

REGULARITIES OF INFLUENCE OF ELECTRON-BEAM TECHNOLOGY ON TECHNICAL AND OPERATIONAL CHARACTERISTICS OF OPTOELECTRONIC DEVICES

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Abstract: Based on the electron-beam technology we suggest the method that increases accuracy and extends the ranges of optoelectronic device measurement, and also increases the probability of their trouble-free operation under conditions of external thermal and mechanical actions. The method is based on the developed experimentally-statistical models to determine the complex influence of parameters of the electron beam on the physical-mechanical properties and optical characteristics in the surface layers of optical elements. At the stage of device manufacturing this method allows forming a database of the superior physical and mechanical properties and the optical characteristics in the surface layers of optical elements depending on the electron beam parameters, by choosing the optimal regimes of their electron-beam processing, that allow maximizing the metrological characteristics of the devices.

Keywords: OPTOELECTRONIC DEVICES, ELECTRON-BEAM TECHNOLOGY, OPTICAL CERAMICS, OPTICAL GLASS.

1. Introduction

Modern optoelectronic devices with optical elements (laser rangefinders of sighting systems with optical windows of transmitting and receiving channels, laser medical devices with cylindrical fiberoptic lightboards, IR-devices with semispherical fairings made of optical materials for homing and surveillance, etc.) when exploited are subjected to intensive external thermal and mechanical influences (increased heating temperatures and external pressures, thermal shock under conditions of shot and flight, etc.) [1 – 4]. Under these conditions, various negative defects are formed on the surface and in the surface layers of optical elements (cracks, hump, hollows, inflows, etc.), the further development of which leads to the destruction of elements (there appear detachments, chips, wavelike surfaces, etc.). It results into the deterioration of their basic quality parameters (the coefficient of IR radiation transmission reduces from the objects observed as well as the surface microhardness, at the same time resistance to external thermal and mechanical pressures also reduces, etc.). This leads to a significant deterioration in the technical and operational characteristics (reduction of accuracy, reduction of measurement ranges, etc.) and the reliability of devices in their operation, taking into account the impact of these influences [5 – 12].

The existing methods of improving technical and operational characteristics of optoelectronic devices do not always provide their normative values, especially under extreme exploitation conditions.

New opportunities for improvement of technical and performance characteristics of the devices open due to the purposeful change of physical and mechanical properties of their surface layers by their modification. One of the effective methods of optical material surface treatment is the movable electron beam, which allows to modify surface layers of optical elements by changing their performance characteristics affecting accuracy, measurement ranges and reliability of devices [5 – 11].

Nowadays the study of the influence of the previous finishing electron-beam processing of the optoelectronic elements on the technical and performance characteristics of optoelectronic devices are quite restricted and unsystematized. That is why the aim of this work is to prevent negative impacts of external thermal and mechanical influences on the technical-operating characteristics of devices by means of finishing electron-beam processing of their optical elements.

2. Results and discussion

Based on the conducted technical-operational research made by authors [5 – 11] they developed the following enhancement method of physical and mechanical properties of the elements, metrological

characteristics and reliability of devices in their functioning with the help of electron-beam technology. The method relies on the developed experimental and statistical models for determining complex influence of the parameters of electronic beam on the physical-mechanical properties and optical characteristics of optical element surface layers (relative Error 5... 7 % [1, 6 – 8]:

$$h(F_n, V) = A_0 \cdot F_n^{A_1 + A_2 V + A_3 V^2} \cdot V^{A_4}, \quad (1)$$

$$h_m(F_n, V) = B_0 \cdot F_n^{B_1 + B_2 V + B_3 V^2} \cdot V^{B_4}, \quad (2)$$

$$H_v(F_n, V) = C_0 \cdot F_n^{C_1 + C_2 V + C_3 V^2} \cdot V^{C_4}, \quad (3)$$

$$H_{sp}(F_n, V) = \sum_{i=1}^4 D_i \cdot V^i + F_n \cdot \sum_{i=1}^4 E_i \cdot V^i + \sum_{j=2}^4 K_j \cdot V^j, \quad (4)$$

$$k_\lambda(\lambda) = \sum_{i=1}^5 \lambda^i \cdot M_i \quad (\text{for optimal values } F_n^{\text{opt}}, V_n^{\text{opt}}), \quad (5)$$

where F_n is thermal influence density of electronic beam, W/m^2 ; V is travel speed of the beam along the treated surface of optical element, m/s ; A_1, B_1, C_1 ($i=0,4$) and D_i, E_i ($i=1,4$), K_j ($j=2,4$) and D_i, E_i ($i=1,4$), K_j ($j=2,4$) are empirical constants, μm ; h – the magnitude of surface microroughness, μm ; h_m – thickness of the melted layer, μm ; H_v – surface microhardness, Pa ; H_{sp} is a critical height of steel ball drop on the surface of the element at which it is destroyed; k_λ is spectral coefficient of IR radiation.

In the process of device manufacturing this method allows, operatively via dialogue and in the real time mode, to form a database on modern PCS. This database comprises improved physical and mechanical properties and the optical characteristics of surface layers of optical elements depending on the parameters of electronic beam, choosing the optimum modes of their electron-beam processing, which allow to maximize the metrological characteristics of the devices and improve their reliability during operation.

In practice, the specified method was used to improve the metrological characteristics and to improve the reliability of the following optoelectronic devices.

Increasing the accuracy of range measurement by pulse laser rangefinders. The device of sighting complex with the working wavelength of laser radiation of $\lambda = 1,06$ microns was used for experimental researches. Transmitting and receiving channels of pulse laser rangefinder are equipped with input and output windows, made of optical glass K8 and BK10 with diameter $d_1, d_2 = 3 \cdot 10^{-2} \dots 5 \cdot 10^{-2} m$ and $H_2 = 4 \cdot 10^{-3} \dots 6 \cdot 10^{-3} m$ thick respectively [2, 3].

Fig. 1a presents general view of the sighting complex device (a) and pulsed laser rangefinder, which consists of optical head with laser rangefinder (1); optical-mechanical unit (2); lense of the device (3); control panel of thermal-conversional camera of the spotter (4).

Simplified schemas of transmission (Fig. 1b) and receiving

channels (Fig. 1c) schematically show: IR radiation flow directed to the object (6); input optical window of rangefinder receiving channel (7); an output optical window of a rangefinder channel (5); IR radiation flow that is dispersed by the object and falls into the input window (8); photo receiving device (FRD); signal formation unit (SFU).

While conducting researches on distance measurement to moving and still objects (targets) by pulse laser radiation (wavelength $\lambda = 1,06 \mu\text{m}$, the operating frequency of generated pulses $\nu = 2 \cdot 10^7 \text{ Hz}$) it has been established, that by finishing electron-beam processing on the surfaces of optical windows of transmitting and receiving channels in pulse laser rangefinder as a result of increase of IR-radiation transmission coefficient by 4... 6% (for optical glass K8 and BK10) [1, 9, 10], the accuracy of its measurement, at the optimum values of the beam parameters $F_n = 8 \cdot 10^8 \text{ W/m}^2$ та $V = 5 \cdot 10^{-3} \text{ m/s}$, can be increased by 10... 15% (Fig. 2, where $\overline{\Delta L} = \frac{\Delta L^{\text{sp}}}{\Delta L_0}$; $\Delta L_0, \Delta L^{\text{sp}}$ is the value of the distance measurement error before and after the electron-beam processing of windows respectively; $\Delta L_0 = 10 \text{ m}$ at a distance of $L = 10^3 \text{ m}$).

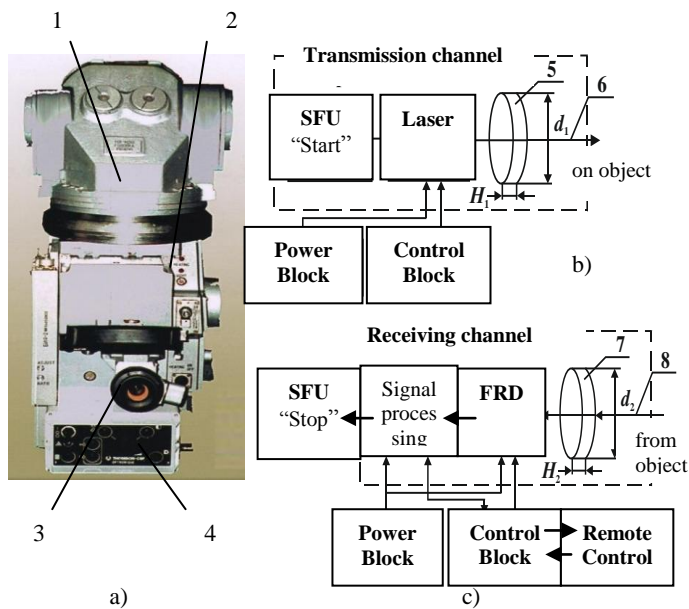


Fig.1 - General view of the sighting complex device (a) and simplified circuits of transmission (b) and reception (c) pulse laser rangefinder channels.

Extending the scope of range measurement by pulse laser rangefinders. To determine the effect of the k_λ , the maximum range was used by the following transcendental equation [3]

$$\overline{L}^2 = \overline{k}_\lambda \cdot e^{-2 \cdot \alpha_a \cdot L_0 \cdot (\overline{L}-1)} \tag{6}$$

where $\overline{L} = \frac{L^{\text{sp}}}{L_0}$ (L_0 – initial range; L^{sp} – range value after electron-beam processing onrof optical glasses (an increase of k_λ)); $\overline{k}_\lambda = \frac{k^{\text{sp}}}{k_0}$ (k_0, k^{sp} is the value of IR radiation transmission coefficient before and after electron-beam processing of windows, respectively); α_a – is attenuation coefficient of laser radiation in the atmosphere, m^{-1} .

Calculations of impulse laser rangefinder of sighting complex, which is equipped with output and input windows of optical glass K8 and BK10, with diameter $d = 3 \cdot 3 \cdot 10^{-2} \text{ m}$ and thickness of $n = 4 \cdot 10^{-3} \text{ m}$ according to the equation (6) were conducted for optical windows processed and unprocessed by electronic beam (heat density of a heat beam $F_n = 2,5 \cdot 10^7 \text{ W/m}^2$ and the speed of its movement $V = 5 \cdot 10^{-2} \text{ m/s}$). Thus, for the meteorological visibility distance $S_M > 10 \cdot L_0$ (the air haze on the object is absent and both the object and its details are clearly perceived ($L_0 = 10^3 \text{ m}$, $S_M = 2 \cdot 10^4 \text{ m}$, $\alpha_a = 0,082$)) [2, 3] The results of the calculations are presented in Fig. 3. The data analysis presented in Fig. 3, shows that with the

increasing IR radiation transmission coefficient k_λ by 4... 5%, magnitude L increases by 7... 10%.

Increase of the reliability of laser medical devices at their functioning. Laser Medical devices during operation are subjected to external thermal actions under the conditions of external thermal influences or using the powerful lasers (heat density more than $10^7 \dots 10^8 \text{ W/m}^2$). This leads to the formation on the end surfaces of lightguides, through which the radiation is inserted from the external laser source of energy of the above mentioned negative defects (cracks, chips, etc.), which lead to a sharp decrease (more than by 3... 4 times) of the IR radiation transmission coefficient, as well as the destruction of the light-emitting diodes, that, ultimately, reduces the reliability of medical devices under their operation in the conditions of intensive external thermal influences.

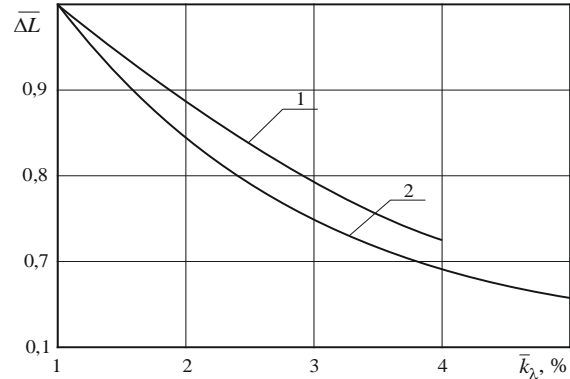


Fig.2 - Dependence of the relative error of distance measurement from relative IR-radiation transmission coefficient by optical windows from optical glass K8 (1) and BK10 (2).

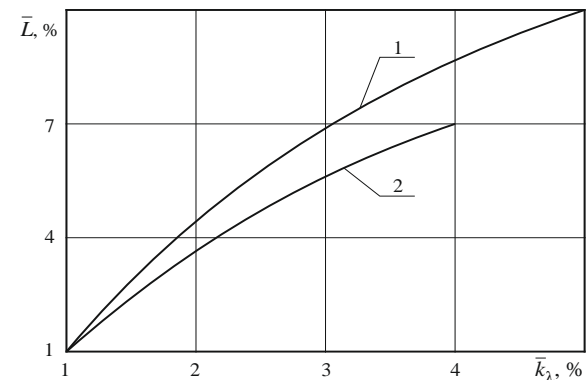


Fig.3 - Dependence of the relative range of pulsed laser rangefinder from relative IR radiation transmission coefficient by optical windows of optical glass (1) and K8 (2).

For experimental research laser therapeutic device was used (Fig. 4a), which consists of control unit of laser therapeutic device (1); remote laser emitter (2).

Fig. 4b presents the input scheme of laser radiation in the lightguide, and Fig. 4c presents the scheme of the finishing thermal processing of the lightguide end surfaces by electronic beam. The diameter of the end surface of the emitter is $D = 7 \cdot 10^{-4} \dots 10^{-3} \text{ m}$, thermal action density of the beam $F_n = 5 \cdot 10^6 \dots 7 \cdot 10^7 \text{ W/m}^2$, its thickness is $2b = 5 \cdot 10^{-4} \dots 8 \cdot 10^{-4} \text{ m}$.

The tests on heating the end surfaces of lightguides of laser therapeutic devices on specialized equipment, that models the internal heating of the optical element surfaces to which the devices are subjected during their operation, showed that in the case of the end surfaces processed by an electronic beam as a result of their resistance increase to the external thermal actions, we observe by a 1,4... 2 times less destruction than for the raw end surfaces of lightguides (table. 1).

Reliability factor as the criterion of performance of laser medical devices at different velocities of external heating is determined by the following formula [12]:

$$W(V_1) = 1 - \frac{N(V_1)}{N_0} \tag{7}$$

where $W(V_1)$ - is the likelihood of maintaining the serviceability of medical devices under conditions of external thermoactions; $N(V_1)$ - is the number of devices that failed at specified heating rates (destruction of end surfaces of lightguides of medical devices were taken for failure of devices as a whole); N_0 - is the total number of lightguides that are subjected to testing.

The results of the studies allowed to establish, that the heating speed increase on the end surfaces of lightguides of medical devices (from 100 K/s to 400 K/s) leads in the case of finish electron-beam processing of these surfaces (under the beam parameters $F_n = 3 \cdot 10^8 \text{ W/m}^2$ $V = 8 \cdot 10^{-3} \text{ m/s}$, which ensure the quartz treatment of the surface of optical elements on the maximum depth (up to 100... 150 nm), that increases their resistance to external thermal loads) to the reliability increase of the specified devices by 10...15% (Fig. 5).

Conducted tests of the semi-spherical fairings in the IR devices on a specialized installation that simulates the supersonic airflow of fairings with the velocity of V_2 to $2 \cdot 10^3 \text{ m/s}$ and their axial-symmetric rotation with angular velocity ω to $4 \cdot 10^3 \text{ rad/s}$ [1], which IR-devices are exposed to during their operation under shot and flight conditions, showed that in the case of the fairings processed by the electron-beam in the areas of the maximum external thermoactions (the most dangerous areas on their surfaces, where fairings are subjected to destructions, as a result of the resistance improvement to external thermal and mechanical actions [1], by 1.7... 2.3 times less destruction is observed than for the raw fairings (table. 2).

The reliability coefficient as the criterion of the IR-device efficiency at supersonic flow is determined by the formula similar to (7).

The results of the studies allowed to determine that the increase of the airflow velocity in the fairings (from $7 \cdot 10^2 \text{ m/s}$ to $2 \cdot 10^3 \text{ m/s}$) in the case of finishing electron beam processing of their surfaces leads (at optimal values of beam parameters $F_n = 5 \cdot 10^8 \text{ W/m}^2$ and $V = 5 \cdot 10^{-3} \text{ m/s}$, which provide maximal increase of surface microhardness in optical elements (up to до $5 \cdot 6 \text{ GPa}$) and the formation of strengthened layers of maximum thickness (up to 200... 250 microns) that significantly increases the resistance of optical elements to external thermoshock influences and mechanical-loads) [15] to the increase of the probability in their non-failure performance by 15... 20 % (Fig. 7).

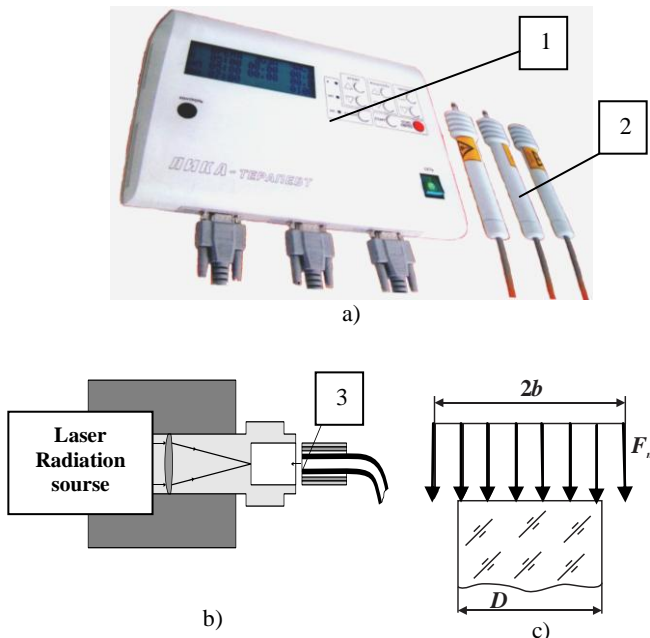


Fig.4 - General view of the laser therapeutic device (a), the introduction scheme of laser radiation in the lightguide (b) and the scheme of the finishing thermal processing of lightguide end surfaces by electronic beam (c): 1 – control Unit of laser therapeutic device; 2 – remote laser emitter; 3 – end surface of fiber optic lightguide.

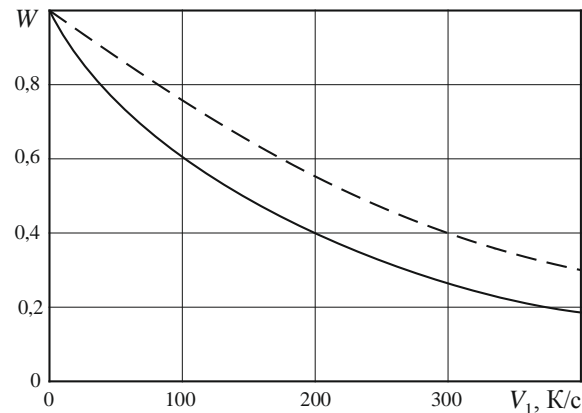


Fig.5 - Probability dependence in the nonfailure operation of laser medical devices from the speed of the external heating in the end surfaces of lighguides from the optical glass K8: end surfaces not processed by an electronic beam (—); end surfaces processed by electronic beam (---).

Table 1
Results of influence of electron-beam processing on end surfaces of laser light therapeutic medical devices on the number of their destruction \bar{k} (%) depending on external heating speed V_1 (K/s)

Lightguide end surface	\bar{k} , %	
	Before electron-beam processing	After electron beam processing
$V_1, \text{K/s}$		
100...200	40...50	20...30
200...300	50...60	30...45
300...400	60...70	45...50

^{*)}Note. Rangefinder from optical glass K8; $\bar{k} = \frac{k}{k_0}$, where k_0 , k is the general number of the tested light guides and the number of light guides which was damaged.

Increased reliability of IR devices for homing and observation under shot and flight conditions. Scheme of a typical IR device of homing and observation with optical fairing, which is subjected to destruction under conditions of shot and flight (central corner of the fairing, where its destruction occurs $\Delta\theta_{max} \approx 4^\circ$ ($\theta_{max} \approx 19...23^\circ$); radius of the external surface of fairing $R_w = 2 \cdot 10^{-2} \text{ m}$; the thickness of the flat layer of a semispherical fairing $H = 4 \cdot 10^{-3} \text{ m}$; maximum density of external thermal influence $(q_w)_{max} = 3 \cdot 10^5...2,5 \cdot 10^6 \text{ W/m}^2$) [1, 4, 5] presented in Fig. 6.

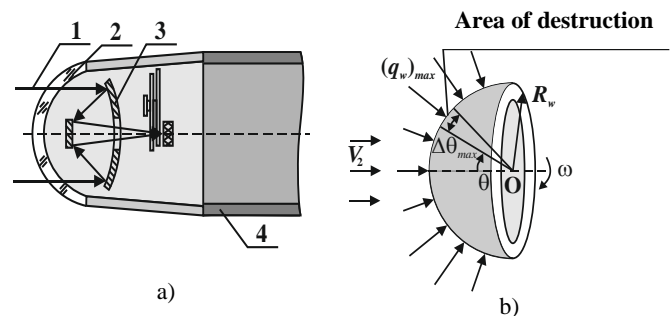


Fig.6 - Scheme of the typical IR devices for homing and observation (a) with optical fairing (b): 1 – input IR radiation from the observed object; 2 – fairing from optical ceramics; 3 – functional scheme of the IR device; 4 – general view of the product.

^{*)} Note. The fairing from optical ceramics KO2; $\bar{n} = \frac{n}{n_0}$, where n_0 , n is the general number of the tested fairings and, respectively, the number which was subjected to destruction; the angular velocity of the ax-symmetrical rotation of the fairings in the observed change rate (to $4 \cdot 10^3 \text{ rad/s}$) does not significantly depend on the number of their destructions.

Table 2

Influence results of electron beam treatment of the semispherical fairings in IR devices for homing and observation to the number of their destructions \bar{n} (%) depending on the airflow velocity V_2 (m/s).

Fairing $V_2, \text{ m/c}$	$\bar{n}, \%$	
	Before electron-beam treatment	After electron-beam treatment
$5 \cdot 10^2 \dots 10^3$	30...40	15...25
$10^3 \dots 1,5 \cdot 10^3$	40...60	25...35
$1,5 \cdot 10^3 \dots 2 \cdot 10^3$	60...80	35...40

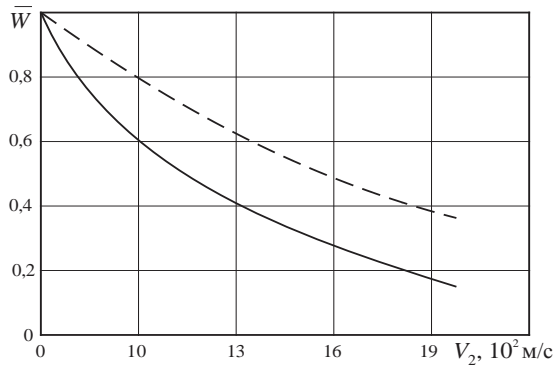


Fig. 7 - Dependence of the reliability of nonfailure performance in IR devices under the conditions of shot and flight from supersonic air flow velocity of their semi-spherical fairings: fairings that are not processed by electronic beam (—), fairings processed by electronic beam (---).

Thus, the finishing electronic-beam processing of working surfaces of the optical windows of laser rangefinders, end surfaces of lightguides of laser therapeutic devices, as well as areas on the optical fairing surfaces of IR devices for homing and observation, where they are subjected to maximum external thermal actions, by increasing the IR radiation transmission coefficient, increasing the resistance of their surface layers to external thermal and mechanical actions will lead to the improvement of technical and operating characteristics of devices and the increase in the probability of their non-failure performance under the conditions of intensive external thermal and mechanical actions.

3. Conclusions

The new method of improvement of technical-operating characteristics in optoelectronic devices was worked out based on the electron-beam processing. This method allows:

- to increase accuracy and extend the range of distance measurements by pulse laser fairings of sighting systems by 7... 15%;
- to increase the probability of nonfailure performance of the optical fairings in the IR devices for homing and observation and for the fiber optical light guides in medical devices at their operation by 10... 20%.

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