DEVELOPMENT OF METHODS FOR THE ASSESSMENT OF VULNERABILITY OF THE RECEIVER INPUT OF FREE-SPACE OPTICAL COMMUNICATION FROM THE EFFECTS OF RADIATION, AS THE EFFECTS OF THE DESTRUCTION OF RADIATION HAZARDOUS OBJECTS

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ABSTRACT

Object of research: Free-space optical communication (FSO).

Investigated problem: Significant advantages of free-space optical communication in comparison with the existing networks of useful data transmission justify their use in various complex environmental conditions, which require the organization of fast and reliable digital communication when it is impossible or limitation to use wired or radio lines.

Main scientific results: One of the factors that can considerably affect the FSO efficiency is radioactive radiation produced by various sources and phenomena of ionizing effects. In the research the issues of the assessment of the vulnerability of the FSO receivers of input signal from the effects of gamma radiation are directly considered. The analysis of the design of the receiving path of the input signal of FSO is conducted and the list and the partial attenuation coefficients of radioactive radiation by the FSO components that separate the receiver of input signal from the external environment are determined.

The area of practical use of research results: The methods has been developed and with its help the assessment of the vulnerability of the FSO receivers of input signal from the effects of gamma radiation, as the effects of the destruction of the radiation-hazardous object has been conducted.

Innovative technological product: The nature of the influence of gamma radiation as the effects of the destruction of the radiation-hazardous object on the FSO receiver of input signal is determined.

Scope of application of an innovative technological product: The results allow to develop a set of measures aimed at reducing the effects of gamma radiation, as the effects of the destruction of the radiation-hazardous object, on the FSO efficiency.

1. Introduction

1. 1. The object of research

The object of research is free-space optical communication.

1. 2. Problem description

Technologies of free-space optical communication (FSO), despite the fundamental disadvantage of this technology – significant dependence of the communication line on external factors, have such advantages as high-speed transmissions, the lack of frequency licensing, the speed of channel arrangement, independence from the influence of the general electromagnetic background in the radio frequency domain that allow them to take their place in the information transmission system.

It should be noted that FSO, as a system of technical support for communication of external location, is characterized by vulnerability to the influence of various negative factors and environmental phenomena and man-made impact factors. One of which may be the effect of radioactive radiation produced by various sources and phenomena of ionizing influence. Such sources could be the factors of a nuclear explosion, outer space ionizing radiation, as well as the consequences of the destruction of radiation-hazardous objects in nuclear industry.

The analysis of the structure and element base of the FSO construction scheme shows that the most radiation-vulnerable structural element of the FSO will be the receiver of the infrared input signal.

The primary factor that can significantly reduce the effects of radioactive radiation directly on the FSO receiver of input signal are the various components that separate the receiver from the external environment.

Holistic methods for estimating the impact of radioactive [1] radiation on the FSO [2, 3] devices mainly assess the impact of radiation defects in the element base on the effectiveness of its application to the effects of penetrating radiation [1, 4, 5]. Therefore, these methods need to be improved to assess the impact on FSO of the probable consequences of a man-made disaster, and there is a need for research to take into account the impact on the receiver of FSO lines of radiation doses, the impact of radiation defects that may occur under the action of radioactive radiation.

1. 3. Suggested solution to the problem

The analysis of the existing methods of forecasting the characteristics of radioactive radiation as the consequence of the disaster, and assessing their impact on FSO allowed to identify the existing shortcomings, the main of which are:

– the lack of accounting for the time model of the probable disaster;

– the lack of forecasting the consequences of the disaster;

– the difficulty of determining the amount of a mixture of radioactive substances in an emergency release;

– the difficulty of determining the power and dose of radioactive radiation without taking into account the characteristics of radioactive radiation generated directly by a mixture of radioactive substances;

– the lack of accounting for the characteristics of the interaction of gaseous and fine solid radioactive substances with the surface of FSO.

In addition, it is necessary to take into account that in the existing methods [4, 5] there is no assessment of the impact of radioactive radiation, as a consequence of a man-made disaster, on FSO.

The analysis of the process of forming a dose rate and a rate of radioactive radiation, that can affect the FSO receivers, shows that their quantitive indicators are influenced by certain features associated with the source of formation of the specified radioactive radiation. One of which can be the effects of a disaster at a radiation-hazardous object of nuclear industry.

The analysis of methods for assessing the impact of radioactive radiation on FSO shows that the created holistic methods assess the impact of radiation effects in the element base on the impact of only penetrating radiation.

Thus, the presence of shortcomings in existing methods does not allow to fully solve the scientific problem of assessing the effects of radioactive radiation on the FSO receivers, as a basis for developing recommendations aimed at preserving the values of the detection ability of the receiver under the influence of radioactive radiation.

The solution of the problem is possible in case of creating input data for the method, which would be able to take into account the stages and duration of the formation of the zone of radioactive contamination, the aggregate composition of the mixture of radio nuclides, the energy and activity characteristics of this mixture and the characteristics of adsorption - desorption interaction of a mixture of radioactive substances with the surfaces of the devices, and would also take into account the peculiarities of the impact on the FSO receivers.

Thereby, the problem of reducing the effects of the destruction of the radiation-hazardous object on the efficiency of FSO creates a new urgent scientific task, namely the development of methods for assessing the protection of the FSO receiver of input signal from the effects of gamma radiation, as the effects of the destruction of the radiation-hazardous object.

The aim of research was to develop methods of assessing the vulnerability of the receiver input of free-space optical communication from the effects of radiation, as the effects of the destruction of radiation hazardous objects.

The analysis of the design of FSO receivers, as well as the conditions of their operation shows that the protection of FSO receivers from gamma radiation will be determined by the deterioration and operating characteristics. From this position the FSO receiver will be least protected from the front of the aperture of the directional FSO antenna. This is explained by the fact that the maximum sensitivity corresponds to the normal incidence of the maximum infrared radiation from the specified direction on the photosensitive surface.

2. Materials and Methods

The peculiarity of the FSO layout is that the receiver from the back and the sides is protected from gamma radiation by a housing, which is usually made of dense materials and metals [6–10].

Along the axis of the receiver from the front part the receiver is separated from the external environment by the receiving path, which may include various lenses and mirrors, which are placed on metal substrates.

The analysis of the schemes of the receiving paths shows that the receiver is protected from gamma radiation by an optical material (up to 2–3 mm thick) and located behind it the elements of the optical system (two or three obstacles made of various materials with a total thickness of up to 4–8 mm) (**Fig. 1**).

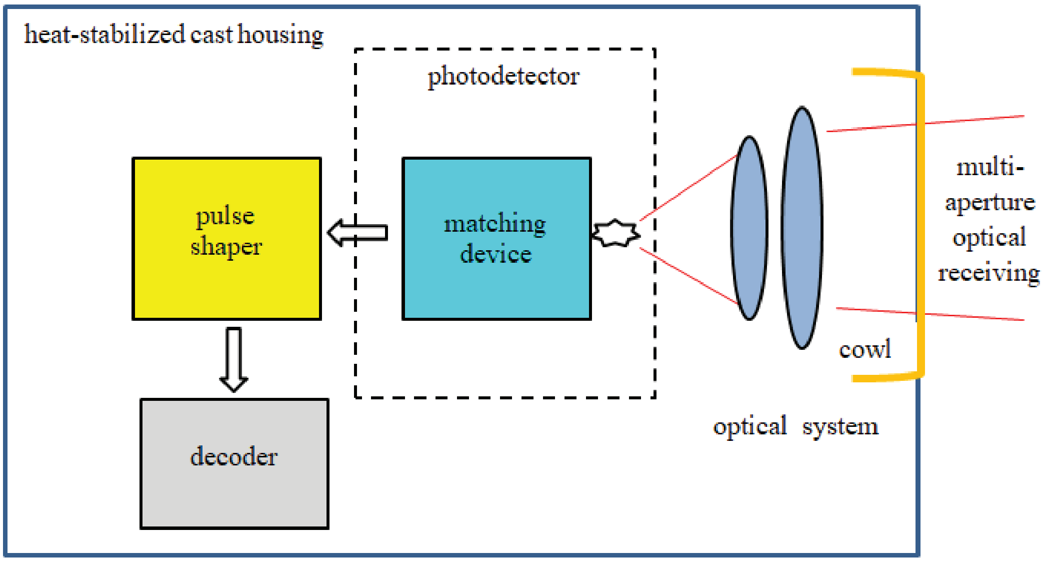

Fig. 1. FSO Receiver circuit

The devices can be made of various materials, such as Calcium aluminate (AlK_2), Arsenic Trisulfide Glass (AsS_3), Synthetic Sapphire (Al_2O_3), Magnesium oxide (MgO_2), crown glass based on Fused Quartz (SiO_2) or Germanium (Ge), as well as Aluminum (Al) or Iron (Fe).

In view of the attenuation of gamma radiation by the elements of the receiving path of the FSO receiver, which directly affect the receiver, the dose rate () and the dose of gamma radiation $\left(D_\gamma^B\right)$ can be defined as:

$$P_\gamma^B = \frac{P_\gamma^p}{K_{W_p}^\gamma}, \tag{1}$$

$$D_\gamma^B = \frac{D_\gamma^p}{K_{W_p}^\gamma}, \tag{2}$$

where P_γ^p and D_γ^p are respectively the dose rate and the dose of gamma radiation, that falls on the aperture of the FSO receiver; $K_{W_p}^\gamma$ is the gamma radiation attenuation coefficient of the elements of the receiving path of the FSO receiver.

The protection of the elements of the receiving path of the FSO receiver from any type of radiation is quantified by the attenuation coefficient (K_W), which is defined as:

$$K_W = \frac{\ln F_0}{\ln F_x d}, \tag{3}$$

where F_0 is the density of radiation flux falling on an obstacle; F_x is the radiation flux density behind an obstacle; d is an obstacle thickness.

The gamma flux falling on the obstacle with the flux density F_{0_γ} having passed the obstacle, will take the value:

$$F_{x_\gamma} = B_\gamma F_{0_\gamma} \exp\left(-\frac{d}{d_{0.5}^\gamma}\right), \tag{4}$$

where B_γ is the accumulation factor of γ – quanta that pass through a substance of thickness; $d_{0.5}^\gamma$ is the layer of half attenuation of gamma radiation.

The accumulation factor takes into account an increase in the density of gamma radiation in the studied space. In this case, its magnitude is affected by both the scattering in the obstacle material of the incident flux of γ-quanta and the secondary bremsstrahlung.

The scattering of gamma radiation in the obstacle is due to the broad form of the flux of incident γ-quanta on the obstacle, which is typical of radiation created as a result of radioactive contamination of an area (for example, a man-made disaster). The appearance of secondary gamma radiation in the obstacle is due to the effect of pair production and the Compton effect.

The value of the parameter B_γ depends on the thickness of the obstacle (X), and if it is less than or equal, $B_\gamma \cong 1$. In the range of energies -quanta that are equal to 0,2–1.5 MeB, the value for optical materials of the FSO receiving path, as well as for some metals used to produce the body and structural elements of FSO are presented in **Table 1**.

The data of the analysis indicates that B_γ can be taken as one. Then the expression for K_W^γ will take the form:

$$K_W^\gamma = 2^{d_{0.5}^\gamma}. \tag{5}$$

The dependence of K_W^γ on the thickness of an obstacle is calculated for the materials that are used to produce optical elements of the receiving path of FSO (**Table 1**).

In the case where gamma radiation passes sequentially through several obstacles:

$$K_{W_p}^\gamma = \prod\nolimits_1^i K_{W_i}^\gamma, \tag{6}$$

where i is the amount of obstacles.

Table 1

The value $d_{0.5}^\gamma$ for optical materials and metals that can be used to produce the FSO elements

Material	$d_{0.5}^\gamma$
Synthetic Sapphire (Al_2O_3)	3.1
Calcium aluminate (AlK_3)	3.1
Magnesium oxide (MgO_2)	4.95
crown glass based on Fused Quartz (SiO_2)	4.75
Germanium (Ge)	2.3
Arsenic Trisulfide Glass (AsS_3)	2.25
Iron (Fe)	1.65
Aluminum (Al)	4.62
Copper (Cu)	2.43

3. Results

Thus, the attenuation function of gamma radiation by the elements of the receiving path of FSO is quantified by the attenuation coefficient $K^{\gamma}_{W_p}$ (Fig. 2), that in relation to the design variant of FSO is defined as the product of the attenuation coefficient by the front of the FSO receiver $\left(K^{\gamma}_{W_p}\right)$ by the attenuation coefficient of the secondary mirror radiation $\left(K^{\gamma}_{W_{B3}}\right)$ and by the attenuation coefficient of the radiation of a corrective lens $\left(K^{\gamma}_{W_{KL}}\right)$.

$$K^{\gamma}_{W_p} = K^{\gamma}_{W_{p0}} + K^{\gamma}_{W_{B3}} + K^{\gamma}_{W_{KL}}. \tag{7}$$

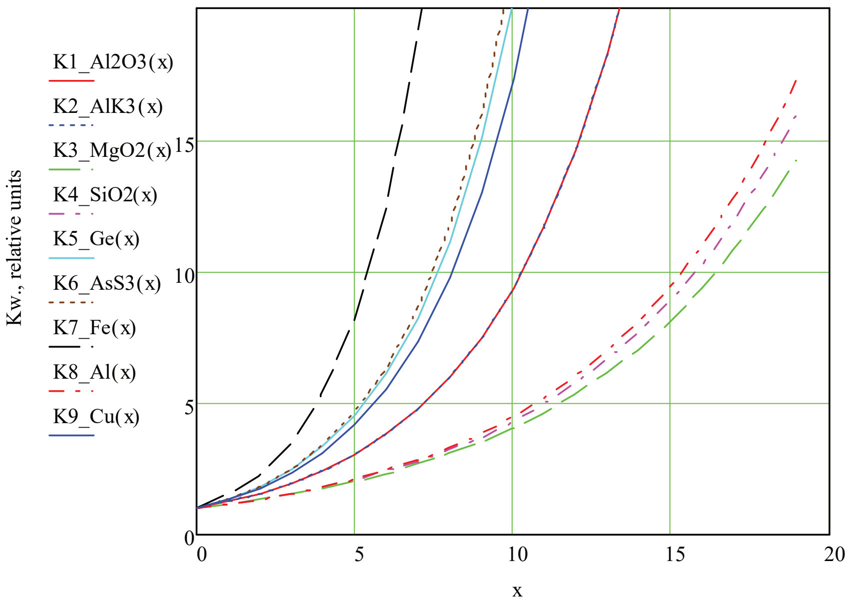

Fig. 2. Dependence on the thickness of the obstacle for: 1– Al_2O_3; 2– AlK_3; 3– MgO_2; 4 – SiO_2; 5– Ge; 6– AsS_3; 7– Fe; 8– Al; 9 – Cu

The occurrence of irreversible radiation processes in semiconductors depends on both the energy of gamma-ray quanta and the type and characteristics of their interaction with the substance from which the FSO receiver is made.

When gamma radiation interacts with the substance through which it passes, two types of reactions can occur: elastic (inelastic) scattering.

As a result of the elastic (inelastic) scattering reaction, only a change in the trajectory of gamma rays is observed, which is accompanied by the loss of some part of their energy. Elastic (inelastic) scattering does not lead to internal changes in the substance.

The effect of gamma-ray quanta on the substance is accompanied by a number of processes that convert their energy into the kinetic energy of particles. Of the known effects that accompany the process of conversion of gamma radiation energy into kinetic energy of particle motion, the most effective (at gamma-ray energies of 0.2–1.1 MeV) for changing the internal structure of the substance will be the effect of pair production and the Compton effect [6].

3. 1. The aim and objectives for the future research

The effect of pair production is observed with the energy of gamma-ray quanta greater than 1.02 MeV. Since the energy of gamma-ray quanta emitted by the nuclear fission products is in the range of 0.3–0.6 MeV, the effect of pair production under the influence of the man-made disaster will not be observed.

The essence of the Compton effect is to ionize atoms under the influence of gamma radiation. This ionization is accompanied by the production of recoil electrons with its own energy $E_{\beta_{0m}}$, which is defined as:

$$E_{\beta_{0m}} = \frac{\overline{E}_\gamma}{1+\dfrac{0.511}{\overline{E}_\gamma(1-\cos\phi)}}, \qquad (8)$$

where φ is the angle for a recoil electron after the collision with an atom of the substance.

The obtained dependence $E_{\beta_{0m}}$ on the angle of incident gamma radiation on a Silicon photodiode is shown in **Fig. 3**.

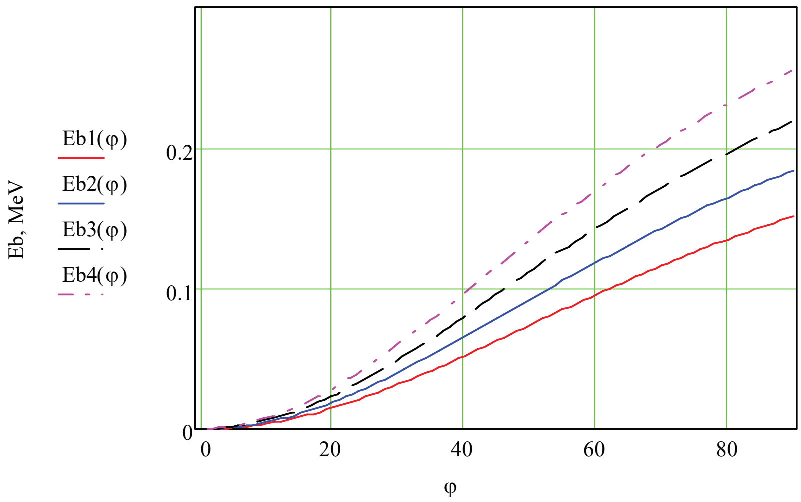

Fig. 3. Dependence of the energy of the recoil electrons on the incident gamma radiation on a Silicon photodiode

In the process of movement in the substance, the recoil electrons after the collision with new atoms transmit to them a certain amount of energy, which is called the energy of displacement E_{d_0}. The value of E_{d_0}, which is transmitted by the recoil electrons after the collision with the atoms in the process of formation and subsequent movement through the crystal lattice of the substance, is determined by the expression:

$$E_{d_0} = \left(\frac{560}{A}\right)\left(\frac{E_\beta}{m_0 C^2}\right)\left(2+\frac{E_\beta}{m_0 C^2}\right), \qquad (9)$$

where A is the atomic mass of the substance; m_0 is the rest mass of the β-particle; C is the light speed; E_β is the energy of the β-particle.

If for an atom of the substance, in which the Compton effect occurs under the influence of gamma-ray quanta, the following inequality will hold:

$$E_{d_{th}} < E_{d_0}, \qquad (10)$$

where $E_{d_{th}}$ is the threshold energy of displacement for the given substance, so in this substance, as a result of a single collision and a subsequent shift of the atom from the node of the crystal lattice, there is a point defect, which leads to a disturbance of the substance structure. For example, in Silicon this will be the Frenkel defect, which results in the formation of a vacant site pair displaced in the internode of the atom.

5. Discussion

With increasing concentration of point defects, which are associated with an increase in the radiation dose absorbed by the substance, complexes of radiation defects are produced, which with further increase in the absorbed dose can form microscopic regions with strongly disturbed crystal lattice [2, 3].

In silicon $E_{d_{th}} = 10$ KeV, the condition (10) will be fulfilled (10), i.e. in the FSO receiver made on the basis of silicon, the process of reproduction of irreversible radiation effect will be observed.

The probability of irreversible radiation effects in the substance is determined by the amount of absorbed dose (D_γ, rad) of gamma radiation.

In the field of influence of gamma radiation there is an increase in current, which ultimately leads to a decrease in the characteristics of the optoelectronic receiving module.

The studies carried out in this work are limited to the scheme of construction of the FSO input signal reception path and do not apply to the output signal path and other similar signal transmission systems in the optical range.

The prospect of the further research is to study the effects of the characteristics of radioactive radiation on the performance of FSO.

6. Conclusions

1. The article considers the protection of the FSO receivers from gamma radiation. Based on the analysis of the formation process of radiation effects, the characteristics of radioactive radiation that affect this process are detected. The procedure of determining the dose rate and the dose of radioactive radiation is defined and the initial data necessary for calculations are determined.

It is determined that the receiver is protected from gamma radiation by an optical material (up to 2–3 mm thick) and located behind it the elements of the optical system (two or three obstacles made of various materials with a total thickness of up to 4–8 mm).

2. The mathematical model and on its basis a methods of assessing the vulnerability of the FSO receiver of input signal from the influence of gamma radiation, as the effects of the destruction of the radiation-hazardous object, are given.

The quantitative criterion of protection of the receiver from the effects of gamma radiation is the attenuation factor, which is determined by the density of the incident radioactive radiation and the thickness of the interference.

3. The assessment of the protection of the FSO receiver of input signal from the effects of gamma radiation is conducted.

It is established that with increasing the thickness of the outer elements of the input signal path from 1 to 5 mm, the attenuation coefficient of gamma radiation will increase, depending on the material of the element, from 1 (MgO_2) to 10 (Fe) or more units.

4. The nature of the influence of gamma radiation as the effects of the destruction of the radiation-hazardous object on the FSO receiver of input signal is determined.

It has been established that both reverse and irreversible radiation effects can be formed in the receivers of the FSO input signal under the action of gamma radiation as the effects of the destruction of the radiation-hazardous object.

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