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Model and Development of Plasma Technology for the Protection of Radio-electronic Means of Laser Emission

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ABSTRACT

The results of the development of a formalized mathematical model for describing the interaction of laser radiation with the plasma material intended to protect radio electronic means (REM) by reflecting this radiation are presented in this research. The basic structure of the physical model of solid-state radioisotope material is presented. It has been found out that the generation of the Langmuir noise in the protective layer of solid-state plasma of the screen of radio-electronic means provides shielding from laser radiation at a sufficiently small value of the field strength of the Langmuir wave. In this case, there is a re-emission of laser energy in the opposite direction.

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

1. INTRODUCTION

Nowadays, powerful laser radiation generators are rapidly developing, which can lead to unintentional destructive effects and the destruction of the radio-electronic means. The most well-known and effective methods of laser radiation protection are ablative protection and structural insulation.

Yet, the use of known methods for protecting radio-electronic means from destructive effects of laser radiation is not always appropriate due to the impossibility of reusable user, weight-dimensional characteristics (the inadmissibility of its usage on light aircraft objects), the lack of the ability to protect the mounting holes, cable entries of the body of the electronic means.

It is possible to make a qualitative leap in improving the effectiveness of remedies on the basis of the usage of radioisotope technologies, the use of physical mechanisms of which will ensure effective absorption, reflection and removal of laser radiation. Figure 1 shows the location of the proposed radioisotope technologies as part of existing REM protection methods against EMR [6].

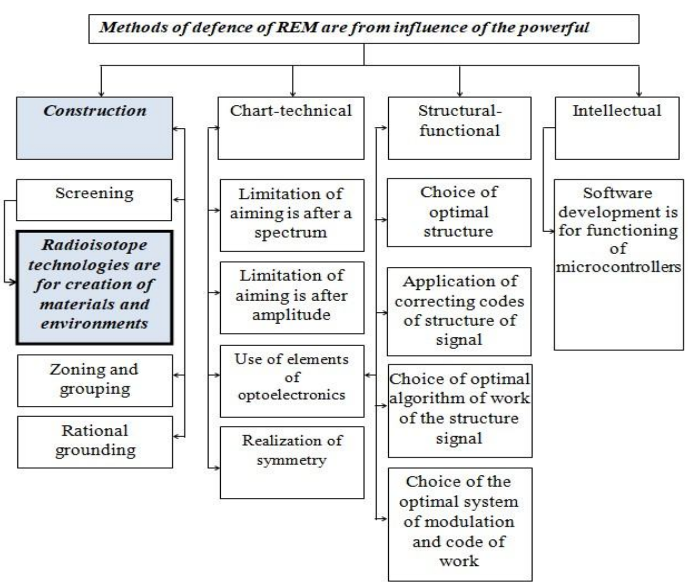

Figure 1: Classification of existing REM protection methods against EMR

Such technologies can be used by environmentally-friendly radioisotope technologies, which satisfy a complex of requirements for the means of protection to the greatest extent [1, 2, 5, 8, 10, 15, 17, 18].

2. MAIN MATERIAL

The impact of high-power laser radiation on materials leads to the appearance of a plasma layer, the parameters of which are determined by laser radiation and the characteristics of the material itself. The flux of the electromagnetic energy falling on the surface of the REM screen is partially reflected, while the remaining part of the flux, penetrating deep into the substance, is absorbed.

Under the influence of the laser energy, there is an increase in the temperature of the protective material made on the magnitude [1, 4]:

$$\Delta T(r,z,t) = f\left(W(r,z,t), t_i\right),$$

where $W(r,z,t) = \bar{W}_z W_0\left(\sigma(r) - \sigma(r-\alpha)\right)e^{-\alpha z} \times f_0(t)$ – is the vector of energy of laser radiation.

In order to protect from laser radiation, the plasma layer can be supplemented with an artificially created solid-state plasma by introducing, for example, the radioisotope elements into a semiconductor layer of the protective screen [1, 3, 4, 7, 9, 11, 15, 16].

Determining the possibility of using solid-state plasma to protect REM from high-power laser radiation calls for an analysis of the interaction of this radiation with the plasma of the shielding material.

To protect REM from laser radiation, the best screen is a mirror, which, regardless of the magnitude of the energy in the EMR, is able to reflect it. Therefore, we will estimate the reflective capabilities of the plasma material.

To screen the laser radiation when creating a plasma “mirror”, a plasma of sufficiently high density n_p is needed.

Electromagnetic waves penetrate into the plasma only to the depths of the skin layer on the condition that $\omega_p > \omega$,

where $\omega_P = \sqrt{\frac{4\pi e^2 n_p}{m_e}}$ is the plasma frequency; ω is the laser radiation frequency; m_e, e – the electron mass and charge, respectively.

The creation of the plasma mirror is possible on the condition that:

$$n_p > n_{cr} = \frac{\omega_p{}^2 m_e}{4\pi e^2}, \qquad (1)$$

where n_{cr} is the critical electron density in plasma.

For radiation frequencies corresponding to the laser ones, $n_{cr} \approx 10^{18}$sm $^{-3}$. The plasma of such density occurs when laser radiation reacts on metal. Therefore, of particular interest is the problem of determining of point of reflection of laser radiation of energy from the surface of a plasma protective REM screen, that is, the determination of the screening conditions of the laser radiation with plasma of lower density than n_{Cr}. It is possible for laser radiation of sufficiently high power due to a number of nonlinear processes.

A significant decrease in the density of the plasma screen reflecting the laser radiation can be achieved by stimulating the parametric decay instabilities that look like this:

$$t' \to t'' + l,$$

where t' is the incident electromagnetic wave; l – is the Langmuir wave; s' – the ion-acoustic wave; t'' – the reflected electromagnetic wave; v_{Te} – the electron thermal velocity; $\omega_{t'}, \omega_l, \omega_{t''}$ – the frequency of the incident, Langmuir and reflected waves, respectively; $\omega_{s'}$ – the ion-acoustic wave; k_0 – the wave vector; E_0 – the electric field strength.

In terms of our studies, of particular interest are the parametric instabilities with the re-emission of electromagnetic waves, i.e. the decay of a transverse electromagnetic wave t' into a Langmuir l or ion-acoustic s' and another electromagnetic wave t'' , spreading in the reflected direction $\left(t' \to l + t'', \quad t' \to t'' + s'\right)$.

The conditions of this type of decay have the following form [3, 13, 18]:

$$\omega_p \geq \omega\left(\frac{v_{Te}}{c}\right) \text{ or } n_p \geq n_{cr}\left(\frac{v_{Te}}{c}\right)^2.$$

It means that the plasma density, which reflects the laser radiation due to decay processed, can be lowered, as compared with n_{cr}, by the value of $\left(\frac{v_{Te}}{c}\right)^2$, which under normal plasma parameters is about 10^{-4}.

Let us consider the example of decay $t' \to t'' + l$, that if the plasma density is $n_p \approx n_{cr} \cdot 10^{-4}$, it is possible to achieve the complete reflection of laser radiation. To do this, we assume that the Langmuir noises (waves) with the wave vector k_l, directed to the plasma boundary are created in the plasma layer.

The resonance conditions of the merging of the incident electromagnetic wave with the wave vector $k_{t'}$ and frequency $\omega_{t'}$ and Langmuir waves (k_l, ω) look like:

$$k_{t'} + k_l = k_{t''};$$
$$\omega_l + \omega_{t'} = \omega_{t''}.$$

Since $|k_l| >> |k_{t'}|$, the electromagnetic wave spreads in the reflected direction, i.e. in the reverse one compared to the incident electromagnetic wave.

Let us present the estimations for the amplitude of the provoked Langmuir noises, which is necessary for the reflection of laser radiation. The equation describing the scattering of a electromagnetic wave by a Langmuir wave looks like:

$$\frac{d^2 H^{(t'')}}{dz^2} + \frac{\omega^2}{c^2} H_x^{t''} = F(z), \qquad (2)$$

where $F(z) \cong \frac{e}{2m_e c\omega} \frac{d}{dz}\left(E_y^{t'} \frac{d}{dz} E_z' \right)$;

$H^{(t'')}$ – is the magnetic field of the reflected electromagnetic wave;

$E_y^{(t')}, E_z^{(1)}$ – the electric fields of the incident and Langmuir waves, respectively.

The flux of energy into the re-emitted electromagnetic wave can be found from (2) and looks like:

$$S_{t''} \approx \frac{cH_x^{(t'')}}{8\pi} \approx \frac{e^2}{(2m_e\omega)^2 c}\left(\frac{k_l}{k_{t''}}\right)^2 A_L^2 A_{lw}^2, \qquad (3)$$

where A_L– is the laser field amplitude;

A_{lw} – the Langmuir waves amplitude.

$S_{t'} = \frac{cH_0{}^2}{8\pi} \approx cA_L^2$ – the incident energy flux;

$S_l = V_g \frac{E^2}{8\pi} \approx v_{Te} A_{lw}^2$ – the flux density of the provoked Langmuir noises.

The conversion factor for the electromagnetic energy flow of the incident wave into the reflected one equals

$$T = \frac{S_{t''}}{S_{t'}} \cong \frac{e^2}{(2m_e c\omega)^2}\left(\frac{k_l}{k_{t''}}\right)^2 A_{lw}^2. \qquad (4)$$

Since $|k_l| >> |k_{\omega'}|$, $|k_l| \sim |k_{\omega''}|$, and $\omega \sim 10\omega_p$, then by substituting the known numerical values in (2), we will get the following:

$$T = \frac{e^2 A_{lw}^2}{4m_e^2 c^2 10^2 \omega_p^2} = \frac{(4.8)^2 10^{-20} 10^{-6} A_{lw}^2}{4(9.1)^2 10^{-56} 9\cdot 10^{20}\cdot 32\cdot 10^{20}} \approx 2.4\cdot 10^{-10} A_{lw}^2.$$

Thus, for the total reflection of the electromagnetic wave (T=1) we need $2.4\cdot 10^{-10} A_{lw}^2 = 1$, that is, if the decay instability is not taken into account, then it is necessary to create the Langmuir noises with a large amplitude equaling $\alpha_{lw} = \frac{1}{3}\cdot 10^5$ (sgs) in the plasma.

In accordance with the expression (2), the reflection coefficient does not depend on the power of the incident laser radiation, but is completely determined by the parameters of the plasma and provoked Langmuir noise. It means that the reflection coefficient has a certain universality with respect to the laser radiation power, that is, the parameters of the plasma and Langmuir noise are identical for different laser powers [18].

Let us estimate the amplitude of the Langmuir noise with the total reflection of laser radiation (T=1) with increasing decay instability.

From the expression (2) with T=1 we will get:

$$a_{lw}^2 \approx \left(\frac{k_{t''}}{k_l}\right)^2 \frac{(2m_e c\omega)^2}{e^2}.$$

Hence, since $|k_{t''}| \approx |k_l|$, $A_{lw}^2 \geq 10^{-14}$, ω^2 (sgs). It should be mentioned that with the development of parametric (delay) instability, the Langmuir noise is amplified:

$$A_{lw} = a_0 e^{\gamma_H t}, \qquad (5)$$

where α_0 – is the amplitude of plasma noise provoked by an external source;

$\gamma_H = \frac{eA_L}{m_e c}\sqrt{\frac{\omega_p}{\omega_{t'}}}$ – the instability increment $t' \to t'' + l$.

Given that $t = L/c$, we will present the expression (2) in the following form [18]:

$$a_0^2 e^{\frac{2\gamma_H L}{c}} \geq 10^{-14}\omega^2$$

or
$$a_0^2 > 10^{-14}\omega^2 e^{\frac{-2\gamma_H L}{c}}, \quad (6)$$

where L is the thickness of the plasma layer.

If the laser energy flux equals

$$S_{t'} = \frac{cE_{t'}^{\,2}}{8\pi} \approx \frac{cA_L^{\,2}}{8\pi} \approx 10^{10} W / sm^2 \approx 10^{10} \cdot 10^7 \, sgs,$$

then $A_L \leq 10^4$.

If L = 30 sm, $\omega = 10^{14}$ we will get:

$$A^2_{lw} > 10^{14} \times 10^{-10}; \quad A_{lw} \geq 10^2.$$

If $\alpha_0 \approx 10\, A_{lw}$; $A_{lw}=10^3 V/sm.$

If $L=20\ sm$, $\omega = 10^{15}$, $E_1 \leq 10^3\ V/sm.$

Thus, with the directed generation of the Langmuir noises in the protective layer of solid-state plasma of the REM screen, the possibility arises of shielding from laser radiation at a sufficiently small value of the field strength of the Langmuir wave. In this case, there is a re-emission of the laser energy in the opposite direction.

In order for the above described mechanism to work in the appearing plasma, it is necessary that during the development of nonlinear interaction $1/\gamma_H = \tau_H$, the density of the expanding plasma of a solid body is reduced to values not less than 10^{10} sm^{-3}, i.e.

$$1/\gamma_H = \tau_H < \tau_b,$$

where τ_b is the time scale of plasma density drop during the evaporation into vacuum:

$$\tau \approx L_f / C_s,$$

where L_f is the characteristic torch size of the scattering plasma;
C_s – the velocity of the solid-state plasma dispersion in vacuum.

To completely shield the laser radiation, it is necessary to conduct the closure process with the help of the appearing plasma, i.e. $L_f = L$ – it is the size of the evaporation depth of a semiconductor at the same time. That is, during the time τ_H the laser must melt a depth of L. Hence, $L = \tau_H v_{pl}$,

where v_{pl} – is the melting point of the protective material.

The melting point of the protective material can be found from the following ratio:

$$V_{пл} = \frac{S_{t'}}{\lambda_1 \left(1 + 2.2 / y_0\right) \rho_0}, \quad (7)$$

where ρ_0 is the electron density in the semiconductor in the solid phase;
λ_1 – the connection energy of the crystal lattice;
$y_0 = \frac{\lambda_1}{kT_0}$, T_0 – the temperature of the surface of the protective screen;

k – the Boltzmann constant.

For $n_0 = 10^{23} sm^{-3}$, $S_{t'} = 10^{10} W / sm^2$, $l_1 \sim 5eV$ и $T_0 \sim 0{,}1\ eV$ we will get $L \sim 0{,}1sm$.

Thus, the aforementioned estimations show that the reflection of the laser radiation can be carried out with the usage of materials having a small thickness and weight.

The structure of the physical model of solid-state plasma materials for protection against the impact of laser radiation is shown in Figure 2.

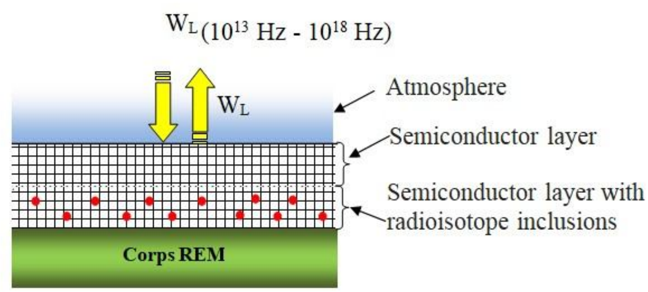

Figure 2: The structure of the physical model of solid-state plasma materials for protection against the impact of laser radiation

The temperature distribution satisfied the inhomogeneous heat conduction equation with the corresponding initial and boundary conditions

$$div(k_T + gradT) - cr\frac{d}{dt}T = y(r,z,t) = -div\overline{W}(r,z,t) \quad (8)$$

The solution of the equation in question (8) will determine the growth of the temperature of the protective material over time along the axis of the laser beam.

The ratio (1) - (4), (8) is a formalized mathematical model for describing the interaction of the laser radiation with a plasma material designed to protect REM by reflecting this radiation.

5. CONCLUSION

The peculiarity of the model that determines its novelty lies in the use of the mechanism of the delay parametric instability in order to provide the necessary magnitude of the concentration of electrons of a non-equilibrium plasma, in which the reflection of impulse laser radiation and its spatial and temporal evolution are carried out, as well as taking into account the dynamics of heating the plasma material depending on the magnitude of the energy of laser radiation and the width of the impulse.

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