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Formalized Model Descriptions of Modified Solid-State Plasma-Like Materials to Protect Radio-Electronic Means from the Effects of Electromagnetic Radiation

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ABSTRACT

The results of the development of a formalized mathematical model for describing the modified electrophysical properties of a solid-state plasma medium with hexaferrite elements, arising under the influence of a pulsed ultrashort duration (USD) electromagnetic radiation (EMR), and provide the screening of X-ray discharges are presented. The basic structure of the physical model of solid-state plasma materials is presented. The effect of pulsed USD EMR on a nonequilibrium solid-state plasma arising in a semiconductor matrix depending on the activity of the ionization source and the concentration of hexaferrite inclusions in reflecting and absorbing properties of the material is taken into account.

The article presents experimental studies of single-layer composites with a semiconductor substrate based on silicon organosiloxane, silicate-kaolinite and thermoplastic elastomers, show the possibility of reducing the reflection coefficient by increasing the concentration of ferrite inclusions to a level above the percolation threshold of plasma material. The dependences of the reflection coefficient, as well as the normalized electrical conductivity of the material are determined. The effect of hexoferritic inclusions on the reflection and electrical conductivity of the plasma material is investigated.

Key words: radio electronic means, electromagnetic radiation, ultrashort pulse duration, plasma protection technologies, plasma media.

1. INTRODUCTION

It is known that electromagnetic radiation of USD is capable of disabling modern radioelectronic means (REM) by affecting the sensitive element base. Considering that modern power generation facilities, communication facilities, control systems, computer and telecommunication networks, life support equipment contain radioelectronic equipment (REE), the task of ensuring the protection of radioelectronic equipment from the effects of a destructive pulsed USD EMR becomes urgent.

A qualitative leap in improving the effectiveness of protective equipment is possible through the use of nature-friendly technologies, the use of which physical mechanisms will ensure efficient absorption, reflection and removal of pulsed USD EMR.

As such technologies, plasma technologies can be used that most satisfy the set of requirements for protective equipment.

1.1 Problem analysis

Analysis of the available literature indicates the great interest of scientists to study the processes of generating powerful EMR [2, 3, 4, 10, 11], the use of generators of powerful EMR including for influencing the element base of a radio electronic system. The results characterizing the state of the latest achievements in the field of protection of REM from EMR are presented in [1, 6, 9]. There are also many works devoted to traditional methods and means of protecting radio electronic

devices against the effects of microwave radiation (MVR) [1,6,]. Recently, there have been publications devoted to the use of radioisotope technologies for the protection of radio-electronic devices from exposure to electromagnetic radiation, which are nature-like [9].
The nature of these technologies is associated with the use of reflecting and absorbing properties of plasma, which is the most common state of matter. Also associated with the use of properties of lightning, as a discharge in air, which in the first approximation can be used to create a highly conductive state of air in the holes in the slots of the housing-screens to protect against powerful electromagnetic radiation by breakdown and further energy removal of electromagnetic radiation.

At the same time, there are no formalized mathematical models for describing the modified electrophysical properties of a solid-state plasma medium with hexaferrite elements, arising under the influence of pulsed USD EMR and provide the screening of the X-ray energy distribution.

The aim of research is development of a formalized model for describing the interaction of pulsed electromagnetic radiation of ultrashort duration with a modified solid-state plasma-like material for the REM protection.

2. Main Material

Taking into account the importance of solving the problem of protecting the REM from the effects of pulsed EMR, which is created by the latest EMR generators, a concept of protecting the REM has been developed, the implementation of which is based on the use of physical absorption and scattering mechanisms, which allow one to neglect the mutual influence of reflection.

Studies, the results of which are given by the authors, such as A. Sotnikov, N. Yasechko, V. Kravchenko, show that in order to protect the REM from impulse USD EMR, which is created by EMR generators, it is necessary to ensure the reduction of the energy level of EMR at the entrances at the access points in the REM to the maximum allowable by using physical mechanisms that will ensure the effective absorption, reflection, closure and removal of this radiation. In this case, the possibilities of their practical implementation, as well as the fact that their use will not lead to technical problems in other technical samples equipped with radio electronic equipment, must be taken into account.

The paper discusses the use of solid plasma-like material for the protection of ground-based X-ray objects, where it is advisable to use primarily such physical mechanisms as absorption and scattering of electromagnetic radiation.

The most appropriate for the REM protection is the use of shielding means in existing samples of the technical fleet. The implementation of certain physical mechanisms is possible in the case of screens in the form of a solid-state plasma coating.

Let's consider the possibility of implementing these approaches to create materials that will provide absorption and scattering of pulsed electromagnetic radiation.
The implementation of the physical mechanisms of absorption of pulsed USD EMR in plasma solid-state materials is possible by providing the necessary complex dielectric and magnetic permeability of the material. For this, a dielectric or semiconductor matrix can be used, in which to ensure complex dielectric constant it is necessary to add elements of a radioactive substance to effect ionization and the occurrence of a non-equilibrium state of the electronic subsystem. To ensure the complex magnetic permeability, it is necessary to introduce the corresponding hexaferrite inclusions. The use of elements of a radioactive substance and hexaferrite inclusions of appropriate sizes will also provide for the scattering of electromagnetic radiation.

1. Development of a formalized mathematical model for describing the modified electrophysical properties of a solid-state plasma medium with hexaferrite elements, arising under the influence of pulsed USD EMR and provide the REM shielding

According to the chosen concept of protecting the REM from pulsed USD EMR shielding of terrestrial radio electronic devices using nature-friendly technologies that will meet the requirements for protective equipment is proposed on the basis of solid-state materials using plasma technologies.

It is known that the synthesis of effective shielding materials necessitates the selection of appropriate types of matter and the determination of the electrophysical characteristics of the synthesized material, first of all, the dielectric and magnetic permeability.

The basic structure of the physical model of solid-state plasma materials is shown in Fig.1.

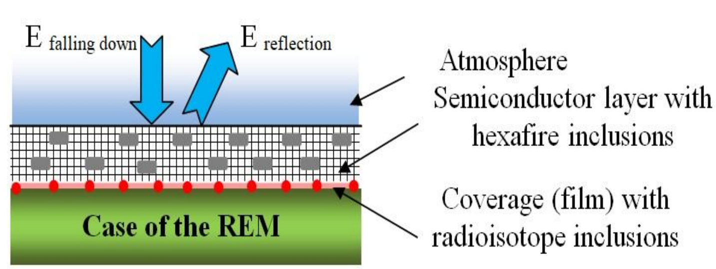

Figure 1: The basic structure of the physical model of solid-state plasma materials

To create a solid-state plasma medium, according to the results of the well-known works [1, 10, 11], let's use a semiconductor matrix in which elements of a radioactive substance will be placed to create a complex dielectric constant. The use of a radioactive substance is necessary for ionization and the occurrence of a nonequilibrium state of the electronic subsystem. The radioactive substance in the form of a film can be placed between the metal case and the semiconductor matrix. In addition, a radioactive substance can be randomly placed in a semiconductor matrix in the form of elements of the corresponding form (round, horseshoe).

Taking into account the above, the dielectric constant of plasma material with hexaferrite inclusions is included in the representation by the following expression:

$$\begin{aligned}\varepsilon_{\Pi}\left(\omega,\vec{k}\right)=&\varepsilon_{M}+\sum_{i=1}^{N}\delta\varepsilon_{in_g}\left(\omega_\rho,\vec{k}\right)+\sum_{\xi=1}^{M}\delta\varepsilon_{noneq_\xi}\left(\omega,\vec{k},Q\right)+\\ &+\sum_{\psi=1}^{U}\delta\varepsilon_{in_i}\left(\omega,\vec{k}\right)+\sum_{\nu=1}^{J}\delta\varepsilon_{noneq_\nu}\left(T(\vec{E},\vec{H})\right)+\\ &+i\left\{\frac{4\pi}{\omega}\left[\sigma_{eff}\left(\omega,\vec{k}\right)+\sigma_{eff}\left(T(\vec{E},\vec{H})\right)+\alpha_e E^2\right]\right\},\end{aligned} \tag{1}$$

where ε_M – dielectric constant of the semiconductor material;

$\sum_{i=1}^{N}\delta\varepsilon_{in_g}\left(\omega_\rho,\vec{k}\right)$ – contribution of hexaferrite inclusions to dielectric constant;

$\sum_{\psi=1}^{U}\delta\varepsilon_{in_i}\left(\omega,\vec{k}\right)$ – contribution of radioisotope inclusions to dielectric constant;

$\sum_{\xi=1}^{M}\delta\varepsilon_{noneq_\xi}\left(\omega,\vec{k},Q\right)$ – contribution of the nonequilibrium state of the electron subsystem arises due to radioisotope inclusions Q to the dielectric constant;

$\sum_{\nu=1}^{J}\delta\varepsilon_{noneq_\nu}\left(T(\vec{E},\vec{H})\right)$ – contribution of the nonequilibrium state of the electronic subsystem arises due to heating under the influence of a pulsed high-power USD EMR to the dielectric constant;

$4\pi\omega^{-1}\left(\sigma_{eff}\left(\omega,\vec{k}\right)+\sigma_{eff}\left(T(\vec{E},\vec{H})\right)+\alpha_e E^2\right)$ – linear and nonlinear components of the imaginary part of the dielectric constant of the semiconductor layer;

α_e, E –effective nonlinear conductivity and average electric field, respectively;

ω, $\vec{k}$ – frequency and wave vector, respectively.

Contribution of hexaferrite and radioisotope inclusions is determined by their electrophysical properties, and the contribution to the dielectric constant of the nonequilibrium state of the electronic subsystem arises due to radioisotope inclusions Q and is influenced by the powerful USD EMR expressions and is determined according to the 2 and 3:

$$\varepsilon^{\ell}\left(\omega,\vec{k}\right)=1+\delta\varepsilon^{\ell},\ \delta\varepsilon^{\ell}=\frac{4\pi e^2}{k^2}\int d\vec{v}\frac{1}{\omega-\vec{k}\vec{v}}\vec{k}\frac{\partial f}{\partial\vec{v}}; \tag{2}$$

$$\varepsilon^{t}\left(\omega,\vec{k}\right)=1+\delta\varepsilon^{t},\ \delta\varepsilon^{t}=\frac{4\pi e^2}{k^2\omega}\int d\vec{v}\frac{\left[\vec{k}\left[\vec{v}\vec{k}\right]\right]}{\omega-\vec{k}\vec{v}}\frac{\partial f}{\partial\vec{v}}. \tag{3}$$

where $\vec{v}$ - electron velocity;

f - velocity distribution function of particles.

By integrating in (2) the angles and, using the fact that $\lim_{\nu\to 0}\frac{1}{x+i\nu}=P\frac{1}{x}-i\pi\delta(x)$ (the symbol means that when integrating, the singularity at x = 0 should be understood in the sense of the main value), let's obtain:

$$\operatorname{Re}\delta\varepsilon=-\frac{16\pi^2e^2}{k^2}\int dv\frac{v^2 f(v)}{\frac{\omega^2}{k^2}-v^2},$$

$$\operatorname{Im}\delta\varepsilon=-\frac{8\pi^3m^2e^2}{\omega^2}\left(\frac{\omega}{k}\right)^3 f\left(\frac{\omega}{k}\right). \tag{4}$$

It is possible to see (4) that the non-equilibrium states of a weakly ionized air medium are characterized when the phase velocity of the wave falls into the inertial range (v_-, v_+) by a high level of EMR absorption.

In this case, the real and imaginary parts of the dielectric constant of a weakly ionized air medium are of the same order, which leads to the complete attenuation of electromagnetic waves.

The distribution function of particles is determined by the basic physical processes occurring in the air environment of the orifice, which include collisions of fast ions resulting from the decay of a radioactive substance with electrons, neutral molecules and ions of weakly ionized air. On this basis, the determination of the corresponding macroscopic parameters through the distribution function of charged particles in the hole requires an analysis of the kinetic processes occurring in the medium of the hole. The results of this analysis will ensure the correct choice of a kinetic equation model.

It is known that the electron distribution function $g=\left|\mathbf{v}-\mathbf{v}_1\right|f(\mathbf{r},\mathbf{v},t)$ determines the average number of electrons $dn_e(\mathbf{r},t) = f(\mathbf{r},\mathbf{v},t)\,d\mathbf{r}d\mathbf{v}$ in an element of the phase space ($\mathbf{r}, \mathbf{v}$) and without taking into account the force term can be found from the Boltzmann kinetic equation:

$$\frac{df}{dt} + \nabla_r \cdot (Vf) = I_3(\mathbf{r},\mathbf{v},t), \tag{5}$$

where ∇_r –gradient operator in the coordinate space r;

$I_3(\mathbf{r},\mathbf{v},t) = \left(\frac{df}{dt}\right)_3$ – collision integral.

With additional ionization of □α-air particles, stationary nonequilibrium states of electronic subsystems appear in the hole, which turns out to be close to power ones:

$$f(E) = A\,E^S, \tag{6}$$

In power solutions to the Boltzmann kinetic equation, the exponent depends on the interaction potential of the particles on the mutual distance.

To create a complex magnetic permeability of the protective material, let's use hexaferrite inclusions that are randomly arranged. The effect of the dielectric constant of hexaferrite inclusions $\varepsilon_{in_i}(\omega)$ in the dielectric constant of the material will be taken into account in accordance with the Maxwell-Garnet approximation. Then, taking into account (1), the dielectric constant of the protective material will be determined in accordance with the relation:

$$\varepsilon_{eff}(\omega,\vec{k}) = \varepsilon_{\Pi}(\omega,\vec{k})\frac{1+2p\dfrac{(\varepsilon_{in_i}(\omega)-\varepsilon_{\Pi}(\omega,\vec{k}))}{(2\varepsilon_{in_i}(\omega)+\varepsilon_{\Pi}(\omega,\vec{k}))}}{1-p\dfrac{(\varepsilon_{in_i}(\omega)-\varepsilon_{\Pi}(\omega,\vec{k}))}{(2\varepsilon_{in_i}(\omega)+\varepsilon_{\Pi}(\omega,\vec{k}))}}, \tag{7}$$

where p – concentration of hexaferrite inclusions.

To ensure the effective shielding of the pulsed USD EMR of hexaferrite inclusions, it is necessary to choose taking into account the dependence of their absorbing properties in the frequency range. In this case, the material can be considered as multi-layered.

The magnetic permeability of the solid-state plasma medium with regard to hexaferrite inclusions will be determined according to the expression:

$$\mu(\omega_\rho) = 1 + \sum_{i=1}^{N}\mu_{in_g}(\omega_\rho), \tag{8}$$

where $\sum_{i=1}^{N}\mu_{in_g}(\omega_\rho)$ – contribution of hexaferrite inclusions to the magnetic permeability, depending on the frequency range.

The components of the dielectric and magnetic permeability are frequency-dependent, which can provide, under certain conditions, the necessary absorbing and scattering properties of the shielding material to protect against the USD EMR effects.

1.2 Study of the effect of hexaferrite inclusions on the reflection coefficient and specific conductivity of the plasma material

As inclusions, it is possible to use complex oxide compounds, for example, $NiCo_2O_4$, Fe_3O_4, with the reverse type spinel structure, have different valence cations in adjacent octahedral pidresites of the elementary molecular cell. Through a small distance between the octahedral positions of different valence cations in this molecular cell, they have a low level of activation energy when implementing the "hopping" mechanism of electrical conductivity. This allows to create protective composite materials with the necessary parameters of reflection and absorption of energy of electromagnetic radiation with a limited concentration of inclusions.

To increase the absorption of electromagnetic radiation depending on its angle of incidence φ, it is necessary by matching the wave impedances at the air-material interface, to ensure appropriate dielectric ε, σ_e and magnetic $\mu, \sigma_м$ and specific conductivities in the form of:

a) under conditions of normal incidence of EMR on the surface of the material, it is necessary that the following conditions be fulfilled:

$$\varepsilon=\mu,\ \sigma_e/\varepsilon_0 = \sigma_м/\mu_0;$$

b) in the conditions of perpendicular polarization of EMR it is necessary that the following conditions be fulfilled:

$$\varepsilon=\mu\cdot\cos^2\varphi,\ \ \sigma_e/\varepsilon_0 = (\sigma_м/\mu_0)\cdot\cos^2\varphi,$$

c) in conditions of parallel polarization of EMR it is necessary that the following conditions be fulfilled:

$$\mu=\varepsilon\cdot\cos^2\varphi,$$
$$\sigma_м/\mu_0 = (\sigma_e/\varepsilon_0)\cdot\cos^2\varphi.$$

Experimental studies of single-layer composite materials with a semiconductor substrate have shown the possibility of reducing the level of reflection coefficient due to an increase in the concentration of ferrite inclusions to a level above the percolation threshold of the plasma material.

The results of experimental studies of the dependence of the reflection coefficient ρ, as well as the normalized specific conductivity of the material $\sigma/\sigma_{\max}$ on the concentration (by mass) of hexaferrite inclusions are shown in Fig. 2

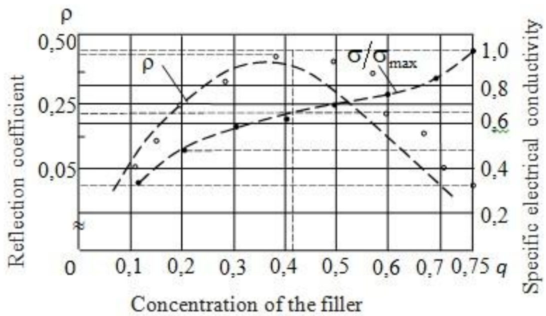

Figure 2: Dependence of reflection coefficient ρ and the specific electrical conductivity σ composite coating on a polymeric (thermoelastoplast) basis.

It is established that an increase in the concentration of inclusions from to increases the relative conductivity of the material in the range of 0.65 ... 0.98. In this case, the reflection coefficient decreases within $\rho = 0{,}46\ldots 0{,}04$ (from minus 3.4 dB to minus 14.0 dB).

5. CONCLUSION

1. A formalized model has been developed for describing the interaction of pulsed electromagnetic radiation of ultrashort duration with a modified solid-state plasma-like material for the protection of REM. A feature of the model is to take into account the effect of a pulsed USB EMR on a nonequilibrium solid-state plasma arising in a semiconductor matrix depending on the activity of the ionization source and the concentration of hexaferrite inclusions in reflective and absorbing properties of the material.

2. The effect of hexaferrite inclusions on the reflection and electrical conductivity of the plasma material was studied. It was found that to ensure the absorption coefficient near the unit (0.96), it is necessary that the concentration of inclusions be $q \approx 0,7...0,75$.

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