similar to phenomena that occur at the boundaries of adjacent media of heterogeneous systems when electromagnetic radiation interacts with these systems. In particular, it was substantiated in [7, 15, 16] that during the electromagnetic radiation propagation in heterogeneous systems, electromagnetic fields characterized by strong discontinuities are formed at the interfaces between their adjacent media. These discontinuities are due to the difference in the permittivities of these media. The tangential components of the magnetic and electric field strength vectors at these boundaries are continuous and finite [7]. In this regard, when constructing a model for the interaction of electromagnetic radiation with rough surfaces, it is impossible to use the Maxwell equations in differential form (equations (2), (3)), since these equations don't take into account strong discontinuities of the electromagnetic field at the interface between adjacent media:

$$\mathbf{j}_{\text{total}} = \nabla \times \mathbf{H}, \qquad \nabla \mathbf{D} = \rho, \tag{2}$$

$$-\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{E}, \qquad \nabla \mathbf{B} = 0, \tag{3}$$

where $\mathbf{j}_{\text{total}} = \lambda \mathbf{E} + \frac{\partial \mathbf{D}}{\partial t}$; $\mathbf{B} = \mu\mu_0 \mathbf{H}, \mathbf{D} = \varepsilon\varepsilon_0 \mathbf{E}$, $\mathbf{B}$ is the axial vector (i. e. pseudovector) of the magnetic induction, $\mathbf{H}$ is the axial vector (i. e. pseudovector) of the magnetic field, $\mathbf{D}$ is the electric induction vector, $\mathbf{E}$ is the electrical field vector, λ is the electrical conductivity of the medium, μ is the relative magnetic permeability of the medium, ρ is the volume charge of the medium, ε is the relative permittivity of the medium.

For an electromagnetic field formed at the interfaces between adjacent media in heterogeneous systems, the following conditions are met [7, 15, 16]:

$$D_{n1} - D_{n2} = \sigma, \tag{4}$$

$$\mathbf{E}_{\tau 1} - \mathbf{E}_{\tau 2} = 0, \tag{5}$$

$$B_{n1} - B_{n2} = 0, \tag{6}$$

$$\mathbf{H}_{\tau 1} - \mathbf{H}_{\tau 2} = [\mathbf{i}_\tau \mathbf{n}], \tag{7}$$

where the $\mathbf{i}_\tau$ is the tangential component of the surface current vector, σ is the surface charge, D_n is the normal component of the electric induction vector, B_n is the normal component of the magnetic induction vector; indices n and τ are used to designate the normal and tangential components of the vectors to the interface between adjacent media; indexes 1 and 2 are used to conditionally designate the first and the second adjacent media in a heterogeneous system.

In the Cartesian coordinate system, conditions (4)–(7) are written as follows:

$$D_{x1} - D_{x2} = \sigma, \tag{8}$$

$$E_{y1} - E_{y2} = 0, \tag{9}$$

$$E_{z1} - E_{z2} = 0, \tag{10}$$

$$B_{x1} - B_{x2} = 0, \tag{11}$$

$$\mathbf{H}_{y1} - \mathbf{H}_{y2} = \mathbf{i}_z, \tag{12}$$

$$\mathbf{H}_{z1} - \mathbf{H}_{z2} = \mathbf{i}_y, \tag{13}$$

where $\mathbf{i}_\tau = \mathbf{i}_y j + \mathbf{i}_z k$ is the surface current density.

As it can be seen from equations (8), (12), (13), there are no closing relations with which the surface charge and surface currents can be determined.) Therefore, it is necessary to make a transition to wave equations that allow us to calculate the surface charge (σ) and surface currents ($\mathbf{i}_y$, $\mathbf{i}_z$) [7]. Taking into account equations (4)–(7), equations (2) and (3) are transformed as follows:

$$\frac{\partial \mathbf{j}_{\text{total}}}{\partial t} = \frac{1}{\mu\mu_0} \nabla^2 \mathbf{E} - \frac{1}{\mu\mu_0} \operatorname{grad}(\operatorname{div} \mathbf{E}), \tag{14}$$

where grad(div**E**) is the function that takes into account the volume charge at the interface between adjacent media due to the flow of electric current through it.

Equation (14) has the following form in the Cartesian coordinate system:

$$\frac{\partial \mathbf{j}_{\text{total}x}}{\partial t} = \frac{1}{\mu\mu_0}\left(\frac{\partial^2 E_x}{\partial x^2} + \frac{\partial^2 E_x}{\partial y^2} + \frac{\partial^2 E_x}{\partial z^2}\right) - \frac{1}{\mu\mu_0}\frac{\partial}{\partial x}\left(\frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} + \frac{\partial E_z}{\partial z}\right), \tag{15}$$

$$\frac{\partial \mathbf{j}_{\text{total}y}}{\partial t} = \frac{1}{\mu\mu_0}\left(\frac{\partial^2 E_y}{\partial x^2} + \frac{\partial^2 E_y}{\partial y^2} + \frac{\partial^2 E_y}{\partial z^2}\right) - \frac{1}{\mu\mu_0}\frac{\partial}{\partial y}\left(\frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} + \frac{\partial E_z}{\partial z}\right), \tag{16}$$

$$\frac{\partial \mathbf{j}_{\text{total}z}}{\partial t} = \frac{1}{\mu\mu_0}\left(\frac{\partial^2 E_z}{\partial x^2} + \frac{\partial^2 E_z}{\partial y^2} + \frac{\partial^2 E_z}{\partial z^2}\right) - \frac{1}{\mu\mu_0}\frac{\partial}{\partial z}\left(\frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y} + \frac{\partial E_z}{\partial z}\right). \tag{17}$$

The authors believe that when electromagnetic radiation propagates from one medium to another, a volume electric charge is induced at the interfaces between these media [7, 16–19]. This fact is taken into account using the volume charge gradient function presented in equation (14). The results of modeling the electromagnetic radiation interaction with media taking into account the induced volume electric charge at their boundaries are characterized by higher accuracy than the results of modeling without such consideration [20, 21]. The transformation of equations (2), (3) into equations (14)–(17) taking into account the influence of the volume electric charge gradient hasn't been presented yet in any literary source, the subject of which is related to modeling the processes of interaction of electromagnetic radiation with media. That is, the idea of such a transformation is new. It should be noted that when modeling the processes of interaction of electromagnetic radiation with media using the Comsol package, it is possible to take into account the influence of the volume electric charge gradient. For this, at the initial stage of such modeling, it is necessary to set equations (15)–(17). If these equations aren't specified, the simulation will be performed taking into account only the classical Maxwell equations.

For an electromagnetic field formed at the interfaces between adjacent media in heterogeneous systems, the following conditions are satisfied, along with the conditions described using equations (4)–(7) or (8)–(13) [9–11]:

– equality of the normal components of the total current;

– equality of the tangential projections of the electric field vortex;

– the law of electric charge conservation;

– equality of the tangential components of the electric field and their derivatives in the tangential direction;

– equality of the derivatives of the normal components of the total current in the direction tangential to the interface between adjacent media, taking into account the influence of surface currents without the explicit introduction of a surface charge.

Taking into account the above conditions, it should be noted that in the course of implementing the model of interaction of electromagnetic radiation with rough surfaces, it is advisable to use through-counting schemes. In this case, discretization must be carried out in such a way that the boundaries of adjacent media have common nodes. In this case, the condition of the equality of total currents, the equality of charge flows [7] will be satisfied at these boundaries.

One of the simplest solutions of the wave equation is the d'Alembert solution:

$$E_x(t) = A[1 + m\cos\theta t][2\sin\omega t - \sin(\omega - 2\Delta)t + \sin(\omega + 2\Delta)t] = 4A[1 \pm m\cos\theta t]\sin^2\Delta t\sin\omega t, \tag{18}$$

$$E_y(t) = A[1 + m\cos\theta t][2\cos\omega t - \cos(\omega - 2\Delta)t + \cos(\omega + 2\Delta)t] = 4A[1 \pm m\cos\theta t]\sin^2\Delta t\cos\omega t, \tag{19}$$

where A is the electromagnetic waves amplitude, m is the modulated electromagnetic waves amplitude, θ is the frequency of the modulated electromagnetic waves, ω is the circular frequency of electromagnetic waves, 2Δ is the broadening of electromagnetic waves reflected from the interface of adjacent media with respect to electromagnetic waves incident on the interface of adjacent media.

The values of the functions represented by equations (18), (19) continuously fill the frequency range $\omega - 2\Delta \le \omega \le \omega + 2\Delta$ (when modeling the process of electromagnetic radiation propagation in a medium, it is necessary to take into account the broadening of the spectral line, which is caused by the spin-spin interaction and the Doppler effect (there are no monochromatic waves in a medium)).

Since the interaction of electromagnetic radiation with the interface between adjacent media is a transient process, equations (18), (19) should be represented as follows:

$$E_x(t) = A\left[\int\limits_{\omega-2\Delta}^{\omega+2\Delta}\left(1-\frac{2}{e^{\lambda_o \sin^2 \omega t}+e^{-\lambda_o \sin^2 \omega t}}\right)\sin^2 \omega t d\omega\right]\frac{(1-m\cos\theta t)\sin\omega t}{4\Delta} =$$
$$= \left[\int\limits_{\omega-2\Delta}^{\omega+2\Delta}\left(1-\frac{1}{\cosh\left(\lambda_o \sin^2 \omega t\right)}\right)\sin^2 \omega t d\omega\right]\frac{(1-m\cos\theta t)\sin\omega t}{4\Delta}, \tag{20}$$

$$E_y(t) = A\left[\int\limits_{\omega-2\Delta}^{\omega+2\Delta}\left(1-\frac{2}{e^{\lambda_o \sin^2 \omega t}+e^{-\lambda_o \sin^2 \omega t}}\right)\sin^2 \omega t d\omega\right]\frac{(1-m\cos\theta t)\sin\omega t}{4\Delta} =$$
$$= \left[\int\limits_{\omega-2\Delta}^{\omega+2\Delta}\left(1-\frac{1}{\cosh(\lambda_o \sin^2 \omega t)}\right)\sin^2 \omega t d\omega\right]\frac{(1-m\cos\theta t)\cos\omega t}{4\Delta}. \tag{21}$$

where $E_x(t)$ and $E_y(t)$ satisfy the following matching conditions [7]: $E_x(0) = 0$, $E_y(0) = 0$, $E'_x(0)=0$, $E'_y(0)=0$; λ_o is a parameter that can be used to determine the duration of the process of establishing the maximum value of the electromagnetic field amplitude.

The presence of a factor with a hyperbolic cosine in the integral expressions of equations (20), (21) is due to the fact that forced oscillations in the medium of electromagnetic radiation propagation (i. e. essentially in the "oscillatory circuit") are established not instantly, but after some time, which is due to the finiteness of the speed of radiation propagation. If $\lambda_o \to 0$, than $1-\frac{1}{\cosh(\lambda_o \sin^2 \omega t)} \to 0$, the process of establishing the oscillations is not realized. If $\lambda_o \to \infty$, that $1-\frac{1}{\cosh(\lambda_o \sin^2 \omega t)} \to 1$, the radiation becomes close to monochromatic one. Thus, the authors propose to base the model of electromagnetic radiation interaction with inhomogeneous surfaces on equations (1), (20) and (21).

The developed model description. The developed model is implemented in the following order.

1. Description of a rough surface using equation (1).

2. Description of the following initial conditions for the implementation of the model, based on the condition described using equation (5):

$$\mathbf{E}\big|_{t=0} = 0, \tag{22}$$

$$\left.\frac{\partial \mathbf{E}}{\partial t}\right|_{t=0} = 0. \tag{23}$$

3. Description of the following boundary condition for the implementation of the model:

$$\mathbf{E}\big|_{\Gamma} = \varphi(t), \tag{24}$$

where Γ is the boundary of the surface area that interacts with electromagnetic radiation, $\varphi(t)$ is a function describing electromagnetic radiation interacting with the surface (function $\varphi(t)$ should be described using equations (20), (21)).

4. Description of the strength of the electric field distributed over and under the surface using the equation:

$$\lambda\frac{\partial \mathbf{E}}{\partial t} + \varepsilon\varepsilon_0\frac{\partial^2 \mathbf{E}}{\partial t^2} = \frac{1}{\mu\mu_0}\left(\Delta\mathbf{E} - \mathrm{grad}(\mathrm{div}\,\mathbf{E})\right), \tag{25}$$

where $\Delta\mathbf{E}$ is the Laplacian of vector $\mathbf{E}$. It should be noted that equation (25) is a direct consequence of Maxwell's equations, supplemented by conditions under which the induced surface charges are taken into account and as well as currents at the interfaces of adjacent media using the function grad(div $\mathbf{E}$) [19]. This equation is convenient to use when formulating conditions at the interface of adjacent media, since there is no need to specify the values of the surface charge and current at the interface of adjacent media, which were derived for the cases of magnetostatics and electrostatics, i.e. for cases in which there is no alternating electromagnetic field [22, p. 11; 23].

5. Transformation of equation (25) to the following form, taking into account the described initial conditions:

$$\lambda\frac{\partial E_x}{\partial t}+\varepsilon\varepsilon_0\frac{\partial^2 E_x}{\partial t^2}=\frac{1}{\mu\mu_0}\left(\frac{\partial^2 E_x}{\partial y^2}-\frac{\partial^2 E_y}{\partial x\partial y}\right), \tag{26}$$

$$\lambda\frac{\partial E_y}{\partial t}+\varepsilon\varepsilon_0\frac{\partial^2 E_y}{\partial t^2}=\frac{1}{\mu\mu_0}\left(\frac{\partial^2 E_y}{\partial y^2}-\frac{\partial^2 E_x}{\partial x\partial y}\right), \tag{27}$$

$$E_x\big|_{t=0}=0,\qquad E_y\big|_{t=0}=0, \tag{28}$$

$$\left.\frac{\partial E_x}{\partial t}\right|_{t=0}=0,\qquad \left.\frac{\partial E_y}{\partial t}\right|_{t=0}=0, \tag{29}$$

$$E_x\big|_{x=0}=\varphi_x(t),\qquad E_y\big|_{x=0}=\varphi_y(t), \tag{30}$$

$$E_x\big|_{x=x1}=\varphi_x(t),\qquad E_y\big|_{x=x1}=\varphi_y(t), \tag{31}$$

$$E_x\big|_{y=0}=\varphi_x(t),\qquad E_y\big|_{y=0}=\varphi_y(t), \tag{32}$$

$$E_x\big|_{y=y1}=\varphi_x(t),\qquad E_y\big|_{y=y1}=\varphi_y(t), \tag{33}$$

where x_1, y_1 are the coordinates of the boundary points of the simulation domain.

6. Description of the process of electromagnetic wave passage through the interfaces of adjacent media using equations (15)–(17), which are a representation of equation (14) in the Cartesian coordinate system. Equations (15)–(17) take into account the condition of continuity of the total current, which is a consequence of the first Maxwell equation, due to which these equations can be solved using standard programs for electrodynamic modeling. Otherwise, without taking into account surface currents and surface charges, the use of standard programs for electrodynamic modeling is not possible due to strong discontinuities in the electromagnetic field.

It should be noted that at the interfaces between air and a rough surface (i. e. above and below the rough surface) identical fields are excited.

The results of simulation with the use of the developed model. In the course of approbation of the developed model, the process of interaction of electromagnetic radiation with a rough surface (silver plate) was simulated in the Comsol Multiphysics software package. The following values were used during the simulation:

– $n_{\max}=3$, $D=1.7$, $\gamma=1.5$ MHz, $L=2$ μm, $G=2$;

– $t\in[0;5\cdot10^{-5}]$ s;

– $x_1=y_1=1$;

– E_x = 5.0 mV/m; E_y = 0.1 mV/m;

– relative magnetic permeability is 1.0 rel. units; specific electrical conductivity is $6.3\cdot10^7$ Sm/m.

The computational area was the interface between the air and the silver plate. Fig. 1 shows a three-dimensional image of a simulated rough surface. The specified image was obtained from the results of calculations carried out using equation (1).

Fig. 2 shows the profile of the simulated rough surface and Fig. 3 shows the physical area within which calculations were carried out during the simulation. It can be seen from Fig. 2 that the rough surface is located at the bottom of the physical area within which the calculations were carried out during the simulation. Based on this, it can be concluded that this area contains the interface between adjacent media.

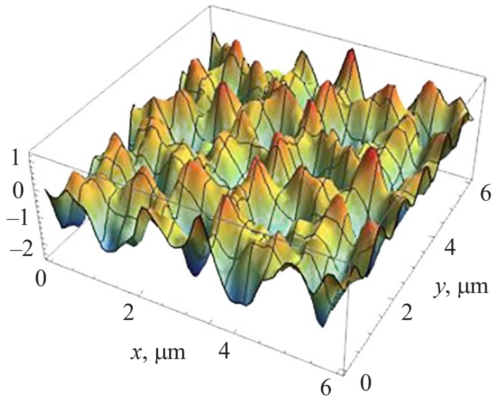


Fig. 1. Three-dimensional image of the simulated rough surface

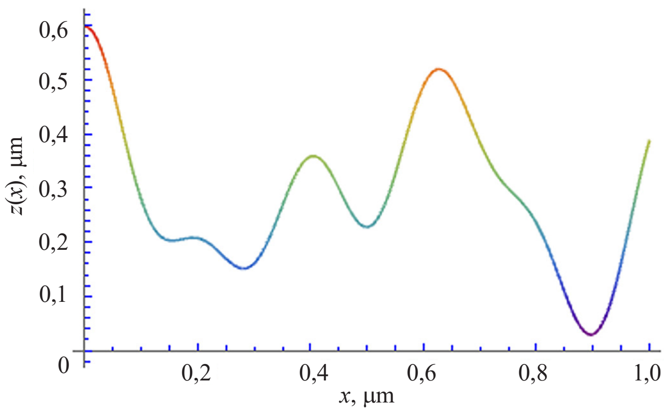


Fig. 2. Profile of the simulated rough surface

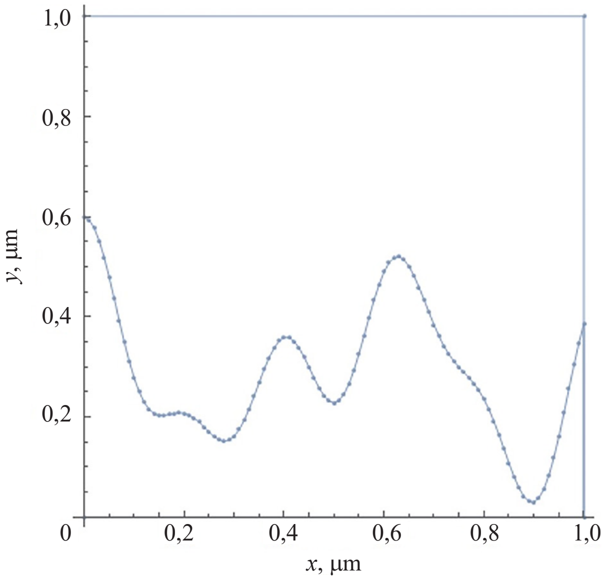
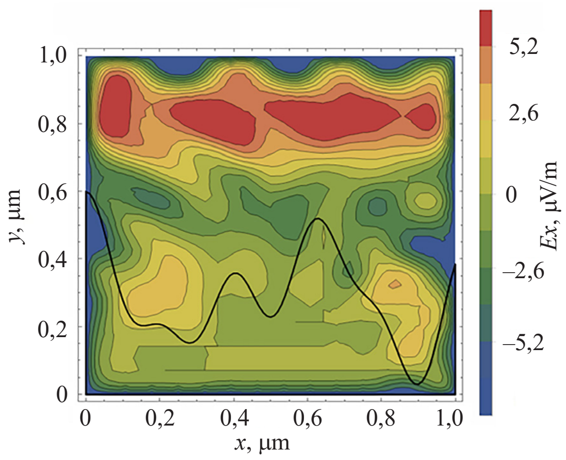
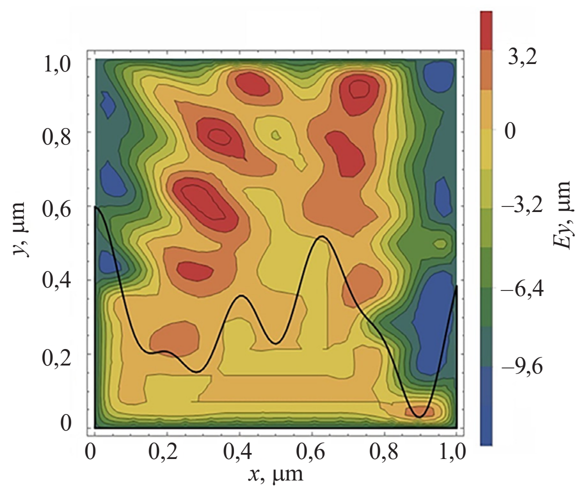


Fig. 3. Physical area within which the calculations were carried out during the simulation



a



b

Fig. 4. The distribution of the electromagnetic field strength in the physical area, within which the calculations were carried out during the simulation ($a – E_x$; $b – E_y$)

Fig. 4 shows the distribution of the electromagnetic field strength in the physical region within which the calculations were carried out during the simulation. Fig. 4 shows that higher values of the electromagnetic field strength are recorded not at the tops of the surface roughness, but in some areas located above them. However, the value of the electromagnetic field strength at the tops of the roughness is higher than the average value of the electromagnetic field strength in the physical region within which the calculations were carried out during the simulation. The lowest values of the electromagnetic field strength are again fixed not in the recesses between the roughness, but closer to the edges of the physical region or at local maxima. Naturally, the ensemble of peaks and depressions forms its own unique structure and the peaks and depressions affect the distribution of the electromagnetic field strengths. With a certain topology, it is possible to fix the maximum strength of the electromagnetic field not only in the area close to the tops, but also about the troughs. Similarly for the minimum, it is quite normal if the minimum of strength is located at the top, which is a local maximum in some part of the region.

According to the obtained simulation results it's possible to conclude, that the presence of roughness on the surface of the film results in an improvement in its absorbing properties due to the fact that electromagnetic waves are scattered by these roughnesses.

Conclusion. The main advantages of the developed model of the interaction of electromagnetic radiation with rough surfaces in comparison with its analogues are as follows:

1) the model is consistent;

2) the model takes into account the peculiarity of the distribution of the electromagnetic field over rough surfaces;

3) the results of calculations performed using the model are characterized by high accuracy.

The indicated advantages of the developed model determine the prospects for its application in the framework of processes associated with the design of thin-film electromagnetic shields for microelectronics products protection from external and internal interference impact. It should be noted that it seems possible, if necessary, to take into account, in the framework of this model, the surface charge density and the surface current at the interface between adjacent media.

The other application areas of the developed model are the following.

1. Design of microelectronics products (the PCB surfaces are characterized by the presence of roughness the maximum size of which is 0.05–1.0 microns [5]).

2. Design of radiophotonics products, specifically, guide systems. The materials used to make guide systems are not ideal. This imperfection is due to both the finiteness of the specific conductivity of materials and the roughness of their surfaces, the dimensions of which depend on the quality of its processing. From general physical considerations, it follows that the influence of the surface roughness of the materials of guide systems on the energy loss of electromagnetic radiation propagating in these systems can be neglected if the dimensions of such roughness are much smaller than the depth of penetration of the electromagnetic radiation into the materials. This condition is met when the frequency of electromagnetic radiation is less than 100.0 MHz. However, if microwave, EHF, and optical electromagnetic radiation propagate in guiding systems, then the surface roughness of the materials of these systems becomes the main factor determining the degree of energy loss of this radiation [24].

3. Theoretical evaluation of the optical and thermal properties of materials (in particular, the spectral brightness coefficient, the polarization degree, the thermal conductivity coefficient).

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