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DETERMINATION OF NON-INTENSIVE LIGHT FLUX INTENSITY AFTER PROPAGATION THROUGH LAYERED BIOLOGICAL ENVIRONMENT

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Summary. *The results of the research of the problem of determining the intensity of the light flux of low intensity after its propagation through the layered bioenvironment are given. It was defined that the transfer of radiation energy of a light-emitting diode and the estimation of the intensity of the flow of this energy on the object of irradiation, located in layered, „non-periodic" environment, creates a new combination of „the source of efficient, directed radiation and its propagation channel". The intensity of the low-energy energy flux after the radiation through a multilayered biological environment is determined by the radiation pattern of the LED. The diagram is used as a wave function of the source of radiation, which enabled to take into account the influence of the layered environment on the intensity of the object irradiation in such environment. Recursive method and algorithm for determining the intensity of the low-level energy flow after its transfer through a multilayered biological environment was developed.*

Key words: *light emitting diode, radiation diagram, layered bioenvironment, irradiation of bioobject.*

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Problem setting and its relation with scientific and practical tasks. The use of human body bioobjects stimulation during its state monitoring and correction will follow sufficient downward trend of stimulation energy intensity together with getting optimum separating capacity in bioobject space and its response [1]. According to Carnot-Brillouin classification [2] light energy quality due to high light energy conversion efficiency into bioeffect energy [3] is optimal for stimulation. For investigations in this field, development of corresponding means and their aprovement (verification and validation), the appropriate computer models of low-intensity light flux transfer through multilayered bioenvironment to the stimulation object are needed. In this case, the light source becomes an element of biotechnical system with feedback to provide radiant energy management while optimizing its intensity flow on the radiation object located in layered bioenvironment. Such requirements to biotechnical systems are new and determine rationale of low-intensity light flux transfer in multilayered bioenvironment.

Analysis of the latest researches. Light emitting diode is an effective mean to reach low intensity and high quality of energy flow [4]. Energy efficiency of only light radiation by semiconductors contact is not the same for light-wave propagation channel on the radiation object. Therefore, special a) structures of this channel, b) materials, c) mathematical models of energy flow determined by applied problem, are used. Applications of light wave theory and periodically layered structures for primary energy flow forming are known [5]. The problem of further radiation energy transfer determination and evaluation this energy flow intensity on radiation object located in layered „non-periodical" environment creates new combination „the source of effective direct radiation on its propagation channel". Determination of further radiation diagram is provided by computer simulation of dipole radiation propagation through periodically layered structure (as diffraction latitude) and resonator is provided. Radiometric approach during modeling of space intensity distribution of encapsulated light emitting diode based on dipole model of light emitting diode chip is given in [6], where analytic dependences between radiation character and parameters of light emitting diode, encapsulant and reflectors are derived. For biomedical engineering, the use of adaptive, optimum light emitting diode control is preferred. Relative space distribution of light energy in space (light emitting diode diagram) is always known. Thus there is an opportunity to use it as wave function of radiation source to investigate the influence of layered environment– diffraction effects, interference, refraction on object radiation intensity in such environment. Theoretical and physical models of real light energy rendering in researches of this area are based on Maxwell equations [7], especially surfaces with Poynting „wavy" vector explained as energy flow lines are obtained [8].

Research objective is to determine low energy flow intensity after its transfer through multilayered biological environment by light emitting diode radiation diagram.

Problem statement. To develop calculation method and algorithm of determination of low energy flow intensity after its transfer through multilayered biological environment by light emitting diode radiation diagram.

Main material. Mathematical model of light emitting diode radiation is substantiated due to physical abstract object – dipole use [9]. Mathematical expression of point source radiation in distant area taking into account the influence of structural members of such radiation distribution channel contains dipole mathematical representation [10].

The diagram measured experimentally [11, 12], (Fig. 1), wave energy propagation are represented by dipole and optical system parameters changes in space and time [9].

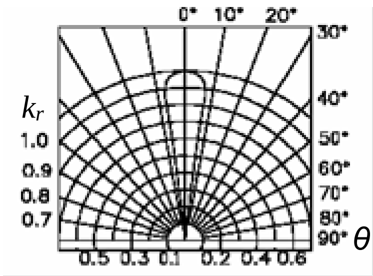

Figure 1. LED radiation diagram [12]. $k_r = l_0 / r$, l_0 – standard distance, θ – angle

The diagram is used for determination of dipole radiation strength vectors [7, 9]. As these vectors enable to determine the field (diagram) after the first environment layer then repetition of such calculations for the following layers lead to determination of radiation intensity on a surface of stimulated boiobject. During light stimulation the wave frequency is $f = \omega / 2\pi = (3{,}75\text{-}7{,}5)\times 10^{13}$ sec^{-1}, the field influence on bioobject is energetic, i.e. time average energy transferred through area unit is used and is determined by vectors of electric and magnetic strengths

$$I = c\left|\left\langle E \times H \right\rangle\right| / 4\pi \,. \tag{1}$$

In space distant from the source the waves are represented by strengths

$$\vec{E}_0 = \vec{e}(r)e^{ik_0\ell(r)},\ \vec{H}_0 = \vec{h}(r)e^{ik_0\ell(r)}, \tag{2}$$

where r – distance from dipole, $\ell(r)$ – „optical length", $\vec{e}$ and $\vec{h}$ – vector-function of dipole location, $k_0 = \omega / c = 2\pi / \lambda_0$. Dependences set between $\vec{e}(r)$, $\vec{h}(r)$ and ℓ [9] results from Maxwell equations. For small λ_0 function ℓ is the solution of differential equation, which does not depend on amplitude vectors $\vec{e}(r)$ and $\vec{h}(r)$:

$$\nabla \ell \times \vec{h} + \varepsilon \vec{e} = 0, \ \nabla \ell \times \vec{e} - \mu \vec{h} = 0, \tag{3, 4}$$

$$\vec{e} \cdot \nabla \ell = 0, \ \vec{h} \cdot \nabla \ell = 0. \tag{5, 6}$$

At each moment of time the equations (3) and (4) represent six homogeneous linear equations for scalar descartes ($x_i, i = 1, 2, 3$) component e_{x_i}, h_{x_i} with $\vec{e}$ and $\vec{h}$. These equations have non-trivial solution only if $(\nabla \ell)^2 = n^2(x_1, x_2, x_3)$, $n = (\varepsilon\mu)^{(1/2)}$ – being refraction index. Function ℓ – of surface $\ell(r)$ = constant (geometric wave surfaces – wavefronts).

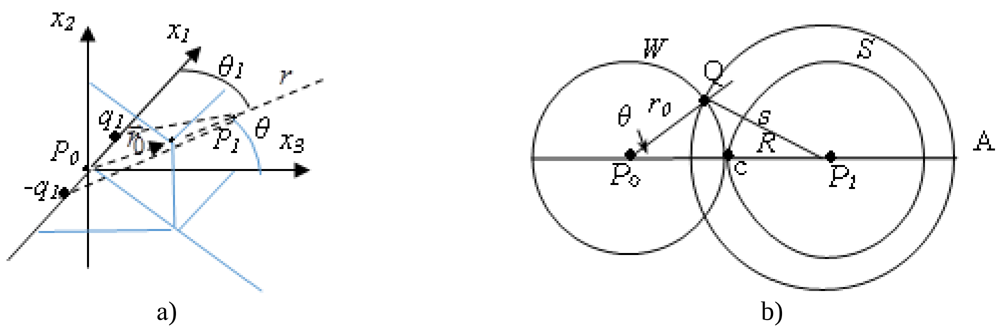

Figure 2. a) Scheme of the dipoles system of light emitting diode (LED) radiation source (dipoles x_2, x_3 are not shown), b) W – wave sphere front, S – reference sphere front, Q(x', y', z') – typical point, s – distance from typical point (x', y', z') to P_1, c – centre of the LED lens

Time averaging of Poynting vector $<\mathbf{S}> = (c/8\pi)\,\mathrm{Re}(\vec{e} \times \vec{h}^*)$ using (8) we get [7, 9]:

$$\vec{H}_0 = \vec{h}(r) e^{ik_0 \ell(r)}, \langle \mathbf{S} \rangle = \frac{c}{8\pi\mu} \left\{ (\vec{e} \cdot \vec{e}^*) \nabla \ell - (\vec{e} \cdot \nabla \ell) \vec{e}^* \right\} = \left(2c/n^2 \right) \langle w_e \rangle \nabla \ell , \tag{7}$$

where $\langle w_e \rangle$ – is time averaging energy density of magnetic field; as $\langle w_e \rangle = \langle w_h \rangle$, then the density of the whole fiel energy $\langle w \rangle = \langle w_h \rangle + \langle w_e \rangle = 2\langle w_e \rangle$, $c/n = v$ – is its transfer velocity, $(\nabla \ell)/n = \vec{s}$ – is the vector of single length in the direction of this transfer. Hence

$$\langle \mathbf{S} \rangle = v \langle w \rangle \vec{s} \, . \tag{8}$$

Applied content of the left side (8) – is observed time averaging Poynting vector through expression

$$\langle w \rangle \vec{s} = \langle \mathbf{S} \rangle / v \tag{9}$$

provides determination of intensity vectors $\vec{e}, \vec{h}$, whereas $\left(\vec{e} \cdot \vec{e}^* \right) \vec{s} = \dfrac{8\pi}{\varepsilon v} \langle \mathbf{S} \rangle$, where $\langle \mathbf{S} \rangle \equiv I_0$ – is radiated light intensity from diagram [7].

The typical geometric front W of light emitting diode wave in object space on the distance r_0 from P_0, (Fig. 2) is large in comparison with wave λ_{-0} length, and angles θ, formed by the beams with system axis A are not large. It results from (2) what at any specific moment of time Fourier transformations $\vec{E}_\omega$ and $\vec{H}_\omega$ do not obvoiusly change their size and direction to *W*. In cartesian reference system (*x, y, z*) with the origin in Gauss representation P_l of point P_0, in direction *z* along cP_1, approximate field expression in all points in aperture area of light emitting diode lens (except those located close to aperture edge) is written as [7, 10]:

$$\vec{E}_\omega(x,y,z,t) = \mathrm{Re}\left\{\frac{\omega^2}{c^2}\vec{e}_\omega(x,y,z)e^{i\left\{\delta(\omega)-\omega\left[t-\frac{1}{c}\ell_\omega(x,y,z)\right]\right\}}\right\}$$
$$\vec{H}_\omega(x,y,z,t) = \mathrm{Re}\left\{\frac{\omega^2}{c^2}\vec{h}_\omega(x,y,z)e^{i\left\{\delta(\omega)-\omega\left[t-\frac{1}{c}\ell_\omega(x,y,z)\right]\right\}}\right\} \quad (10)$$

Reference for P_1 sphere *S* passes through the lens c center of light emitting diode, R= cP_1. When integrating expression (10) by that part *S'* from reference sphere *S* which practically covers the lens the curvature factor is neglected. In homogeneous non-magnetic environment $\left|\vec{h}_\omega\right| = n\left|\vec{e}_\omega\right|$, where *n* – is refraction index. The distance $P_0P_1|_{Q\to c}$ and $_{\theta\to 0}$ $\to r_0 \triangleq \ell_\omega(x,y,z)$, $\ell_\omega(x,y,z)$ – being the optical length from point P_0 to point $P_1(x, y, z)$. For *S* as well as for *W* amplitude vectors e_ω i h_ω are practically constant in size and direction. Lens diameters subtended to P_1 are not large. If at distance *s* from typical point (*x'*, *y'*, *z'*) on reference sphere to P_1 the vectors $\vec{e}_\omega(x',y',z')$ and $\vec{h}_\omega(x',y',z')$ do not noticeably change on integration surface, then they are substituted by values $\vec{e}_\omega(0,0,-R)$ and $\vec{h}_\omega(0,0,-R)$ which they gain in the centre c of light emitting diode lens. If $n = 1$, then $\vec{e}_\omega(0,0,-R) = a(\omega)\vec{\alpha}(\omega)$, $\vec{h}_\omega(0,0,-R) = a(\omega)\vec{\beta}(\omega)$, where $\vec{\alpha}(\omega)$ and $\vec{\beta}(\omega)$ are unit orthogonal vectors in the plane perpendicular to direction *z*. The result of integration for points $P_1(X, Y, Z)$ in the image area where intensity is determined equals [10]:

$$\vec{E}_\omega(X,Y,Z,t) = \mathrm{Re}\left\{\frac{\omega^2}{c^2}U_\omega(X,Y,Z)a(\omega)\vec{\alpha}(\omega)e^{i[\delta(\omega)-\omega t]}\right\},$$
$$\vec{H}_\omega(X,Y,Z,t) = \mathrm{Re}\left\{\frac{\omega^2}{c^2}U_\omega(X,Y,Z)a(\omega)\vec{\beta}(\omega)e^{i[\delta(\omega)-\omega t]}\right\}, \quad (11)$$

where

$$U_\omega(X,Y,Z) = \frac{\omega}{2\pi i c}\iint_{S'}\frac{e^{i\omega[\ell_\omega(x',y',z')+s]/c}}{s}dS \quad (12)$$

scalar wave function defined from eikonal function of radiation in point P_0 [7].

From (12), by calculating Poynting vector $\mathbf{S}_\omega = c[E_\omega \times H_\omega]/4\pi$ and averaging with respect to time we derive that intensity in point $P_1(X, Y, Z)$ of the sum dipole in P_0 is proportional to squared absolute value of scalar wave function (12). While calculating intensity in the image area averaging in respect to time is carried out for each frequency component of every Cartesian component *E* and *H* of the whole field [7]. Contribution component of along axes (*x, y*) dipole in Fig. 2 is substantial. For angles $\theta_1(\omega)$ i $\theta_2(\omega)$ (between unit vectors $\alpha_1(\omega)$ i $\alpha_2(\omega)$ and axes (x, y) in the image space) and $\alpha_1(\omega)$, $\beta_1(\omega)$ and $\alpha_2(\omega)$, $\beta_2(\omega)$ – real, mutually orthogonal vectors in the plane perpendicular to direction z, the components E and H are approximated in the following way [7]:

$$E_z(X,Y,Z,t) = H_z(X,Y,Z,t) = 0, \tag{13}$$

$$E_y(X,Y,Z,t) = -H_x(X,Y,Z,t) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{+\infty} U_\omega(X,Y,Z)g(\omega)e^{-i\omega t}d\omega,$$

where

$$f(\omega) = \frac{\omega^2}{c^2}\left[a_1(\omega)\cos\theta_1(\omega)e^{i\delta_1(\omega)} + a_2(\omega)\cos\theta_2(\omega)e^{i\delta_2(\omega)}\right],$$
$$g(\omega) = \frac{\omega^2}{c^2}\left[a_1(\omega)\sin\theta_1(\omega)e^{i\delta_1(\omega)} + a_2(\omega)\sin\theta_2(\omega)e^{i\delta_2(\omega)}\right]. \tag{14}$$

On the basis of convergence considerations let us assume that radiation field exists only between moments $t= - T$ and $t = T$, where $T >> 2\pi/\omega_0$, to transfer to the limit $T \to \infty$. Consequently in point $P_1(X, Y, Z)$ contained in the image area intensity $I (X, Y.Z)$ is determined as average in time from energy U^2, transferred through unit area [7]:

$$I(X,Y,Z) = \frac{c}{4\pi T}\int_0^\infty |U_\omega(X,Y,Z)|^2[|f(\omega)|^2 + |g(\omega)|^2]d\omega = C\int_0^\infty |U_\omega(X,Y,Z)|^2 d\omega, \tag{15}$$

$$C = \frac{c}{4\pi T}\int_0^\infty [|f(\omega)|^2 + |g(\omega)|^2]d\omega. \tag{16}$$

If the interval |Δω| is rather small then $|U_\omega|$ practically does not depend ω in effective frequency range, so $|U_\omega|$ can be put outside the integral:

$$I(X,Y,Z) = C|U_{\omega_0}(X,Y,Z)|^2. \tag{17}$$

Boundary and material conditions of bioenvironment, light emitting diode type and its radiation diagram are determined by analytical foundations and specifications of the problem and provide reasons for development of the algorithm for determination of light energy flow intensity on the bioobject surface of such kind (Fig. 3):

1) To arrange and input data about radiation diagram, boundary and material conditions of boienvironment, number value of boienvironment layer m=0;

2) To determine values $\vec{e}(r)$ and $\vec{h}(r)$ according to the expression (9);

3) To determine coefficient C according to the expression (16) and correct diagram D using expression (17);

4) To increase number value of the layer, m←m+1, check m<M, go to step 2;

5) To determine energy flow intensity on the surface M of the layer (bioobject), store results in data base for further application.

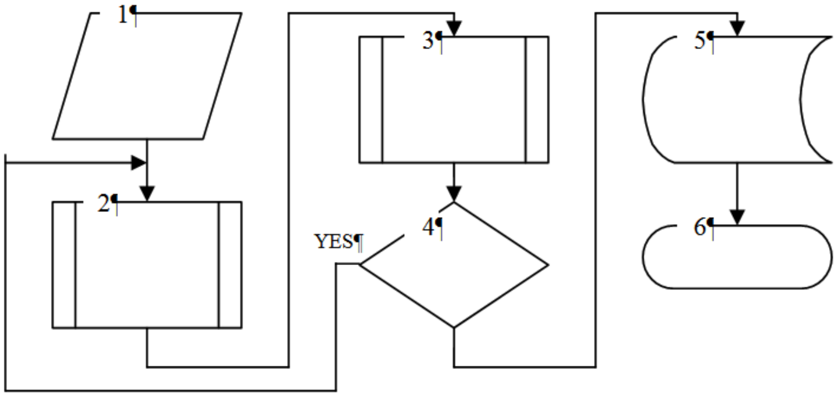

Figure 3. Algorithm of determination of energy transferred to the bioobject through M bioenvironment layers. (1 – Data: diagram D of the LED, the number of M layers of the environment, m=0); 2 – the calculation of values $\vec{e}(r)$, and $\vec{h}(r)$; 3 – calculation of the coefficient C and correction of the diagram D, m=m+1; 4 – verification, m<M; 5 – calculation of the intensity of the energy flow on M surface and store the result; 6 – complete

Recursive algorithm provides decreasing for complexity of calculation while determining energy intensity value on bioobject surface. Calculations according to steps 2, 3 of the algorithm are not original. Symmetry of the standard light emitting diodes diagram, approximation of the bioobject dimensions to the wave lengths do not sufficiently increase the calculation complexity of these calculations.

Conclusions. Transfer of the light emitting diode energy, and evaluation of this energy flow intensity that irradiate the object are located in the layered „non-periodically" environment, create:

a) new combination „the source of effective, directed radiation and its propagation channel";

b) availability for using the light emitting diode diagram as the wave function of radiation source;

c) retry feature of the layered environment for determining the recursive procedure using light emitting diode radiation diagram on the first step, and corrected radiation diagram after energy transfer through each next layer of the biological environment.

The problem research results of determination of light flux intensity of low intensity after its propagation through the layered bioenvironment provide the decreasing of estimation reliability of human body state by stimulation caused by such light bioobject responses of appropriate organs and body systems.

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ВИЗНАЧЕННЯ ІНТЕНСИВНОСТІ НЕІНТЕНСИВНОГО ПОТОКУ СВІТЛА ПІСЛЯ ПОШИРЕННЯ ЧЕРЕЗ ШАРУВАТЕ БІОЛОГІЧНЕ СЕРЕДОВИЩЕ

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Резюме. *Наведено результати дослідження проблеми визначення інтенсивності потоку світла низької інтенсивності після поширення його крізь шарувате біосередовище. Встановлено, що перенесення енергії випромінювання світлодіода та оцінювання інтенсивності потоку цієї енергії на об'єкті опромінення, який знаходиться в шаруватому, «неперіодичному» середовищі, створює нову комбінацію «джерело ефективного, спрямованого випромінювання та канал поширення його». Визначено за діаграмою випромінювання світлодіода інтенсивність потоку енергії низького рівня після перенесення її через багатошарове біологічне середовище. Діаграму використано як хвильову функцію джерела випромінювання, що дало змогу врахувати вплив шаруватого середовища на інтенсивність опромінення об'єкта в такому середовищі. Побудовано рекурсивний метод та алгоритм визначення інтенсивності потоку енергії низького рівня після перенесення її через багатошарове біологічне середовище.*

Ключові слова: *світлодіод, діаграма випромінювання, шарувате біосередовище, опромінення біооб'єкта.*

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