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ANALYSIS OF THE ELECTROMAGNETIC FIELD OF MULTILAYERED BIOLOGICAL OBJECTS FOR THEIR IRRADIATION IN A WAVEGUIDE SYSTEM

V. Popriadukhin
PhD*
Department of Theoretical and General Electrical Engineering named after V. V. Ovcharova
Tavria state agrotechnological university
Khmelnytskoho ave., 18, Melitopol, Ukraine, 72300
E-mail: vadim05051988@gmail.com

I. Popova
PhD*
E-mail: irinapopova54@gmail.com

N. Kosulina
Doctor of technical Sciences, Professor, Head of Department**
E-mail: kosnatgen@ukr.net

A. Cherenkov
Doctor of technical Sciences, Professor**
E-mail: aleksander.cherenkov@gmail.com

M. Chorna
PhD**
E-mail: chyornaya.mary@yandex.ua

*Department of Theoretical and General Electrical Engineering named after V. V. Ovcharova
Tavria state agrotechnological university
Khmelnytskoho ave., 18, Melitopol, Ukraine, 72300

**Department of technotrance and theoretical electrical engineering
Kharkiv Petro Vasylenko National Technical University of Agriculture
Alchevskih str., 44, Kharkiv, Ukraine, 61012

Розглянуто хвилеводну систему з металевою сферою для опромінення біологічних об'єктів електромагнітним полем. Для створення хвилеводної системи було проведено теоретичний аналіз розподілу електромагнітного поля всередині біологічних об'єктів. Теоретичний аналіз взаємодії електромагнітного поля з біологічними об'єктами проведений для багатошарових структур. Розміри багатошарових біологічних об'єктів малі порівняно з довжиною падаючої хвилі. Вирази теоретичного аналізу можуть бути використані для дослідження механізму взаємодії електромагнітного поля з біологічними об'єктами

Ключові слова електромагнітне поле, багатошарові біологічні об'єкти, хвилеводна система, опромінення біологічних об'єктів

Рассмотрена волноводная система с металлической сферой для облучения биологических объектов электромагнитным полем. Для создания волноводной системы был проведен теоретический анализ по распределению электромагнитного поля внутри биологических объектов. Теоретический анализ взаимодействия электромагнитного поля с биологическими объектами был проведен для многослойных структур. Размеры многослойных биологических объектов малы по сравнению с длиной падающей волны. Выражения теоретического анализа могут быть использованы для исследования механизма взаимодействия электромагнитного поля с биологическими объектами

Ключевые слова: электромагнитное поле, многослойные биологические объекты, волноводная система, облучение биологических объектов

1. Introduction

Systemic information approach is linked to studying the effect of electromagnetic field on biological objects. It is based on the principles that a living organism is a finely-tuned informoenergetic field structure [1]. The ultimate biological effect depends on the biotropic parameters of electromagnetic field and exposure [2].

It follows from paper [3] that equipment for examining biological objects under the action of electromagnetic field should include a biological object and technical devices. In order to apply an electromagnetic method, it is required that a biological object is in the antinode of the irradiated electromagnetic field. Creation of such a technical system for the effective radiation of biological objects with information electromagnetic radiation is an important task.

2. Literature review and problem statement

Creation of a technical system for the radiation of biological objects with electromagnetic field is impossible without theoretical research. Theoretical study must take into consideration the complex multi-layer structure of a biological object [4].

In paper [5], authors substantiated principles for the creation of technical systems for the irradiation of biological objects with an electromagnetic field. These principles include: modeling the structure of bioobjects and their functions, design of technical systems for the irradiation of bio-objects, development of methods for information processing, assessment of equipment effectiveness.

Article [6] considered modeling of interaction processes between biological objects and electromagnetic field. A biological object is represented by a homogeneous dielectric body, the authors, however, failed to perform analysis of the distribution of the field inside the object.

In paper [7], the processes of interaction between electromagnetic radiation, a biological object and a technical system were outlined. A biological object is represented by a homogeneous structure. Field distribution inside the object was not addressed.

The process of diffraction of electromagnetic waves on the organs of animals was investigated in [8]; the dimensions of organs exceeded length of the incident wave. The expressions presented were obtained in a zero approximation and do not reflect the process of wave distribution inside organs.

In paper [9], authors considered the process of applying electromagnetic fields for suppressing infectious microorganisms of seeds. Microorganisms are represented as single-layer objects. The analysis was performed without taking into consideration the distribution of electromagnetic field inside the microorganisms.

Effect of microwave radiation on biological pests in soil was investigated in [10]. Pests are modulated by a uniform medium; expressions for field distribution, however, are given only for the surface of the model.

In article [11], authors addressed the treatment of patients. Millimeter waves were used for treatment. In these cases, the wavelength was smaller than the dimensions of a patient. Distribution of electromagnetic field in the body of patients was not considered.

Study [12] explored effect of electromagnetic field on the cell's membrane potential. The expressions obtained reflect only an incident field on the surface of the cell membrane. The cell membrane is represented by a single-layer model.

Authors of ref. [13], in order to improve productivity of animals, conducted a study into effect of electromagnetic radiation on embryos of animals. A model of embryos was represented by a single-layer ellipsoid. Field distribution inside the ellipsoid was not considered.

In paper [14], based on the models of microorganisms, authors formulated ideas about the information nature of millimeter waves and efficiency of their impact on processes of vital activity of microorganisms. This study examined single-layer models without an internal distribution of electromagnetic fields.

The possibility of creating the equipment for exploring properties of biological objects that are exposed to electromagnetic radiation was shown in paper [15]. However, this requires the study of processes of interaction between a biological object, a technical device, and electromagnetic field.

Analysis of scientific literature [4–15] revealed that investigating energy-informational processes in bio-objects is possible with respect to their multilayer structure. An analysis of EMF distribution inside such objects would make it possible to design a technical system not only for the irradiation of bio-objects, but for assessing the biological quality of objects as well. Since experimental study of the field distribution inside multilayer bio-objects is impossible, a theoretical research is important.

3. The aim and objectives of the study

The aim of present work is to conduct theoretical research on the distribution of electromagnetic field in biological objects. The study under consideration would enable creation of a waveguide system in which a biological object is located in the antinode of the informational electromagnetic field.

To accomplish the set aim, the following tasks had to be solved:

– to explore the distribution of electromagnetic field in biological objects with a layered structure;

– to create a waveguide system for the irradiation of small bio-objects.

4. Determining internal electromagnetic fields exposed to the irradiation in biological objects

Let the space in which the object exposed to radiation be uniform and characterized by dielectric and magnetic permittivity ε_c and $\mu_c=\mu_0$. Then electromagnetic field $\vec{E}$ and $\vec{H}$ at all points of a given space will be described by integral equations equivalent to Maxwell's equations, together with boundary conditions at the interface between two media [16, 17]:

$$\vec{E}(\vec{r})=\vec{E}_0(\vec{r})+$$
$$+\frac{1}{4\pi}(\operatorname{grad}\operatorname{div}+k^2)\int\limits_V\left(\frac{\varepsilon}{\varepsilon_c}-1\right)\vec{E}(\vec{r'})f\left(\left|\vec{r}-\vec{r'}\right|\right)\mathrm{d}\vec{r'};$$

$$\vec{H}(\vec{r})=\vec{H}_0(\vec{r})+\frac{1\omega\varepsilon_c}{4\pi}\operatorname{rot}\int\limits_V\left(\frac{\varepsilon}{\varepsilon_c}-1\right)\vec{E}(\vec{r'})f\left(\left|\vec{r}-\vec{r'}\right|\right)d\vec{r'}, \quad (1)$$

where

$$f\left(\left|\vec{r}-\vec{r'}\right|\right)=\frac{e^{-ik\left|\vec{r}-\vec{r'}\right|}}{\left|\vec{r}-\vec{r'}\right|}. \quad (2)$$

The meaning of fields in the left side of expressions (1) depends on the position of point $\vec{r}$. If this point is inside volume *V*, occupied by a bio-object, then the fields on the left are the fields in the same body, that is, the same fields as those under the sign of the integral on the right. But if point $\vec{r}$ lies outside region V, then (1) are the equalities that determine the entire field (first term) and the scattered field (the second term).

A scattered wave can be expressed through electric and magnetic potentials by Hertz $\vec{P}^e$ and $\vec{P}^m$ using known ratios [3]:

$$\begin{cases}\vec{E}_{scatt} = (\text{graddiv} + k^2)\vec{P}^e - i\omega\mu_0 rot\vec{P}^m, \\ \vec{H}_{scatt} = (\text{graddiv} + k^2)\vec{P}^m - i\omega\varepsilon_c rot\vec{P}^e.\end{cases} \quad (3)$$

By comparing (3) with (1), one can conclude that:

$$\vec{P}^E = \frac{1}{4\pi}\int_V\left(\frac{\varepsilon}{\varepsilon_c} - 1\right)\vec{E}(\vec{r}')f\left(\left|\vec{r} - \vec{r}'\right|\right)d\vec{r}'. \quad (4)$$

With respect to $(\varepsilon - \varepsilon_c)\vec{E} = \vec{P}^e$ being actually the vector of electric polarization, we obtain:

$$\vec{P}^e = \frac{1}{4\pi\varepsilon_c}\int_V \vec{P}^e(\vec{r}')f\left(\left|\vec{r} - \vec{r}'\right|\right)d\vec{r}'. \quad (5)$$

Given (4), expressions for fields with respect to scattering on a bio-object (1) can be represented in the following form:

$$\begin{cases}\vec{E}(\vec{r}) = \vec{E}_0(\vec{r}) + (\text{graddiv} + k^2)\vec{P}^e, \\ \vec{H}(\vec{r}) = \vec{H}_0(\vec{r}) + i\omega\varepsilon_c \text{rot}\vec{P}^e.\end{cases} \quad (6)$$

In equations (5) and (6), $\vec{E}_0(\vec{r})$ and $\vec{H}_0(\vec{r})$ are the electric and magnetic fields, respectively, which would be at point $\vec{r}$ in the absence of a biological diffuser.

5. Study of the distribution of electromagnetic fields in biological objects with a layered structure

Let the electromagnetic wave falls on an ellipsoidal-shaped body that has two layers. The outer layer is number 1 and is characterized by permittivity ε_1, μ_0, layer number 2 is characterized by permittivity ε_2, μ_0. The ambient medium has dielectric permittivity ε_c and magnetic permittivity μ_0.

Surface of internal layer 2 is described by equation

$$\frac{x^2}{a^2(1+\xi_1)} + \frac{y^2}{b^2(1+\xi_1)} + \frac{z^2}{c^2(1+\xi_1)} = 1, \quad (7)$$

where ξ_1 is a constant that connects dimensions of semi-axes of the second layer and the semi-axes of the first layer.

Incident field $\vec{E}_0$ will obviously excite the internal field in the first layer, which in turn will excite a field in layer 2. However, the electromagnetic field in layer 2 will cause a wave, scattered in the near region, in layer 1. Thus, the field in layer 1 can be recorded in the following form:

$$\vec{E}^1 = \vec{E}^1_{fall} + \vec{E}^1_{refl}, \quad (8)$$

in layer 2:

$$\vec{E}^2 = \vec{E}^2_{fall}. \quad (9)$$

Symbol *fall.* denotes the fields excited inside a layer by the fields, external relative to them; symbol *refl.* marks the fields caused by scattering on the inner layer.

Consequently, we obtained a system of two equations.

To write the summands in (8), (9) with index *fall.*, we shall use expression

$$\vec{E}^{(0)} = \frac{\hat{A}}{\Delta}\vec{E}_0,$$

$$\vec{H}^{(0)} = \vec{H}_0, \quad (10)$$

where $\hat{A}$ is the matrix in the form

$$\begin{pmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{pmatrix}. \quad (11)$$

Matrix elements are derived from the following expressions:

$$a_{11} = 1 + \left(\frac{\varepsilon}{\varepsilon_c} - 1\right)\frac{abc}{2}(I_2 + I_3) - \left(\frac{2\varepsilon}{\varepsilon_c} - 1\right)\left(\frac{abc}{2}\right)^2 I_2 I_3,$$

$$a_{12} = -\frac{\varepsilon}{\varepsilon_c}\left(\frac{abc}{2}\right)^2 I_1(I_1 + I_2),$$

$$a_{13} = -\frac{\varepsilon}{\varepsilon_c}\left(\frac{abc}{2}\right)^2 I_1(I_1 + I_3),$$

$$a_{21} = -\frac{\varepsilon}{\varepsilon_c}\left(\frac{abc}{2}\right)^2 I_2(I_1 + I_2),$$

$$a_{22} = 1 + \left(\frac{\varepsilon}{\varepsilon_c} - 1\right)\frac{abc}{2}(I_1 + I_3) - \left(\frac{2\varepsilon}{\varepsilon_c} - 1\right)\left(\frac{abc}{2}\right)^2 I_1 I_3, \quad (12)$$

$$a_{23} = -\frac{\varepsilon}{\varepsilon_c}\left(\frac{abc}{2}\right)^2 I_2(I_2 + I_3),$$

$$a_{31} = -\frac{\varepsilon}{\varepsilon_c}\left(\frac{abc}{2}\right)^2 I_3(I_1 + I_3),$$

$$a_{32} = -\frac{\varepsilon}{\varepsilon_c}\left(\frac{abc}{2}\right)^2 I_3(I_2 + I_3),$$

$$a_{33} = 1 + \left(\frac{\varepsilon}{\varepsilon_c} - 1\right)\frac{abc}{2}(I_1 + I_2) - \left(\frac{2\varepsilon}{\varepsilon_c} - 1\right)\left(\frac{abc}{2}\right)^2 I_1 I_2.$$

Here I_1, I_2, I_3 are the elliptic integrals.

Following the transforms, we obtained a linear system of two equations with two unknowns $\vec{E}^{(0)1}$ and $\vec{E}^{(0)2}$.

$$\begin{cases} \vec{E}^{(0)1} = \dfrac{\hat{A}_1}{\Delta_1}\vec{E}_0 + \dfrac{\hat{A}_2}{4\pi\Delta_2}\left(\dfrac{\varepsilon_2}{\varepsilon_1}-1\right)\hat{P}\vec{E}^{(0)1}W_1', \\ \vec{E}^{(0)2} = \dfrac{\hat{A}_2}{\Delta_2}\vec{E}^{(0)1}. \end{cases} \tag{13}$$

Transform a given system:

$$\begin{cases} \left[1-\dfrac{\hat{A}_2}{4\pi\Delta_2}\left(\dfrac{\varepsilon_2}{\varepsilon_1}-1\right)\hat{P}W_1'\right]\vec{E}^{(0)1} = \dfrac{\hat{A}_1}{\Delta_1}\vec{E}_0^{(0)}, \\ -\dfrac{\hat{A}_2}{\Delta_2}\vec{E}^{(0)1} + \vec{E}^{(0)2} = 0. \end{cases} \tag{14}$$

System (14) has a unique solution if its determinant is nonzero. It is easy to verify by way of computations.

Solution to system (14) is easy to find by expressing $\vec{E}^{(0)1}$ from the first equation, and then finding $\vec{E}^{(0)2}$ from the second equation.

For brevity, we shall denote the matrix:

$$\hat{E} - \frac{\hat{A}_2}{4\pi\Delta_2}\left(\frac{\varepsilon_2}{\varepsilon_1}-1\right)\hat{P}W_1' = \hat{B}_1, \tag{15}$$

where $\hat{E}$ is the identity matrix of the same order as $\hat{A}$. Then, from the first equation of system (14):

$$\hat{B}_1\vec{E}^{(0)1} = \frac{\hat{A}_1}{\Delta_1}\vec{E}_0.$$

It follows:

$$\vec{E}^{(0)1} = \hat{B}_1^{-1}\frac{\hat{A}_1}{\Delta_1}\vec{E}_0. \tag{16}$$

From the second equation

$$\vec{E}^{(0)2} = \frac{\hat{A}_2}{\Delta_2}\vec{E}^{(0)1}$$

we obtain:

$$\vec{E}^{(0)2} = \frac{\hat{A}_2}{\Delta_2}\hat{B}_1^{-1}\frac{\hat{A}_1}{\Delta_1}\vec{E}_0. \tag{17}$$

Here $\hat{B}_1^{-1}$ is the matrix inverse to matrix $\hat{B}_1$. Matrix multiplication in (16), (17) must be made in the same order in which they appear in formulae.

Similarly, it is possible to find the components of magnetic field in each of the two layers for the case considered above. They will be described by equalities:

$$\vec{H}^1 = \vec{H}^1_{fall.} + \vec{H}^1_{refl.}, \quad \vec{H}^2 = \vec{H}^2_{fall}. \tag{18}$$

Confined to zero approximation, expression (18) takes the following form:

$$\begin{cases} \vec{H}^{(0)1} = \vec{H}_0 + i\omega\varepsilon_1\dfrac{\hat{A}_2}{4\pi\Delta_2}\left(\dfrac{\varepsilon_2}{\varepsilon_1}-1\right)\hat{Q}\vec{E}_0^{(0)1}W_1', \\ \vec{H}^{(0)2} = \vec{H}^{(0)1}. \end{cases} \tag{19}$$

Substituting result (15) into (19), we obtain, for the first layer:

$$\vec{H}^{(0)1} = \vec{H}_0 + i\omega\varepsilon_1\frac{\hat{A}_2}{4\pi\Delta_2}\left(\frac{\varepsilon_2}{\varepsilon_1}-1\right)\hat{Q}W_1'\hat{B}_1^{-1}\frac{\hat{A}_1}{\Delta_1}\vec{E}_0, \tag{20}$$

for the second layer:

$$\vec{H}^{(0)2} = \vec{H}^{(0)1}. \tag{21}$$

For a spherical diffuser:

$$\hat{P}W' = \hat{R}, \ \hat{Q}W' = \hat{S}, \tag{22}$$

where

$$\hat{R} = \begin{pmatrix} -\dfrac{4\pi}{3}+k^2W' & 0 & 0 \\ 0 & -\dfrac{4\pi}{3}+k^2W' & 0 \\ 0 & 0 & -\dfrac{4\pi}{3}+k^2W' \end{pmatrix}; \tag{23}$$

$$\hat{S} = \begin{pmatrix} 0 & \dfrac{4}{3}\pi z & \dfrac{4}{3}\pi y \\ -\dfrac{4}{3}\pi z & 0 & \dfrac{4}{3}\pi x \\ \dfrac{4}{3}\pi y & \dfrac{4}{3}\pi x & 0 \end{pmatrix}. \tag{24}$$

Using the expressions obtained for the internal fields of a double-layer biological object, it is possible to explore the relationship between the tension and the processes occurring inside the diffuser.

For the scattered fields in zero approximation a dipole moment is:

$$\vec{d} = \frac{V}{4\pi}\left(\frac{\varepsilon}{\varepsilon_c}-1\right)\vec{E}^{(0)}_{INT.}, \tag{25}$$

where $\vec{E}^{(0)}_{INT.}$ is the internal field determined by expression (10).

Since in the case of a double-layer bio-object external scattering proceeds from layer number 1, given that the role of $\vec{E}^{(0)}_{BH.}$ in this case will belong to $\vec{E}^{(0)1}$ (16), we obtain:

$$\vec{d} = \frac{V}{4\pi}\left(\frac{\varepsilon_1}{\varepsilon_c}-1\right)\hat{B}_1^{-1}\frac{\hat{A}_1}{\Delta_1}\vec{E}_0. \tag{26}$$

Expression (26) should be used to derive scattered fields on a double-layer object.

6. Irradiation of biological objects in a waveguide system

In order to irradiate bio-objects with electromagnetic radiation, they are placed in a waveguide system. By changing, in this case, the location of a bio-object, it is possible to ensure that the bio-object is in the antinode of the electromagnetic field and to increase thereby the efficiency of research. By applying the above results, one can easily solve this task.

Thus, let the biological object be placed in a rectangular waveguide. In this case, electromagnetic fields must satisfy boundary conditions on surfaces with different geometry: on flat waveguide walls and on the surface of the ellipsoid. The solution is quite simple if the external fields are decomposed into own waveguide functions and an integral form of the Maxwell equations is employed.

It follows from paper [17] that the scattered fields in a zero (or dipole) approximation do not depend on the particular type of function $f\left(\left|\vec{r}-\vec{r}_0\right|\right)$.

For this purpose, we shall calculate the reflection coefficient of the main H_{10}-wave from a biological object in a rectangular waveguide.

Let the walls of the waveguide be determined by planes $x=0$, $x=d$, $y=0$, $y=h$, the z axis is directed along the axis of the waveguide from the generator, and the coordinates of the center of the diffuser are equal to numbers $x=x_0$, $y=y_0$, $z=0$. Then the Hertz electric vector $\vec{P}^e_{(0)}$ satisfies a wave equation with the delta-like right side:

$$\Delta\vec{P}^e_{(0)}+k^2\vec{P}^e_{(0)}=-4\pi\vec{d}\delta\left(\left|\vec{r}-\vec{r}_0\right|\right). \tag{27}$$

Search for the components of vector $\vec{P}^e_{(0)}$ in the form:

$$\vec{P}^e_{(0)x}+d_xf_x;\quad \vec{P}^e_{(0)y}+d_yf_y;\quad \vec{P}^e_{(0)z}+d_zf_z. \tag{28}$$

Solution of equation (28) with respect to:

$$\delta(z)=\frac{1}{2\pi}\int_{-\infty}^{\infty}e^{-ik_3z}\mathrm{d}k_3, \tag{29}$$

produces the following result for the scattered wave ($z<0$):

$$f_x=-\frac{8\pi i}{dh}\sum_{m,n=0}^{\infty}\frac{1}{\beta_{mn}}\left(\cos\frac{\pi m}{d}x_0\sin\frac{\pi n}{h}y_0\times\cos\frac{\pi m}{d}x\sin\frac{\pi n}{h}y\right)e^{i\beta_{mn}z},$$

$$f_y=-\frac{8\pi i}{dh}\sum_{m,n=0}^{\infty}\frac{1}{\beta_{mn}}\left(\sin\frac{\pi m}{d}x_0\cos\frac{\pi n}{h}y_0\times\sin\frac{\pi m}{d}x\cos\frac{\pi n}{h}y\right)e^{i\beta_{mn}z}, \tag{30}$$

$$f_z=-\frac{8\pi i}{dh}\sum_{m,n=0}^{\infty}\frac{1}{\beta_{mn}}\left(\sin\frac{\pi m}{d}x_0\sin\frac{\pi n}{h}y_0\times\sin\frac{\pi m}{d}x\sin\frac{\pi n}{h}y\right)e^{i\beta_{mn}z},$$

where β_{mn} is the waveguide propagation constant.

It should be noted that a reflected wave takes the form of a superposition of an infinite number of waves only formally. In fact, a field at a distance greater than the wavelength will take the form of a finite sum, as, considering a dispersion equation, only those waves will not attenuate, for which

$$\left(\frac{\pi m}{d}\right)^2+\left(\frac{\pi n}{h}\right)^2<k^2. \tag{31}$$

Specifically, if the frequency of an incident wave is such that only main H_{10}-wave can propagate in a waveguide, then the reflected wave at great distances would consist of one main H_{10}-wave.

Thus, in this case the reflected wave will have the following components for a single-layer diffuser:

$$E^{(0)}_{yrefl.}=-i\frac{2V}{\Delta dh\beta_{10}}\left(\frac{\varepsilon}{\varepsilon_c}-1\right)a_{22}k^2Sin\frac{\pi}{d}x_0Sin\frac{\pi}{d}xe^{i\beta_{10}z}E_{0y}; \tag{32}$$

$$H^{(0)}_{xrefl.}=i\frac{2V}{\Delta dh}\left(\frac{\varepsilon}{\varepsilon_c}-1\right)a_{22}\omega\varepsilon_cSin\frac{\pi}{d}x_0Sin\frac{\pi}{d}xe^{i\beta_{10}z}E_{0y}; \tag{33}$$

$$H^{(0)}_{zrefl.}=\frac{2V\pi}{d^2h\beta_{10}}\left(\frac{\varepsilon}{\varepsilon_c}-1\right)a_{22}\omega\varepsilon_cSin\frac{\pi}{d}x_0Cos\frac{\pi}{d}xe^{i\beta_{10}z}E_{0y}. \tag{34}$$

Because the magnitude of the reflected wave depends linearly on the magnitude of the wave incident to a bio-object at each specific point, the reflection coefficient is an objective indicator of efficiency of the location of diffuser. The magnitude of reflection coefficient is determined from expression [17]:

$$\eta=\frac{E_{0\,|fall.}}{E_{0\,|fall.}}, \tag{35}$$

where the numerator and denominator are the amplitude values of cross components of the scattered and incident electric field. A module of this expression produces a numerical value of the coefficient of reflection, the argument – its phase.

In the case of H_{10} -wave:

$$\eta=\frac{E^0_{yrefl.}}{E_{0y}}, \tag{36}$$

which, considering (33), yields for a single-layer biological object:

$$|\eta|=\frac{2V}{\Delta dh\beta_{10}}\left(\frac{\varepsilon}{\varepsilon_c}-1\right)a_{22}k^2\sin\frac{\pi}{d}x_0\sin\frac{\pi}{d}x. \tag{37}$$

In the case when the probe that detects a reflected wave is in the middle of a broad wall of the waveguide, then

$$x=\frac{d}{2}$$

and

$$|\eta|=\frac{2V}{\Delta dh\beta_{10}}\left(\frac{\varepsilon}{\varepsilon_c}-1\right)a_{22}k^2\sin\frac{\pi}{d}x_0. \tag{38}$$

Here, reflectance coefficient module does not depend on the longitudinal location of the diffuser and changes sinusoidally as it moves across a broad wall of the waveguide.

7. Analysis of electromagnetic field in a waveguide system with a bio-object and a metallic sphere

The result obtained above shows that the intensity of internal field in the bio-object, and, therefore, the intensity of processes occurring in it linearly depend on a change in the amplitude of electric field in the cross-section of the waveguide. To strengthen the impact of this field on the intensity of processes, it is necessary to increase power of the generator. However, there is another way as well.

We shall consider a system of two diffusers placed along a waveguide. The first diffuser is a biological object, and the second is a metallic sphere. Based on the principle of superposition, the dipole moment of the entire system will be the sum of the moments of the element:

$$\vec{d}=\sum_{p=1}^{z}\vec{d}^{(p)}(\vec{r}_p), \tag{39}$$

where $\vec{d}^{(1)}(\vec{r}_1)$ is defined by expression (26), and $\vec{d}^{(2)}(\vec{r}_2)$ for the metallic sphere is equal [16] to:

$$\vec{d}^{(2)}(\vec{r}_2)=R^3\vec{E}_{0\ fall.}, \tag{40}$$

where R is the radius of the sphere; $\vec{E}_{0\ \text{inc.}}$ is the amplitude of its incident electric field.

For a biological object, the electric field incident to it is equal to:

$$\vec{E}^{(1)}_{0\ fall.}(\vec{r}_1) = \vec{E}_0(\vec{r}_1) + \vec{E}^{(2)}_{scatt.}(\vec{r}_1 - \vec{r}_2), \qquad (41)$$

for a metallic sphere:

$$\vec{E}^{(2)}_{0\ fall.}(\vec{r}_2) = \vec{E}_0(\vec{r}_2) + \vec{E}^{(1)}_{scatt.}(\vec{r}_2 - \vec{r}_1). \qquad (42)$$

Verified transforms resulted in [9, 10]:

$$\vec{d}^{(1)}(\vec{r}_1) = \vec{d}^{(1)}_0(\vec{r}_1) + \vec{d}^{(1,2)}(\vec{r}_1), \qquad (43)$$

$$\vec{d}^{(2)}(\vec{r}_2) = \vec{d}^{(2)}_0(\vec{r}_2) + \vec{d}^{(2,1)}(\vec{r}_2),$$

where $\vec{d}^{(1)}_0(\vec{r}_1)$ and $\vec{d}^{(2)}_0(\vec{r}_2)$ is a part of the dipole moment, which is induced in the absence of a second diffuser; $\vec{d}^{(1,2)}(\vec{r}_1)$ and $\vec{d}^{(2,1)}(\vec{r}_2)$ are the additions to the dipole moments related to re-scattering.

Thus, in the case of a single-layer biological object, the fields that are scattered on each of the heterogeneities take the form

$$\begin{cases} E^{(1)}_{\text{scatt.}}(\vec{r}) = \dfrac{V}{4\pi\Delta}\left(\dfrac{\varepsilon}{\varepsilon_c} - 1\right)\hat{P}\hat{A}\left[\vec{E}_0(\vec{r}_1) - \vec{E}^{(2)}_{\text{scatt.}}(\vec{r}_1)\right] f\left(\left|\vec{r} - \vec{r}_1\right|\right), \\ E^{(2)}_{\text{scatt.}}(\vec{r}) = R^3\hat{P}\left[\vec{E}_0(\vec{r}_2) - \vec{E}^{(1)}_{\text{scatt.}}(\vec{r}_2)\right] f\left(\left|\vec{r} - \vec{r}_2\right|\right). \end{cases} \qquad (44)$$

We obtained a system of two equations with two unknowns.

Solving a given system is convenient for point $\vec{r}_1$, because the fields that are scattered on a bio-object are of interest. To this end, it should be taken into consideration that all the waves re-scattered from the second heterogeneity will arrive to the first one with a phase shift determined by multiplier $e^{-i2\beta_{10}s}$, where s is the distance between the diffusers. In addition, for the case of H_{10} waves of electric field will only have the y-component, while the heterogeneities will be conveniently placed in the middle of a broad wall of the waveguide. Then system (45) will take the form:

$$\begin{cases} E^{(1)}_{y\ \text{scatt.}} = -i\dfrac{2V}{\Delta dh\beta_{10}}\left(\dfrac{\varepsilon}{\varepsilon_c} - 1\right)a_{22}k^2\left[E_{0y} - E^{(2)}_{y\ \text{scatt.}}e^{-i2\beta_{10}s}\right], \\ E^{(2)}_{y\ \text{scatt.}} = -i\dfrac{8\pi R^3}{dh\beta_{10}}k^2\left[E_{0y} - E^{(1)}_{y\ \text{scatt.}}\right]. \end{cases} \qquad (45)$$

$$F = -i\frac{2V}{\Delta dh\beta_{10}}\left(\frac{\varepsilon}{\varepsilon_c} - 1\right)a_{22}k^2, \qquad (46)$$

$$G = -i\frac{8\pi R^3}{dh\beta_{10}}k^2. \qquad (47)$$

Then the solutions to system (45) are:

$$E^{(1)}_{y\ \text{scatt.}} = \frac{\left(1 - Ge^{-i2\beta_{10}s}\right)FE_{0y}}{1 + FGe^{-i2\beta_{10}s}}, \qquad (48)$$

$$E^{(2)}_{y\ \text{scatt.}} = \left[1 + \frac{\left(1 - Ge^{-i2\beta_{10}s}\right)F}{1 + FGe^{-i2\beta_{10}s}}\right]Ge_{0y}. \qquad (49)$$

The total scattered field at point $\vec{r}_1$ will be determined from:

$$E^{(1)}_{y\ \text{scatt.}} + E^{(2)}_{y\ \text{scatt.}} = \left[G + \frac{1 - Ge^{-i2\beta_{10}s}}{1 + FGe^{-i2\beta_{10}s}}(F + FG)\right]E_{0y}. \qquad (50)$$

Reflectance coefficient module in this case is, accordingly:

$$|\eta| = \left|\frac{E^{(1)}_{y\ \text{scatt.}} + E^{(2)}_{y\ \text{scatt.}}}{E_{0y}}\right| = \left|G + \frac{\left(1 - Ge^{-i2\beta_{10}s}\right)F}{1 + FGe^{-i2\beta_{10}s}}(1 + G)\right|. \qquad (51)$$

By choosing s in appropriate way, it is possible to achieve a maximum of reflectance coefficient, which will indicate maximum amplitude of the electric field at the point of location of the biological object.

8. Reflectance coefficient calculations in a waveguide system with a biological object and a metallic sphere

To solve a given problem, the following is proposed: there are two diffusers on a segment of the waveguide (1), the first is the examined object (2), its location is permanent; the second is a metallic sphere that moves horizontally (3). By choosing the distance between diffusers in appropriate way, it is possible to achieve maximum intensity of EMF at the point where the biological object is located. Fig. 1 shows prospective design of a waveguide system for the irradiation of biological objects.

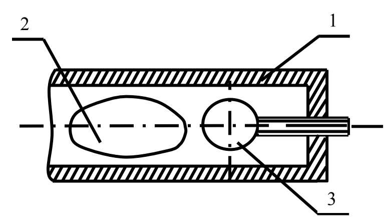

Fig. 1. Waveguide system for the irradiation of biological objects: 1 — section of waveguide; 2 — bio-object; 3 — metallic sphere

Calculation of reflectance coefficient for the following parameters:

Frequency of generator that powers the chamber is $f_{gen} = 58{,}6$ GHz. Waveguide dimensions are d=10.668 mm, h=4.318 mm. Generator wavelength λ, C is the speed of light.

$$C := 3\cdot10^{11}\ \text{mm/s},$$

$$f_{\text{gen}} := 58{,}6\cdot10^{9}\ \text{Hz},$$

$$\lambda := \frac{C}{f_{\text{gen}}} \quad \lambda = 5.119\ \text{mm}.$$

For a wave of the type H_{10}, critical wavelength in a waveguide $\lambda_{\text{cr.}}$

$$d := 10.668\ \text{mm},$$

$$\lambda_{cr} := 2\cdot d \quad \lambda_{cr} = 21.336\ \text{mm},$$

$$h := 4.318\ \text{mm}.$$

Wavelength in waveguide L:

$$L := \frac{\lambda}{\sqrt{1-\left[\frac{\lambda}{\lambda_{cr}}\right]^2}}, \quad L = 5.274 \text{ mm}.$$

Waveguide propagation constant B:

$$B := 2\frac{y}{L}, \; B = 1.191.$$

We shall calculate constants I_1, I_2, I_3 expressed through elliptical integrals for an elongated ellipsoid, for which $a=c<b$:

$$a := 0.35, \quad b := 1.2, \quad c := a;$$

$$I_1 := \frac{1}{\sqrt{\left[a^2-b^2\right]^3}} \cdot \left[a\cos\left[\frac{b}{a}\right] - \frac{b}{a^2}\cdot\sqrt{a^2-b^2}\right];$$

$$I_2 := \frac{2}{\sqrt{\left[a^2-b^2\right]^3}} \cdot \left[\frac{1}{b}\cdot\sqrt{a^2-b^2} - a\cos\left[\frac{b}{a}\right]\right];$$

$$I_1 = -6.177, \quad I_2 = -1.252, \quad I_3 = I_1.$$

Determine determinant D:

$E_c := 1.001$ is the air dielectric permittivity; E is the dielectric permittivity of a bio-object.

$$E_1 := 2.0, \quad E_2 := 3.0, \quad E_3 := 4.0, \quad E_4 := 5.0, \quad E_5 := 6.0,$$

$$E_6 := 7.0, \quad E_7 := 8.0, \quad E_8 := 9.0, \quad E_9 := 10.0, \quad E_{10} := 11.0,$$

$$E_{11} := 12.0, \quad E_{12} := 13.0, \quad j := 0...8.$$

$$E := \begin{bmatrix} E_1 \\ E_2 \\ E_3 \\ E_4 \\ E_5 \\ E_6 \\ E_7 \\ E_8 \\ E_9 \\ E_{10} \\ E_{11} \\ E_{12} \end{bmatrix},$$

$$D(E) := \frac{E_j}{E_c} - \left[2\cdot\frac{E_j}{E_c}-1\right]\cdot\left[a\cdot b\cdot\frac{c}{2}\right]^2\cdot(I_1\cdot I_2 + I_1\cdot I_3 + I_2\cdot I_3)...$$
$$+\left[3\cdot\frac{E_j}{E_c}-1\right]\cdot\left[a\cdot b\cdot\frac{c}{2}\right]^3\cdot I_1\cdot I_2\cdot I_3.$$

Calculate matrix element a_{22}:

$$a_{22}(E) := 1 + \left[\frac{E_j}{E_c}-1\right]\cdot a\cdot b\frac{c}{2}(I_1+I_3) -$$
$$-\left[2\cdot\frac{E_j}{E_c}-1\right]\cdot\left[a\cdot b\cdot\frac{c}{2}\right]^2 + I_1\cdot I_3;$$

$k := 2\frac{y}{\lambda}$, $k := 1.22$ is the wave number.

Calculate volume of the scattering bio-object V:

$$V := \frac{4}{3}\cdot y\cdot a\cdot b\cdot c, \quad V := 0.616 \text{ mm}^3,$$

where y is the Pi number $i := \sqrt{-1}$, R is the radius of a metallic ball R=0.4 mm.

$$F(E) := -i\cdot 2\frac{V}{D(E)\cdot d\cdot h\cdot B}\cdot\left[\frac{E_j}{E_c}-1\right]\cdot a_{22}(E)\cdot k^2,$$

$$G := -i\cdot\frac{8\cdot y\cdot R^3}{d\cdot h\cdot B}\cdot k^2, \quad k := 0..15, \quad S_k := 0.25\cdot k + 5,$$

$$|\eta| = N(j,S) := \left| G + \frac{\left[1-G\cdot\exp\left[-i\cdot 2\cdot B\cdot S_k\right]\right]\cdot F(E)}{1+F(E)\cdot G\cdot\exp\left[-i\cdot 2\cdot B\cdot S_k\right]}\cdot(1+G)\right|,$$

$$M_{j,k} := N(j,S).$$

The obtained dependences of reflectance coefficient on the distance between an object and a metallic sphere are given in Table 1.

Table 1

Dependence of reflectance coefficient on the distance between an object and a metallic sphere

S_k	$M_{0,k}$	$M_{1,k}$	$M_{2,k}$	$M_{3,k}$	$M_{4,k}$	$M_{5,k}$	$M_{6,k}$	$M_{7,k}$	$M_{8,k}$
5	0.028	0.042	0.132	0.231	0.334	0.44	0.547	0.655	0.763
5.25	0.027	0.044	0.136	0.237	0.342	0.45	0.559	0.668	0.778
5.5	0.027	0.047	0.141	0.244	0.353	0.464	0.576	0.689	0.803
5.75	0.026	0.048	0.144	0.251	0.362	0.477	0.594	0.712	0.83
6	0.026	0.049	0.146	0.254	0.368	0.486	0.606	0.728	0.852
6.25	0.027	0.048	0.145	0.253	0.367	0.486	0.609	0.734	0.861
6.5	0.027	0.046	0.141	0.247	0.361	0.479	0.6	0.725	0.852
6.75	0.027	0.044	0.136	0.24	0.35	0.465	0.583	0.704	0.828
7	0.028	0.042	0.132	0.233	0.339	0.45	0.563	0.679	0.797
7.25	0.028	0.041	0.13	0.228	0.332	0.439	0.549	0.66	0.772
7.5	0.028	0.041	0.13	0.228	0.332	0.437	0.545	0.653	0.762
7.75	0.027	0.043	0.134	0.233	0.337	0.444	0.552	0.66	0.768
8	0.027	0.045	0.138	0.24	0.347	0.456	0.566	0.677	0.788
8.25	0.027	0.047	0.143	0.247	0.357	0.47	0.585	0.7	0.815
8.5	0.026	0.049	0.145	0.253	0.365	0.482	0.6	0.72	0.841
8.75	0.026	0.049	0.146	0.254	0.368	0.487	0.609	0.733	0.858

9. Discussion of results of studying the irradiation of biological objects in a waveguide system with electromagnetic radiation

Creating a waveguide system for the irradiation of biological objects (seeds of grain crops) has required a theoretical research on the distribution of electromagnetic field inside objects. Theoretical analysis of interaction between EMF and biological objects was conducted for the multilayer structures whose dimensions are small compared with the length of the incident wave. In this case, fields inside objects can be decomposed by small parameter $\frac{a}{\lambda}$, where a are the linear dimensions of a bio-object, λ is the length of the incident wave. Then it is possible to construct ratios for different approximations of internal fields.

Through decomposition of the electromagnetic field inside a biological object by a small parameter we obtained expressions for reflectance coefficient. These expressions form the basis for creating a waveguide system for the irradiation of biological objects.

The benefit of present study on the distribution of EMF inside biological objects is that they can be used for multilayer biological objects.

Diffraction problems of a given type employ only common approaches and do not take into consideration:

– the structure of irradiated objects;

– the magnitude of losses at various points in a bio-object;

– geometric dimensions and the type of device to which a bio-object is placed.

A shortcoming of the proposed research is that they are related to the decomposition of internal field in biological objects for small parameter $\frac{a}{\lambda} << 1$. Accuracy of the obtained expressions depends on the number of ratios for different approximations of internal fields.

The study conducted is relevant for determining the electromagnetic field inside biological objects of cylindrical or spherical shape. Analysis of EMF distribution in bio-objects of different shape is connected with complexities of mathematical character.

10. Conclusions

1. In order to study processes of interaction between electromagnetic field and double-layer biological objects, one should use expressions for the internal electromagnetic field of bio-objects with respect to their dielectric permittivity in the range from 2 to 13 units and with dimensions $\frac{a}{\lambda} << 1$.

2. In order to irradiate biological objects with electromagnetic radiation, they should be placed in a waveguide system with a metallic sphere for a wavelength from 3 cm to 5 mm.

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