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Influence of Nanoparticle Interactions on Their Spatial Distribution in Liquid under a Uniform Light Field

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The article investigates the sedimentation process of interacting nanoparticles in a liquid under the action of light pressure forces. A model is proposed that allows determining the dependence of nanoparticle concentration on the coordinate along which a constant external influence acts, taking into account the interaction forces (attraction and repulsion) between nanoparticles. The study showed that this dependence can significantly differ from the result predicted by the classical model of an ideal gas of nanoparticles. The obtained conclusion is important for developing methods to control the arrangement of nanoparticles in liquids, which is relevant for creating optical techniques for forming thin films and structures.

Keywords: nanosuspension, light pressure, nanoparticle deposition, inhomogeneous concentration, particle interactions.

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Introduction

The problem of forming non-uniform distributions of nanoparticles in liquid suspensions under the action of external fields, including light pressure, is a major challenge for applications in biophotonics, environmental monitoring, and deposition nanotechnology. The range of practical tasks is extremely broad: from targeted drug delivery using magnetic nanoparticles [1] and biofilm formation [2] to the purification of aqueous solutions from polyethylene microparticles [3]. Methods for controlling particle separation, including the use of optical lasers, were reviewed in [4]. Currently, experimental and theoretical studies on the effect of lasers on nanosuspensions are being actively conducted [5–7]. Most authors focus on the horizontal dynamics of particles in laser beams or thermodiffusion [8, 9], while the vertical geometry accounting for gravity has been

insufficiently studied. At the same time, the task of investigating the behavior of nanosuspensions under external influence in a vertically oriented cuvette is quite relevant. In particular, paper [10] considers the possibilities of forming various structures on a substrate, which is the bottom of the cuvette containing the nanosuspension.

Papers [11, 12] analyzed the optical deposition of nanoparticles within the ideal gas model, where the sizes of the nanoparticles and their interactions with each other were neglected. However, it is obvious that the interaction of nanoparticles cannot be neglected at their sufficiently high concentrations. Paper [14] considered the stationary distribution of nanosuspension particles with finite volume in a uniform force field, which corresponds to repulsive forces between nanoparticles.

This paper considers not only the repulsion between suspension nanoparticles, which are

acted upon by an external force (light pressure force), but also their mutual attraction.

As is known (see, for example, [15]), in the equation of state for real dilute gas state, the interaction of gas molecules in the second virial coefficient is described by two parameters a and b , where b “accounts for” the repulsion of molecules, and a – for their attraction. The parameter b is of the order of the molecular volume, while the parameter a is expressed through the integral of the potential energy of pairwise molecular interaction over the distance between molecules with a weight equal to the square of that distance. When considering a real gas with an arbitrary density, these quantities become fitting parameters in an interpolation equation (see, for example, [15, 16]).

A similar approach is applied here (as in [14]) to interacting nanoparticles that are in a liquid in equilibrium.

Indeed, nanoparticles located in a macroscopic volume V , which is small compared to the cuvette volume, can be considered as a quasi-closed and statistically independent subsystem with a variable number of particles. The probability of finding the subsystem in a certain state with an exact number of particles N is determined by the grand canonical distribution [15], which contains the potential energy of the interacting nanoparticles. If this energy can be represented as pairwise, triple, etc., interactions between particles, then the thermal equation of state $P = P(V, T, \bar{N})$ for a sufficiently dilute “gas” of nanoparticles can be written in a virial form, just as for a conventional real gas. In this equation, T is the temperature (we will use energy units), and $\bar{N}$ is the average number of particles. When transitioning to an arbitrary nanoparticle density, the equation of state containing virial coefficients can be replaced by one of the interpolation equations [15, 16] by analogy with a real gas. The most well-known of these equations are the van der Waals equation, the first and second Dieterici equations, and the Berthelot equation [16].

Here we will use the van der Waals equation:

$$\left(P + a \left(\frac{\bar{N}}{V} \right)^2 \right) (V - b\bar{N}) = \bar{N}T, \quad (1)$$

which allows us to determine the relationship between the nanoparticle concentration n and the coordinate z , along which a constant and uniform force F acts on the nanoparticles.

Problem Formulation and Main Results

Let N nanoparticles be placed in a cuvette containing a liquid. Its volume is equal to Sh (S is the base area, h is the height). Initially, the nanofluid is homogeneous, with nanoparticle concentration equal to $\tilde{n} = N / Sh$. At some point in time, constant external force $\mathbf{F} = (0, 0, -F)$ begins to act on each nanoparticle. This force is directed antiparallel to the $\bar{z}$ axis of the Cartesian coordinate system, with plane $\bar{z} = 0$ corresponding to the cuvette base. Following the activation of the external force, the nanoparticle concentration begins to change, and thermodynamic equilibrium is established after a sufficiently long (theoretically infinite) time interval. Moreover, for a nanofluid located in a thin layer $Sd\bar{z}$, where it can be considered homogeneous, the equation of state (1) holds if we replace V with $Sd\bar{z}$ and $\bar{N}$ with dN . Then, denoting $n = dN / Sd\bar{z}$ as the nanoparticle concentration in the cross-section of the nanofluid at coordinate $\bar{z}$, we rewrite (1) as

$$P = \frac{nT}{(1-bn)} - an^2.$$

Considering that $T = \text{const}$, we obtain

$$dP = T \frac{dn}{(1-bn)^2} - 2andn. \quad (2)$$

Let us introduce the following notations $z = \bar{z} / h$, $x(z) = bn(z)$, $x_0 = x(0)$, $x_1 = x(1)$, $\tilde{x} = b\tilde{n}$. Hereinafter, $\tilde{n}$ is the average concentration of nanoparticles in the cuvette.

After substituting (2) into the expression

$$dP = -nFhdz,$$

we obtain

$$\frac{dx}{x(1-x)^2} - \frac{2a}{bT} dx = -\frac{Fh}{T} dz.$$

Integrating this expression from arbitrary value x to x_1 on the left-hand side and from an

arbitrary z to unity on the right-hand side, after straightforward transformations, we arrive at equation:

$$z = 1 + \frac{1}{q} \left\{ \frac{1}{1-x_1} - \frac{1}{1-x} + \ln \left| \frac{1-x}{1-x_1} \right| + \ln \frac{x_1}{x} + \frac{2a}{Tb} (x-x_1) \right\}, \quad (3)$$

where $q = Fh/T$ is dimensionless parameter.

If we set both a and b equal to zero in (3), we obtain the Boltzmann formula (for an ideal gas concentration), which can be written as:

$$\frac{1}{q} \ln \left(\frac{n_0}{n} \right) = z. \quad (4)$$

After substituting $z = 0$ into (3), we obtain the relations between x_0 and x_1 :

$$1 = \frac{1}{q} \left\{ \frac{1}{1-x_0} - \frac{1}{1-x_1} + \ln \left| \frac{1-x_1}{1-x_0} \right| + \ln \frac{x_0}{x_1} - \frac{2a}{Tb} (x_0-x_1) \right\}. \quad (5)$$

To determine the concentrations of particles at $z = 0$ and $z = 1$ in terms of a , b and q , we use the relation

$$Shd(zn(z)) = Shn(z)dz + Shzdn.$$

Integrating this expression over z from 0 to 1, and over n from $n_0 = n(0)$ to $n_1 = n(1)$, and considering that $N = Sh \int_0^1 n(z) dz$, we obtain

$$\bar{x} = x_1 - \int_{x_0}^{x_1} z dx. \quad (6)$$

Substituting expression (3) into (6) and evaluating the integrals over x , we obtain the equality.

$$\bar{x} = x_1 - \frac{1}{q} \left[\frac{x_1-x_0}{1-x_0} + x_1 \ln \frac{x_0(1-x_1)}{x_1(1-x_0)} + \frac{a}{Tb} (x_0-x_1)^2 \right]$$

or (after cancelling b)

$$\bar{n} = n_1 - \frac{1}{q} \left[\frac{n_1-n_0}{1-bn_0} + n_1 \ln \frac{n_0(1-bn_1)}{n_1(1-bn_0)} + \frac{a}{T} (n_0-n_1)^2 \right]. \quad (7)$$

From (7) and (5), at $a = 0$, it is easy to express n_0 and n_1 in terms of $\bar{n}$, as was done in [14]:

$$n_0 = \frac{q\bar{n}}{1+bq\bar{n} - \exp[-q(1-b\bar{n})]} \quad (8)$$

and

$$n_1 = \frac{q\bar{n} \exp[-q(1-b\bar{n})]}{1+(bq\bar{n}-1)\exp[-q(1-b\bar{n})]}. \quad (9)$$

However, obtaining analytical expressions for $a \neq 0$ analogous to (8) and (9) appears to be impossible. Therefore, in this work, we will investigate the effect of nanoparticle attraction, i.e., the parameter a , on their equilibrium distribution graphically, using expression (3). We assume that at $z = 1$, the attraction between nanoparticles can be neglected, and consequently, the value of n_1 is determined by formula (9).

Analysis of the Results

For a graphical study of expression (3) at a finite value of parameter a , we introduce the following dimensionless quantities: $y = n/\bar{n}$, $y_1 = n_1/\bar{n}$, $y_0 = n_0/\bar{n}$, $g = \bar{n}b$, $k = 2a\bar{n}/T$.

Then (3) can be written in the following form:

$$z = 1 + \frac{1}{q} \left\{ \frac{1}{1-gy_1} - \frac{1}{1-gy} + \ln \left| \frac{1-gy}{1-gy_1} \right| + \ln \frac{y_1}{y} + k(y-y_1) \right\}, \quad (10)$$

that is, the concentration dependence on depth will be determined by three parameters: q , g , k .

In the new notation, relation (9) takes the form:

$$y_1 = \frac{q \exp[-q(1-g)]}{1+(gq-1)\exp[-q(1-g)]}. \quad (11)$$

It was shown in [14] that the dependence $z = z(y)$ (or $y = y(z)$) differs significantly from the

case when $b = 0$ for $q = 10^7$ and $g = 10^{-5}$; therefore, it is reasonable to consider the effect of attraction between nanoparticles for the same values of q and g .

Figure 1 shows dependencies $z = z(y)$ at $y \in (1, y_0)$, when $q = 10^7$, $g = 10^{-5}$, while parameter k takes the values 0; 0.0001; 0.0002; 0.0003; 0.0004; 0.0005.

The curve corresponding to $k = 0$ coincides with the curve obtained in [14].

From the obtained curves, it can be seen that a relative concentration of particles with an extremely large gradient is created in a very thin

layer near the cuvette bottom. With a increasing, the downward migration of particles intensifies, and the curves reach a greater maximum at a longer distance from the cuvette bottom.

Figure 2 shows the same dependencies $z = z(y)$, as in Figure 1, but at $y \in [y_0, 99334, 51654]$. Analysis of the results shows that, with a increasing, the concentration of nanoparticles at the cuvette bottom increases (the authors do not show the functions $z = z(y)$ for negative z , which have no physical meaning in the chosen formulation of the problem).

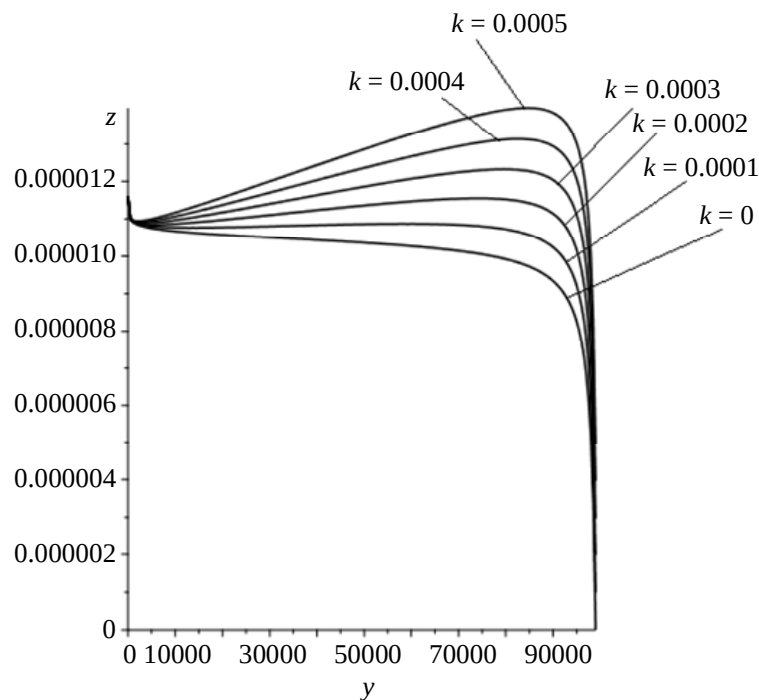


Fig. 1. Functions $z = z(y)$ at $g = 10^{-5}$ and $q = 10^7$, $y \in (1, y_0)$

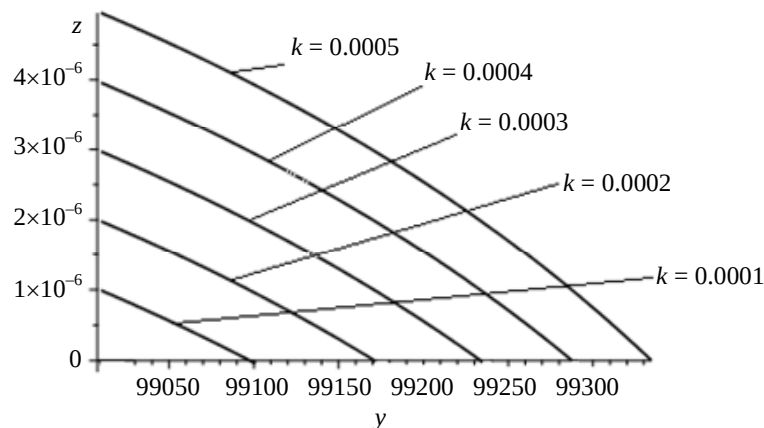


Fig. 2. Functions $z = z(y)$ at $g = 10^{-5}$ and $q = 10^7$, $y \in (y_0, 99334, 51654)$

Figure 3 shows the derivative $dz/dy = u(y)$ (multiplied by 10^9) at $k = 0.0000675$. The equation $u(y) = 0$ has two multiple real roots (in the region of non-negative z) equal to 33333.3333. Consequently, for such a value of k , the function $z = z(y)$ has an inflection point (Fig. 4).

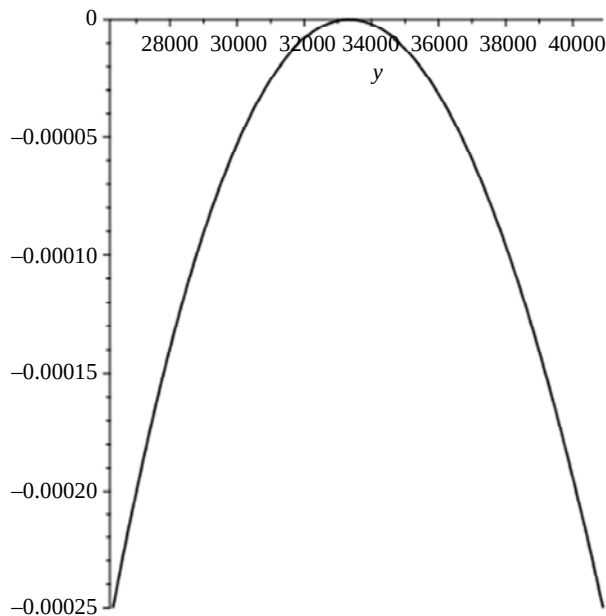


Fig. 3. Functions $u = u(y)$ at $k = 0.0000675$, $g = 10^{-5}$ and $q = 10^7$

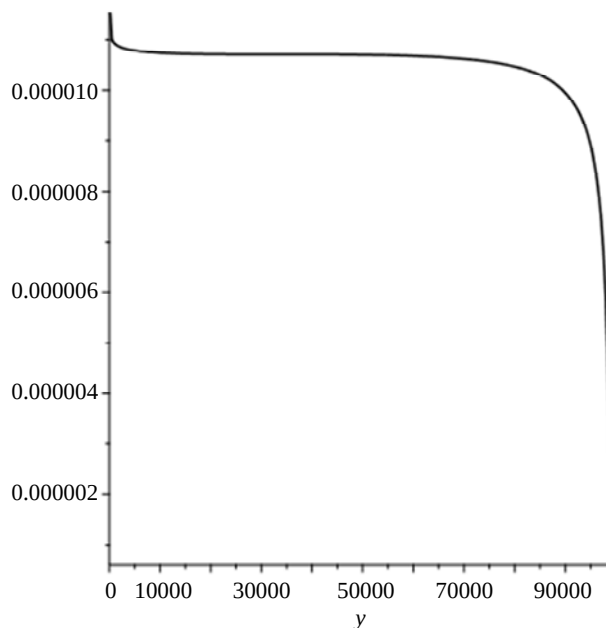


Fig. 4. Functions $z = z(y)$ at $g = 10^{-5}$ and $q = 10^7$, $k = 0.0000675$, $y \in (1, y_0)$

If, for the chosen values of q and g , the parameter k exceeds 0.0000675, then the equation $u = 0$ will have two distinct roots, with the

smaller root corresponding to the minimum of the function $z(y)$, and the larger root to its maximum. Figure 5 shows the functions z and u (for clarity, the latter is multiplied by 10^9) for $k = 0.0000676$. In this figure, the function $z = z(y)$ is shown as a horizontal segment; in reality, this is an illusion. It is simply that $z(y_{\max}) - z(y_{\min}) \ll 0.00001$.

Thus, we find that for sufficiently large q , and starting from certain values of k , the function $y = y(z)$ (the inverse of $z = z(y)$) becomes multivalued over some intervals of the coordinate z . Physically, this may correspond to different “phases” of the nanosuspension, by analogy with the van der Waals gas.

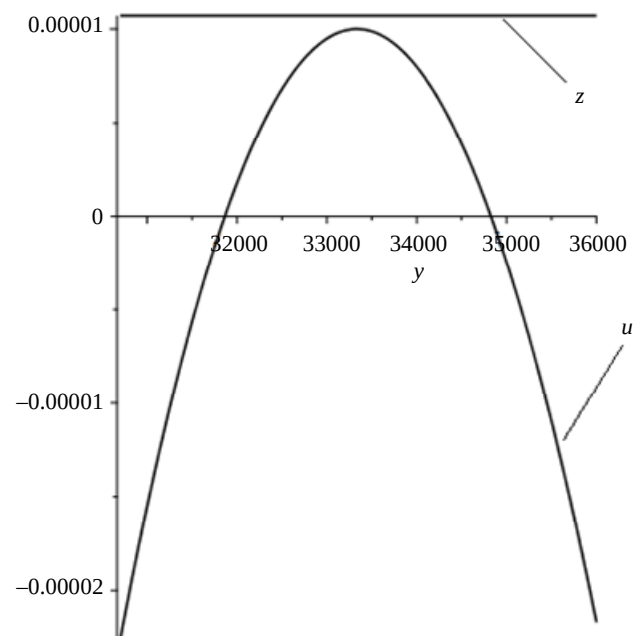


Fig. 5. Functions $z = z(y)$ and $u = u(y)$ at $g = 10^{-5}$ and $q = 10^7$, $k = 0.0000675$, $y \in (26302.32..40899.1)$

Conclusion

The problem of nanoparticle deposition in a liquid under external impact is of significant scientific interest due to a wide range of practical applications. The results obtained show that taking into account nanoparticle interactions fundamentally changes the pattern of their distribution in the liquid. Based on the performed studies, it can be expected that in a nonuniform suspension of interacting nanoparticles subjected to intense laser radiation, spatial regions may exist in which different phases of the suspension coexist, similar to the different phases of the van der Waals gas.

Moreover, it offers a possibility of the targeted formation of layers with increased particle concentration under laser irradiation. The obtained expressions (3) and (10) show that it is possible to control nanoparticles in a liquid to form thin-film structures, which is of interest for the development of optical methods for particle manipulation, as well as for methods of nonlinear optics and diagnostics of liquid-phase media.

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REFERENCES

1. Mayorova O. A., Gusliakova O. I., Prikhozhenko E. S., Verkhovskii R. A., and Bratashov D. N., *Pharmaceutics* **15** (1), 214 (2023). <https://doi.org/10.3390/pharmaceutics15010214>.
2. Camba C., Walter-Lakes B., Digal P., Taheri-Araghi S., and Bezryadina A., *Biomedical Optics Express* **15** (2), 1181–1191 (2024). <https://doi.org/10.1364/BOE.510836>.
3. Filinkova M. S., Bakhteeva Yu. A., Medvedeva I. V., et al., *Kolloidnyy zhurnal* **86** (6), 824–837 (2024). <https://doi.org/10.31857/S0023291224060146> [in Russian].
4. Evstrapov A. A., *Nauchnoe priborostroenie* **15** (1), 3–20 (2005) [in Russian].
5. Afanas'ev A. A., Novitsky D. V., and Rubinov A. N., *Nonlinear Phenomena in Complex Systems* **20** (2), 194–198 (2017).
6. Huang H., Xu Y., Luo G., Xie Z., and Ming W., *Nanomaterials* **12**, 1524 (2022). <https://doi.org/10.3390/nano12091524>.
7. Bunkin A. F., Mikhalevich V. G., Oshurko V. B., and Strel'tsov V. N., *Physics of Wave Phenomena* **33** (6), 458–462 (2025). <https://doi.org/10.3103/S1541308X25700360>.
8. Ta V., Carter R., Esenturk E., Connaughton C., Wasley T., Li J., Kay R., Stringer J., Smith P., and Shephard J., *Soft Matter*, No. 12, 4530–4536 (2016). <https://doi.org/10.1039/c6sm00465b>.
9. Pin C., Fujiwara H., and Sasaki K., *Journal of Photochemistry and Photobiology C: Photochemistry Reviews* **52**, 100534 (2022). <https://doi.org/10.1016/j.jphotochemrev.2022.100534>.
10. Egoershin I. N. and Ivanov V. I., *Fiziko-khimicheskie aspekty izucheniya klasterov, nanostruktur i nanomaterialov*, No. 17, 52–58 (2025). <https://doi.org/10.26456/pcascnn/2025.17.052> [in Russian].
11. Dühr S. and Braun D., *Applied Physics Letters* **86**, 131921 (2005). <https://doi.org/10.1063/1.1888036>.
12. Ivanov V. I. and Pyachin S. A., *Fiziko-khimicheskie aspekty izucheniya klasterov, nanostruktur i nanomaterialov*, No. 13, 146–155 (2021). <https://doi.org/10.26456/pcascnn/2025.17.052> [in Russian].
13. Ivanov V. I., Ivanova G. D., Krylov V. I., and Khe V. K., *Fiziko-khimicheskie aspekty izucheniya klasterov, nanostruktur i nanomaterialov*, No. 10, 286–290 (2018). <https://doi.org/10.26456/pcascnn/2018.10.286> [in Russian].
14. Krylov V. I., Ivanova G. D., and Egorshin I. N., *Applied Physics*, No. 3, 11–16 (2020) [in Russian].
15. Landau L. D. and Lifshitz E. M. *Statistical physics*. Moscow, Nauka, 1964 [in Russian].
16. Bazarov I. P. *Thermodynamics*. Moscow, Vysshaya shkola, 1991 [in Russian].

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Cherenkov X-ray radiation in the area of the water transparency window with broken azimuthal symmetry

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The features of Cherenkov and parametric radiation in the X-ray frequency range in the spectral range of the “Water Transparency Window” during the passage of relativistic particles through an isolated target and a regular stack of plates are analyzed and established. Numerical calculations of the output of polarized radiation have been performed for electrons with an energy of 10 MeV and a titanium target. The principal possibility of applying the effect to create innovative quasi-monochromatic directional sources of polarized X-ray radiation with high angular density is shown.

Keywords: cherenkov radiation, transient radiation, X-ray radiation, titanium, vanadium, water transparency window.

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Introduction

The study of phenomena related to Vavilov-Cherenkov radiation and transition radiation arising from the motion of accelerated relativistic particles through various materials has traditionally been a promising direction for the development of innovative detectors and radiation sources in various regions of the electromagnetic spectrum. Recent advances and prospects in this field are presented, in particular, in the recent review article [1].

As was shown in [2], the dielectric permittivity of certain substances near the edges of K- and L-absorption lines can exceed unity. This creates conditions for the occurrence of Cherenkov radiation in the X-ray frequency range. A theoretical analysis of the possibility of X-ray Cherenkov radiation in various materials was carried out in [3]. A discussion of the possible generation of X-ray Cherenkov radiation by ultrarelativistic electrons in carbon was first conducted in the experiments [4]. Paper [5]

reports the observation of X-ray Cherenkov radiation from electrons with an energy of 5 MeV in silicon near the L-absorption line edge at 99.7 eV. The authors of [6] detected the Cherenkov radiation from relativistic electrons with an energy $E = 10$ MeV in titanium and vanadium targets with a thickness of 10 μm at photon energies of 453 eV and 512 eV, respectively, at the normal incidence of particles on the target surface. The recorded photon yield per electron was 3.5×10^{-4} for the titanium target and 4.3×10^{-4} for the vanadium target, respectively. The region of the electromagnetic spectrum in the frequency range from 300 to 500 eV is of particular interest. Water is transparent in this spectral range (the so-called water window), but carbon and its organic compounds are not. The quasi-monochromatic Cherenkov radiation in this spectral region can be used to create X-ray microscopes for imaging biological tissue structures [7]. In this regard, the measurement results of [6] are of particular interest.

According to the data in [8], the maximum values of the real and imaginary parts of the dielectric permittivity in titanium are reached at a quantum energy of 454 eV, and the region where $\varepsilon' > 1$ is approximately 5 eV wide. At a quantum energy of 454 eV, $\varepsilon' = 1.007$ and $\varepsilon'' = 0.006$. It is easy to estimate that the threshold for the occurrence of the X-ray Cherenkov radiation with quantum energies near the L-absorption edge, for example in titanium, is reached a Lorentz factor $\gamma > 12$, which corresponds to an electron energy $E > 6$ MeV. The Cherenkov radiation angle relative to the electron velocity vector for electrons with the 10 MeV energy and a photon energy of 454 eV is $\theta_c \approx 3.78^\circ$. For relativistic electrons entering the target perpendicularly to the surface, the radiation is polarized in the plane of the wave vector and the normal to the surface (longitudinal polarization). For the oblique incidence of particles on the target, a radiation component polarized in the plane orthogonal to the radiation plane (transverse polarization) appears due to the breaking of azimuthal symmetry, and the angular distribution of radiation becomes asymmetric. The features of transition radiation and Cherenkov radiation for the oblique incidence of particles on the target were investigated in a number of monographs [9, 10], as well as in papers [11–17]. As shown in [11, 12], for oblique incidence, the intensity of the longitudinally polarized wave increases, while the width of the angular distribution decreases. In addition, azimuthal oscillations arise due to the interference of waves reflected from the front and rear surfaces of the target [13]. The method of polarization currents was used in [14] to study the spectral-angular distribution and polarization properties of the so-called X-ray "hybrid" radiation, i.e., under conditions where the interference between Cherenkov and transition radiation is significant.

Given below is an the analysis of Cherenkov radiation in the spectral region of the water transparency window for relativistic electrons entering a titanium target, as well as a regular stack of titanium plates under the conditions of the experiments cited above [6].

Spectral-Angular Distribution

One of the methods for solving the problem in this formulation is to match the normal and

tangential components of the fields at the interfaces. A general solution to such a problem is given in [10, 16]. However, it is possible to solve such problems without resorting to direct field matching. For this purpose, one can use the well-known result that the Fourier component of the field of a moving particle is equivalent to the field of summed stationary dipoles located along the particle trajectory. This approach was effectively used in [17] (the so-called "image method") for solving a number of problems on radiation from charged particles in a medium. Following that approach, we will represent the angular distribution of radiation in terms of direction cosines $\cos\theta_x$ and $\cos\theta_y$ (orthogonal axes x and y lie in the plane of the target surface, and the z -axis is directed along the normal to the surface). In contrast to the variables θ and φ (where θ and φ are the polar and azimuthal angles, respectively), this provides greater clarity. We assume that the front and rear surfaces of the target are parallel and have no roughness, and that the particle velocity is constant.

Analytical formulas for the spectral-angular density of radiation with longitudinal $dI^\parallel(\mathbf{k}, \omega) = I^\parallel(\mathbf{k}, \omega) d\omega d\Omega$ and transverse polarization $dI^\perp(\mathbf{k}, \omega) = I^\perp(\mathbf{k}, \omega) d\omega d\Omega$ in the frequency range $\omega, \omega + d\omega$ and the solid angle $d\Omega$ oriented in the direction of particle motion in a target of thickness L with a complex dielectric permittivity are given in [17] (formulas 18.25 and 18.26) and are rather cumbersome. However, more compact asymptotic formulas can be used for analyzing the radiation yield under the conditions of the above-cited experiments [6].

Indeed, such factors as the finite target thickness, a sufficiently large value of the imaginary part of the dielectric permittivity, and a relatively small difference of the real part from unity will lead to some features in the angular distribution of the resulting radiation when azimuthal symmetry is broken. First of all, we note that Cherenkov radiation is summed coherently along the entire trajectory in a transparent medium. When the imaginary part of the dielectric permittivity is equal to zero and the threshold condition is satisfied, this leads to the obvious divergence of the corresponding formulas. On the other hand, existence of absorption leads to the fact that the trajectory length, over which the radiation summation

occurs, becomes finite. This length can be easily estimated from relation $L_c \approx c / \omega \epsilon$ (see, e.g., [10]), from which we obtain the estimate of $L_c / \lambda \approx 1 / \epsilon'' \approx 166$ (λ is the radiation wavelength). Under the conditions of the experiments cited above, the thickness of the titanium target used is $10 \mu\text{m}$, so $L / \lambda \approx 3500$, which is much larger than length L_c (if the

wavelength is 0.28 nm , then $L_c \approx 0.5 \mu\text{m}$). Consequently, the wave reflected from the front surface in the direction of the rear surface will be strongly suppressed. Therefore, one can use the asymptotics of formulas (18.25) and (18.26) from [17] as $L / \lambda \rightarrow \infty$ for calculations of radiation intensity. We have the following for the spectral-angular density of radiation for the longitudinal polarization component:

$$I^{\parallel}(\mathbf{n}, \omega) = \frac{\beta_z^2 \cos^2 \theta_z |1 - \epsilon|^2}{\left[(1 - \beta_x \cos \theta_x)^2 - \beta_z^2 \cos^2 \theta_z \right]^2 \sin^2 \theta_z} \times \left| \frac{(1 - \beta_z \sqrt{\epsilon - \sin^2 \theta_z} - \beta_z^2 - \beta_x \cos \theta_x) \sin^2 \theta_z + \beta_x \beta_z \cos \theta_x \sqrt{\epsilon - \sin^2 \theta_z}}{(1 - \beta_x \cos \theta_x - \beta_z \sqrt{\epsilon - \sin^2 \theta_z})(\sqrt{\epsilon - \sin^2 \theta_z} + \epsilon \cos \theta_x)} \right|^2. \quad (1)$$

The spectral-angular density of radiation perpendicular to the radiation plane is determined for the component with polarization by formula:

$$I^{\perp}(\mathbf{n}, \omega) = \frac{\beta_x^2 \beta_z^4 \cos^2 \theta_y \cos^2 \theta_z |1 - \epsilon|^2}{\left[(1 - \beta_x \cos \theta_x)^2 - \beta_z^2 \cos^2 \theta_z \right]^2 \sin^2 \theta_z} \times \left| \left(1 - \beta_x \cos \theta_x - \beta_z \sqrt{\epsilon - \sin^2 \theta_z} \right) \left(\sqrt{\epsilon - \sin^2 \theta_z} + \cos \theta_x \right) \right|^{-2}. \quad (2)$$

The direction of the electron velocity forms an angle ψ with the normal to the target surface, such that $\beta_x = \beta \sin \psi$, $\beta_z = \beta \cos \psi$, $\beta = v / c$. The direction of radiation is determined by the direction cosines relative to the coordinate axes (z -axis coincides with the normal to the surface): $\cos \theta_x = \sin \theta \cos \varphi$, $\cos \theta_y = \sin \theta \sin \varphi$, $\cos \theta_z = \cos \theta$. The dimensionless spectral-angular density of radiation intensity in formulas (1) and (2) is expressed in units of $Z^2 e^2 / \pi^2 c$ (Ze is the particle charge).

Fig. 1 shows calculations of the angular distribution of polarized radiation from electrons with an energy of 10 MeV in a titanium target of $10 \mu\text{m}$ thickness near the L -absorption edge (454 eV) at incidence angles of 50° and 70° , respectively. The vertical line marks the

direction cosines of the particle incidence angle ψ relative to the surface normal. Fig. 2 presents the results of calculations of the angular distribution of radiation at zero azimuthal angle. Two maxima corresponding to the Cherenkov radiation cone are clearly visible. As follows from the performed calculations, the intensity of the longitudinally polarized wave increases with an increasing particle incidence angle into the crystal, while the angular width of the maximum decreases. At an incidence angle into the titanium target of 70° , the radiation yield at the maximum can exceed the yield at normal incidence by approximately a factor of twenty. Given the measurement results [6], this would amount to approximately 7×10^{-3} photons per electron.

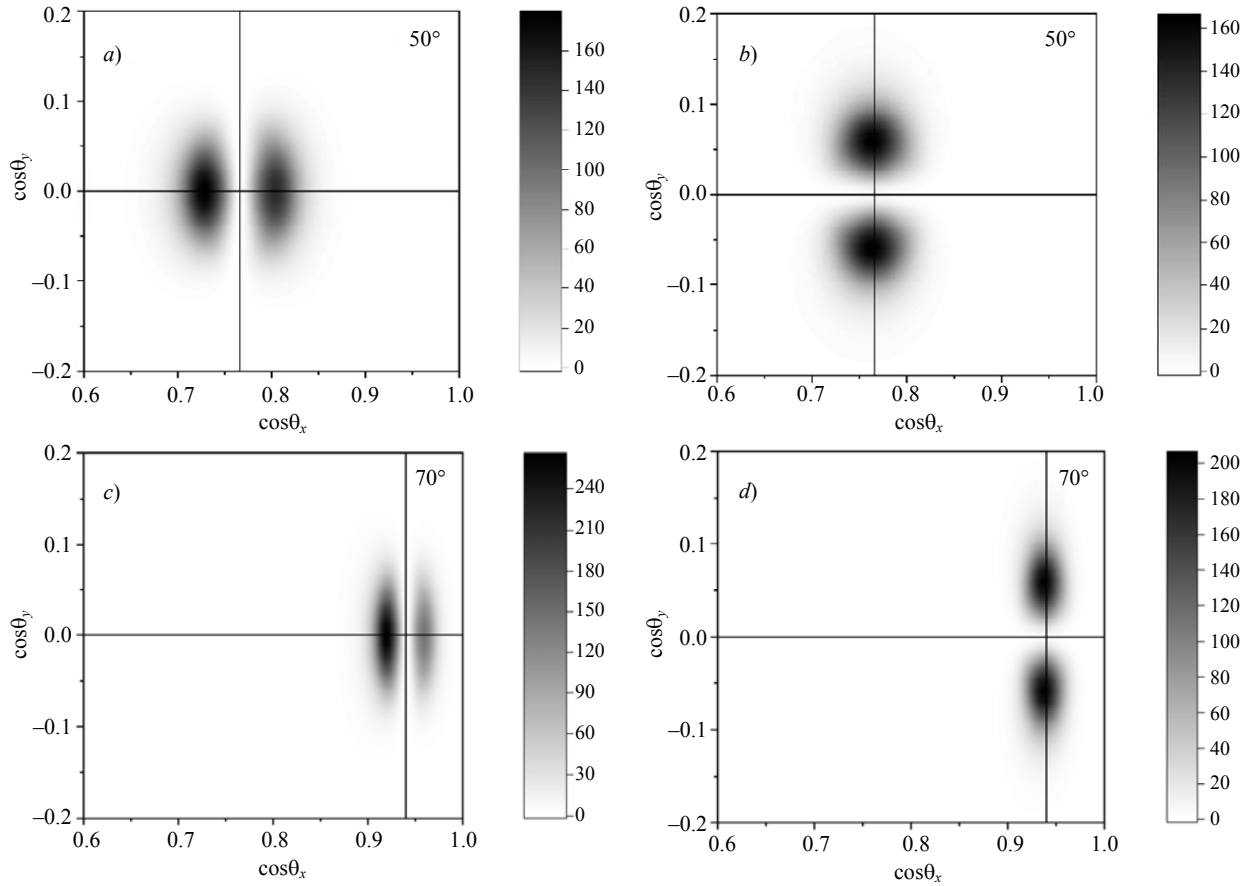


Fig. 1. Calculated angular distribution of the longitudinally polarized (a, c) and transversely polarized (b, d) components of Cherenkov radiation from relativistic electrons with the 10 MeV energy in the X-ray frequency range ($\omega = 454$ eV) in the titanium target at different particle incidence angles: (a, b) – $\psi = 50^\circ$, (c, d) – $\psi = 70^\circ$

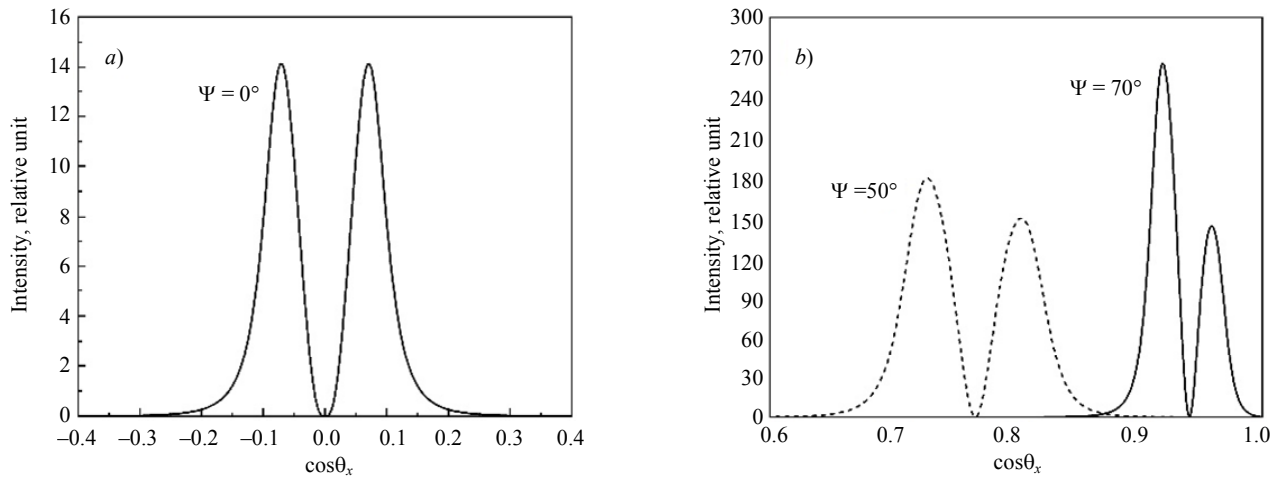


Fig. 2. Calculated angular distribution in the polar angle in the plane of Cherenkov radiation (azimuthal angle $\psi = 0$) with longitudinal polarization for relativistic electrons with the 10 MeV energy in the X-ray frequency range ($\omega = 454$ eV) in the titanium target at different particle incidence angles.

Parametric X-Ray Radiation

When relativistic electrons pass through a regular stack of plates, along with the well-known Cherenkov and transition radiation, the so-called resonant parametric (or structural) Cherenkov radiation arises. The intensity of the resonant

parametric radiation can, in some cases, exceed the radiation intensity of an isolated target by many times. Under ideal conditions with no absorption, the intensity at the parametric maxima of the angular distribution is proportional to the square of the number of plates, N , and their angular width is proportional to $1/N$. In this case,

the position of the maxima in the angular distribution can be determined from kinematic relations [10]. In particular, if the conditions $|\varepsilon - 1| \ll 1$ and $L \ll d$ are satisfied, where d is the distance between the plates, then the angular position of the parametric maxima is determined by a well-known relation $\cos \theta_n \approx 1 / \sqrt{\varepsilon' \beta + 2\pi n c / \omega d}$, where $n = \pm 1, \pm 2 \dots$. As was noted in the previous section, the existence of absorption leads to the fact that the trajectory length of the particle in the target over which coherent summation of radiation occurs becomes finite, and under the conditions chosen above, it does not exceed $0.5 \mu\text{m}$ according to estimates. If in an isolated target this results in radiation being formed in a thin layer near the rear surface, then in a regular stack of thin plates ($L < 0.5 \mu\text{m}$) this may limit the number of plates whose radiation will be summed up coherently. In this case, the position of the maxima in the angular distribution, their width, and intensity will not be determined by simple kinematic relations, but can only be found by numerical calculation of the spectral-angular characteristics of the radiation [9]. In this section, we consider the X-ray parametric radiation in the water window range from relativistic electrons with an energy of 10 MeV that pass through several identical titanium plates regularly spaced in a vacuum and placed parallel to each other.

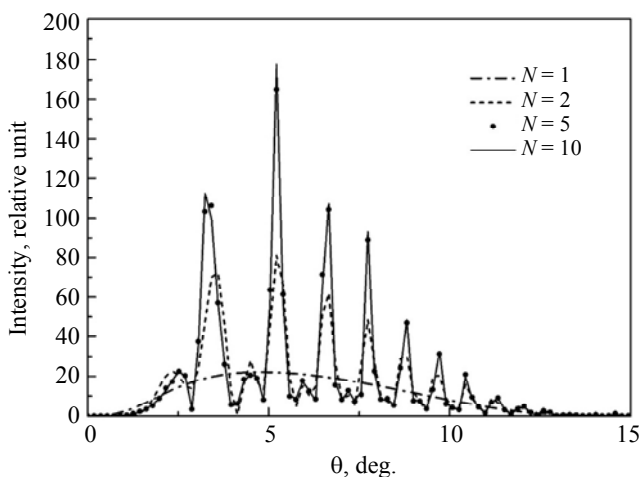


Fig. 3. The calculated angular distribution of parametric radiation from relativistic electrons with an energy of 10 MeV in the X-ray frequency range ($\omega = 454 \text{ eV}$) in a target consisting of a regular stack of N titanium plates of $0.1 \mu\text{m}$ thickness and a $1 \mu\text{m}$ vacuum gap between the plates

For calculations of the parametric X-ray radiation yield, we use the well-known result from [9], which applies recurrent relations expressing the fields in a given vacuum gap through the fields in the previous gap. The resulting exact expressions are rather cumbersome (see formula (3.1) in [9]) and will not be presented here. Fig. 3 shows the results of calculations of the angular distribution of parametric radiation from electrons at the normal incidence of 10 MeV relativistic electrons on the stack of thin titanium plates. As before, the intensity is expressed in dimensionless units of $Z^2 e^2 / \pi^2 c$. Due to the constructive interference of radiation when the particle passes through different plates, the angular distribution has a number of additional parametric maxima as compared to the analogous distribution for a single plate. Unlike the oblique incidence on an isolated target, the angular width of these radiation maxima is significantly smaller. Analysis of the calculation results shows that, as noted above, the existence of absorption leads to the fact that radiation from the regular stack of thin (no more than $0.5 \mu\text{m}$) titanium plates is formed mainly in the last few plates. Therefore, it is impossible to achieve an increase in the radiation yield by more than a factor of ten by increasing the number of plates, as shown by the calculation results in Fig. 3: namely, starting from $N = 5$, the radiation yield practically does not change.

Conclusion

The performed analysis and the established features of the Cherenkov and parametric radiation in the X-ray frequency range may be useful in the design of radiation sources and demonstrate the fundamental feasibility of using the effect to create quasi-monochromatic directional sources of polarized X-ray radiation in the spectral range of the water transparency window.

REFERENCES

1. Ruoxi Chen, Zheng Gong, Jialin Chen, et al., *Materials Today Electronics* **3**, 100025 (2023). <https://doi.org/10.1016/j.mtelec.2023.100025>
2. Bazylev V. A., Glebov V. I., Denisov E. I., et al., *Letters to the JETF* **24**, 406 (1976).
3. Gary C., Kaplin V., Kubankin A., et al., *Nucl. Instrum. Methods Phys. Res., Sect. B* **227**, 95 (2005). <https://doi.org/10.1016/j.nimb.2004.06.015>
4. Bazylev V. A., Glebov V. I., Denisov E. I. et al., *Letters to the JETF* **34**, 103 (1981).
5. Knulst W., Luiten O. J., and van der Wiel M. J., *Applied Physics Letters* **79** (18), 2999 (2001). <https://doi.org/10.1063/1.1415049>.
6. Knulst W., van der Wiel M. J., Luiten O. J., and Verhoeven J., *Applied Physics Letters* **32** (19), 4050200 (2003). <https://doi.org/10.1063/1.1625999>.
7. Johansson G. A., Holmberg A., Hertz H. M., and Berglund M., *Review of Science Instruments* **73** (3), 1193 (2002). <https://doi.org/10.1063/1.1445870>.
8. Henke B. L., Gullikson E. M., and Davis J. C., *Atomic Data and Nuclear Data Tables* **54** (2), 181–342 (1993).
9. Gharibyan G. M. and Yang Shi. X-ray transient radiation. Yerevan: Publishing House of the Academy of Sciences of the Armenian SSR, 1983.
10. Ter-Mikaelian M. L. The influence of the environment on electromagnetic processes at high energies. Yerevan: Publishing House of the Academy of Sciences of the Armenian SSR, 1969.
11. Bulgakova M. V., Malyshevsky V. S., and Fomin G. V., *Surface. X-ray, synchrotron, and neutron studies*, № 3, 89 (2022). <https://doi.org/10.1134/S1027451022020070>.
12. Kubankin A., Nasonov N., Kaplin V., Uglov S., Piestrup M., and Gary C., *Radiation Physics and Chemistry* **75**, 913 (2006). <https://doi.org/10.1016/j.radphyschem.2005.12.016>.
13. Bulgakova M. V., Malyshevsky V. S., and Fomin G. V., *Journal of Surface Investigation: X-ray, Synchrotron and Neutron Techniques* **17** (1), S409 (2023). <https://doi.org/10.1134/S1027451023070054>.
14. Shevelev M., Konkov A., and Alekseev B., *Nuclear Inst. and Methods in Physics Research B* **464**, 117 (2020). <https://doi.org/10.1016/j.nimb.2019.12.010>
15. Potylitsyn A. P. and Gogolev S. Y., *Letters to ECHAYA* **16** (2 (221)), 147 (2019).
16. Yeginbaryan V. A. and Khachatryan B. V., *Izv AN Arm. SSR, physics* **1**, 11 (1966).
17. Paphomov V. E., *Proceedings of the Order of Lenin of the Physical Institute of the USSR Academy of Sciences* **44**, 28 (1969).

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On-board optical television system for underwater vision across the air-sea interface

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This article examines the feasibility of developing an airborne optical television underwater vision system for detecting and recognizing underwater objects across the air-sea interface from a helicopter. The article analyzes the physical mechanisms of optical radiation attenuation in seawater, including absorption and scattering, as well as the influence of phytoplankton, organic, and inorganic impurities on the transparency of the aquatic environment. Passive and active-pulse optical television underwater vision systems are considered, substantiating the advantages of the active-pulse method, which reduces the influence of backscatter and increases the range and contrast of observation. The key elements of the system are described: a photodetector module based on a III+ generation image intensifier with a "blue" photocathode and a pulsed Nd:YAG laser. It is concluded that active-pulse optical television systems offer potential for obtaining high-quality visual information about underwater objects and expanding the capabilities of search and rescue operations.

Keywords: underwater vision, optical television system, active-pulse method, laser illumination, III+ generation image intensifier tube.

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Introduction

Recently, obtaining information about underwater objects has become increasingly important not only for their detection and localization, but also for their recognition and identification using images of these objects. In particular, such tasks arise when using special equipment installed on an aircraft, such as a helicopter, for searching, detecting, and identifying submerged objects, as well as for conducting search and rescue operations. At the same time, the search time for underwater objects from a helicopter's flight altitude is significantly

reduced due to the increased area of the covered observation region.

Attenuation of Radiation

The problem of using radars for these purposes arises from the fact that electromagnetic radiation in the entire radio frequency range used for terrestrial radio communications is unable to propagate in salt seawater, which is a good conductor of electric current. The depth of electromagnetic radiation penetration into seawater can be calculated using the following formula [1]:

$$h = \frac{1}{2 \cdot \pi \cdot f \cdot \mu \cdot \sigma}, \quad (1)$$

where f is the frequency of the electromagnetic radiation, μ is the magnetic permeability of seawater ($\mu = 4\pi \times 10^{-7}$ H/m), and σ is the electrical conductivity of seawater (from 1 to 4 S/m).

However, there is a range of radio waves that can propagate in salt seawater; these are very long radio waves in the extremely low frequency band (from 3 to 30 Hz) and the super-low frequency band (from 30 to 300 Hz). But operation with very long radio waves poses significant technical difficulties. The most difficult task is to create a transmit-receive antenna system due to the very large wavelength, which, for example, at a frequency of 82 Hz is 3658 km. Building an efficient antenna system with dimensions comparable to such a wave geometry is not feasible.

The use of sonar equipment for searching and recognizing underwater objects has fundamental drawbacks inherent to sonar systems: dependence on hydrological conditions, information delay caused by the low speed of sound propagation in water, low spatial resolution, vulnerability to noise, lower accuracy in determining the coordinates of underwater objects, as well as design complexity, increased weight and size characteristics, and high power consumption.

The potential advantages of optoelectronic systems for obtaining images of underwater objects through a disturbed air-seawater interface from a helicopter for detection and recognition purposes include: high spatial resolution, high sensitivity, a high signal-to-noise ratio, and high accuracy in determining the spatial coordinates and range to the detected underwater objects.

This gives rise to the task of considering the use of optical radiation to obtain images of underwater objects through a disturbed air-seawater interface from a helicopter (Fig. 1).

In this case, the processes of scattering and selective absorption of optical radiation in seawater have a significant influence on the image quality even at relatively short distances between the underwater objects and the helicopter-mounted observation system. This influence manifests itself in the decreased brightness and contrast of the image, its distorted

spatial structure, the loss of information about the object's color, a relatively increased noise component of the image, and, finally, in a limited visibility range determined mainly by the following factors. The first factor is associated with multiple scattering, which leads to the blurring of the underwater object's image, the second factor is due to the fluctuating distribution of underwater illumination caused by the random nature of optical radiation refraction at the disturbed surface.

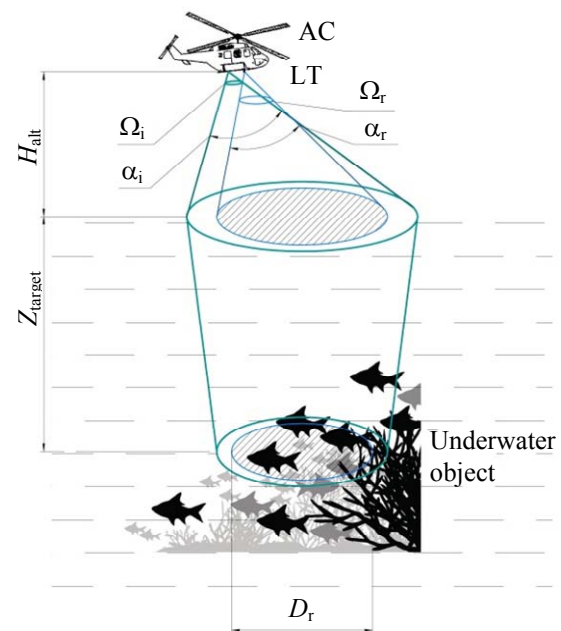


Fig. 1. Formation of images of underwater objects through the air-seawater interface from a helicopter

These fluctuations account for a fluctuation component in the signal, which is caused by wave motion, and the distortion of the image topology. Assuming that these factors are not mutually correlated, their influence on the image quality can be assessed separately. In addition, it is necessary to take into account the helicopter's speed and the multiple interactions with surfaces that the optical radiation undergoes when passing through the air, interacting with the water surface, propagating in the water, and then re-passing through the same surfaces. These interactions become even more complex when the scattering and absorbing substances present in the water have higher concentrations near the surface. All these difficulties together significantly reduce the overall return signal and thus limit the use of an

optoelectronic underwater vision system in shallow areas of the sea surface.

Taking into account the specific features of optical radiation propagation in the sea environment, this paper considers the use of high-resolution optoelectronic television systems to provide observation of the underwater space from a helicopter by recording the illuminating optical radiation reflected from underwater objects and forming an image of underwater objects on a monitor screen, which is used by the onboard operator for recognition of underwater objects under certain observation conditions.

Along the propagation path, the illuminating optical radiation undergoes several types of interactions with the medium (air and seawater) that attenuate its power, including scattering and absorption, which can be estimated using the Bouguer law [1]:

$$\Phi(r) = \Phi_0 \exp \left\{ - \int_0^r [\alpha(r) + \beta(r)] dr \right\}, \quad (2)$$

where $\Phi(r)$ and Φ_0 are the current and initial optical radiation fluxes, r is the thickness of the medium (air and seawater), $\alpha(r)$ is the absorption coefficient of the medium (air and seawater), $\beta(r)$ is the backscattering coefficient of the medium (air and seawater).

Absorption of optical radiation is the main attenuation mechanism that must be taken into account when optical radiation propagates in seawater. The optical radiation is absorbed when photons are absorbed by water molecules, increasing the electronic energy states of the molecules. Due to absorption, the attenuation of the laser radiation in seawater is influenced by a number of factors: the pure seawater itself, phytoplankton, decomposed plant material, and other inorganic particles.

For pure water, absorption of the optical radiation is quite low for wavelengths up to ~ 600 nm. As the wavelength of the probing optical radiation increases, stronger vibrational energy transitions cause a noticeable and significant increase in absorption intensity. The spectral characteristic of pure water absorption is shown in Fig. 2 [1].

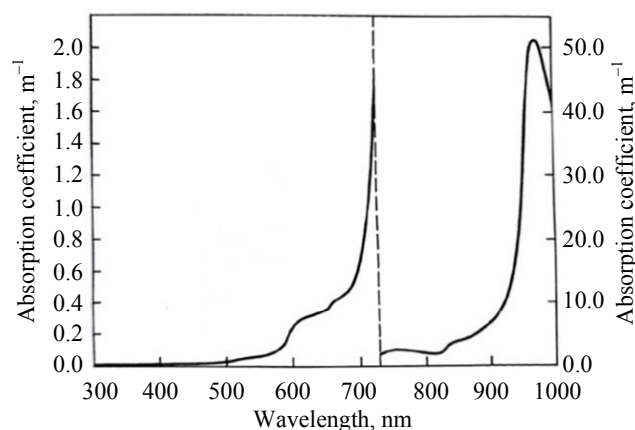


Fig. 2. Spectral characteristic of pure water absorption

The introduction of salt with concentrations typical only of seawater causes a very small increase in the absorption coefficient (on the order of 0.002 m^{-1}) in the wavelength range from 400 nm to 680 nm [3]. This is negligibly small compared to any other attenuating factor in the water medium. Therefore, seawater absorption for any given wavelength can be approximated by pure water absorption for the same given wavelength.

Phytoplankton and other photosynthesizing materials absorb the optical radiation significantly more strongly than pure seawater. The main absorbing component of photosynthesizing materials is chlorophyll, which exists in two types: chlorophyll *a* and chlorophyll *b*. Regardless of the type, chlorophyll has two main absorption bands – one in the “red” region of the visible spectrum, and the other in the “blue” region. Although this indicates that chlorophyll will absorb the optical radiation in these parts of the spectrum more readily, any wavelength of the optical radiation has a probability of being absorbed [1]. The level of optical radiation absorption by phytoplankton and other photosynthesizing materials depends on the location and concentration of chlorophyll in the water. In shallow areas, phytoplankton and photosynthetic materials can occupy the entire water column from the surface to the seabed. In deeper coastal waters or the open ocean, the concentration of photosynthetic materials depends on the intensity of ambient sunlight.

Thus, near the ocean surface, higher concentrations of chlorophyll-containing materials are observed, which partially extend into the water column until sunlight is completely absorbed, and, as the depth increases, the level of

optical radiation losses will be determined by absorption by the water medium. Therefore, the intensity of optical radiation absorption by chlorophyll-containing materials varies greatly depending on the location of the observation system's application. For example, there is no high concentration of these materials in the open ocean, and the absorption intensity caused by them is extremely low. However, in coastal waters, the absorption intensity from these materials can significantly increase the level of optical radiation losses.

In addition, the intensity of optical radiation absorption in seawater is affected by various non-photosynthesizing materials – such as decomposed plant materials known as colored dissolved organic matter, and other inorganic particles that absorb the optical radiation [1].

The spectral dependence of the optical radiation absorption intensity in the open ocean due to the aforementioned loss factors in seawater is shown in Fig. 3 [2].

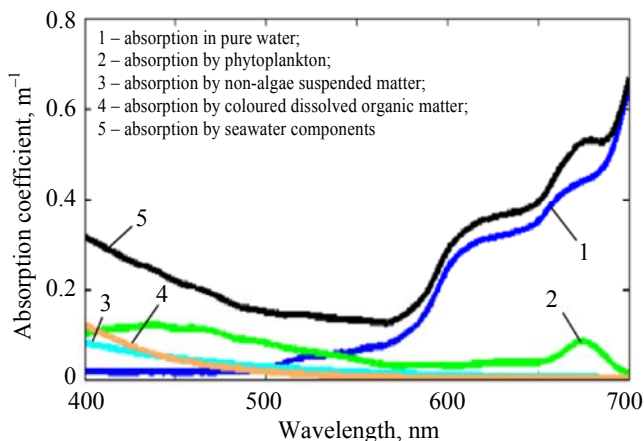


Fig. 3. Spectral dependence of the optical radiation absorption intensity in the open ocean

Optical radiation scattering is also a main attenuation mechanism that must be considered for the optical radiation propagating in seawater, and it takes two forms: elastic and inelastic. Elastic scattering does not result in a change in the wavelength and is often modeled in two different ways: Rayleigh scattering and Mie scattering. The model is chosen depending on the size of the scattering particles and the optical radiation wavelength. Considering that optical radiation absorption is minimal in the spectral range from 450 nm to 550 nm, and the diameter of water molecules is on the order of 0.3 nm,

Rayleigh scattering can be considered only for interaction with pure seawater.

The second elastic interaction of the optical radiation with the sea medium is Mie scattering, which occurs upon interaction with larger particles. The Mie scattering theory considers particles of any size suspended in seawater as a medium through which the optical radiation propagates, and it describes empirical data on the angular distribution of the scattered optical radiation in seawater quite accurately [1]. The angular distribution of the scattered optical radiation in various types of seawater is shown in Fig. 4 as a volume scattering function, which describes the distribution of the scattered radiation power from the incident flux among individual scattering angles [2].

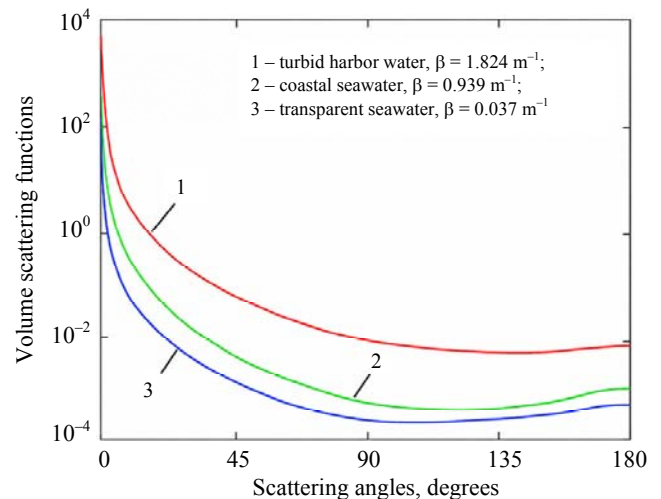


Fig. 4. Distribution of the scattered optical radiation power vs. scattering angles

The curves shown in Fig. 4 and plotted for laser radiation with a wavelength of 515 nm show the contribution of Mie scattering to the total attenuation of the optical radiation during propagation through various seawater types: turbid harbor water, coastal seawater and clear seawater [4]. The scattering values in the curves of Fig. 4 at angles of 0° represent the optical radiation that was either forward-scattered or not scattered at all, while at angles of 180° they show the level of optical radiation that was scattered in the backward direction. All other angles describe the distribution of the optical radiation scattered in any other direction. Analysis of the curves in Fig. 5 shows that most of the incident optical radiation continues to propagate in the forward

direction (~ 0 degrees), and only a small fraction propagates in the backward direction (near scattering angles of 180°). These curves are used to estimate the fraction of the scattered optical radiation in the forward and backward propagation of the optical radiation in various types of seawater.

Since the scattering and absorption characteristics of the optical radiation in seawater depend on the concentration of suspended substances in the water, the ocean depth is usually divided into three zones: the euphotic, dysphotic, and aphotic zones. The most interesting zone for the development of optoelectronic underwater vision systems (OUVS) is the euphotic zone – the region that absorbs 99% of the incident solar radiation at the ocean surface. Typically, the maximum depth for this zone is about 200 m, but it can vary depending on the availability of sunlight. The euphotic zone is the region with the maximum concentration of phytoplankton and other photosynthesizing substances; therefore, the attenuation of the optical radiation will be at its maximum here, and consequently, this region is the most important when designing optoelectronic underwater vision systems [1].

The concentration of phytoplankton and other photosynthesizing material decreases significantly from the ocean surface to the bottom of the euphotic zone, although in some regions of the world, a secondary maximum of the chlorophyll concentration exists at greater depths [2]. In coastal waters, there is a fairly high concentration of the dissolved organic matter throughout the water column, thus causing significant attenuation of the optical radiation. All this affects the perceived transparency of seawater and, consequently, the ability of the optical radiation to propagate through the aquatic environment. For example, most of the foreign impurities characteristic of coastal waters are absent in the open ocean, so the optical radiation losses during propagation in the seawater of the open ocean will be significantly lower than in coastal waters. A classification of the water medium that takes into account specific concentrations of chlorophyll and phytoplankton in seawater has been performed, which makes it possible to better predict how the probing optical radiation will be absorbed and scattered in seawater [5]. According to this classification,

seawater from the open ocean to coastal areas was divided into groups based on optical transmission. The stronger the attenuation of the optical radiation, the higher the number assigned to it. The spectral characteristics of seawater transmission based on the introduced classification are shown in Fig. 5.

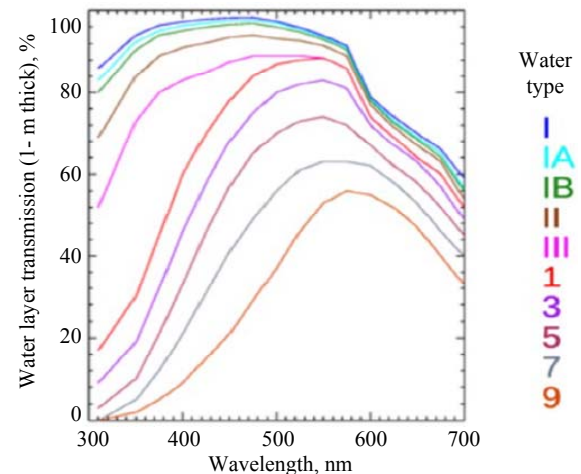


Fig. 5. Spectral transmission of seawater based on the introduced classification

The generalized spectral characteristic of optical radiation attenuation by seawater due to absorption and volume scattering is shown in Fig. 6. Analysis of the obtained characteristic shows that airborne OUVS should have maximum sensitivity in the spectral range of maximum seawater transparency (from 450 nm to 550 nm). Such systems can be divided into two large groups: passive and active-pulsed optoelectronic underwater vision systems.

In passive OUVS, the image is formed under natural (sunlight) illumination, although usually there is no illuminating solar radiation at great depths, or by using powerful searchlight illuminators for the continuous illumination of underwater targets.

The luminous flux is known to be attenuated significantly more strongly in seawater than in the atmosphere. The attenuation of the illuminating optical radiation can be compensated for by increasing the power of the optical radiation flux. However, this leads to increased brightness of the backscattering noise (hereinafter referred to as BSN), which reduces the image contrast. Experience in the operation of passive optoelectronic underwater vision systems shows that increasing the maximum range by 15–20% requires a tenfold increase in the searchlight light

source power [6]. Analysis of the results of operating Russian passive OUVS by specialists at FSUE SPMBM “Malachite” allows us to conclude that the capabilities of searchlight

illuminators to increase the underwater vision range have been practically exhausted. At the same time, their greatest advantage is their relatively low cost [6].

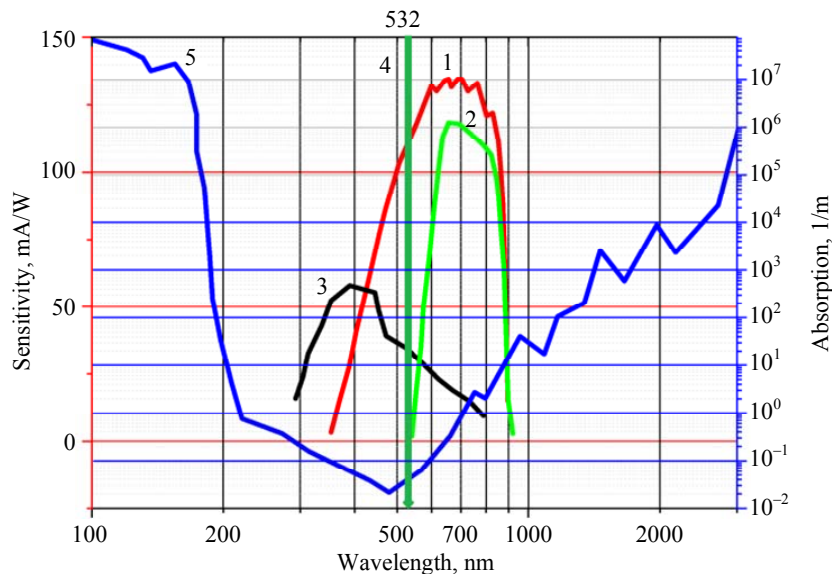


Fig. 6. Spectral characteristics of seawater transparency and the III+ generation image intensifier tube and Nd:YAG laser radiation: 1 – spectral photosensitivity of the III+ generation image intensifier tube with a “blue” photocathode; 2 – spectral photosensitivity of a standard III+ generation image intensifier tube with a GaAs photocathode; 3 – spectral photosensitivity of a II+ generation image intensifier tube; 4 – Nd:YAG laser radiation; 5 – spectral absorption characteristic of seawater

The use of the active-pulse method for forming underwater video images allows for the elimination of the “parasitic” effect of BSN caused by optical noise, such as scattering by seawater and phytoplankton, which is superimposed on the useful image of observed underwater objects, thereby reducing their contrast. The echo signal profile of an active-pulse OUVS located above the sea surface on board a helicopter is shown in Fig. 7.

Active-pulse optoelectronic underwater vision systems use artificial illumination in the spectral range of maximum seawater transparency ($\Delta\lambda = 450\div 550$ nm), which is generated by high-efficiency pulsed laser sources operating synchronously with a gated photodetector optoelectronic television channel sensitive in the same spectral range ($\Delta\lambda = 450\div 550$ nm), also operates in a pulsed mode.

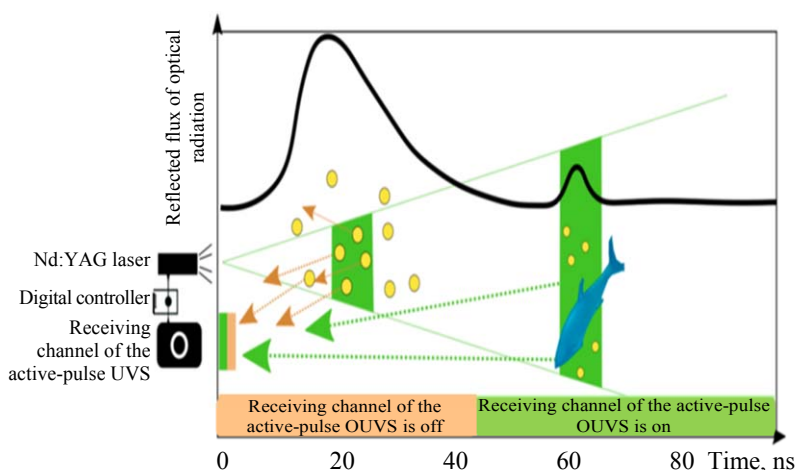


Fig. 7. Echo signal profile of an active-pulse OUVS: 1 – BSN of the marine environment, 2 – reflected signal from the underwater object

The key elements used to create high-efficiency laser active-pulse OUVS are a high-speed photodetector optoelectronic television channel, a high-efficiency pulsed laser, and a high-speed digital controller.

The high-speed photodetector optoelectronic television channel is based on a photodetector module of the FPM-5-1 type with a sensitive structure comprising a “III+ generation image intensifier tube and a programmable gated digital TV camera based on a large-format digital CMOS

array”. The module structure uses a specially designed photodetector optoelectronic television channel featuring a negative-electron-affinity (NEA) photocathode with an extended spectral response into the blue-green region of the seawater transparency spectrum (Fig. 6), which is called a III+ generation image intensifier tube with a “blue” photocathode [7]. The developed III+ generation image intensifier tubes have a number of advantages compared to standard generation III+ image intensifier tubes, which have very low photosensitivity in the spectral range of seawater transparency (Fig. 6). Furthermore, generation II+, SuperII+, HyperII+ tubes have significantly lower photosensitivity in the spectral range of seawater transparency (Fig. 6), as well as very low photocathode resistivity, which does not allow for their gating with short pulses (down to a few nanoseconds).

The appearance of the optoelectronic television channel of the active-pulse OUVS based on the FPM-5-1 module type and developed by Joint Stock Company «RPC GEOFIZIKA-NV» is shown in Fig. 8, and its main parameters are given in Table 1.



Fig. 8. Appearance of the photodetector optoelectronic television channel of the active-pulse OUVS based on the FPM-5-1 type module

Table 1

Parameter name	Parameter values
Angular field, degrees	20
Spatial resolution across the field, TV lines	450
Diameter of the generation III+ image intensifier tube photocathode with a “blue” photocathode	18 mm
Spectral range of photosensitivity, μm	0.4÷0.8
Integral photosensitivity, $\mu\text{A/lm}$	2800
Spectral photosensitivity at $\lambda = 530 \text{ nm}$, mA/W	140
Type of digital TV camera based on a CMOS array	e2v EV76C560 ABT
TV camera format	1/1.8"
TV camera resolution, pixels	1282×1026
TV camera pixel size, μm	5.3×5.3
Frame rate, Hz	60
Power consumption, W	20
Weight, kg	1
Overall dimensions, mm	110×80×215

Another key element of the active-pulse OUVS is a high-efficiency pulsed laser, whose active medium is a Nd:YAG crystal. The laser active medium is pumped by diode bars, Q-switching is accomplished by an electro-optical switch, and the oscillation frequency is doubled by a KTP-crystal-based element to

achieve a wavelength of 527 nm, which ensures radiation in the spectral region of seawater transparency (Fig. 6). The appearance of the pulsed Nd:YAG laser of the N-R50-532 type, developed by the Institute of Physics of the National Academy of Sciences of Belarus (Republic of Belarus) as part of the active-pulse

OUVS, is shown in Fig. 9, and its main parameters are given in Table 2.



Fig. 9. Appearance of the pulsed Nd:YAG laser of the N-R50-532 type

To control the pulsed power supply of the generation III+ image intensifier tube with the “blue” photocathode, the digital CMOS array and the pulsed Nd: YAG laser, as well as for the primary processing of digital images of detected underwater objects, a high-speed digital controller is used. The adjustable time-gating control turns on the receiving channel of the active-pulse OUVS at a specific range, eliminates BSN, and provides observation of the underwater space through its depth in the absence of solar radiation.

Table 2

Parameter name	Parameter values
Radiation wavelength, nm	532 ± 5
Pulse energy, mJ	> 50
Fixed pulse repetition rate, Hz	20
Pulse duration, ns	< 10
Beam diameter, mm	< 5
Beam divergence, mrad	< 3
Power consumption, W	300
Weight, kg	2
Dimensions (without cooling system), mm	50×60×165

Conclusion

The implementation of active-pulse technology has led to the creation of optoelectronic television systems that provide observation of the underwater space from a helicopter by recording the illuminating optical radiation reflected from underwater objects and forming an image of objects on a monitor screen, which is used by the onboard operator for recognition of underwater objects under certain observation conditions.

The practical significance of the active-pulse mode consists in achieving a longer underwater vision range compared to other passive optical and optoelectronic devices, as well as high-frequency sector-scanning sonars operating under identical conditions. Changing to a qualitatively new level of obtaining visual information acquisition will expand the naturally limited capabilities of the human eye.

REFERENCES

1. Kirk J. T. O. Light and Photosynthesis in Aquatic Ecosystems. Cambridge, UK: Cambridge University Press, 1983.
2. Mobley C. Light and Water: Radiative Transfer in Natural Waters. Academic Press, 1994.
3. Sullivan J. M., Twardowski J. R., Moore C., Barnard A., Donaghay P. L., and Rhoades B., App. Opt. **45** (21), 5294–5309 (2006).
4. Petzold T. J. Volume scattering functions for selected ocean waters. San Diego: University of California, 1972.
5. Morel A., J. Geophys. Res. **93** (C9), 10749–10768 (Sep. 1988).

6. Martynov V. L., Krasnopol'skiy V. Ye., and Maltsev A. B., Sudostroenie, No. 4, 46–48 (2005).
Gruzevich Yu. K., Alkov P. S., Balyasny L. M., and Volkov D. V., Applied Physics, No. 1, 70–78 (2025) [in Russian].

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Determination of light and heavy hole parameters in *p*-GaSb single crystals on the basis of complex analysis of the Hall effect

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In this work we present the results of measurements of electrophysical parameters of commercially available single-crystal *p*-GaSb substrates in the temperature range of 80–300 K. We perform comparative analysis of temperature and field dependences of Hall resistivity with and without taking into account the degeneracy of the valence band. The limitations of applicability of the standard model, which assumes the existence of only one type of holes, for describing transport properties of *p*-GaSb are shown. It is shown that non-monotonic temperature dependence of substrates resistivity arises due to monotonic change of carrier concentrations and mobilities. Basing on the results of the analysis using model, which takes into account contributions of light and heavy holes, we estimated the variation of the chemical potential in substrate material with temperature. The obtained results are necessary for further design of photosensitive heterostructures, obtained using studied substrates.

Keywords: gallium antimonide, *p*-type conductivity, semiconductor substrates, Hall effect, magnetoresistance, multi-band semiconductors.

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Introduction

New approaches in IR photosensorics based on antimony-containing semiconductor epitaxial A^{III}B^V heterostructures have been actively developing recently [1, 2]. When short-period superlattices are used as absorbing layers, these heterostructures cover an extremely wide spectral range, including the atmospheric transparency windows of 3–5 μm and 8–12 μm, while simultaneously providing specific detectivity close to the fundamental limit at temperatures of 80–150 K [3]. Along with the choice of heterostructure design, the substrate material used for the epitaxial growth of the structure plays a

key role in achieving high photovoltaic characteristics.

Due to the possibility of precise lattice constant matching, monocrystalline GaSb wafers of *n*- or *p*-type are among the most convenient substrates for growing photosensitive heterostructures based on superlattices is [2, 4]. Regardless of the type of photosensitive element architecture, the transport properties of the substrate inevitably affect the performance of the photosensitive elements, even when the substrates are thinned down to thicknesses of 10–20 μm. This influence is determined by two main factors: the presence of additional resistance connected in parallel to the contact layer, and band bending

caused by the alignment of the chemical potential between the substrate and the photosensitive element. To ensure reliable prediction of the operating modes of the photosensitive elements, these factors must be accounted for correctly at the heterostructure design stage. Consequently, the transport properties of substrates used for epitaxy must be studied over a wide temperature range.

This paper presents the results of electrophysical studies of epi-ready *p*-GaSb substrates manufactured by Pam Xiamen (China). These substrates are the primary *p*-type substrates with low doping levels currently available in the Russian Federation. The paper presents the results of conductivity and Hall resistance measurements in a wide temperature range, which allowed for the determination of the concentration, mobility, and chemical potential of majority carriers vs. temperature. A correct assessment of the chemical potential is achieved by using a two-band model that considers the contributions of light and heavy holes to the transport properties, and by comparing it to the results of processing within the framework of the single-band model, which is much more commonly used for the standard characterization of semiconductor materials.

Samples and Measurement Procedure

Three *p*-type GaSb samples (T1, P1, and P2) cleaved from commercially available two-inch wafers with a thickness of 0.53 mm have been studied in this paper (Pam Xiamen, China).

For the measurements, contact pads of Ti/Au (T1) or Ti/Pd/Au (P1 and P2) were deposited on the samples. Samples T1 and P1 were cleaved from the same wafer, while sample P2 was cleaved from another one. In fact, this study considers three samples to demonstrate the reproducibility of the electrophysical characteristics and associated material parameters. To perform the measurements, the samples were mounted on a holder, and the contact pads on the holder and the sample were connected by ultrasonic bonding of an aluminum wire.

The transport and magnetotransport properties of these samples were studied on a setup based on an electromagnet in the temperature range $T = 80\text{--}300$ K and in magnetic

fields up to $B = 0.9$ T. The measurements were carried out using direct current switched according to a four-probe scheme. A combination of a voltage source and a reference resistor was used for the measurements; the current in the measuring circuit was measured independently.

Findings and Discussion

The field and temperature dependences of the longitudinal (ρ_{xx}) and Hall (ρ_{xy}) resistances of the samples under study were measured as part of this study. Fig. 1*a–b* shows the field dependences of the Hall resistance ρ_{xy} at temperatures of 300 K and 80 K. The sign of the obtained curves indicates that conductivity is of *p*-type throughout the entire temperature range studied. Some difference can be seen between the experimental curves, which is obviously related to minor fluctuation in the properties of the wafers under study. However, as will be shown below, the corresponding difference in the transport parameter values for different samples turns out to be insignificant, thus confirming the good reproducibility of the material properties.

Hall data are often analyzed within the framework of a single-band model, where only one group of charge carriers is assumed to exist. In this case, the $\rho_{xy}(B)$ dependence should be linear, while the concentration p^* and mobility μ^* of the charge carriers are derived from the value of the linear slope $R_H = d\rho_{xy}/dB$ using the standard relations:

$$p^* = \frac{r_H}{eR_H}, \quad (1)$$

$$\mu^* = \frac{R_H}{r_H \rho_{xx}}, \quad (2)$$

where e is the electron charge, and r_H is the Hall factor determined by the dominant charge carrier scattering mechanism. In most cases $r_H = 1$ is assumed. Such an analysis of $\rho_{xy}(B)$ is often carried out in a very narrow field range and is used for the characterization of commercially available materials (including those by the manufacturer of the wafers studied herein). In our case, the linear approximation (examples are

shown by the orange dashed line in Fig. *a–b*) was performed in the range up to ± 0.5 T. As can be seen from the figures, the linear function describes the experimental data well over the entire field range at the room temperature, but a clear mismatch can be observed at low temperatures in higher fields, thereby indicating the inapplicability of the simplest model in this

case. The hole concentration and mobility values calculated using formulas (1) and (2) are presented in Table 1. Even these results prove that a temperature decrease is accompanied by a significant decrease in the charge carrier density and an increase in their mobility. The obtained values correspond well to the certified values stated by the wafer manufacturer.

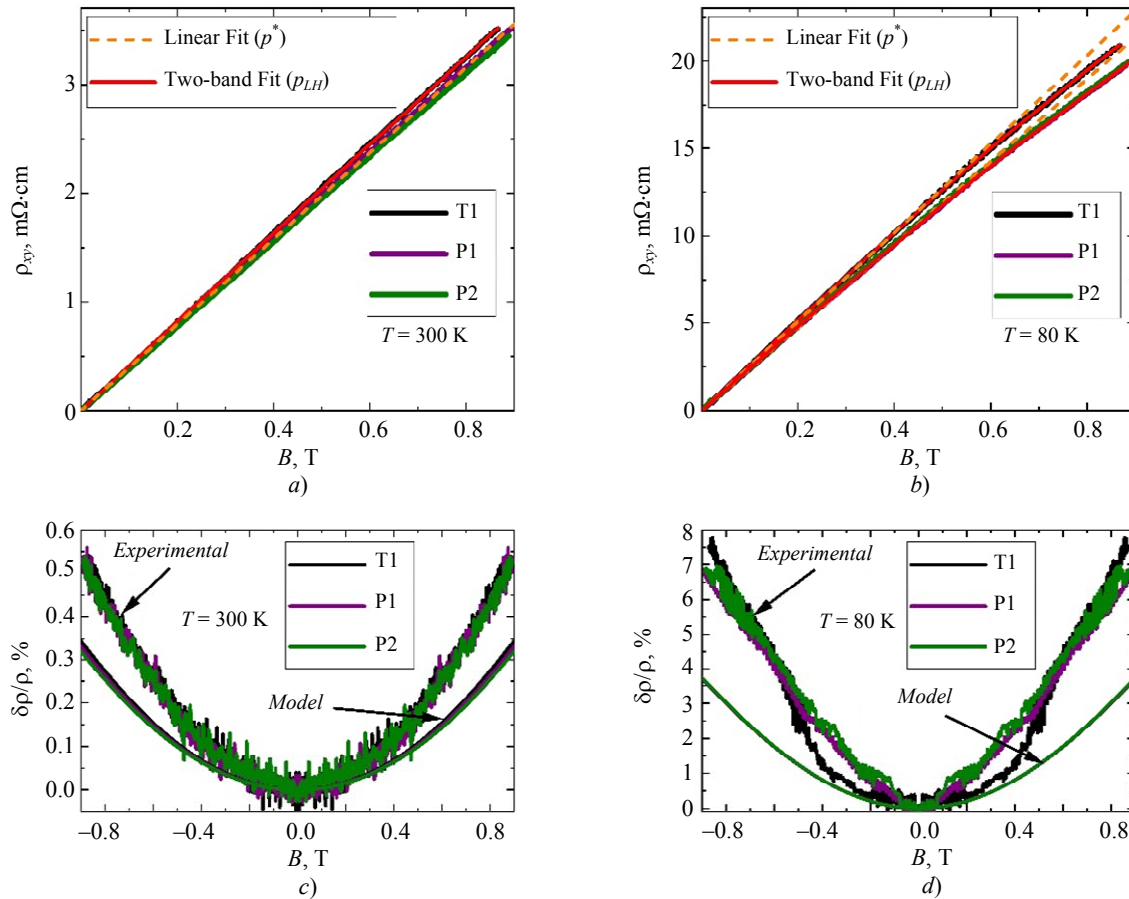


Fig. 1. Field dependences (*a, b*) of the Hall resistance and (*c, d*) of the magnetoresistance of the samples under study at temperatures of (*a, c*) 300 K and (*b, d*) 80 K. In figures (*a, b*), the orange dashed line shows the linear approximation of the data in the range up to ± 0.5 T, and the red line shows the approximation of the data using the two-band model (7–8). In addition to the experimental data, figures (*c, d*) show the magnetoresistance model curves calculated using formulas (7–10) with the parameter values listed in Table 1

Table 1

Transport parameters of the samples under study at the temperatures of 300 K and 80 K: resistivity ρ_{xx} , hole concentrations and mobilities (p^* and μ^*) obtained within the framework of the single-band model (1–2), and parameters of light (LH) and heavy (HH) holes calculated using the two-band model (7–8) at $K_n = 22.6$, $K_\mu = 0,1$

Sample	T , K	ρ_{xx} , mΩ·cm	p^* , $\times 10^{16}$ cm $^{-3}$	μ^* , cm 2 /(V·s)	p_{LH} , $\times 10^{16}$ cm $^{-3}$	μ_{LH} , cm 2 /(V·s)	p_{HH} , $\times 10^{16}$ cm $^{-3}$	μ_{HH} , cm 2 /(V·s)
T1	300	68.75	15.3	590	1.76	1580	39.8	158
	80	125.4	2.46	2030	0.279	5480	6.29	548
P1	300	68.14	15.8	580	1.81	1550	41.0	155
	80	117.0	2.63	2030	0.299	5480	6.76	548
P2	300	68.15	16.1	570	1.85	1520	41.8	152
	80	117.4	2.61	2040	0.297	5500	6.71	550

The deviation from the linear dependence of $\rho_{xy}(B)$, in the absence of a magnetic component in the system, is usually associated with the presence of several groups of charge carriers, which is typical for p -type $A^{III}B^V$ semiconductors, due to the existence of light-hole (LH) and heavy-hole (HH) bands in their structure. In the general case, each group of carriers makes an additive contribution to the corresponding conductivity tensor components σ as functions of the magnetic field B :

$$\sigma_{xx}(B) = \sum_i \frac{en_i\mu_i}{1 + \mu_i^2 B^2}, \quad (3)$$

$$\sigma_{xy}(B) = \sum_i \frac{en_i\mu_i \cdot \mu_i B}{1 + \mu_i^2 B^2}, \quad (4)$$

where n_i and μ_i are the concentration and mobility of carriers in i -band. In the case of p -type GaSb, $i=2$, and the parameters of the heavy-hole band can be determined through the corresponding proportionality coefficients:

$$K_n = \frac{p_{HH}}{p_{LH}}, \quad (5)$$

$$K_\mu = \frac{\mu_{HH}}{\mu_{LH}}, \quad (6)$$

Then the original components of the conductivity tensor can be rewritten in the following form:

$$\sigma_{xx} = ep_{LH}\mu_{LH} \left(\frac{1}{1 + \mu_{LH}^2 B^2} + \frac{K_n K_\mu}{1 + K_\mu^2 \mu_{LH}^2 B^2} \right), \quad (7)$$

$$\sigma_{xy} = ep_{LH}\mu_{LH}^2 B \left(\frac{1}{1 + \mu_{LH}^2 B^2} + \frac{K_n K_\mu}{1 + K_\mu^2 \mu_{LH}^2 B^2} \right). \quad (8)$$

Accordingly, the experimentally measured field dependences of resistances ρ_{xx} and ρ_{xy} can be described within the framework of the two-band model using formulas (7–8) via the corresponding inversion of the conductivity tensor components, which is written for an isotropic material in the following form:

$$\rho_{xx}(B) = \frac{\sigma_{xx}(B)}{\sigma_{xx}^2(B) + \sigma_{xy}^2(B)}, \quad (9)$$

$$\rho_{xy}(B) = \frac{\sigma_{xy}(B)}{\sigma_{xx}^2(B) + \sigma_{xy}^2(B)}. \quad (10)$$

It is quite obvious that the actual shape of the theoretical curves is determined by the values of μ_{LH} , K_n and K_μ , while the value of p_{LH} is simply a scaling factor. Nevertheless, the approximation of a single curve $\rho_{xy}(B)$ with a function containing four fitting parameters can lead to noticeable ambiguities in the results obtained, especially in a limited magnetic field range. Therefore, in some cases, it is recommended to perform a simultaneous approximation of curves $\rho_{xy}(B)$ and $\rho_{xx}(B)$ with a single set of parameters. The applicability of this approach requires the presence of a contribution only from the classical magnetoresistance (MR) mechanism described by formula (9). However, most materials exhibit contributions from several MR mechanisms, for example, the amplitude of the linear MR contribution can exceed that of the classical mechanism by orders of magnitude [5]. Thus, the recording of data of $\rho_{xx}(B)$ can significantly increase the error in the results obtained. Therefore, a more convenient way to improve the accuracy of the Hall data approximation within the framework of the two-band model is to consider the zero-field resistance, which in the case of p -GaSb is written as:

$$\rho_{xx}(B=0) = \frac{1}{ep_{LH}\mu_{LH}(1 + K_n K_\mu)}. \quad (11)$$

It is easy to see that when the ratio $\rho_{xy}/\rho_{xx}(B=0)$ is used, the dependence on p_{LH} disappears, which somewhat simplifies the fitting procedure without introducing additional errors. Therefore, in this paper, curves $\rho_{xy}/\rho_{xx}(B=0)$ were first approximated, and then the parameters obtained were used to approximate curves $\rho_{xy}(B)$ and to determine the values of p_{LH} .

For $A^{III}B^V$ semiconductors, both in the case of degenerate and non-degenerate statistics, the concentrations of free charge carriers in the light-hole and heavy-hole bands turn out to be proportional to each other with $K_n = (m_{HH}^* / m_{LH}^*)^{3/2}$, where m_{HH}^* and m_{LH}^* are the effective masses of heavy and light holes. For GaSb, the corresponding values vary somewhat in the literature [6–9], but this paper uses value $1/\gamma_m = m_{HH}^* / m_{LH}^* = 8$ [10]. Accordingly, we can assume $K_n \approx 22.6$, without considering band nonparabolicity effects of the bands (which is justified in the case of low charge carrier densities). Since the temperature dependence of effective masses in classical semiconductors is rather weak [11], this value of K_n can be assumed constant over the temperature range under consideration. In turn, based on the ratio of effective masses γ_m , one may expect $K_\mu \sim \gamma_m = 0,125$ in the case of GaSb under the condition of equal relaxation times for the two types of holes. However, since such an assumption seems unjustified, the value of K_μ was determined from the approximation of the low-temperature data (Fig. 1b), as a result of which the average value was taken to be $K_\mu = 0,1$. The data at room temperature (Fig. 1a) are almost linear, for which reason independent determination of K_μ is impossible in this case; therefore, value $K_\mu = 0,1$ was used over the entire temperature range under consideration. It is worth noting that the actual ratio K_μ is determined by summing the contributions from various scattering mechanisms [12]; for example, in the simplest case, scattering by longitudinal acoustic phonons implies $K_\mu \sim \gamma_m^{5/2} \approx 0,0055$, while scattering by ionized impurity atoms implies $K_\mu \sim \gamma_m^{1/2} \approx 0,354$. Thus, a more detailed analysis of the value of K_μ and its possible variation over a wider temperature range can provide valuable information about the evolution of the contributions of different charge carrier scattering channels, which, however, is beyond the scope of this paper.

The described approximation algorithm allowed us to achieve good alignment of experimental curves with model curves (shown

by red lines in Fig. 1a–b) over the entire magnetic field range. The approximation parameters obtained are presented in Table 1. It can be seen that the concentration values p^* and p_{LH} differ by almost an order of magnitude. In principle, value p^* , which is often used for the characterization of p -type $A^{III}B^V$ semiconductors, is a kind of mathematical abstraction, since the ratio p^* / p_{LH} depends on the parameters μ_{LH} , K_n and K_μ significantly. Thus, the value p^* can only be used as a derived parameter for analyzing the effect of small modifications of the material (when comparing samples with each other), while a more systematic study requires analysis within the framework of model (7–10).

Fig. 1c–d shows the MR curves for the samples under study, which were determined in the standard way:

$$\frac{\delta\rho}{\rho} = 100\% \times \frac{\rho_{xx}(B) - \rho_{xx}(B=0)}{\rho_{xx}(B=0)}. \quad (12)$$

It can be seen from the figure that the samples exhibit a positive MR amounting to approximately 0.52% at the room temperature (Fig. 1c), and about 7% at the liquid nitrogen temperature (Fig. 1d). In principle, the observed MR indicates a significant role of the classical MR mechanism, and its amplitude increase upon cooling is associated with the accompanying growth of the charge carrier mobility. For verification purposes, model MR curves with the parameter values listed in Table 1 were obtained based on formulas (7–10). The corresponding curves are also shown in Fig. 1c–d. It is clearly seen that the model curves have a smaller amplitude compared to the experimental data at both temperatures. Such a discrepancy is indicative of additional contributions from other MR mechanisms in the samples under consideration.

Then, the temperature dependences of the resistance tensor components of the samples under study were analyzed. Fig. 2a shows the dependences of $\rho_{xx}(T)$ in a zero magnetic field. It can be seen that the dependence is non-monotonic: a metallic character at high temperatures changes to a semiconductor one below about 170 K. Further cooling to 80 K

causes the resistance to increase by approximately a factor of two. This character of the $\rho_{xx}(T)$ curves suggests the presence of competing contributions to the temperature variation of the system conductivity. To visualize them, the temperature dependence of the Hall effect in a constant magnetic field was measured. In this case, two curves were measured at different field polarities, after which an antisymmetrization procedure was applied to the curves (to eliminate the parasitic contribution of the longitudinal resistance in the signal associated with the asymmetry of the Hall contacts). The resulting curves $\rho_{xy}(T)$ are shown in Fig. 2b.

As can be seen from the figure, in contrast to the $\rho_{xx}(T)$ curves, the amplitude of the Hall effect in the samples under study exhibits a strictly monotonic temperature dependence that indicates a decrease in the free charge carrier concentration upon cooling, which is characteristic of a non-degenerate semiconductor.

Similarly to the analysis of the field dependences, the temperature dependences of the hole concentrations and mobilities can be determined both within the framework of the single-band model (1–2) (curves $p^*(T)$ and $\mu^*(T)$ were obtained by this method) and within the framework of the two-band model (7–10). However, a number of complications arise in the latter case. In contrast to the analysis of curves $\rho_{xy}(B)$, in the case of temperature dependences, it is impossible to approximate the experimental curve without assuming a specific form (model) for the temperature dependence of the concentrations and mobilities of the charge carriers in both bands (which could be described by a finite set of parameters). Technically, general models can be applied for known systems quite successfully; however, in our case, the objective of the analysis is to determine the form of the dependences $p_{LH}(T)$ and $\mu_{LH}(T)$. Therefore, the analysis within the framework of the two-band model practically reduces to solving

the system of equations (7, 8, 10) at each point of dependence $\rho_{xy}(T)$. For this purpose, by means of the values of K_n and K_μ employed in the analysis of the field data, the modulus of the difference between the experimental values of $\rho_{xy} / \rho_{xy}(B=0)$ and the theoretical expression for this quantity was minimized for the corresponding quantity. The theoretical values were obtained by substituting (7–8) into (10) and dividing by (11)). This minimization was carried out using standard methods in the Python environment, in particular, using the “Nelder-Mead” algorithm from the SciPy library). Thus, the curves $\mu_{LH}(T)$ were obtained, from which (using the known K_n and K_μ) the curve $p_{LH}(T)$ was calculated from the data $\rho_{xx}(T, B=0)$, and then the curves for the heavy-hole band were calculated. It should be noted here that, under the assumptions used, the latter are completely identical to the curves for light holes (up to a constant factor), and therefore are not presented here.

Fig. 2c shows the temperature dependences of the hole mobilities calculated within the single-band and two-band models. It is clearly seen that the character of all dependences is strictly monotonic and corresponds to a mobility decrease upon warming, with no significant qualitative difference observed between the curves obtained within different models. It is important to note that the latter may be partly due to the choice of the magnetic field magnitude during measurement of $p_{xy}(T)$, since, as noted above, in fields up to 0.5 T the dependences of $p_{xy}(B)$ appear to be nearly linear. Accordingly, when measuring $p_{xy}(T)$ in higher magnetic fields or down to lower temperatures (where the nonlinearity of $p_{xy}(B)$ begins to manifest in lower fields), the differences between the single-band and two-band models are expected to become more noticeable.

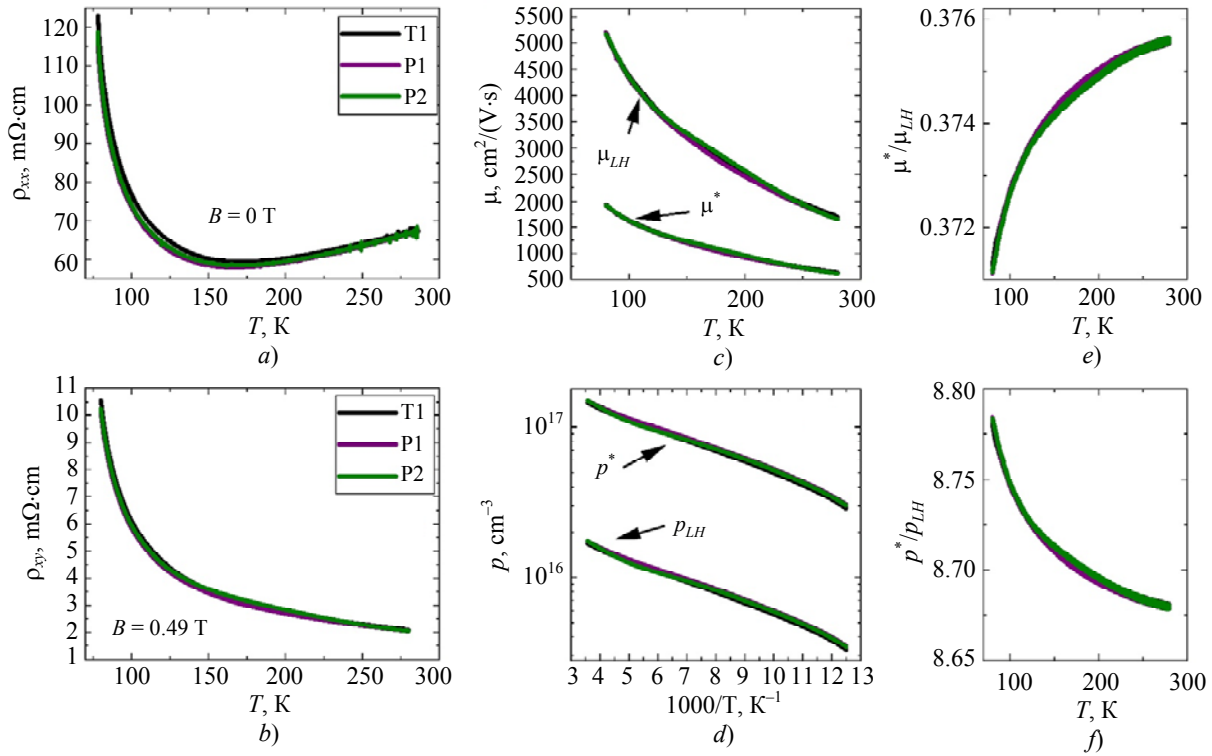


Fig. 2. Temperature dependences of (a) resistivity and (b) Hall resistance in a fixed magnetic field for the studied samples. Temperature dependences of (c) mobilities and (d) hole concentrations calculated within the single-band and two-band models. Temperature dependences of ratios of (e) mobilities and (f) hole concentrations obtained within the two models

The general shape of the temperature dependences of the hole mobilities in Fig. 2c is typical for non-degenerate semiconductors and is usually described by a superposition of scattering contributions from phonons and ionized impurity atoms [13]. Accordingly, the mobility increase upon cooling is attributed to decreasing phonon occupation numbers and a reduced fraction of ionized impurities (due to the return of electrons from the acceptor level to the valence band). In general, additional features may be associated with different types of screening of the impurity potential by charge carriers, the presence of a significant contribution from optical phonon scattering [14], as well as the existence of minority charge carriers and the associated electron-hole scattering [15].

Fig. 2d shows the curves of $p_{LH}(T)$ in comparison with the curves of $p^*(T)$ obtained within the single-band model. It can be seen from Fig. 2d that the character of the concentration dependences is also qualitatively similar. At the same time, the deviation from the linear character of the curves in the presented coordinates suggests that several impurity levels exist in the

wafers under study (since the concentration of intrinsic charge carriers in GaSb in the temperature range under consideration does not exceed 10^{12} cm^{-3}). Thus, the non-monotonic character of the initial $\rho_{xx}(T)$ curves is determined by the monotonic changes in the concentration and mobilities of the charge carriers along with temperature.

It is important to note that despite the similarity of the curves obtained within the single-band and two-band models, a more detailed analysis of the temperature dependences of the ratios μ^*/μ_{LH} and p^*/p_{LH} shown in Figs. 2e–f proves that even in our case, the values vary somewhat along with the temperature, i.e. the curve shapes turn out to be different. This difference can be much more noticeable if coefficients K_n and K_μ change along with the temperature. Therefore, the results obtained within the single-band model may, in the general case, not only be numerically incorrect but also introduce significant distortion into the determined change of transport parameters with temperature. This becomes essential for the subsequent analysis of such dependences, for

example, for estimating energies of impurity levels in the system.

A much more obvious limitation of the single-band model is the lack of a simple relationship between the obtained values and the actual parameters of a multiband semiconductor. In particular, to estimate the chemical potential (position of the Fermi level ε_F relative to the valence band top ε_V) in a p -type semiconductor, the standard expression is used [16]:

$$\varepsilon_F(T) - \varepsilon_V = -kT \cdot \ln(p(T)/\Phi_V(T)), \quad (13)$$

where p is the free hole concentration, and $\Phi_V(T)$ is the density of states in the valence band, which is calculated (in units of m^{-3}) as

$$\Phi_V(T) = 4.83 \cdot 10^{21} \cdot \left(T \frac{m^*}{m_e} \right)^{3/2}, \quad (14)$$

where m^* is the density-of-states effective mass of carriers in the band, and m_e which depends on the free electron mass. Accordingly, when the data $p^*(T)$ obtained within the single-band model are used, quantity m^* loses its meaning as an effective mass and becomes a “gauge” constant, i.e., a fitting parameter, and cannot be estimated independently without applying the two-band model. In turn, there is no such problem for the $p_{LH}(T)$ curves, since in this case one can use the tabulated value of $m_{LH}^* = 0.05m_e$ [7, 8, 10]. The result of the corresponding calculation is shown in Fig. 3, and the inset shows the change of the degeneracy factor $p_{LH}(T)/\Phi_{LH}(T)$ along with the temperature. For the samples under study, the ratio $p_{LH}(T)/\Phi_{LH}(T)$ does not exceed 0.12, this confirming the applicability of non-degenerate statistics for describing the studied wafers (classical criterion ≤ 0.15 [16]). In its turn, the chemical potential (Fig. 3) shifts toward the middle of the bandgap upon warming, which is typical for an extrinsic semiconductor.

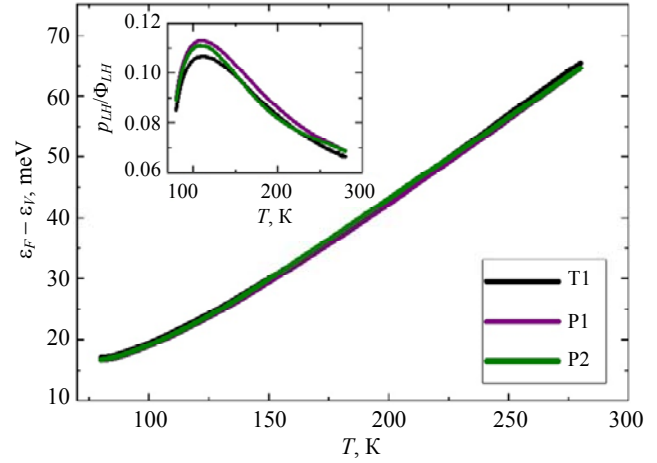


Fig. 3. Temperature dependence of the chemical potential position measured from the valence band top for the samples under study. The inset shows the change of degeneracy factor $p_{LH}(T)/\Phi_{LH}(T)$ along with the temperature

Conclusion

This paper presents a study on the magnetotransport properties of commercially available p -GaSb wafers. The temperature dependence of the sample resistance was shown to be non-monotonic, resulting from the monotonic changes in the underlying transport parameters. The Hall effect analysis was performed both within the framework of the standard single-band model and considering the existence of both light-hole and heavy-hole bands. An algorithm for data processing within the two-band model has been described. The values of the hole concentrations and mobilities obtained within the two models turned out to be significantly different. Furthermore, the proportionality coefficient between the corresponding results depends on a number of system parameters and cannot be calculated independently. From the temperature dependence of the charge carrier concentration calculated within the two-band model, the change of the chemical potential along with temperature has been determined. Since the position of the substrate's chemical potential determines the band bending for a layer grown on it, the obtained values of $\varepsilon_F(T)$ can be used for further design of heterostructures based on epi-ready p -GaSb substrates manufactured by Pam Xiamen (China).

REFERENCES

1. Jia C., Deng G., Liu L., Zhao P., Song G., Liu J., and Zhang Y., *J. Phys. D: Appl. Phys.* **56**, 433001 (2023).
2. Rogalski A., Kopytko M., Hu W., and Martyniuk P., *Sensors* **23** (17), 7564 (2023).
3. Roh Y. T., Kim B.-H., Kim Y. H., and Jung H., *SPIE Proc. (Infr. Tech. Appl. LI)* **13469**, 182–187 (2025).
4. Rogalski A., *Rep. Prog. Phys.* **85**, 126501 (2022).
5. Oveshnikov L. N., Ril' A. I., Mekhiya A. B., Davydov A. B., Marenkin S. F., and Aronzon B. A., *EPJ Plus.* **137**, 374 (2022).
6. Walton A. K. and Mishra U. K., *J. Phys. C: Solid State Phys.* **1** (2), 533–538 (1968).
7. Heller M. W. and Hamerly R. G., *J. Appl. Phys.* **57** (10), 4626–4632 (1985).
8. Dutta P. S., Bhat H. L., and Kumar V., *J. Appl. Phys.* **81** (9), 5821–5870 (1997).
9. Kim Y.-S., Marsman M., Kresse G., Tran F., and Blaha P., *Phys. Rev. B* **82**, 205212 (2010).
10. https://www.matprop.ru/GaSb_bandstr
11. Cavassilas N., Autran J.-L., Aniel F., and Fishman G., *J. Appl. Phys.* **92** (3), 1431–1433 (2002).
12. Smith R. A. *Semiconductors*. Cambridge University Press, 1959; Moscow, Izdatel'stvo innostrannoi literatury, 1962.
13. Micocci G., Tepore A., Rella R., and Siciliano P., *J. Appl. Phys.* **75** (8), 3982–3986 (1994).
14. Donmez O., Erol A., Cetinkaya C., Cokduygulular E., Aydin M., Yildirim S., Puustein J., Hilska J., and Guina M., *Semicond. Sci. Techn.* **36**, 115017 (2021).
15. Klaassen D. B. M., *Solid-State Electr.* **35** (7), 961–967 (1992).
16. Blakemore J. S. *Solid State Physics*. Cambridge University Press, 1985; Moscow, Mir, 1988.

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Confinement of microparticles in a quadrupole trap with rectangular voltage at atmospheric pressure

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The areas of confinement of charged microparticles with a diameter of 5–50 microns in a linear quadrupole trap with a pulsed alternating rectangular voltage in air at atmospheric pressure have been numerically calculated and experimentally confirmed. The influence of the voltage amplitude, its frequency, and the asymmetry of rectangular pulses on the position and width of the retention areas has been established. It is confirmed that the retention areas depend on the particle diameter. It has been found that in a trap with a sinusoidal voltage, it is possible to stabilize the trajectories of a particle or make them unstable by using additional rectangular pulses of an external alternating electric field by changing its frequency. The possibility of capturing and retaining microparticles in a quadrupole trap with a corona discharge on electrodes has been experimentally investigated.

Keywords: linear quadrupole trap, pulse-periodic voltage, charged microparticles, air, atmospheric pressure.

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Introduction

Linear electrodynamic traps with a sinusoidal confining voltage are used for various tasks: studying the properties of both individual particles and Coulomb structures, and determining the particle size and charge based on their trajectories in a quadrupole field, etc. [1–4]. Structurally, a linear quadrupole trap is close to mass spectrometers and mass filters. To improve the capabilities of the latter, the application of a rectangular (often called digital) waveform of the filtering voltage has recently been investigated [5–13]. Our studies have shown [14–16] that the rectangular voltage waveform has a number of advantages for confining micron-sized charged particles in quadrupole linear traps in air at atmospheric pressure. For rectangular voltage, theoretical studies of the stability regions of

filters [5–12] and ion traps [13] have been performed for vacuum conditions, where the particle dynamics depends only on the charge-to-mass ratio Q/m , i.e., the similarity law is true. Since the confinement of micron-sized charged particles in a trap in air at atmospheric pressure is significantly affected by gravity and viscous friction forces, the confinement region calculations made for a vacuum are inapplicable. Calculations considering gravity and viscous friction forces are required for each particle size. The aim of this paper is to calculate the confinement regions for particles of various sizes (5–50 μm) under asymmetric voltage pulses of different frequencies, to perform experimental studies, and to describe the effect of an external electric field and a corona discharge plasma on confinement.

Experimental Setup and Calculation Model

The experimental scheme is similar to that described in [14–16]. Linear cylindrical electrodes of the trap are 4 mm in diameter and 10 cm in length, and are fixed at the vertices of a square with a 2-cm side. A pulsed periodic alternating voltage of rectangular waveform with a frequency of 50 and 100 Hz and an adjustable amplitude V of up to 10 kV is applied to the linear electrodes. For asymmetric pulses, the ratio of the positive pulse duration to the pulse repetition period is defined as the positive pulse duty factor K_p . The effect of the corona discharge plasma was studied in a quadrupole trap with thin electrodes 110 mm in length and diameters of 63, 120, and 200 μm , spaced 1 cm apart. Dielectric polydisperse Al_2O_3 particles with sizes of 1–80 μm were used. Microparticles were charged inductively on a metal plate at a constant potential of 5–7 kV.

Since finding the confinement regions for such conditions through an analytical investigation of the equations is a complex task, a numerical method based on calculations of stable and unstable particle trajectories was used. The physical parameters of the model were chosen in accordance with the experiments. The calculation scheme is detailed in [15, 16] and consists of solving the Langevin equation considering the gravity and the friction force according to the Stokes' formula $F_f = -6\pi\mu r v$, where r is the particle radius, μ is the air viscosity, and v is the particle velocity. The initial position of the particle in the trap is 350 μm below the center of the trap potential well, and the initial particle velocity is zero. The calculation was performed for particles sized 5, 10, 20, and 50 μm in air at the atmospheric pressure for different waveforms of the voltage applied to the electrodes (sinusoidal and rectangular).

Findings and Discussion

Figure 1 shows the confinement regions (calculation) in “voltage amplitude – particle charge” coordinates for sinusoidal and rectangular (meander) voltages at a frequency of 50 Hz for particles sized 50 and 20 μm . The regions expand as the voltage decreases. The electric field forces of the trap at the lower

boundary are insufficient to compensate for gravity, and the particle falls out of the trap. At the upper boundary, the electric forces are so large that the particles escape from the trap. For 50- μm particles, the regions for the sinusoidal (1) and rectangular (2) voltages are similar in size, but region 2 is shifted toward lower charges, which agrees with the previously obtained experimental result [14], where a charged particle was confined at a lower amplitude of the rectangular voltage. Since in the case of the rectangular potential, the electric field at its peak value acts for a significantly longer time than in the case of the sinusoidal one, particles are confined at a lower voltage amplitude. For the same reason, particles at the upper boundary escape from the trap at a lower voltage amplitude, and as a result, the entire confinement region shifts to the left and downward. Confinement region 3 for particles sized 20 μm is shifted to even lower charges compared to region 2 for 50- μm particles. As the diameter decreases, the gravity force and viscous friction decrease, so the particle is more easily confined at a low charge.

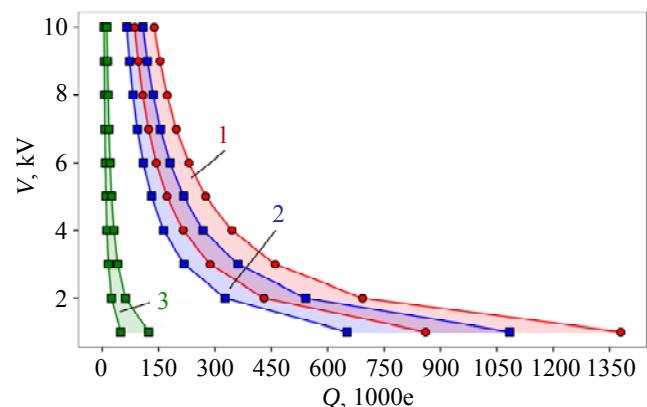


Fig. 1. Confinement regions of particles for different voltage waveforms at the frequency of 50 Hz (calculation): 1 (red) – sinusoidal, 50 μm ; 2 (blue) – rectangular (meander, $K_p = 50\%$), 50 μm ; 3 (green) – rectangular, 20 μm

Figure 2 shows the confinement regions (calculation) for 50- μm particles under meander voltage at frequencies of 50 Hz (2, blue) and 100 Hz (1, red). When the frequency was increased to 100 Hz, confinement region 1 shifted toward higher particle charges so far that regions 1 and 2 did not overlap. Consequently, particles that were confined in the trap at a frequency of 50 Hz would not be confined when the frequency was increased to 100 Hz. This fact was verified

experimentally. At a voltage amplitude of 4 kV (meander) and a frequency of 50 Hz, a cloud consisting of a large number of particles was confined in the trap. As the frequency was increased in 20-Hz steps, the number of particles gradually decreased, and at 100 Hz, no particles remained in the trap.

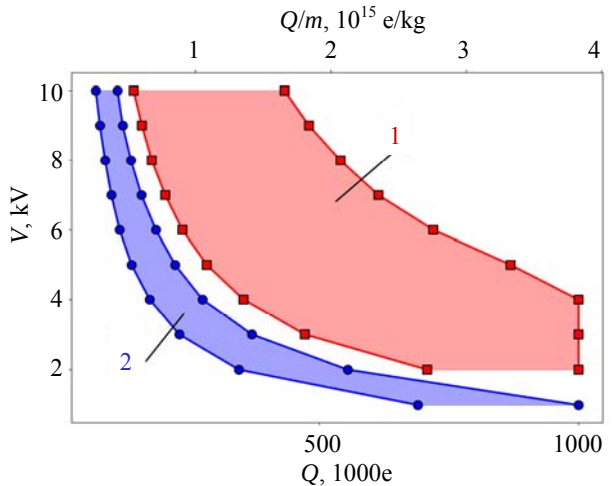


Fig. 2. Confinement regions for particles with a diameter of 50 μm under meander voltage. 1 (red) – frequency of 100 Hz; 2 (blue) – 50 Hz

For a sinusoidal confining voltage with a 5 kV amplitude, a 50 Hz frequency, and a 2.5-kV voltage on the charging plate, particles sized from 2 to 60 μm were confined in the experiment, with an average size of 26 μm . The estimate of the physically possible charge for 20- μm particles (15,625–195,312 e) completely covers the calculated confinement region (12.600–32.800 e). For 5- μm particles, the overlap is 87% (976–12.207 e vs. 2.600–9.300 e); for 50 μm particles, it was about 30% (97.656–1.220.703 e vs. 178.100–278.100 e). Since the original mixture initially contained few particles smaller than 10 μm or larger than 40 μm – the experimentally obtained particle size distribution was similar to that of the original mixture. Thus, the experiment confirms the calculations.

Fig. 3 shows the effect of positive half-cycle duty factor K_p on the confinement regions (calculation) for 20- μm particles at a 50-Hz frequency. Confinement was possible at $K_p = 50\%$, 40%, 35% due to the balance of forces. At $K_p = 40\%$, region 2 lies inside region 1 ($K_p = 50\%$) and was shifted to the right toward higher charges; at $K_p = 35\%$, region 3 became even narrower and shifted further to the right,

extending beyond the boundary of region 1. Consequently, as the pulse asymmetry increased, the range of stable charges narrowed. For particles sized 5 and 50 μm , confinement was possible only at $K_p = 50\%$ (meander). Light particles (5 μm) were more strongly shifted under asymmetric pulses and were attracted to the electrodes, while large particles (50 μm) did not have time to return during the short half-cycle due to inertia. Particles sized 10 μm were confined at $K_p = 50\%$ и 40%. The experimental data on the deposition of trapped particles were in qualitative agreement with the calculations.

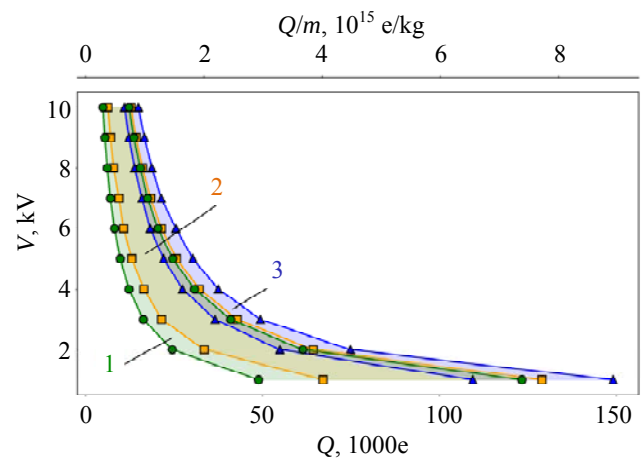


Fig. 3. Confinement regions for microparticles with a 20- μm diameter at a 50-Hz frequency for different values of positive pulse duty factor K_p : 1 – meander $K_p = 50\%$ (green region); 2 – 40% (orange); 3 – 35% (blue)

The effect of an external pulsed periodic alternating electric field, with the frequency varying in the range of 20–170 Hz, on the particle trajectories in the trap under a sinusoidal confining voltage (5–7 kV, 50 Hz) was studied experimentally and numerically. The external electric field was generated by two metal plates placed at a distance of 2 cm from the trap electrodes, to which a meander-shaped pulsed voltage (3–5 kV) was applied. It was found that the external electric field excited two different instabilities: particle ejection at a 27 Hz frequency and particle loss at 200 Hz, both in calculations and experiments. At 125 Hz, the trajectories stabilized, particle oscillations decreased and the distance between particles was reduced. The calculation results are in alignment with the experiments. Figure 4 shows the calculated trajectories: a stable trajectory without

an external electric field is shown on the left; the instability excited at an external field frequency of 27 Hz is shown on the right, where the trajectory amplitude increased with each oscillation, causing the particle escapes from the trap.

The effect of the plasma on particle confinement was studied in a quadrupole trap with electrodes having diameters of 63, 120, and 200 μm , 11 cm in length, and a 1-cm distance between the electrodes. The threshold ignition voltage was 2.6 kV for the 63 and 120- μm electrodes, and 4.0 kV for the 200- μm electrodes.

With the electrodes of 63 and 120 μm , particles sized 2–8 μm were trapped; for the electrodes of 200 μm , particles sized 40–60 μm were trapped. Stable particle confinement was observed at corona discharge currents of 15–70 μA . Figure 5 shows an image of particles confined in the trap with an electrode diameter of 63 μm under rectangular voltage pulses (meander) with a 3.2 kV amplitude, a 50 Hz frequency, and 30 μA corona discharge current. The number of trapped particles at the meander voltage was much larger than at the sinusoidal voltage of the same amplitude.

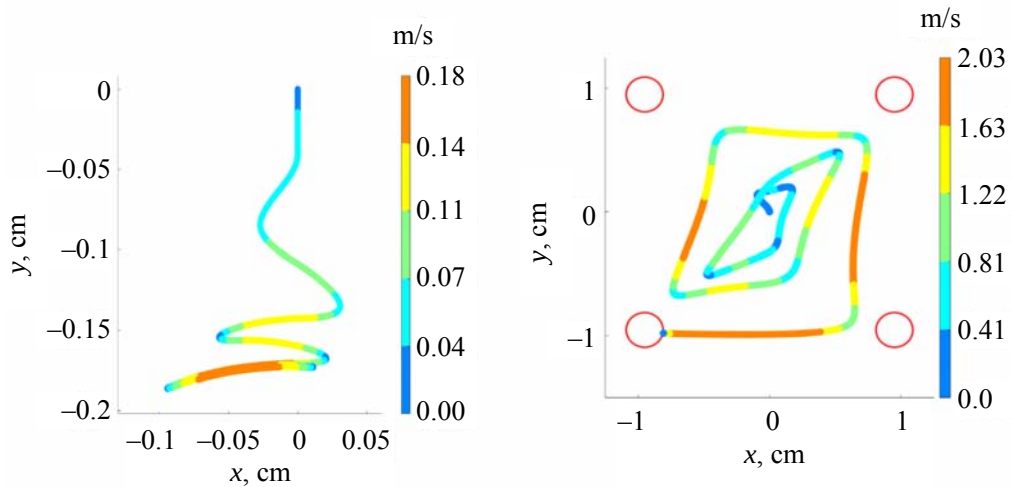


Fig. 4. Left: stable trajectory without the external electric field. Right: trajectory of the particle escaping from the trap at the external field frequency of 27 Hz. The colour indicates the particle velocities. Particle: charge 98,000 e, diameter 20 μm . Rectangular voltage (meander) on the plates: $V = 5$ kV. Confining sinusoidal voltage on the trap electrodes: $V = 7$ kV, 50 Hz

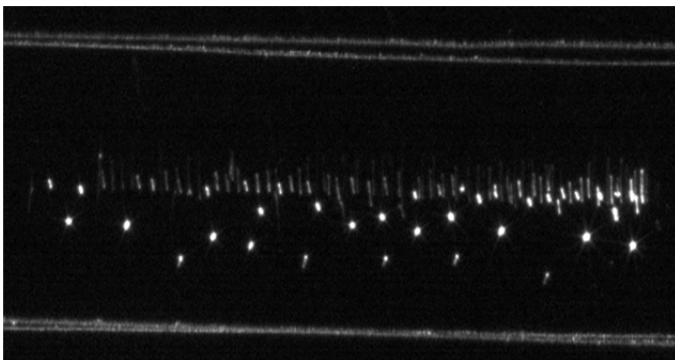


Fig. 5. Photo of microparticles trapped by the trap with corona discharge plasma

Conclusion

Experimental and numerical studies have shown that the confinement regions depend on the particle sizes, and the similarity law for the charge-to-mass ratio does not hold. This

difference allows for selectively influencing particles of a specific size. The waveform of the confining voltage has been found to have a significant effect on the stability regions. The rectangular confining voltage (meander) allows for the confinement of particles with a lower

charge than the sinusoidal voltage does, due to the longer application of the electric field at its amplitude value. An increase in the frequency of the confining voltage shifts and expands the confinement regions toward higher voltages and charges, which allows for the selective screening of particles. As for asymmetric rectangular voltage pulses, as the duty factor K_p decreases, the confinement region narrows and shifts toward higher charges, thus allowing for the selective confinement or screening of particles of different sizes. An external meander-shaped electric field allows for controlling the particle dynamics in a trap with a sinusoidal confining voltage: by varying the frequency of the external electric field, one can cause a loss of particles or the excitement of instability, leading to particle

escape from the trap. There is a frequency range in which the external electric field stabilizes unstable particle trajectories in the trap, thus reducing the oscillation amplitude and the distance between particles. It was experimentally found that, in a quadrupole linear trap with a corona discharge plasma under a meander-shaped rectangular voltage, much more particles are confined than under a sinusoidal voltage. This occurs only in a narrow range of corona discharge currents, while the size of the confined particles depends on the diameter of the corona electrodes.

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REFERENCES

1. Mihalcea B. M., Filinov V. S., Syrovatka R. A., and Vasilyak L. M., Phys. Rep. **1016**, 1–103 (2023).
2. Rybin V. V., Rudy S. S., and Kokorina O., JVE **32**, 156–159 (2020).
3. Rudy S. S., Vasilyev M., Rybin V. V., and Rozhdestvensky Yu. V., Int. J. Mass Spectrom. **479**, 116894 (2022).
4. Rybin V. V., Rudy S. S., and Rozhdestvensky Yu. V., Int. J. Non-Linear Mech. **147**, 104227 (2022). <https://doi.org/10.1016/j.ijnonlinmec.2022.104227>
5. Reilly P. T. A., Chakravorty S., Bailey C. F., Obe F. O., and Huntley A. P., J. Am. Soc. Mass Spectrom. **32** (10), 2615 (2021).
6. Simke F., Fischer P., Marx G., and Schweikhard L., Int. J. Mass Spectrom. **473**, e116779 (2021).
7. Ivanov A. I., Sysoev A. A., and Kononov N. V., Eur. J. Mass Spectrom. **30** (3–4), 143 (2024).
8. Ivanov A. I., Sysoev A. A., Kononov A. N., and Kononov N. V., J. Mass Spectrom. **59** (6), e5030 (2024).
9. Sheretov E. P. and Terentev V. I., Technical Physics **42**, 953 (1972) [in Russian].
10. Richards J. A., Huey R. M., and Hiller J., Int. J. Mass Spectrom. **12**, 317 (1973).
11. Ding L., Sudakov M., and Kumashiro S., Int. J. Mass Spectrom. **221**, 117 (2002).
12. Sudakov M. and Nikolaev E., Eur. J. Mass Spectrom. **8**, 191 (2002).
13. Ding Li, Sun Lulu, and Wang Weimin, Mass Spectrometry Reviews **336** (2026). <https://doi.org/10.1002/mas.70022>
14. Dobroklonskaya M. S., Vasilyak L. M., Vladimirov V. I., and Pecherkin V. Ya., Applied Physics, No. 2, 29–34 (2023) [in Russian].
15. Dobroklonskaya M. S., Vasilyak L. M., Vladimirov V. I., and Pecherkin V. Ya., Applied Physics, No. 3, 93–98 (2024) [in Russian].
16. Dobroklonskaya M. S., Pecherkin V. Ya., Vladimirov V. V., and Vasilyak L. M., Herald of the Joint Institute for High Temperatures **15**, 44–48 (2024) [in Russian].

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Steam-water reforming of methane using a AC plasmatron of megawatt power

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This paper presents the results of a study of steam-water conversion of methane using a three-phase AC plasmatron of megawatt power operating on methane. The process was carried out with the simultaneous supply of methane to the arc channels of the plasmatron and water to the plasmatron chamber. It was established that the studied methane decomposition process occurs according to a two-stage scheme: methane pyrolysis in the arc channels in the first stage, followed by steam-water conversion together with water supplied to the plasmatron chamber in the second stage. Data on the influence of the ratio of methane and water consumption on the concentration of pyrolysis products were obtained. The plasmatron operating modes during the study varied within the following ranges: arc power from 1.32 to 1.61 MW, methane flow rate from 43 to 57.5 g/s, and water flow rate from 0 to 67 g/s.

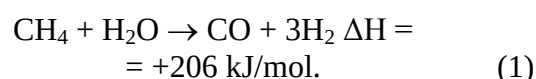
Keywords: plasmatron, electric arc, hydrogen production, methane pyrolysis, methane conversion, synthesis gas.

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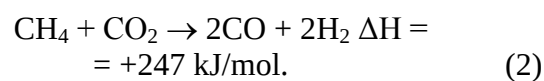
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Introduction

Methane steam-water reforming is one of the methods for producing synthesis gas, which serves as an intermediate feedstock in many chemical processes. There are several methods for its production from natural gas: steam catalytic reforming, CO₂ reforming, and partial oxidation [1–3]. During steam reforming, methane reacts with steam under a pressure of 0.3–2.5 MPa in the presence of a catalyst and produces synthesis gas. Reaction (1) is endothermic, the energy required to carry out the reaction should be obtained from an external source. Currently, steam reforming of methane is the main industrial method of producing hydrogen:



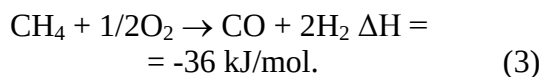
During CO₂ reforming, methane reacts with carbon dioxide to form synthesis gas with an increased content of carbon monoxide. This method has recently attracted considerable interest due to the simultaneous use and reduction of emissions of two common and undesirable greenhouse gases CH₄ and CO₂.



As a result of this process, synthesis gas is produced with a molar H₂/CO ratio close to 1, which is optimal for subsequent Fischer–Tropsch synthesis.

Both reactions (1) and (2) are highly endothermic, requiring energy supply.

Partial oxidation of methane is also an attractive alternative method for producing synthesis gas [3]. The reaction is exothermic, reducing the energy consumption of the reforming process.



The non-plasma technologies considered above have limitations related to the need for catalysts, which gradually deactivate during the process at high temperatures due to agglomeration and carbon deposition.

Unlike these traditional technologies, plasma reforming has a number of important advantages, in particular, high quality of the gas produced and ease of control of its composition, compactness, fast response time, compatibility with a wide range of hydrocarbons and elimination of problems with catalysts. Moreover, plasma technologies are environmentally friendly processes because they do not emit greenhouse gases.

Plasma technologies are based on the use of non-equilibrium plasma or thermal plasma. Corona discharge [4], microwave discharge [5], sliding arcs [6], barrier discharge [7], and glow discharge [8] are used as non-equilibrium plasma. In this case, active particles are formed that participate in the chemical mechanism, however, a break in the chemical process chain at the endothermic stages is extremely likely. Therefore, these methods are very energy-consuming and can only be used in conjunction with catalysts.

In higher-performance devices, thermal plasma of carbon dioxide [9, 10] and water vapor [11] is used. In this case, the conversion rate and selectivity are determined by the process temperature. Significant methanation under the action of water vapor and carbon dioxide occurs at high temperatures (above 1,100 °C) [12]. At the same time, higher temperatures lead to increased selectivity towards acetylene. The economic features of this method are determined by the service life of the electrode assembly, productivity and efficiency of using electrical energy [13].

Experimental conditions and their analysis

In the present work, the AC plasmatron with megawatt power "Zvezda" was used as a source of plasma heating of methane and water (Fig. 1). The plasmatron design features and the description of operation with various gases are given in [14–19]. In this work, methane was supplied to the arc channels (electrodes), pos. 1 in Fig. 1, and water was supplied to the plasmatron chamber, pos. 2 in Fig. 1. To enable operation with methane and use the plasmatron in plasma-chemical technologies, the plasmatron design was modified to avoid negative effects associated with the possible deposition of carbon in the insulator area and methane injection points into the arc channels [20–22]. Towards the camera, pos. 2 in Fig. 1, through the nozzle, pos. 7 in Fig. 1, the adapter is attached, pos. 8 in Fig. 1, designed to increase the residence time of pyrolysis products. Gas is extracted at the end of the mouthpiece for chromatographic analysis from the channel, pos. 10 in Fig. 1. The gas composition of the pyrolysis products was measured using a Crystallux 4000M chromatograph, with argon as the gas carrier. Pyrolysis products flow through the adapter nozzle, pos. 9 in Fig. 1, into the test box and burn up in the atmosphere, as shown in Fig. 2. The total volume of the chamber and the adapter is 2.8 liters, and the total residence time of the pyrolysis products is ~2.5 ms.

The described scheme for supplying plasma-supporting gas into the arc channels and liquid into the chamber was previously used [14] for plasma gasification of a coal-water slurry (CVS) of the composition 40% H₂O, 60% C with a plasmatron power of 680 kW, a plasma-supporting gas flow rate of 97 g/s, and CVS flow rate of 70 g/s.

In the present work, the power of the plasma torch varied in the range from 1.32 to 1.61 MW, and the efficiency measured by heat loss to the plasma torch cooling system was $\eta = 85\%$.

Table 1 contains the test parameters. In all experiments except No. 7, water was supplied to the chamber. Specific energy deposition to methane and water (Table. 1), was calculated as follows:

$$N_{sp} = N_d \cdot \eta / (G_{\text{CH}_4} + G_{\text{H}_2\text{O}}),$$

where G_{CH_4} , $G_{\text{H}_2\text{O}}$ are methane and water flow rate; N_d is the arc power.

The pressure in the plasmatron chamber P_{ch} varied in the range from 0.21 to 0.25 MPa and was determined by both the flow rates of methane and water, as well as the diameters of the adapter outlet nozzles d_n and the plasmatron chamber d_c .

Table 2 contains the results of the measurements of the volumetric fractions of upyrolysis products and the mass fractions μ obtained by calculation. The calculation of mass fractions was based on the results of volumetric

fractions measurements and on the condition that the number of carbon, hydrogen and oxygen atoms in a mixture of methane and water with a total flow of $G_{CH_4} + G_{H_2O}$ is preserved. The fraction of water that reacted was determined using the volumetric fractions of CO in the pyrolysis products. It was assumed that the rest of the unreacted water was discharged with a plume. The last column of Table 2 shows v_{H_2}/v_{CO} , the ratio of the volumetric fractions of H_2 and CO.

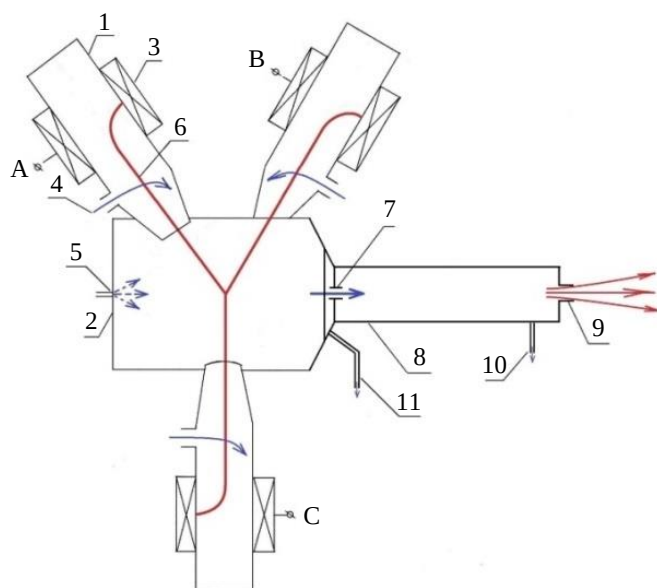


Fig. 1. The plasmatron "Zvezda" scheme: 1 – electrode; 2 – chamber; 3 – magnetic coils; 4 – CH_4 supply to electrodes; 5 – H_2O supply to the plasmatron chamber; 6 – electric arc; 7 – chamber outlet nozzle; 8 – adapter; 9 – nozzle at the adapter outlet; 10, 11 – sampling for chromatographic analysis

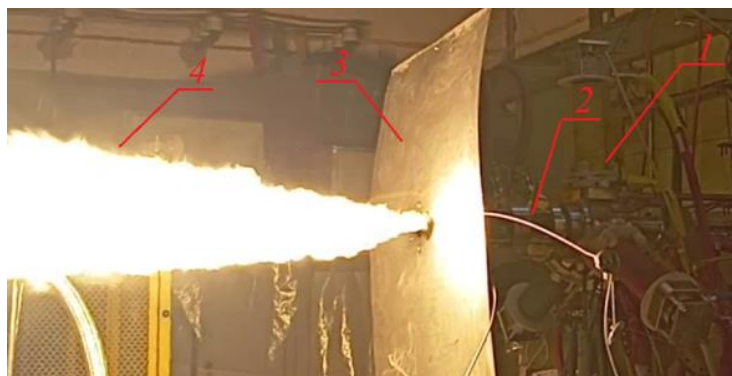


Fig. 2. Photo of the plasmatron start-up: 1 – plasmatron; 2 – adapter; 3 – protective shield; 4 – combustion of pyrolysis products in the atmosphere

Figure 3 shows the dependence of the pyrolysis products volumetric fractions on the inlet ratio of G_{H_2O}/G_{CH_4} flow rates. As can be seen, the hydrogen concentration decreases from 82% to 74% as the flow rate of the supplied water increases. In turn, the CO concentration also decreases, but more significantly, from 15.8% to 10%. There is a significant increase in acetylene concentration as water flow rate increases: from 1% to 8%, the percentage of ethylene and unreacted methane also increases. Water was not

detected in the gaseous pyrolysis products due to its condensation in the pipeline connecting the sampling device to the chromatograph. The ratio of volumetric fractions v_{H_2}/v_{CO} increases from 5.2 to 7.3 with increasing water flow into the plasmatron chamber (Curve 6 in Fig. 3).

The water and carbon concentrations were guided by the dependences of the mass fraction distributions presented in Table 2 and Figure 4, which show the flow rates of pyrolysis products directly in g/s. At the minimum water supply

$G_{\text{H}_2\text{O}}/G_{\text{CH}_4} = 0.55$, the mass fraction of water in the pyrolysis gas is minimal and amounts to 2.6%, the remaining water participated in the reaction. At the same time, the methane conversion rate is more than 99%. As $G_{\text{H}_2\text{O}}/G_{\text{CH}_4}$ increases, the concentration of water in the pyrolysis gas increases to 48% by weight. Figure 4 also shows the dependence of the

equilibrium temperatures in the chamber Te (curve 8), obtained by calculation [23] using data on specific energy consumption N_{sp} . It can be seen that an increase in $G_{\text{H}_2\text{O}}/G_{\text{CH}_4}$ at the inlet leads to a decrease in Te , while a decrease in the content of CO and C is accompanied by an increase in the content of acetylene by more than 4 times.

Table 1

Experimental setting

Experiment No.	G_{CH_4} , g/s	$G_{\text{H}_2\text{O}}$, g/s	$G_{\text{H}_2\text{O}}/G_{\text{CH}_4}$	N_d , kW	N_{sp} , MJ/kg	d_c , mm	d_H , mm	P_k , MPa
1	43.28	24	0.555	1.61	20.62	30	32	0.216
2	44.99	36	0.800	1.52	16.17	30	32	0.235
3	44.08	36	0.817	1.49	15.97	30	32	0.233
4	47.2	66	1.398	1.32	10.02	30	32	0.246
5	46.95	67	1.427	1.35	10.21	30	28	0.241
6	46.92	67	1.428	1.64	12.39	30	28	0.238
7	57.54	0	0	1.384	20.67	30	60	0.182

Table 2

Composition of pyrolysis products

Experiment No.		H_2	C_2H_4	C_2H_2	CH_4	CO	C	H_2O	$\nu_{\text{H}_2}/\nu_{\text{CO}}$
1	ν , %	82.18	0.48	1.02	0.49	15.83	0	0	5.19
	μ , %	19.07	1.56	3.08	0.91	51.43	21.35	2.61	
2	ν , %	77.82	0.45	5.17	1.95	14.62	0	0	5.32
	μ , %	14.77	1.2	12.75	2.96	38.84	10.01	19.48	
3	ν , %	78.87	0.597	5.23	1.06	14.24	0	0	5.53
	μ , %	14.83	1.57	12.78	1.59	37.51	10.87	20.84	
4	ν , %	74.68	0.65	8.12	5.78	10.77	0	0	6.93
	μ , %	9.17	1.12	12.94	5.68	18.52	6.17	46.39	
5	ν , %	74.99	0.91	7.89	6.12	10.07	0	0	7.44
	μ , %	8.89	1.51	12.17	5.81	16.72	6.85	48.05	
6	ν , %	74.61	0.77	8.12	6.3	10.20	0	0	7.31
	μ , %	8.86	1.28	12.54	5.99	16.97	6.46	47.91	
7	ν , %	77.61	0.97	12.29	9.13	0	0	0	—
	μ , %	17.62	3.08	36.28	16.59	0.000	26.42	0.000	

Using the dependence of Te on $G_{\text{H}_2\text{O}}/G_{\text{CH}_4}$ shown in Fig. 4, calculations of $\nu_{\text{H}_2\text{O}}/\nu_{\text{CO}}$ were performed in the equilibrium approximation using [23] (curve 7 in Fig. 3). As can be seen, the nature of the curve obtained as a result of calculations differs significantly from the experimental one: an increase in $G_{\text{H}_2\text{O}}/G_{\text{CH}_4}$ leads

to a decrease in $\nu_{\text{H}_2}/\nu_{\text{CO}}$ to ~ 3.2 , while in the experiment there is an increase in $\nu_{\text{H}_2}/\nu_{\text{CO}}$ (curve 6 in Fig. 3). This is due to the processes non-equilibrium in a chamber. This is confirmed by the results obtained without supplying water to the chamber (line 7 in Tables 1 and 2). In this case, the composition was measured directly before entry into the adapter through the existing

gas sampling channel, item 11 in Fig. 1. As can be seen, in this case, the maximum concentration occurs for acetylene, which indicates the processes non-equilibrium due to the short residence time. As a result, when water is supplied to the chamber from the nozzle, it interacts with both undecomposed methane (16.6% by weight) and acetylene (36.3% by weight). The interaction of acetylene with water has been sufficiently studied at low temperatures

(the Kuchеров reaction). For high temperatures, without catalysts, the kinetic process has been poorly studied. However, the equilibrium calculation shows that, for example, at $G_{H_2O}/G_{C_2H_2} \sim 1$ and a temperature of 1,500 K, the pyrolysis products consist of H_2 , CO , C in a molar fractions ratio of 4.4 : 2.5 : 1, in the absence of C_2H_2 . This indirectly confirms the two-stage nature of methane steam-water reforming in the structure under consideration.

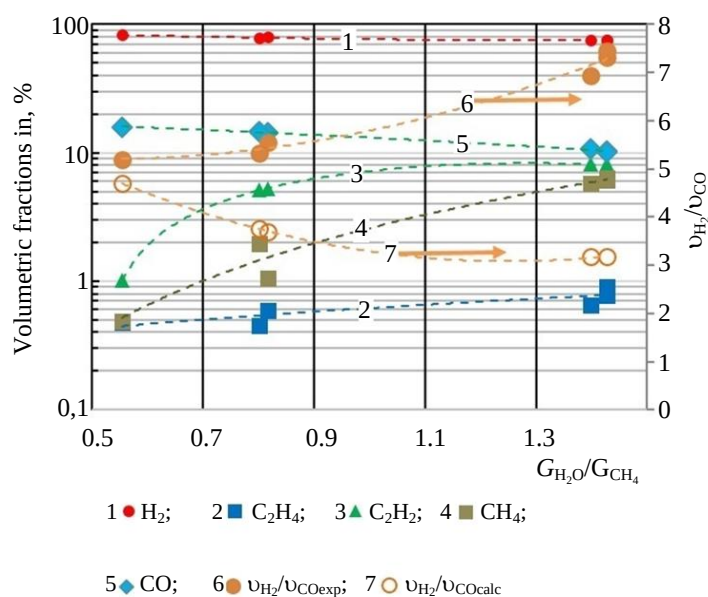


Fig. 3. Dependence of the volumetric fractions of pyrolysis products on the ratio G_{H_2O}/G_{CH_4}

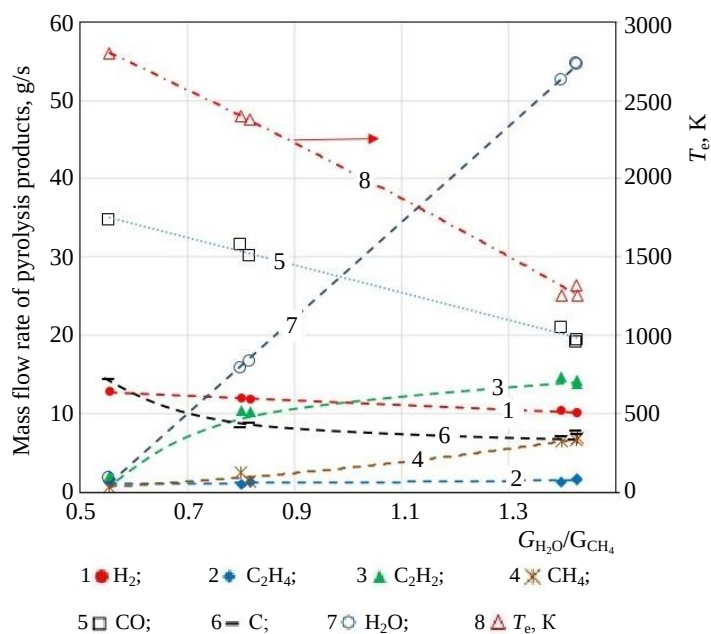


Fig. 4. Dependence of mass flow rates of pyrolysis products on the ratio G_{H_2O}/G_{CH_4}

Conclusion

1. The possibility of autonomous operation on methane of the AC plasmatron with megawatt power, as well as when supplying water to carry out steam–water methane reforming, during which methane is supplied to the arc channels of the plasmatron, and water supply to the plasmatron chamber has been demonstrated. Data on the influence of the methane-to-water flow rate ratio on the concentration of pyrolysis products have been obtained. The operating modes of the plasmatron varied in the following ranges: arc power from 1.32 to 1.61 MW, methane flow rate from 43 to 57.5 g/s, water flow rate from 0 to 67 g/s.

2. It was demonstrated that reducing the water-to-methane flow rate ratio to $G_{H_2O}/G_{CH_4} = 0.55$ results in a minimum $v_{H_2}/v_{CO} \sim$ ratio of 5.2 at a methane pyrolysis degree exceeding 99%. When increasing G_{H_2O}/G_{CH_4} to ~ 1.42 , the ratio of v_{H_2}/v_{CO} increases to ~ 7.3 .

3. It has been established that the investigated processes are significantly influenced by non-equilibrium conditions due to the short residence time of pyrolysis products, and the decomposition process itself proceeds via a two-stage scheme: methane pyrolysis in arc channels – at the first stage, followed by steam–water reforming together with water supplied into the plasmatron chamber – at the second stage.

REFERENCES

- Holladay J. D., Hu J., King D. L., and Wang Y., *Catalysis Today* **139**, 244–260 (2009).
- Lubitz W. and Tumas B., *Chem Rev.* **107** (10), 3900–3903 (2007).
- Oyama S. T., Hacıoğlu P., Gu Y., and Lee D., *Int J Hydrogen Energy* **37**, 10444–10450 (2012).
- Nguyen H. and Kim K., *Catalysis Today* **256**, 88–95 (2015).
- Czyłkowski D., Hrycak B., Jasiński M., Dors M., and Mizeraczyk J., *Energy* **113**, 653–661 (2016).
- Shekhawat D., Spivey J. J., and Berry D. *Fuel Cells: Technologies for Fuel Processing*; Amsterdam, Elsevier Science, 2011.
- Górska A., Krawczyk K., Jodzis S., and Schmidt-Szałowski K., *Fuel* **90** (5), 1946–1952 (2011).
- Guo F., Xu J.-Q., and Chu W., *Catalysis Today* **256**, 124–129 (2015).
- Tao X., Qi F., Yin Y., and Dai X., *International Journal of Hydrogen Energy* **33** (4), 1262–1265 (2008).
- Yanpeng S., Yong N., Angshan W., Dengxiang J., Fengwen Y., and Jianbing J., *Plasma Science and Technology* **14**, 252–256 (2012).
- Rutberg G., Kuznetsov V. A., Popov V. E., Popov S. D., Surov A. V., Subbotin D. I., and Bratsev A. N., *Applied Energy* **148**, 159–168 (2015).
- Boulos M. I., Fauchais P., and Pfender E. *Thermal Plasmas: Fundamentals and Applications*. New York, Springer Science+Business Media, 1994.
- SriBala G., Michiels D., Leys C., Van Geem K. M., Marin G. B., and Nikiforov A., *Journal of Cleaner Production* **209**, 655–664 (2019).
- Koshlakov V. V., Rebrov S. G., Golikov A. N., Fedorov I. A., Morozov A. G., and Ilyusha A. V., *Thermal processes in engineering* **12** (8), 374–384 (2020) [in Russian].
- Koroteyev A. S., Mironov V. M., and Svirchuk Yu. S. *Plasmatrones: design, characteristics, calculation*. Moscow: Mechanical Engineering, 1993 [in Russian].
- Svirchuk Y. S. and Golikov A. N., *IEEE Transaction on Plasma Science* **44** (12), 3042 (2016).
- Golikov A. N., Zaikin N. S., and Svirchuk Yu. S. Three-phase electric arc plasma generator and method for start-up thereof. Patent for invention No. 2577332 (RF). 2016.
- Golikov A. N., Kochetkov Yu. M., Polyansky M. N., and Svirchuk Yu. S., *Thermal processes in engineering* **1** (9), 390–396 (2009) [in Russian].
- Koshlakov V. V., Rebrov S. G., Golikov A. N., and Fedorov I. A., *Applied Physics*, No. 4, 32–39 (2021) [in Russian].
- Koshlakov V. V., Volkov N. N., and Kozaev A. Sh. Plasma-chemical synthesis gas production method and installation for its implementation. Patent for invention No. 2699124 (RF). 2019.
- Koroteev A. S. Method for producing hydrogen and acetylene and installation for implementation thereof. Patent for invention No. 2765466 (RF). 2021.
- Koshlakov V. V., Rebrov S. G., Golikov A. N., and Fedorov I. A. Method for producing hydrogen and carbon black from natural gas. Patent for invention No. 2803529 (RF). 2022.
- Trusov B. G., *Bulletin of MSTU im. N. E. Bauman (Instrument engineering)* **1** (1), 240–249 (2012) [in Russian].

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The influence of crystal diameter on the directed electric discharge in water along a thin trace with NaCl salt ions

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A recent study demonstrated that it is possible to control the trajectory of an electrical discharge in water using a thin trail of increased electrical conductivity formed by the movement of a sodium chloride (NaCl) crystal in water. An unusual structure of the discharge channel was also noted, namely the formation of separate, unconnected plasma regions that subsequently merge into a single discharge channel. An explanation for this phenomenon was provided based on shadowgraph images depicting the distribution of dissolved salt around the crystal and the results of numerical simulations of concentration. These revealed the influence of a vortex forming behind the crystal on the distribution of salt, conductivity, and ultimately, energy release in the region immediately following the crystal, the maximum of which was found to be significantly displaced from the surface. In the present work, the investigation was conducted using a crystal of smaller diameter (195 μm vs. 518 μm), and a comparison of the results is presented. The reduction in diameter led to a vortex-free flow regime and a more monotonic distribution of salt concentration within the trail. This, in turn, altered the discharge development, which became sequential – propagating from the electrode to the crystal and then continuously further into the trail. Numerical simulations, implemented in a new, refined three-dimensional formulation, revealed a pattern of heat release distribution distinct from the case of the 518 μm crystal and consistent with the results of the present experiment.

Keywords: guided discharge, breakdown, water, electrolyte, salt, NaCl, crystal, non-uniform conductivity field.

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Introduction

Controlling the trajectory and dynamics of a pulsed electric discharge in condensed media is a fundamental scientific and engineering task. This problem is most acute in liquids, in particular in water, where high heat capacity and the presence of ionic conductivity create obstacles to the formation of extended discharge channels. Classical approaches to solving this problem,

originating from the work of L. A. Yutkin on the electrohydraulic effect [1], include the use of exploded wires (metal wire) or the use of laser radiation to create an area of reduced density or optical breakdown along the discharge path [2, 3]. However, both methods have a number of features and limitations. The wire method requires mechanical reinstallation of the electrode after each pulse and leads to contamination of the working medium and electrodes with erosion

products [1]. Laser control, although contactless, involves the use of more complex and expensive equipment [4, 5]. Therefore, the search for alternative, simpler, and more cost-effective methods of creating guiding channels with enhanced conductivity in water is currently relevant.

A new approach proposed in [6] is the use of a crystal of table salt (NaCl) moving in the interelectrode gap. As the crystal dissolves, it leaves a trace with a locally increased concentration of ions, which determines the preferred trajectory for the development of the discharge [6]. The paper not only confirmed the fundamental possibility of such control, but also revealed the unusual nature of the discharge process: the formation of two separate, unrelated plasma regions – at the electrode and in the wake of the crystal, which subsequently combined into a single channel. It was hypothesized that this phenomenon is related to the hydrodynamic regime of crystal flow. When using a crystal with a diameter of 518 microns, a trailing-vortex wake formed behind it, leading to a nonmonotonic distribution of salt concentration (and therefore conductivity) and, as a result, to the localization of energy release at some distance from the crystal surface. The obtained results suggest a broader formulation of the question: how do the geometric parameters of the initiating element (crystal) influence the hydrodynamics of the flow, the spatial distribution of conductivity in the wake, and ultimately – the dynamics of discharge channel formation?

The purpose of this paper is an experimental and numerical study of the effect of the diameter of a NaCl crystal on its flow regimes and the features of the development of a pulsed electric discharge in water. In this paper, the results obtained for a crystal with a diameter of 195 microns are compared with previously published data for a crystal with a diameter of 518 microns [6]. Reducing the diameter made it possible to implement a vortex-free flow around regime, which led to a more monotonous distribution of salt concentration inside the wake and a fundamentally different sequential breakdown dynamics. A refined three-dimensional numerical model has been developed to interpret experimental data and imaging the heat release distribution.

Experimental setup

The task in the experimental part of the study is set as follows. The study focuses on the discharge channel development path in weakly conducting water, where regions of high electric field intensity (near the pointed electrode) and sodium chloride crystal moving in water are simultaneously present in close proximity. The crystal leaves behind a thin brine wake of relatively high conductivity due to partial dissolution.

An experimental setup described in detail in [6, 7] was used to study the behavior of the discharge channel in the presence of the wake behind a falling salt crystal. Here we will give only a brief description of it, with an emphasis on its main parts and properties. The breakdown was carried out in a needle-plane electrode system, where "needle" refers to a pointed tungsten electrode (a cone ~0.1 mm rounded tip radius) to which a high-voltage pulse was applied, and "plane" refers to a grounded round plate made of stainless steel. This configuration of the electrodes was chosen in order to ensure the maximum electric-field intensity near the high-voltage electrode, where the salt crystal fell and high-speed imaging of the process was conducted. The electrodes were placed in a ~0.5 L cell with transparent walls filled with distilled water so that the entire surface of the electrodes was under water, the axis of the pointed electrode was perpendicular to the plane of the grounded electrode and parallel to the surface of the water. The distance from the pointed electrode top to the surface of the grounded one was 8 mm, and to the surface of the water – 1 cm.

To ensure that the crystal falls, a tube with an inner surface in the form of a cone is used, so that when the crystal falls through it into the water, its path is well controlled. By adjusting the position of the tube, we achieved the crystal transmission in the immediate vicinity of the crystal edge. The optical scheme described in [6, 7] was used to control the crystal path. Here we briefly note that a shadow imaging method was used, which allows observing not only the crystal and the electrode, but also the thin wake with increased salt concentration. The spatial resolution of the system was approximately 3 microns/pixel, and the frames exposure was 10 microseconds. It should be noted that the

ability to control the location of the crystal drop made it possible to use a high-speed video camera as a trigger for the rest equipment used in the experiment: a high-voltage switch, an oscilloscope [6, 7].

The high-voltage supply to the pointed electrode was realized using a high-voltage switch of the "half-bridge" type, which, with a rise time of ~ 100 ns and a fall time of ~ 100 ns, applied voltage to the electrode and removed it, respectively. The voltage was applied from a high-voltage capacitor through a current shunt and a current-limiting resistor, triggered by a high-speed video camera signal—i.e., at the moment the crystal reached the region near the pointed end of the high-voltage electrode. During the experiment the following was recorded: voltage waveforms on the pointed electrode, the current between the electrodes, as well as high-speed shadow film of frame strips of the development of an electric discharge between them. The study used salt crystals of two diameters: 195 and 518 microns.

Mathematical modeling methods

The electrical breakdown modeling of a salt crystal moving in water is divided into two stages. On the first stage, the flow around the crystal from the surface of which the salt dissolves is calculated. The crystal size (the ball radius) is considered unchanged when flowing around. For particle motion in the gravity field, the velocity distribution and salt concentration are calculated based on the Navier–Stokes equations solution, impurity transfer, and ODE (ordinary differential equations). The model uses a non-inertial moving cylindrical coordinate system associated with a particle. The viscous friction force acting on a particle from a continuous medium is calculated by integrating the normal component of the stress tensor over the particle surface. Due to the axial symmetry of the problem, only the force component along the z axis differs from zero. On the particle surface, an adhesion condition is set as a boundary one. At the inflow boundary, the velocity of the liquid is equal to the crystal falling velocity. On the region outer boundary (the normal velocity and tangential stress are zero) a symmetry condition is set. At the initial moment of time, the crystal is

considered stationary. The impurity transfer equation is solved in mass fraction variables, and the diffusion model is based on Fick's law. The solution density is determined based on the mass fractions of the mixture. A Dirichlet type condition is set on the surface of the sphere, i.e. the maximum mass fraction of salt is set based on the solubility limit. In addition, the conditions of axial symmetry, zero flow, as well as the condition for the free flow of passive impurities are set. The diameter is a characteristic parameter for the size of the computational region, as well as the size of the grid cells. In dimensionless coordinates, taking into account the axial symmetry setting, the ball center is 3 calibers away from the lower boundary. The trailing edge is located at a distance of 12 calibers from the center of the ball. The lateral (vertical) boundary of the computational region is located 4 calibers from the axis. The region dimensions were chosen in such a way that, in the local coordinate system of the falling body, the velocity field disturbances introduced by it into the flow are small at the boundaries. At start time, there is no admixture of salt in the solution. The solution conductivity is determined based on the obtained asymptotic distribution of the salt concentration based on experimental data from other authors [8].

At the second stage, the obtained distribution is used for a stationary tasks in a three-dimensional formulation based on Maxwell's equations and relations for material parameters. On the electrode left surface (modeling a high-voltage pointed electrode), a constant potential is set with an amplitude corresponding to the experimental value ($V = 8$ kV), the right (grounded) electrode of the same shape is grounded ($V = 0$ C), the remaining boundaries are provided with zero charge condition. At a distance from the crystal, the liquid parameters (permittivity, conductivity) are assumed to be equal to the values of distilled water. The results of the second modeling stage include the distributions of electric potential, current, and heat source density.

Results and discussion. Experimental results

Earlier, the authors showed [7] that the development of an electric discharge in the wake

of a moving crystal has a feature: in the early stages of development, the discharge channel is not continuous, but consists of separate sections – the first is located between the electrode and the crystal, and the second is inside the wake at a distance from the crystal of the order of its diameter. The explanation of this effect was given based on the results of numerical modeling of the crystal flow around, taking into account its dissolution and the salt concentration distribution, which provides increased electrical conductivity of individual regions. The formation of a toroidal vortex immediately behind the crystal led to the formation of a large region with increased conductivity and, thus, with a current density insufficient for boiling. At the same time, within the thin part of the wake behind the crystal, the current density becomes higher, and the heat generation is sufficient to form a vapor, and subsequently a plasma region.

The crystal size plays an important role in terms of the formation of plasma regions and the formation of a discharge channel. It affects the motion rate, which in turn affects the absolute amount of dissolved salt, the increase in the diameter of the wake due to diffusion, the Reynolds number and the crystal flow around. The above factors ultimately determine the distribution pattern of electrical conductivity, heat generation, and the structure of the discharge channel.

Figure 1 presents the film of frame strips of discharge development for crystals with diameters of 195 microns (upper row) and 518 microns (lower row). In both cases, the discharge takes place between the electrode surface and the crystal surface facing it. Initiation takes place almost simultaneously with a correction for a larger distance for a crystal with a diameter of 195 microns. A distinctive feature in the case of a crystal with a diameter of 518 microns is additional boiling (followed by plasma formation) in the wake of the crystal at some distance. Starting from frame #3 (31 microseconds), the channel for a 195 micron diameter crystal develops in one direction – from the electrode towards the far end of the wake, and for a diameter of 518 microns – in three directions at once: from the electrode to the crystal, from the wake to the crystal, and from the wake towards its far end. With further

development (frame #5, bottom row), a part of the channel is clearly visible, which formed later than the others and connecting the upper pole of the crystal with the rest portion of the wake, the diameter of which is several times smaller compared to the more distant part of the discharge channel.

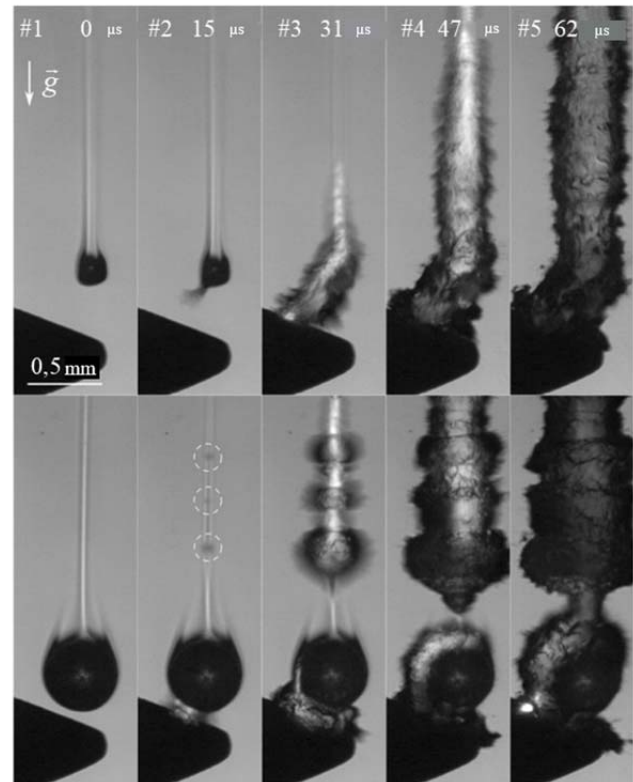


Fig. 1. Film of frame strips of the development of an electric discharge in water, guided by a trace of a moving salt crystal of different diameters: the upper row is 195 microns, the lower one is 518 microns. Exposure time of 10 microseconds, 64,000 fps

The detected difference in the nature of the discharge development can also be traced on the oscillograph record of voltage, current and gap resistance (Fig. 2). When comparing the course of the oscillograph record (solid lines for 195 microns, dotted lines for 518 microns), it can be seen that the current rise and resistance decrease for 195 microns take place monotonously and correspond to the development pattern of the discharge channel, and the only jump is associated with ionization and plasma formation in a single channel. For a crystal with a diameter of 518 microns, on the contrary, the rise and fall of the current between frames #2 and #3 coincide with the phases of heating and vaporization in the far part of the wake, which

briefly hinders the flow of current, which then increases abruptly after ionization in this region.

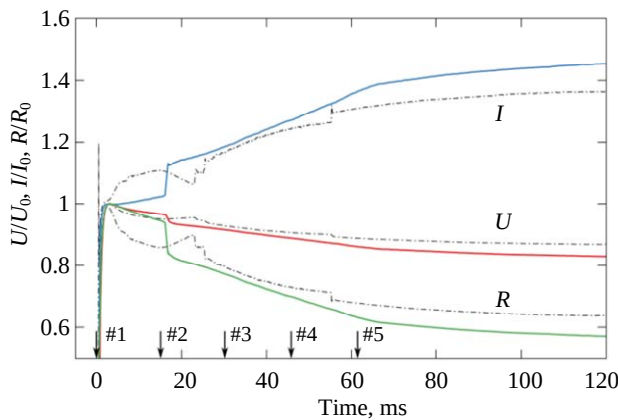


Fig. 2. The waveforms of voltage (U), current (I), and resistance (R) at the discharge gap, corresponding to the film of frame strips in Fig. 1, are normalized to their values immediately after the voltage is applied. The frame numbers are marked at the bottom. Solid lines are for a crystal with a diameter of 195 microns, dotted lines are for a diameter of 518 microns.

The observed difference in the behavior of the discharge channel is well interpreted by the results of the numerical modeling. Figure 3 presents the distribution of concentration (left) and velocity (right) for both crystals. In addition to the obvious difference in the characteristic dimension of the conductive region with a high salt concentration, the difference in its distribution in the region between the crystal surface and the thin part of the wake is clearly visible: due to the larger dimension of the crystal with a diameter of 518 microns, a vortex forms when it flows around the upper pole, which leads to a non-monotonic concentration distribution across the wake and an increase in the region transverse dimension of increased concentration. For a 195 μm crystal, on the contrary, the distribution across the wake is monotonic with a maximum near the wake axis. This distribution of concentration leads to the fact that the distribution of heat release along the wake axis has a maximum closer to the crystal surface for a diameter of 195 microns compared with the case for a diameter of 518 microns (Fig. 4, curves 1 and 2, respectively). At the same time, in the range from 0 to about 0.8 mm, the energy release for a crystal with a diameter of 195 microns significantly exceeds its value for a crystal with a diameter of 518 microns (curves 3 and 4, respectively), which corresponds to the results of optical detection (see Fig. 1).

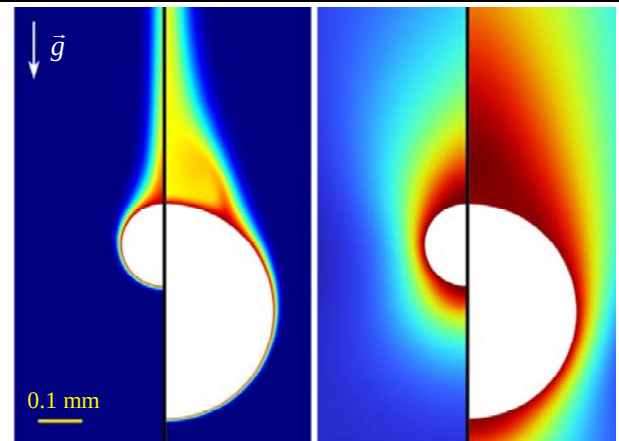


Fig. 3. Modeling results of the crystals flow around with diameters of 195 and 518 microns for the concentration of dissolved salt (left) and the medium velocity (right)

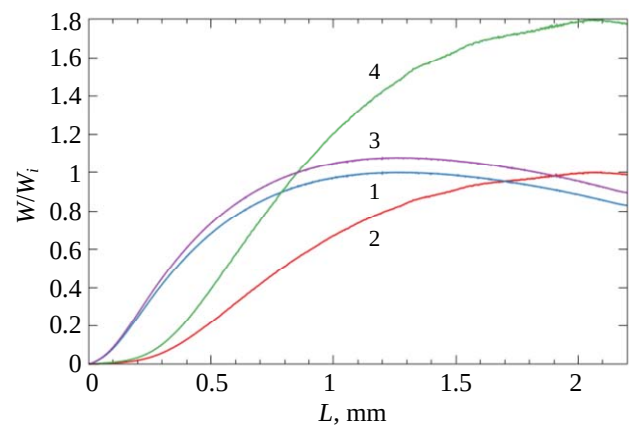


Fig. 4. The distribution of the normalized energy release along the wake axis, the distance L is calculated from the upper pole of the crystal. Curves 1 (195 microns) and 2 (518 microns) are normalized to their global maxima along the entire length of the wake. Curves 3 (195 microns) and 4 (518 microns) are normalized to the value at their intersection point at $L \approx 0.85$ mm

Findings

The development of an electric discharge in water, guided by a conductive wake from a moving NaCl salt crystal, has a number of features related to the distribution of the concentration of dissolved salt in the wake.

When a small crystal (195 microns in diameter) moves, the breakdown takes place sequentially from the high-voltage electrode along the surface of the crystal and further into the wake – without ruptures of the plasma channel, which is explained by the vortex-free regime of its flow around.

When a larger crystal (518 microns in diameter) moves, a discharge channel is initiated

at a high-voltage electrode, moves along the surface of the crystal, but then becomes a part of the wake far from it, leaving a non-ionized area located immediately behind the crystal in its bottom part.

This effect is explained by the difference in the distribution of the dissolved salt concentration (and, accordingly, the resulting conductivity) in the region immediately behind the crystal: the

flow around of a smaller crystal takes place without the formation of a vortex in the bottom area and leads to a fairly monotonous distribution of conductivity; the flow around of a large crystal leads to the appearance of a vortex in the bottom area, increasing the size of the area with increased and heterogeneous conductivity, which results in a lower current density and heat generation, insufficient for steam and plasma formation.

REFERENCES

1. Yutkin L. A. Elektrogidravlicheskiy effekt i ego primeneniye v promyshlennosti. Leningrad: Mashinostroyeniye, 1986 [in Russian].
2. Aihara Y., Shindo T., Miki M., and Suzuki T., Electrical Engineering in Japan **113** (4), 66–77 (1993).
3. Woodworth J. R., Zamoski N. D., Johnson D. L., Sarkisov G. S., Blickem J. R., Valde D. M. V. D., Starbird R. L., and Wilkins F. L. Laser Triggering of Water Switches in Terrawatt-Class Pulse Power Accelerators. Sandia National Laboratories, 2005.
4. Vasilyak L., Kostyuchenko S., Kudryavtsev N., and Filyugin I., Uspekhi Fizicheskikh Nauk **164** (3), 263 (1994).
5. Ball L. M., Applied Optics **13** (10), 2292 (1974).
6. Panov V. A., Saveliev A. S., and Kulikov Yu. M., Applied Physics, No. 6, 30–34 (2025).
7. Panov V. A., Saveliev A. S., Kulikov Yu. M., Applied Physics, No. 5, 48–53 (2025).
8. Rao S. M. and Thyagaraj T., Appl. Clay Sci. **38** (1–2), 113–129 (2007).

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Application of artificial neural networks to optimization the parameters of ion-plasma deposition of thermionic coatings

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A method for optimizing the parameters of the ion-plasma sputtering process of triple carbonates of alkaline-earth metals Ba, Sr, Ca is proposed. An artificial neural network (ANN) with a genetic algorithm is used to build a predictive model. The sputtering parameters are determined to obtain an emission current in the range of 70–120 μ A for thin-film thermionic microcathodes. The prediction results are compared with the actual emission data of the manufactured microcathodes and those calculated by other machine learning models. Based on the comparison, it was shown that the ANN allowed for finding a more accurate combination of coating deposition parameters to obtain efficient thermionic microcathodes.

Keywords: molecular sputter-deposited oxide microcathode (MSOC), ion-plasma deposition, machine learning, forecasting, artificial neural network, genetic algorithm.

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Introduction

Ion-plasma (magnetron) sputtering (IPS) technologies allow for control over the deposited film thickness and composition. A plasma medium is employed in these processes to eject target material for deposition onto a substrate to form a thin film. Complex physicochemical phenomena occurring during coating deposition require precise control of key process parameters, such as pressure, working gas flow rate, substrate temperature, and sputtering power. The study of these processes enables control over film stoichiometry and structure, which, in turn, affects their functional characteristics [1].

The authors of [2] developed a hybrid machine learning (ML) approach that combines respective classification and regression models to address challenges related to producing high-mobility amorphous $\text{In}_{0.9}\text{O}_{0.1}\text{Sn}$ films deposited via RF magnetron sputtering.

In [3], various characteristics of low-temperature plasma were reviewed along with

their complexity, which is driven by diverse gas-phase compositions, operating pressures, power densities, and spatial boundaries. Under these conditions, the direct application of machine learning methods is not always feasible. To overcome these difficulties, progress is required in plasma diagnostics and data acquisition systems. Processing large amounts of data is one of the key tasks to achieve this goal.

By simulating the transport of argon ions bombarding a Ti–Al composite, the authors of [4] obtained a series of representative energy distribution functions of incident particles. Subsequently, a multilayer artificial neural network (ANN) was trained and tested on this dataset of input and output distributions. Following the training phase, an error analysis was performed, and the model performance was compared for two sets of hyperparameters. The trained ANN demonstrates the ability to predict sputtered particle distributions for unknown incident ion energy distributions of arbitrary shape.

In [5], an efficient process design system was introduced to determine optimal operating conditions through a combination of deep learning and plasma simulation. To create the training model, a dataset was generated using a two-dimensional (2D) hybrid plasma equipment model code for an inductively coupled argon plasma system. The model was trained on the generated dataset to investigate the functional dependencies between operating conditions and subsequent plasma states.

The refractive indices of SiN_x films deposited on silicon substrates via magnetron sputtering were predicted in [6] using an ANN. Experimental wavelength and temperature values were utilized as inputs for ANN training, with the refractive index as the output parameter. The simulation and prediction results obtained using the model were compared with experimental data. The results demonstrate that the ANN approach is suitable for the simulation and prediction of the refractive index.

Soft computing techniques, including genetic algorithms (GAs) and ANNs, are widely utilized in addressing various nonlinear problems, owing to the superior performance of these models [7, 8]. ANNs enable the extraction of complex patterns from data.

The subject of this study is thin-film molecularly deposited oxide cathodes (MOCs) used in cyclotron protection devices (CPDs), which are deposited via ion-plasma sputtering (IPS) of cathode targets prepared from alkaline earth metal carbonates. They provide a current density of 1–2 A/cm² for 5,000–10,000 hours. The thickness of the deposited emission film on the micro-cathodes is $\approx 1 \mu\text{m}$ [1, 9].

The objective of this study is to construct and optimize a model to predict the target variable, micro-cathode current (I_{cat}), based on a set of deposition process parameters.

Materials and Methods

The deposition of coatings onto the micro-cathodes was carried out using an URM3.279.011 vacuum ion-plasma sputtering system manufactured in Russia. The geometric dimensions, operating principles, and key electrical parameters of the cathode-heater

assembly (CHA) and the working chamber of this system are identical to those described in [10,11]. The (Ba, Sr, Ca)CO₃ cathode targets for IPS were prepared by spraying from powdered AEM carbonates of the KTA-1-6-sp grade. The ratio of active AEM elements in the target was 47:45:8, and the thickness was 130–135 μm . The turbo-molecular pump provided a pumping speed of 500 L/s. The ultimate vacuum level was 1×10^{-6} Pa. After target carbonate decomposition, the DC voltage applied between the target and the substrate provided the energy required to ionize argon atoms and dissociate CO₂ gas, resulting in a plasma state. Driven by the applied electric field, argon ions bombard the target, causing material sputtering. As the sputtered atoms and molecules move toward the substrate holder, they react with the gas and deposit onto the micro-cathode cores, forming thin films of AEM oxides and carbonates. The sputtering process is regulated by adjusting the operating parameters of the system.

The dataset was generated by depositing coatings onto MOCs and then measuring the emission current of the micro-cathodes inside the vacuum devices. This dataset was obtained from processes conducted under various conditions with varying coating deposition parameters. The target variable I_{cat} was separated from the features. The dataset was split into training (80%) and testing (20%) sets. All features were scaled using the training set and then the transformation was applied to the testing set. The initial dataset contained 253 rows and 13 columns.

The study consisted of the following stages: data collection and processing, model development and prediction using ANNs, and optimization via GAs. Columns with completely missing values were removed. The missing data was checked and processed. Twelve deposition parameters were selected: discharge voltage U_{dis} , V; discharge current I_{dis} , mA; target heating voltage during sputtering U_{nm} , V; target heating current during sputtering I_{nm} , A; reflector voltage U_{otr} , V; reflector current I_{otr} , A; solenoid current I_{sol} , A; sputtering pressure P , Pa; substrate temperature T_{sub} , °C; target carbonate decomposition time t_{dec} , min; maximum target decomposition current I_{dec} , A; and sputtering time t_{sup} , min. The GA was adapted to find the optimal combination of parameter settings. The objective

function of this study was to maximize the cathode emission current I_{cat} . The result obtained using the GA was verified with the ANN and compared against experimental data as well as results from other machine learning (ML) methods, such as support vector regression (SVR), random forest (RF), gradient boosting (GB), and XGBoost (extreme gradient boosting) [12–14, 15]. The GA is based on the evolutionary principle and involves four main stages. These include creating a population of solutions, evaluating the fitness of each solution, selecting individuals, and forming a new population based on three genetic operations: reproduction, crossover, and mutation [7, 8]. Reproduction occurs when each individual is duplicated based on its fitness values [16]. The mutation selected in this study replaces the cathode current with a uniformly distributed random value within the specified lower and upper limits of 60–120 μA , corresponding to the low-temperature range (480–490 $^{\circ}\text{C}$) of the MOC emission characteristics [1, 11]. This low-temperature region was chosen because it characterizes and determines the emission activity and quality of the micro-cathode across the entire emission curve. The objective function of the study was to maximize the emission current of the sputtered cathodes in a specific low-temperature range of underheating characteristics. The model inputs were the sputtering parameters, while the output was the micro-cathode current. The neural network architecture was defined using the Keras library. The baseline model consisted of four fully connected layers with LeakyReLU activation functions (with a parameter of 0.01) and batch normalization layers. L2 regularization was applied to control overfitting and improve the generalization capability of the model. The input layer consisted of 12 neurons. The hidden layers had 128, 128, 64, and 32 neurons, respectively. The output layer contained a single neuron with a

linear activation function for the regression task. The model was trained for 100 epochs with early stopping. The model was compiled with the Adam optimizer (learning rate of 0.001), the MSE (mean squared error) loss function, and evaluation metrics including MAE (mean absolute error) and R^2 . The metrics of the baseline model with four hidden layers on the test data were as follows: MSE: 431.9; MAE: 15.5; R^2 score: 0.47. The R^2 score represents the percentage of variability in the dependent variable that is predictable from the independent variables used in the model. The target metric for optimization was R^2 with a maximization direction. A total of 30 trials were conducted, where each model configuration was trained twice to enhance the stability of the evaluation.

Training the optimized model using the selected hyperparameters demonstrated a significant performance improvement. The model was trained for 250 epochs. The Keras library along with the `keras_tuner` package and the RandomSearch algorithm were used. Different combinations of hyperparameters were randomly selected. The algorithm trained the model on the training data for each selected hyperparameter combination. Based on the optimized hyperparameters, an ANN model was constructed with the following architecture and training configuration: four hidden layers. The first layer had 480 neurons with the 'relu' activation function, the second layer had 160 neurons with 'tanh', the third layer had 96 neurons with the 'leaky_relu' activation function, and the fourth layer had 128 neurons with 'relu'.

After training the optimized ANN, its performance metrics on the testing set changed as follows: MSE: 229.68; MAE: 12.17; and R^2 : 0.72. The tuning process significantly improved the predictive performance of the model. The learning curves of the optimized model are presented in Fig. 1 (a, b).

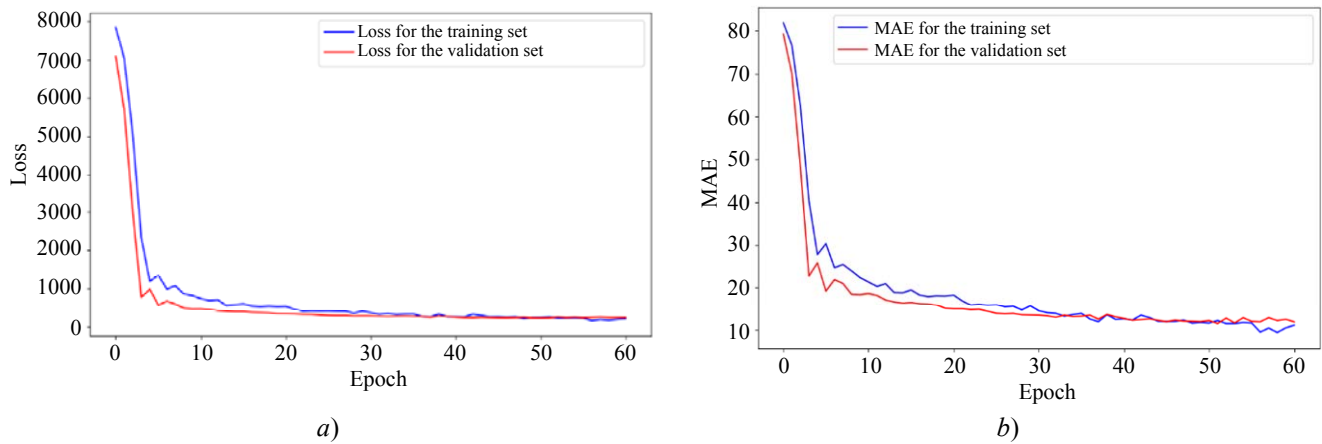


Fig. 1. Model training history on the training and validation sets: a) loss, b) MAE

Results and Discussion

The process data related to target carbonate heating and decomposition, coating deposition in the IPS system, and emission measurements were used in this study. Values recorded at other stages this re only indirectly related to the emission current, such as vacuum pumping or assembly of the sputtered cathodes, were not considered. The addition of these stages would have required the creation of a much larger dataset, thereby significantly increasing the complexity of the problem.

The training history curves (Fig. 1a, b) show that both training and validation errors decreased over the epochs, demonstrating that the model learned successfully. Two key metrics are evaluated: loss (Loss) and mean absolute error (MAE). For each metric, two lines are displayed: the blue line shows the metric values on the training set (the data the model learned from), while the red line represents the metric values on the validation set (data excluded from the training process to evaluate the model's generalization capability). The loss curve illustrates the evolution of the model error over the training epochs. As observes, the validation loss does not significantly diverge from the training loss, indicating that no overfitting occurs and the model performs well on new data, thus maintaining its generalization capability. The MAE metric reflects the mean absolute deviation of predicted values from the actual values, where a lower MAE metric reflects that the model's predictions are closer to the actual values on average. Similar to the loss, both MAE lines also decrease and then stabilize. The low MAE values

on the validation set confirm that the model delivers accurate predictions. The similarity between the training and validation MAE indicates the absence of significant overfitting.

A feature importance analysis was conducted based on the averaged absolute connection weights of the first layer of the optimized model. The feature importance of the optimized ANN model was calculated and sorted in ascending order. The resulting vertical bar chart (Fig. 2a) illustrates the numerical importance of each feature.

According to the analysis results (Fig. 2a), the most important features (with the largest average absolute weights in the first layer) are the deposition parameters: I_{dec} , U_{dis} , I_{nm} , I_{dis} , while the least important are I_{otr} , U_{nm} , P . The parameter I_{dec} has the highest importance. Randomly varying this parameter significantly degrades the model's prediction quality. The subsequent thermionic emission capability and gas ionization for cathode target sputtering depend on the correctness of the vacuum thermal decomposition of the cathode target carbonates prior to the actual coating deposition onto the micro-cathode cores. This decomposition process, in turn, depends on the temperature of the AEM carbonates, the duration of this process step, and the residual gas pressure in the chamber. During thermal target decomposition, critical physicochemical processes occur both within its bulk and on its surface, forming an oxide layer of the appropriate composition from which the sputtering onto the micro-cathodes takes place. U_{dis} determines the accelerating voltage required for cathode target sputtering. Simultaneously, I_{nm} along with U_{nm}

determine the heating power essential for the heating and the diffusion of active substance

atoms to the target surface during coating deposition.

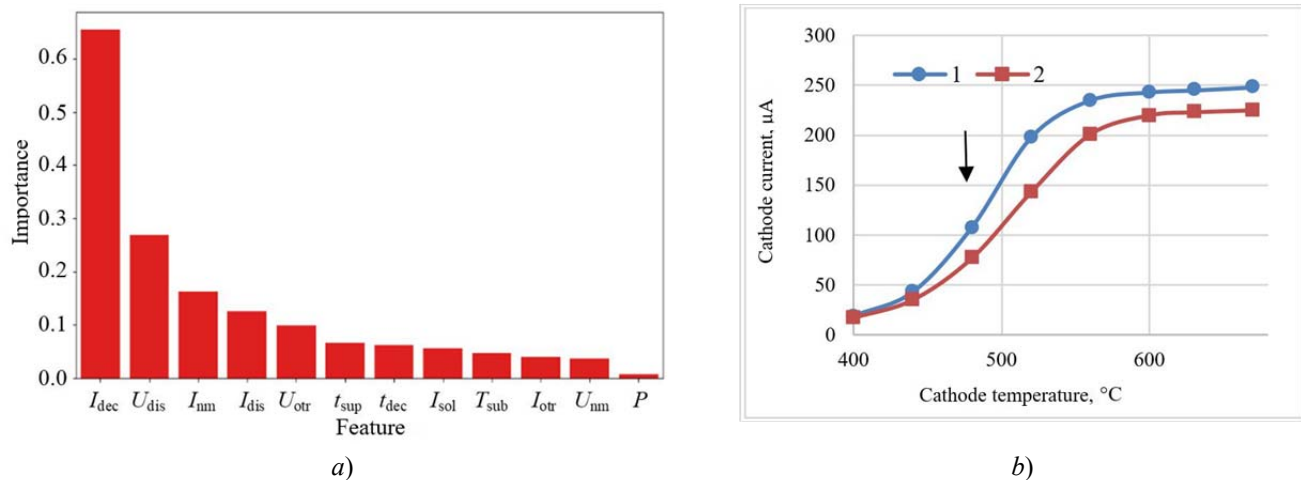


Fig. 2. Feature importance chart for the optimized model (a). Emission characteristics of two experimental MOCs obtained after thin-film deposition using GA (b)

As a result of the GA application, a set of input features (the best solution) was found that, when fed into the optimized ANN, determined the predicted value $I_{cat} = 90 \mu A$. This value corresponds to the center of the target range and maximizes the fitness function (Table 1).

The study also yielded the dependencies of the predicted cathode current on the sputtering process parameters. The predicted MOC current increases with rising accelerating discharge voltage, target carbonate decomposition, and discharge currents. Conversely, a decrease in the working gas pressure from 0.13 to 0.11 Pa results in an increase in the predicted I_{cat} . The results obtained are consistent with earlier studies reported in experimental works [1, 9–11].

After conducting the experimental sputtering onto the micro-cathodes using process parameters close to the GA-optimized values from the table, the I_{cat} values were measured for

two MOCs integrated into vacuum device mock-ups. The obtained underheating characteristics of the micro-cathodes are shown in Fig. 2b. In the low-temperature region of the emission curves (480–490 $^{\circ}C$), the measured I_{cat} values were 108 μA (No. 1) and 77 μA (No. 2), which fall within the target objective function range.

Other machine learning models (RF, GB, SVR, and XGBoost) were trained and evaluated for performance, with the R^2 metric used as the evaluation criterion. The comparison results for the models were as follows: ANN: 0.72; RF: 0.61; GB: 0.62; XGBoost: 0.42; and SVR: 0.25. The prediction accuracy of the ANN is higher than that of the other traditional ML methods. While the ANN, GB, and RF models proved to be the most suitable for predicting I_{cat} based on the current dataset, but the ANN outperformed all other models, demonstrating the highest predictive capability.

Table

Process Parameter Optimization Using GA

U_{dis} , V	I_{dis} , mA	U_{nm} , V	I_{nm} , A	U_{otr} , V	I_{otr} , A	I_{sol} , A	P , Pa	T_{sup} , $^{\circ}C$	t_{dec} , min	I_{dec} , A	t_{sup} , min	I_{cat} , μA
821	226	23	9.5	24	36	0.38	0.12	228	86	9.7	177	90

Conclusion

In conclusion, an ANN model architecture was developed and trained to predict the subsequent thermionic emission current of micro-cathodes based on experimental data from the vacuum ion-plasma sputtering of emission coatings. A method for optimizing the IPS process parameters was proposed for the fabrication of efficient thin-film emitters. Using a

genetic algorithm, the best set of sputtering parameters was found, ensuring a micro-cathode current in the range of 60–120 μA within the low-temperature region of the emission characteristics. The ANN showed acceptable prediction accuracy on the test data with an R^2 score of 0.72, surpassing traditional regression ML models. These simulation results can be used for scaling up sputtering processes in industry.

REFERENCES

1. Zhabin G. A., Pelipets O. V., and Sharapov N. A., *Technical Physics Letters* **50** (11), 38–41 (2024). <https://doi.org/10.61011/PJTF.2024.11.57909.19827>.
2. Kamataki K. et al., *Journal of Applied Physics* **134** (16), (2023). <https://doi.org/10.1063/5.0160228>.
3. Sakai O., Kawaguchi S., and Murakami T., *Japanese Journal of Applied Physics* **61** (7), 070101 (2022). <https://doi.org/10.35848/1347-4065/ac76fa>.
4. Kruger F., Gerges T., and Trishman J., *Science and technology of plasma sources* **28** (3), 035002 (2019).
5. Ko J. et al., *Physics Journal D: Applied Physics* **56** (34), 344001 (2023). <https://doi.org/10.1088/1361-6463/acd1fd>.
6. Yuksek A. G. et al., *Physics in: Condensed media* **695**, 416581 (2024). <https://doi.org/10.1016/j.physb.2024.416581>.
7. Mohd Sabri et al., *Modern Materials Research* **1109**, 481–485 (2015). <https://doi.org/10.4028/www.scientific.net/AMR.1109.48>.
8. Ko Yu. D. et al., *Expert systems with applications*, **36** (2), 4061–4066 (2009). <https://doi.org/10.1016/j.eswa.2008.03.010>.
9. Zhabin G. A., Arkhipov D. Yu., and Temiryazeva M. P., *Applied Physics*, No. 5, 54 (2019) [in Russian].
10. Zhabin G. A., Loginov B. A., Loginov A. B., and Chichalin K. V., *Journal of Radio Electronics*, No. 6, (2025). <https://doi.org/10.30898/1684-1719.2025.6.5>.
11. Zhabin G. A., Arkhipov D. Yu., Sedlovets D. M., and Temiryazeva M. P., *Electronnaya tekhnika. Ser. 1. Svch-tekhnika*, No. 1 (544), 46–55 (2020) [in Russian].
12. Khan A. A., Chaudhary O., and Chandra R., *Expert systems with applications* **244**, 122778 (2024). <https://doi.org/10.1016/j.eswa.2023.122778>.
13. Vijayaraghavan V., Garg A., and Gao L., *Journal of Energy Storage* **135**, 118374 (2025).
14. Chen T., Cornell University, (2016). <https://doi.org/10.1145/2939672.2939785>.
15. Klyukovkin G. K., *Aktual'nyye issledovaniya*, No. 37 (219), (2024). <https://doi.org/10.5281/zenodo.16131539>.
16. Katoch S., Chauhan S. S., and Kumar V., *Multimedia tools and applications* **80** (5), 8091 (2021). <https://doi.org/10.1007/s11042-020-10139-6>.

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The possibilities of using optical coherence tomography as a method for detecting defects in polymer composites

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Research has been carried out in the field of using optical coherence tomography to detect defects at the "matrix-fiber" interface in polymer composite materials based on continuous carbon fiber and superconstructive thermoplastic polyesteresterketone. Defective areas were recorded on the received B-scans. Binarization of various degrees has been carried out. The percentage of binarization has been identified, providing visual information content while reducing artifacts and noise typical of B-scans. To form a graphical expression and further quantify the results obtained from binarized B-scans, A-scans were generated. It was found that the binarization of B-scans at the level of 40% makes it possible to informatively display the polymer layer, determine its thickness, reduce the appearance and evaluate the continuity at the polymer-filler boundary.

Keywords: optical coherence tomography, polymer composite materials, binarization, structural defects, matrix-fiber boundary.

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Introduction

Various defects can take place during the production of fibrous PCMs, including surface damage caused by contact with the guide rollers, as well as problems associated with static electricity and uneven coating [1, 2]. Other important defects include issues related to nanoparticle aggregation at the filler–matrix interface, caused by differences in the chemical nature and surface properties of the fibers and the matrix, as well as nonregular distribution of fibers within the matrix [3]. They directly affect the finite properties of the product. Particle aggregation makes it difficult to fully impregnate

the fiber with the binder, resulting in areas with reduced strength [3]. The uneven distribution of fibers in the matrix volume creates local stress concentrations, thereby causing a decrease in strength and toughness, as well as an increased tendency to delamination. The consequence of these defects is a reduction in operational performance under load. Even materials with high strength indices, such as carbon fiber-reinforced plastics, are critically sensitive to this factor due to their low toughness [3, 4].

Due to the fact that the structure of the PCM is complicated, and the materials themselves are multicomponent, it is relevant to control the parts made from them, not only at the

stage of production and release, but also during operation. The presence of defects of various origins, sizes, and localization have a significant impact on the formation of PCM complex of physical and mechanical characteristics [5].

Currently, diagnostic methods and the search for ways to increase their informative value are actively developing. The latter is ensured by increasing the sensitivity of the relevant elements of the research equipment, using confirmed dependencies used for signal processing, and algorithms for information analysis.

One of the promising methods for diagnosing defects in the form of air inclusions (pores, cracks) in polymer composite materials (PCM) is optical coherence reflectometry (OCR). It should be noted that the long-term experience of using this method in relation to biological objects is widely used in medicine [6-10]. Due to the micrometer resolution and the ability to perform cross-sectional imaging in the volume of the material, the OCR provides unique data on the morphology of internal structures, the distribution of reinforcing elements, flaw detection on the subsurface level and the quality of adhesive compounds [8].

The main research vector on using OCR for PCM is the transition from qualitative imaging to quantitative, high-speed analysis and prediction of properties, as well as to a non-invasive method of CM research. Thus, in [11-16], OCR was used to examine an epoxy mixture made of fiberglass, which is usually used to manufacture the spars of wind turbine blades. Cracks and delamination sites were detected through OCR images obtained during static testing of a delaminated fiberglass composite material.

The OCR fundamental principle is based on Michelson interferometry using a low-coherence light source, which is separated from the source by a beam splitter into reference and test beams [12]. The key parameter for the PCM analysis is the scattering capacity. Different components of such materials (polymer matrix, glass/carbon fibers, interfaces) have different refractive indices, which leads to partial backscattering of light. By recording the amplitude and time delay of this signal, the OCR system builds a one-dimensional A-scan. Sequential scanning in two coordinates allows you to reconstruct a two-

dimensional B-scan image (cross-section) or a three-dimensional volume.

Currently, there is very little literature describing the application of this method to a wide range of polymer composite materials (PCMs), which highlights the relevance of this research direction. In this regard, it is relevant to determine the capabilities of OCR in relation to PCM made by fuse deposition modeling of carbon fibers and thermoplastics, which is due to the developed morphology of the filler surface and the short period of increased viscosity of the thermoplastic melt, in particular polyesteresterketone (PEEK).

Materials and methods

In this paper, we studied samples of a monolayer formed on an Anisoprint Composer A4 3D printer from a prepreg reinforced with a bundle of continuous carbon fibers, impregnated with ED-20 epoxy resin and coated with polyesteresterketone (PEEK). The samples top layer was represented by a PEEK layer. Below it was a thin layer of thermosetting polymer (ED-20 epoxy resin cured with polyethylene polyamine (PEPA) hardener), with carbon fibers located in the central part. The structural features of the composite material used are described in papers [17].

For the study, two groups of samples with dimensions of 30 × 10 × 1.2 mm were used – control and experimental, subjected to electrophysical exposure, in particular, those that underwent microwave treatment at a frequency of 2450 MHz. The samples were processed in a microwave electromagnetic field at laboratory microwave processing plants manufactured by SPE AgroEcoTech LLC (Obninsk, Kaluga Region).

An OSC 1300 SS optical coherence tomograph (ThorLabs, USA) with a probe wavelength of 1300 nm, a maximum probe depth of 3 mm, and a scan track length of 5 mm with an image size of 512 by 720 pixels in B-scan mode was used for instrumental implementation of the low-coherence reflectometry method.

After obtaining a set of experimental data, B-scans and A-scans were analyzed.

Results and discussion

The analysis of the obtained B-scan images makes it possible to identify the characteristic features of the modified control samples (Fig. 1). Carbon fiber fibers absorb the probing radiation to a large extent. The upper layer of the material under study, represented by the polymer, is permeable to it, which makes it possible to use OCR to control the state of the upper layer of the polymer and region at the polymer–matrix interface.

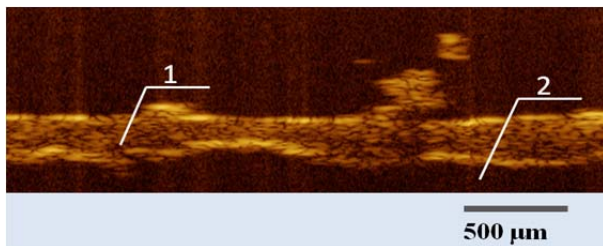


Fig. 1. B-scan of the control sample: 1 – matrix, 2 – fiber

It has been noted that for control samples, there is a clearly expressed region of refractive index step at the "polymer-fiber" interface, which is visually displayed as a bright horizontal line. In the treated samples, the regions with a refractive index step are significantly less extensive.

The analysis of the B-scans revealed a similar pattern of bright lines during the transition of probing radiation across the "air-polymer" and "matrix-filler" interfaces, which determined the expediency of searching for objective methods for their comparison.

The binarization of the generated B-scans was carried out as a quantitative assessment of the results obtained (Fig. 2).

The maximum pixel intensity of the image was considered and a boundary condition was introduced. Pixels with a lower intensity were

assigned a value of zero, while those with a higher intensity were assigned a value of one. The resulting images have greater contrast, highlight areas with the desired response values, and display regions with sharp step in the refractive index. The system of equations (1) has been formed

$$\begin{cases} I_{\text{bin}}(i, j) = 1, & \text{if } I(i, j) \geq I_b, \\ I_{\text{bin}}(i, j) = 0, & \text{if } I(i, j) < I_b, \end{cases} \quad (1)$$

where $I(i, j)$ is the pixel intensity of the original B-scan, $I_{\text{bin}}(i, j)$ is the binarized value of the B-scan intensity, and I_b is the binarization boundary condition.

The boundary condition for binarization is determined by a fraction of the maximum intensity I_{max} of the initial B-scan:

$$I_b = K \times I_{\text{max}}, \quad (2)$$

where K is the binarization coefficient.

Low values of the boundary conditions – $K = 30\%$ binarization – preserve information about the inhomogeneities formed in the B-scan in the polymer layer (Fig. 2), and high values – $K = 50\%$ binarization – leave only the brightest areas of the boundaries and do not allow obtaining information about the polymer layer (Fig. 2). The intermediate variants, respectively, leave part of the heterogeneity in the polymer layer.

The initial and binarized A-scans were also evaluated. The evaluation of a single A-scan along a vertical line is also carried out in accordance with the boundary conditions of binarization, which makes it possible to identify the boundaries and distribution of signal intensity in the polymer volume.

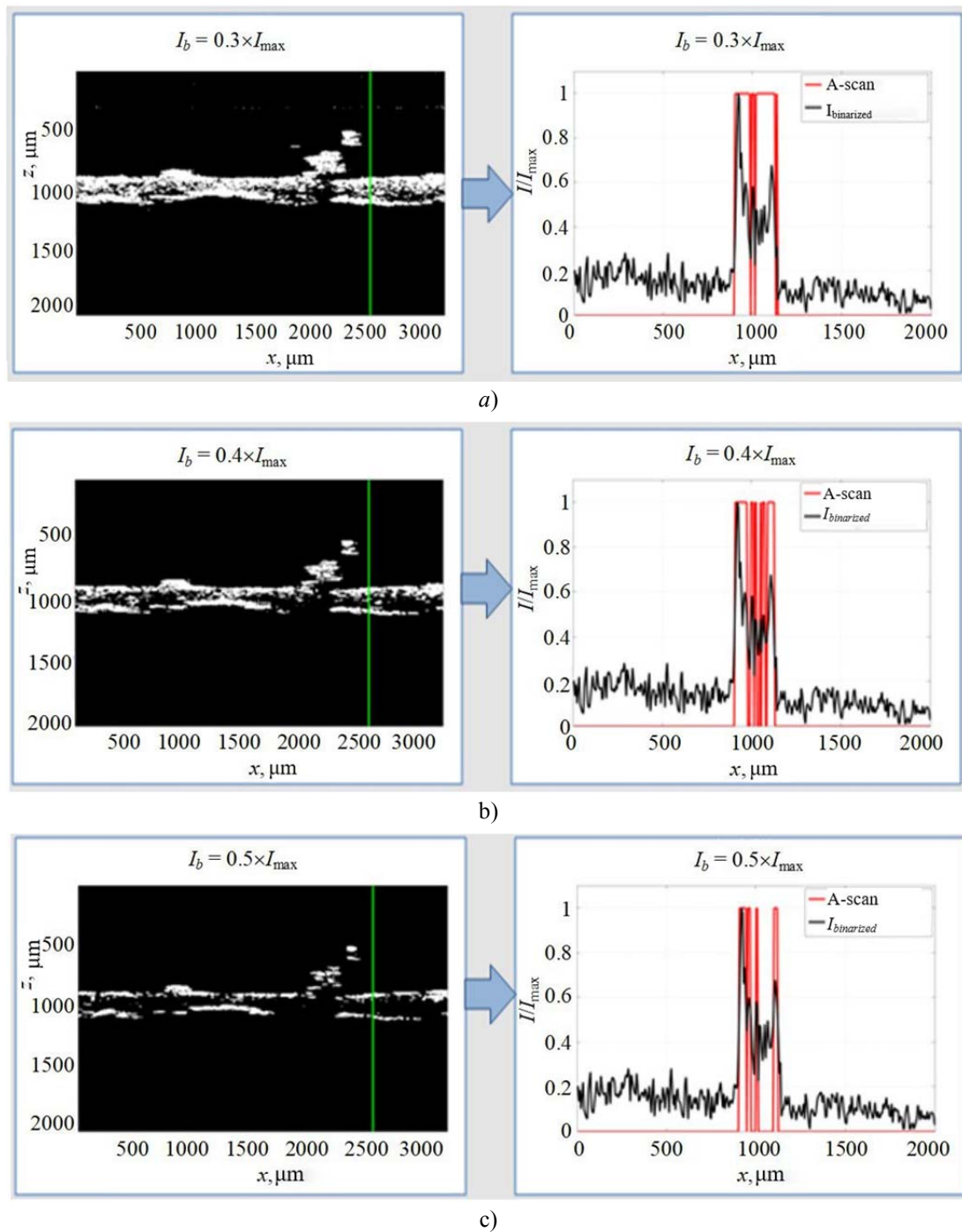


Fig. 2. The results of binarization of B-scans (on the left) and their corresponding A-scans (on the right). Binarization of 30% (a), 40% (b) and 50% (c)

To obtain a graphical representation enabling quantitative assessment of the results from binarized B-scans, A-scans were allocated.

The most informative is the A-scan corresponding to the B-scan, which is binarized by 40%. The polymer boundaries and the contrasting area of the polymer-fiber boundary are clearly shown. The condition for this binarization was to decrease the intensity by a factor of e relative to the maximum value. The

average binarization condition value of approximately 40% of the maximum intensity provides an informative display of the matrix-fiber boundary (without loss of information resulting from $I_b = 0.5 \times I_{\max}$, and without unnecessary noise, which persists at a low binarization threshold).

A high value of the response peak at the polymer-fiber interface characterizes the refractive index step of a substance reaching

values close to the refractive index of air. Taking into account the manufacturing technology of such composite materials and the specifics of the surface structure of carbon fibers, it can be concluded that part of the contact area between the matrix and the filler contains air, which partially dissolves in the polymer under modifying action on the samples, which is consistent with the results of a comparative analysis of the physico-mechanical characteristics of samples of a similar composition [17, 18].

Conclusion

Binarization of B-scans with a low threshold makes it possible to informatively display the polymer layer, determine the thickness of the polymer layer and estimate its distribution over the surface of the studied PCM.

Binarization of B-scans with a high threshold makes it possible to identify areas with a refractive index step, and identify defects in the polymer and carbon fiber connection.

An intermediate binarization level preserves information about the polymer layer thickness and the presence of contrast fragments at the "matrix–fiber" interface, enabling a comprehensive assessment of these parameters.

Considering the signal intensity distribution with exponential decay, the binarization boundary condition is proposed to be set at the intensity level reduced by a factor of e (Euler's number) from the maximum value.

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REFERENCES

1. Muravskii A. A., Alikin M. B., Dvorko I. M., and Lavrov N. A., Proc. St. Petersburg State Institute of Technology, No. 90, 58–66 (2023).
2. Biggham C. J., Resinate, No. 5, (2018).
3. Kolosova A. S., Sokol'skaya M. K., Vitkalova I. A., Torlova A. S., and Nikalov E. S., Fundamental Research, No. 5, 459 (2018) [in Russian].
4. Mahboubizadeh S., Sadeq A., Arzaqi Z., Ashkani O., and Samadoghi M., Discover Materials **4** (1), 47 (2024).
5. Dektiareva M. A. and Zhirnova E. A., Aktualnye Problemy Aviatsii i Kosmonavtiki – Actual Problems of Aviation and Cosmonautics **2**, 78–80 (2015) [in Russian].
6. Grishanov V. N. Optical Coherence Tomography in Medical Diagnostics [Electronic Methodological Guidelines]. Samara: Samara State Aerospace University Press, 2015 [in Russian].
7. Zaitsev V. Yu., Vitkin I. A., Matveev L. A., Gelikonov V. M., Matveev A. L., and Gelikonov G. V., Izvestiya Vysshikh Uchebnykh Zavedenii. Radiofizika [Radiophysics and Quantum Electronics] **57** (3), 231–250 (2014).
8. Stifter D., Applied Physics B **88** (3), 337–357.
9. Liu P., Yao L., and Groves R., Proc. 7th Int. Symp. on NDT in Aerospace, 2015, pp. 2–5.
10. Huang D., Swanson E., Lin C. et al., Science **254** (5035), 1178–1181 (1991).
11. Dunkers J. P., Optika i Lazery v Tekhnike [Optics and Lasers in Engineering] **35** (3), 135–147 (2001) [in Russian].
12. Liu P., Groves R. M., and Benedictus R., NDT & E International **65**, 2–9 (2014).
13. Gurov I. P., Zhukova E. V., and Margaryants N. B., Scientific and Technical Journal of Information Technologies, Mechanics and Optics **12** (3), 40–45 (2012).
14. Fercher A. F., Z. Med. Phys. **20** (4), 251–276 (2010).
15. Gurov I. P., Scientific and Technical Journal of Information Technologies, Mechanics and Optics **5** (21), 5–20 (2005).
16. Wenninger M., Marschik C., Felbermayer K., and Heise B., AIP Conf. Proc. **2884**, 6 (2023).
17. Bekrenev N. V. and Zlobina I. V. Proc. XIV All-Russ. Sci. and Student Conf. with Int. Participation, St. Petersburg, 14–18 May 2024. St. Petersburg: St. Petersburg State University of Industrial Technologies and Design, 2024, pp. 11–12 [in Russian].
18. Zlobina I. V., Bekrenev N. V., Churikov D. O., and Pasechnaya A. A., Proc. All-Russ. Conf. Dedicated to the 75th Anniv. of the Yakutsk Scientific Center of the Siberian Branch of the RAS, Yakutsk, 19–23 Sept. 2024. Kirov: MTSITO, 2024, pp. 217–219 [in Russian].

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Increase in conductivity in 2-(4-peridil)-5-phenyl-1,3,4-oxadiazolium (triphenylphosphine) copper iodide films when exposed to UV radiation

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The paper presents a study of optical, luminescent and electrical characteristics of organometallic compounds based on copper iodide, the method of obtaining, microscopy, and the results of IR spectroscopy of thin-film structures. The results of the current-voltage characteristics of Cu(I) in the ITO–Al contact system are presented. As a result of the analysis of the current-voltage characteristics, it was demonstrated that thin films of copper iodide have rectifying light characteristics under the action of ultraviolet radiation. It is shown that irradiation experimental structures with electromagnetic radiation of the UV range led to an increase in direct currents by 3.5 times.

Keywords: thin films; volt-amp characteristics; quantum efficiency; copper iodide.

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Introduction

During the past decade, multicolor luminescent materials have become a subject of growing interest in the fields of light-emitting diodes, sensors, solar cells, and artificial photosynthesis [1–4]. Organometallic complexes based on copper iodide, i.e. Cu(I) complexes, are attracting increasing attention from researchers as advanced and environmentally friendly materials due to their adjustable structural and photophysical properties [5, 6]. Cu(I) complexes featuring excellent luminescent properties and a high quantum yield at room temperature are promising for materials science and the semiconductor industry [7, 8]. The development of new copper-based Cu(I) systems, especially heteroleptic complexes, is highly motivated, as they represent an attractive alternative to the systems utilizing more expensive platinum-group metals and rare-earth elements [9, 10]. Current

advances in semiconductor manufacturing technologies make a significant and unique contribution to the development of electronic devices [11]. Thin films are mainly fabricated using solution-processing methods, including drop-casting, spin-coating, the doctor-blade technique, and spray-coating [12–15]. Systematic studies on the use of Cu(I) organometallic compounds in the field of semiconductor electronics are clearly insufficient; therefore, the aim of this work was to study the optical, luminescent, as well as resistive properties of Cu(I) complexes based on 2-(4-pyridyl)-5-phenyl-1,3,4-oxadiazole (triphenylphosphine) copper iodide.

Experiment procedure

The objects of the study were the compounds: 2-(4-pyridyl)-5-phenyl-1,3,4-

oxadiazole (triphenylphosphine) copper iodide (see Fig. 1), prepared using a similar procedure [16]. A 20-ml volume of methanol and a 20-ml volume of chloroform were poured into a 100-ml flat-bottomed conical flask. Then, 0.262 g (0.001 mol) of triphenylphosphine and 0.232 g (0.001 mol) of oxadiazole were successively dissolved while being stirred without heating, after which 0.190 g (0.001 mol) of copper(I) iodide was added. Then the reaction mixture was heated to 60 °C and stirred for 15 minutes, after which the heating was turned off and the mixture was stirred for an additional 40 minutes. The reaction mixture was then filtered through a

pleated paper filter. The resulting filtrate was left to evaporate slowly for the target product to settle; due to the high evaporation rate of the solvents, the evaporation vessel was equipped with a thin permeable film to slow down the evaporation process in order to improve the target product quality. Over the next two days, a mixture of the target product and unreacted reagents accumulated on the vessel walls; the target product settled as yellow, rhombic crystals that luminesced yellow-orange under ultraviolet irradiation. The structural formula of the obtained Cu(I) organometallic compound is shown in the inset of Fig. 1.

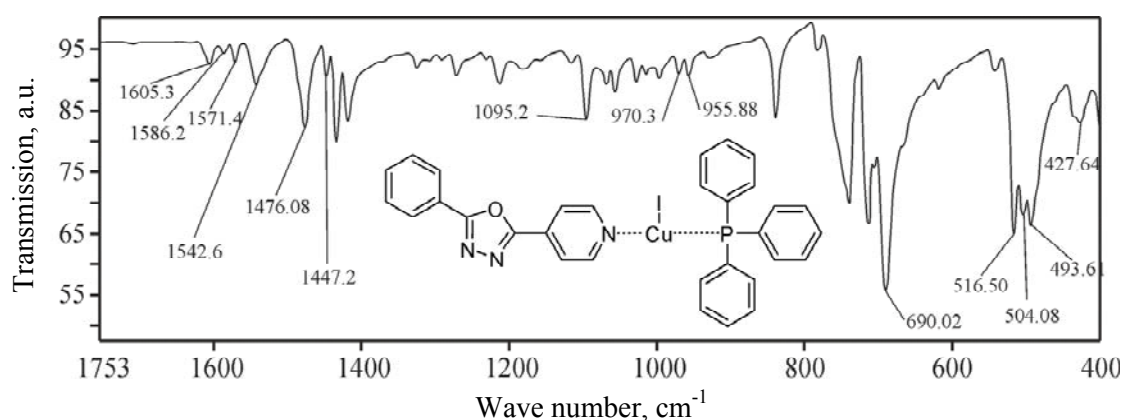


Fig. 1. IR transmission spectra of 2-(4-pyridyl)-5-phenyl-1,3,4-oxadiazole (triphenylphosphine) copper iodide and the molecular structure of the obtained compound (inset).

Thin films were formed from the starting powdered materials using a PE 6900 centrifuge by layer-by-layer deposition. Non-aromatic chloroform CHCl_3 was used as a solvent. The mass of the powdered materials was checked using Sartogism CE124-C high-precision analytical balances. The concentration of the starting materials in the solution was 1 mg/ml. After being thoroughly mixed and held for at least 48 hours at room temperature, 1 ml of the resulting solution was applied using a pipette dispenser onto optically transparent dielectric and conductive substrates. The centrifugation speed was gradually increased to 1500–3000 rpm with an increment of 500 rpm.

IR spectra of the Cu(I) organometallic compound under study were recorded with a PerkinElmer Spectrum Two FTIR spectrometer featuring a Fourier transform range of 8300–350 cm^{-1} and a resolution of 0.5 cm^{-1} . Luminescence spectra were investigated at room temperature with the use of a Fluorolog-FL 3-22

instrument (HORIBA Jobin-Yvon Inc.). To determine the optimal excitation radiation maximum, a standard pulsed excitation technique was used, which involves repeated irradiation of the working layers of organic film structures. Luminescence spectra were measured with account of the excitation maxima parameters. The surface morphology of the thin Cu(I) films was evaluated by reflection and transmission microscopy using a LOMO MII-4M microinterferometer with additional illumination, a semiconductor laser, and an extended optical path onto CCD matrices ranging from $\frac{1}{4}\text{FF}$ to $\frac{1}{2}\text{FF}$ with a resolution of 0.5 to 15 MP. Thermogravimetric analysis (TGA) was performed using a PerkinElmer STA6000 thermogravimetric analyzer.

Conductive properties under direct-current mode were investigated using a Keysight B1500A semiconductor device analyzer. To study the current-voltage characteristics (I-V characteristics) of the Cu(I) organometallic

compounds, the solution was deposited onto thin aluminum films, which were obtained by vacuum deposition on siall and had a thickness of 120 nm and a sheet resistance of 20 Ω /square [15], followed by the formation of an Al-Cu(I)-ITO sandwich structure. Measurements were carried out in the voltage range from of -1 to 1 V. The thin aluminum film forms an ohmic contact with Cu(I), since its work function is comparable to the work function of Cu(I). The geometric parameters of the conductive substrates were 10×10 mm.

Results of experiments and discussion

Primary analysis of the surface of thin copper iodide films showed relative homogeneity of the obtained thin films (Fig. 2a). The thickness of the Cu(I) film was approximately $2 \mu\text{m}$. Individual agglomerations with a diameter of $\sim 40 \mu\text{m}$ were also seen to form on the film surface. The luminescence quantum yield, namely the triplet-level energy values of the corresponding materials, was determined based on photoluminescence spectra. The relative luminescence quantum yield was calculated by the following formula (1):

$$Q = \frac{S}{S_{\text{эТ}}} \times \frac{(1-R)}{(1-R_{\text{эТ}})}, \quad (1)$$

where S is the area under the luminescence spectrum curve, A is the absorbance at the excitation wavelength, and R is the reflectance. Quinine sulfate, rhodamine B, and sodium salicylate were used as references; the measurement accuracy was 10%.

Initially, the excitation spectrum maxima of the Cu(I) organometallic compound were established. The excitation peak for Cu(I) was 465 nm (Fig. 2b). The luminescence spectrum maximum of Cu(I) was observed in the range from 510 to 740 nm (Fig. 2b). The studied organometallic compound exhibited yellow-orange emission with a maximum wavelength of 625 nm. It should also be emphasized that the external quantum efficiency (EQE) of the studied compound was as high as 55.84% (inset of Fig. 2b). As a result, it has been clearly demonstrated that the obtained Cu(I) organometallic compound can potentially be used as an active re-emitting material for semiconductor structures.

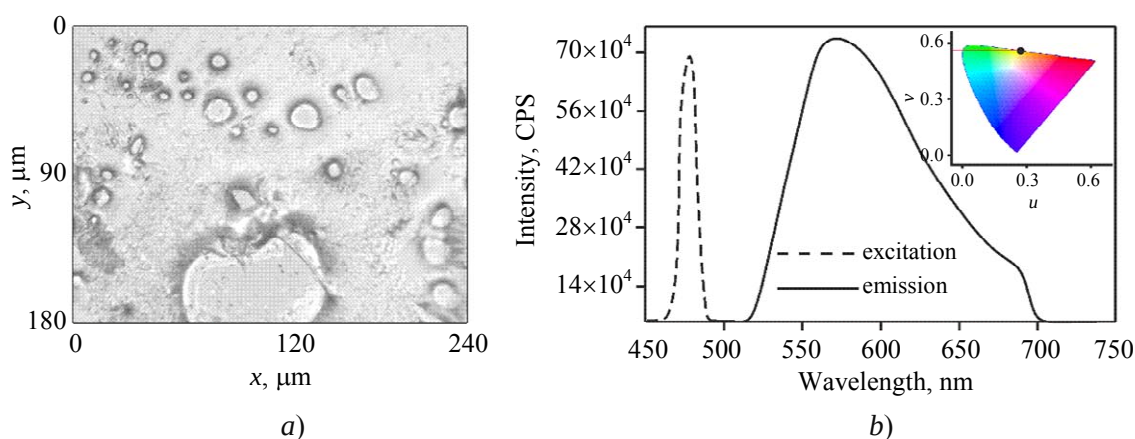


Fig. 2. Surface micrometry of copper iodide (a) and the excitation and luminescence spectra of Cu(I) (b)

Bands lying in the range of 1605.3 – 1447.2 cm^{-1} were recorded in the obtained IR spectrum. Such bands are characteristic of the vibrations of the aromatic ring found in both 2-(4-pyridyl)-5-phenyl-1,3,4-oxadiazole and triphenylphosphine. It is important to note that the band at 1542.6 cm^{-1} exhibits greater intensity compared to the preceding bands, which is specifically typical for aromatic ring vibrations.

Also, a slight shift of the peak characteristic of the Cu(I)–P bond at 1095.2 cm^{-1} can be observed in the spectrum, which arises from the formation of a coordination bond between the copper ion and the donor phosphorus atom of triphenylphosphine. Due to the technical specifications of the instrument, signals with wavenumbers below 400 cm^{-1} cannot be recorded; however, characteristic vibrations for

Cu(I)–I and Cu(I)–N bonds should potentially be found in this region (Fig. 1).

Conductive and photovoltaic properties of the studied structures were measured using a Keysight B1500A semiconductor analyzer with a shielding chamber (Faraday cage). An LED

matrix integrated into the chamber was used as an illumination source. The emission spectrum of the LED matrix is shown in Figure 3a. The total incident power on the sample was approximately 60 mW, and its flux density was about 300 W/m².

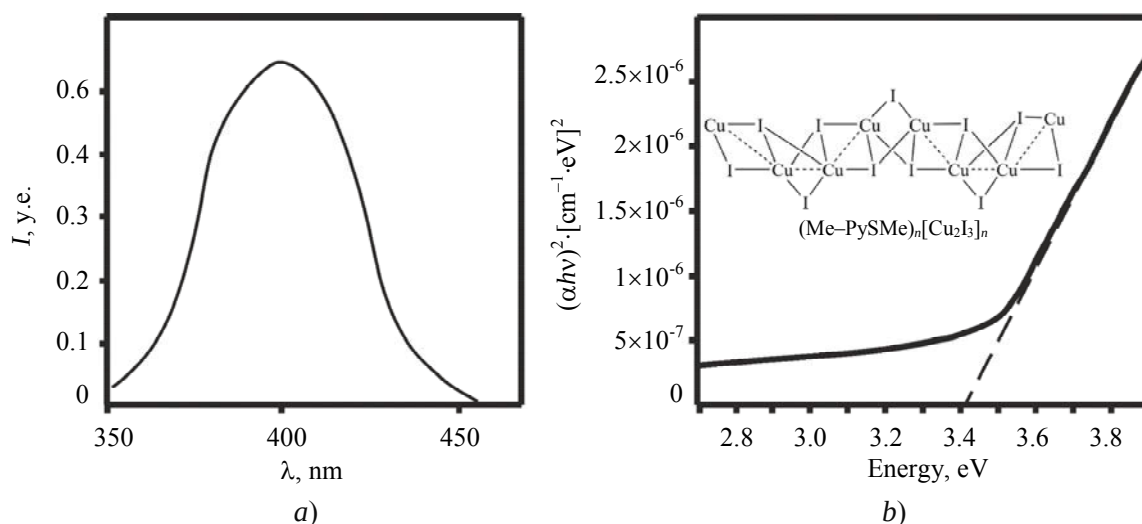


Fig. 3. a) – emission spectrum of the LED matrix, b) – optical band gap of copper iodide

To account for the shift of the fundamental absorption band, an assumption about band-to-band absorption with indirect allowed transitions with an exponent of 2 was made [17, 18].

$$\alpha h\nu = A(h\nu - E_g)^m, \quad (2)$$

where α is absorption coefficient, A is a constant, $h\nu$ is the photon energy, and E_g is the band gap of the material.

The effect of the stoichiometric atomicity of Cu(I) molecules on the shift of the fundamental absorption edge and the change in the band gap of

the organometallic semiconductor was evaluated as 3.4 eV (Fig. 3b). Mass loss of up to 55% accompanied by an endothermic effect was detected in the temperature range of 180–200 °C according to the TGA data (Fig. 4a). This corresponds to the removal of a coordinated water molecule. The compound is thermally stable up to 350 °C. Heating above 350 °C leads to slow decomposition of the sample. Thus, it can be concluded from the obtained results that the compound 2-(4-pyridyl)-5-phenyl-1,3,4-oxadiazole (triphenylphosphine) copper iodide is thermally stable up to 180 °C.

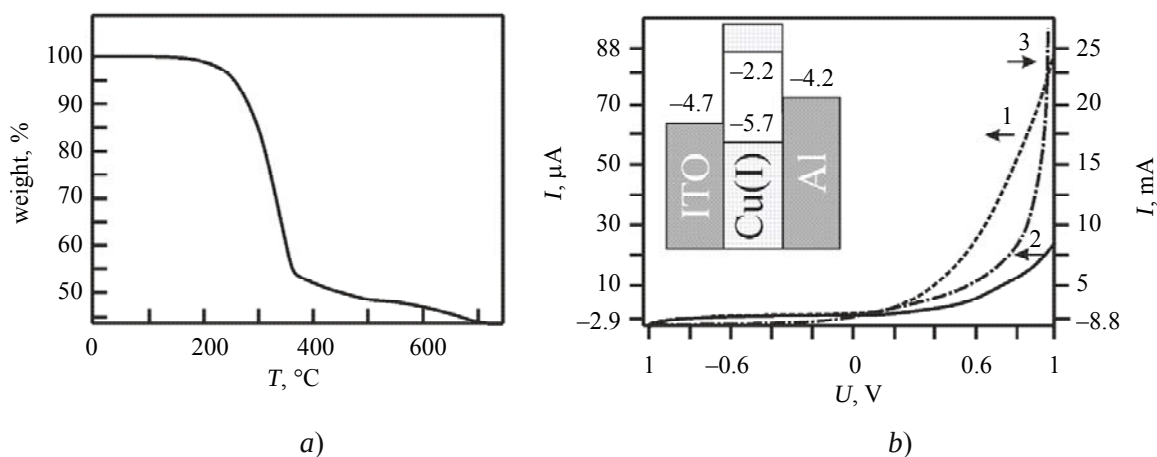


Fig. 4. Thermogravimetric analysis of the obtained Cu(I) compound (a); Dark (2) and light (1) current-voltage characteristics of the ITO–Cu(I)–Al structure (b)

Conductive properties, including photoconductivity, were studied by analyzing current-voltage characteristics (I-V characteristics). Measurements were performed in the voltage range from -1 to 1 V. Figure 4b shows the dark and light I-V characteristics of the ITO–Cu(I)–Al structure (curves 1 and 2), and the ITO–Al contact system (curve 3). The general shape of the current-voltage dependences is nonlinear, asymmetric, and stable within the experimental cycle. Exposure of the Al–Cu(I)–ITO structure to the ultraviolet radiation led to an increase in current in the forward direction from $25\text{ }\mu\text{A}$ to $88\text{ }\mu\text{A}$ due to the generation of photoinduced charge carriers in the copper chain “doped” with iodine (inset of Fig. 3b [19]).

Conclusion

The paper studies the photovoltaic and spectral properties of thin films of the compound 2-(4-pyridyl)-5-phenyl-1,3,4-oxadiazole (triphenylphosphine) copper iodide. The study of IR spectra revealed the presence of numerous

absorption peaks corresponding to this class of compounds. The results of luminescence studies clearly demonstrated the potential of Cu(I) for use as active re-emitting layers, with the quantum efficiency of this material being 55.84%. The excitation maximum of such a complex was observed at a wavelength of 465 nm, with corresponding re-emission in the range of 510–740 nm. The estimated optical band gap was found to be 3.4 eV. The photovoltaic characteristics of the Al–Cu(I)–ITO system, compared with the dark I-V characteristics, showed an increase in forward currents from c $25\text{ }\mu\text{A}$ to $88\text{ }\mu\text{A}$ under UV radiation. The detailed photochemical mechanisms responsible for the large change in electrical conductivity caused by ultraviolet radiation in the polymer appear to be very complex and will be the subject of future research.

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REFERENCES

1. Mirzadeh N., Privér S. H., Blake A. J., Schmidbaur H. and Bhargava S. K., Chemical Reviews (2020).
2. Yang Z., Mao Z., Xie Z., Zhang Y., Liu S., Zhao J. and Aldred M. P., Chemical Society Reviews **46**, 915–1016 (2017).
3. Wang W., Zhang Y. and Jin W. J., Coordination Chemistry Reviews **404**, 213107 (2020).
4. Li H.-Y., Zhao S.-N., Zang S.-Q. and Li J., Chemical Society Reviews (2020).
5. Liu Y., Yiu S.-C., Ho C.-L. and Wong W.-Y., Recent advances in copper complexes for electrical/light energy conversion **375**, 514 (2018).
6. Tsuge K., Chishina Y., Hashiguchi H., Sasaki Y., Kato M., Ishizaka S. and Kitamura N., Coordination Chemistry Reviews **306**, 636–651 (2016).
7. Bissessar D., Thierry T., Egly J., Giuso V. and Achard T., Symmetry **15**, 1210 (2023).
8. Yam V. W.-W., Au V. K.-M. and Leung S. Y.-L., Chemical Reviews **115**, 7589–7728 (2015).
9. Hashimoto M., Igawa S., Yashima M., Kawata I., Hoshino M. and Osawa M., Journal of the American Chemical Society **133**, 10348–10351 (2011).
10. Gusev A., Kiskin M., Braga E. and Zamnius E., Royal Society of Chemistry RSC Advances January **13**, 3899–3909 (2013).
11. Jiang H. and Hu W., Angewandte Chemie International Edition **59**, 1408–1428 (2018).
12. Dobužinskas R., Poškus A., Viliūnas M., Jankauskas V., Daškevičienė M., Getautis V. and Arlauskas K., Physica Status Solidi (2019).
13. Ahmad Z., Zafar Q., Sulaiman K., Akram R. and Karimov K., Sensors **13**, 3615–3624 (2013).
14. Gusev A. N., Mazinov A. S., Tyutyunik A. S. and Baryshnikov G. V., Tech. Phys. **66**, 84–92 (2021).
15. Gusev A. N., Mazinov A. S., Shevchenko A. I., Tyutyunik A. S., Gurchenko V. S. and Braga E. V., Tech. Phys. Lett. **45**, 997–1000 (2019).
16. Gusev A., Braga B., Zamnius E., Kiskin M., Ali A., Baryshnikov G. and Linert W., Dalton Trans. **52**, 14995–15008 (2023).
17. Saravanan S., Anantharaman M. R., Venkatachalam S. and Avasthi D. K., Vacuum **82**, 56–60 (2007).
18. Gusev A. N., Mazinov A. S., Tyutyunik A. S. and Gurchenko V. S., Radio Electronics, Nanophysics and Information Technologies **11**, 331–336 (2019).
19. Strelnik I. D., Kolesnikov I. E., Kalinichev A. A., Gerasimova T. P., Akhmadgaleev K. D., Dayanova I. R. and Karasik A. A., Mendelev Communications **34**, 457–471 (2024).

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Neural network-based methods for optical system measurement

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The paper presents theoretical research and the development results of an intelligent system for the automated inspection of optical system parameters, including focal length, resolving power, and distortion, across various spectral ranges. The system is based on the YOLO convolutional neural network architecture and a specialized hardware-software complex. By employing a neural network-based approach, the software complex performs measurements of optical parameters without continuous operator intervention. This makes the system highly promising for the mass production of optical devices, as it reduces time of measurement, decreases labor costs, and eliminates the impact of the human factor.

Keywords: convolutional neural network, YOLO, computer vision system, object detection, optics, lenses, automated measurements, focal length, distortion, resolving power.

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Introduction

The production of optical systems (hereinafter referred to as OS) includes the control of the final products' output parameters, which include focal length, distortion, and resolving power, which are key for characterizing OS for operation as part of optoelectronic devices [1].

The goal of introducing artificial intelligence systems into the technological process of manufacturing lenses for various machine vision systems is to expand domestic production while reducing product costs. This can be achieved through the development of automated systems that enable faster and more accurate measurements of optical parameters with minimal human intervention.

Russia's modern metrological base used in the production of OS includes methods for

controlling parameters; however, it lacks automation, which gives rise to several problems: a long production cycle, low labor productivity in serial production, and subjectivity in measurements.

To carry out automated measurements of focal length, distortion, and resolving power using AI methods, it was necessary to solve the following tasks:

1. Development of auto-positioning and auto-focusing algorithms for OS;

2. Development of a neural network for recognizing the test object's control points, which is to be used for measuring the focal length and distortion of the OS;

3. Development of a neural network for recognizing the test object's groups of lines, which is required to determine the resolving power of the OS;

4. Development of algorithms for analysis and the calculations required to determine the values of focal length, resolving power, and distortion of the OS.

Technical Implementation

The starting point for the development of a control system using artificial intelligence methods was a set of measurement techniques and the technical implementation of a precision measurement setup designed to measure the focal length, distortion, and resolving power in two spectral ranges: 0.4–2.0 μm and 8–14 μm . A general measurement scheme is shown in Figure 1.

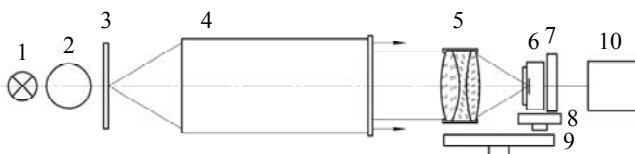


Fig. 1. General scheme for measuring the focal length, distortion, and resolving power of an OS: 1 – radiation source; 2 – integrating sphere (for the spectral range 0.4–2.0 μm); 3 – test object; 4 – collimator; 5 – lens under test; 6 – focal-plane array (FPA); 7 – two-axis linear translator; 8 – linear translator; 9 – rotary platform; 10 – PC with software

The spectral range of the setup is determined primarily by the type of radiation source and FPA used. Radiation source 1 comprises a blackbody model for the spectral range of 8–14 μm and an illumination unit with an incandescent lamp for the spectral range of 0.4–2.0 μm . During operation in the 0.4–2.0 μm spectral range, an integrating sphere 2 may be used if necessary to ensure a uniform radiation distribution in the test object plane. Alternatively, an illumination unit design performing a similar function may be used instead of the integrating sphere. As photodetector array 6 for recording the image in the focal plane of the test object, an uncooled microbolometer and a SWIR camera, which also operates in the visible range, are used alternately as FPA to control lenses in the respective spectral ranges. The test objects 3 are a set of specially developed resolution targets that include groups of lines for determining the resolving power and reference points for estimating the focal length and distortion. To

form a parallel beam of rays simulating an object at infinity, collimator 4 is used. To enable resolving power measurements, the technical implementation of the setup includes an auxiliary projection optical system, which is necessary to address the pixel pitch vs. line images commensurability issue.

Measurement techniques based on the following principles were chosen as objects of interest for automation using neural network methods:

- The method for measuring the lens focal length is based on the classical magnification method. The linear magnification of the optical system consisting of the collimator lens and the lens under test is simultaneously the ratio of the object size to its image size and the ratio of their focal lengths. Therefore, the lens focal length $f'_{\text{к.о}}$ is determined by one of the following formulas (depending on whether the collimator length is known with sufficient accuracy) or by measuring the angular dimensions of the test objects using a theodolite:

$$f'_{\text{к.о}} = f'_{\text{колл}} \cdot \frac{y'}{y}, \quad f'_{\text{к.о}} = \frac{y'}{\text{tg}\varphi}, \quad (1)$$

where $f'_{\text{колл}}$ – focal length of the collimator lens, mm; y – linear size of the test object, mm; y' – linear size of the image of the test object, mm; φ – angular size of the test object, degrees;

- The method for measuring the resolving power of lenses is based on determining the maximum resolvable line target through the lens under test, which corresponds to the smallest resolvable distance between the centers of two adjacent bright and dark lines. The desired resolving power limit $R_{\text{к.о}}$, lines/mm, is determined based on the angular size of the element of the maximally resolvable target $\bar{\varphi}$, degrees, using the formula:

$$R_{\text{к.о}} = \frac{1}{f'_{\text{к.о}} \cdot \text{tg}\bar{\varphi}}; \quad (2)$$

- The method for measuring lens distortion is based on measuring the deviation of the image point coordinates from the calculated value when the lens is rotated using rotary platform 9. This deviation corresponds to the shift of the object

image position at the edge of the lens field caused by the OS distortion. The distortion value v , %, is calculated by the formula

$$v = \frac{y' - l}{l} \cdot 100 \%, \quad (3)$$

where $l = f'_{n.o.} \cdot \tan \omega$ – calculated displacement of the test object image, mm, when the lens is rotated by angle ω , deg; y' – actual displacement of the test object image, mm.

The system is controlled via the interface of the developed software, which implements communication protocols with stepper motor controllers and real-time video stream capture.

Automatic Positioning and Focusing

The basic functions of the automated system are the ability to automatically focus and align the test object's center with that of the FPA. These processes occur during preparation for optical parameter measurements on the bench as follows: automatic positioning of the test object image at the center of the FPA is performed using a two-axis linear translator 7 (see Fig. 1), followed by automatic focusing using linear translator 8.

System focusing is defined as aligning the focal plane of the lens under test with the object plane of the auxiliary projection optical system and is essential for the correct operation of the system and for improving the accuracy of the measurements performed. To automate this process, the system employs a sharpness estimation method based on the Tenengrad criterion [2], which relies on the analysis of image brightness gradients. The idea of the method is as follows: the sharper the image, the stronger the brightness transitions (object edges) and, consequently, the higher the gradient values. This method is based on the Sobel operator and demonstrates high noise immunity in IR frames with elevated noise levels [3]. Accordingly, the autofocus algorithm is reduced to scanning the range of the linear translator responsible for focusing with a predefined step. At each stop, a frame is captured and the sharpness value is calculated using the Tenengrad method. The highest value is saved in the system, and after scanning the entire range, the linear translator is

set to the position with the maximum gradient value.

System positioning involves two stages: axis calibration, which involves calculating the number of motor steps required for the linear translators to move 1 mm, and shifting along each axis to the central point of the image. Axes are calibrated using an alignment table – a set of adjustments for fine-tuning the position. The system uses a neural network to recognize the test object's center and saves the initial position, then the axes are shifted by 1 mm and the recognition is repeated to determine the final position; then the difference between the two positions is calculated, i.e. the distance in pixels traveled by the system during a physical shift of the axis by 1 mm. Several iterations of the shift by a maximum of 1 mm are performed to ensure a more precise calibration. Once the physical distance required to bring the test object's center to the center of the image matrix is determined, the system shifts the axes.

Development of Neural Network Models

Due to recent progress in the field of neural networks, they can be used even with limited computing resources [4, 5], which undoubtedly offers potential for their multifaceted integration into measurement equipment. This opens the way to the development of intelligent systems capable of performing fast and accurate data analysis directly during data acquisition, thus enabling prompt decision-making without significant delays. This increases the operational efficiency of systems under time and resource constraints, while also reducing dependence on external computing infrastructure. Such systems can adapt to changing environmental conditions and ensure a high-level of automation across the entire production process. As a result, their range of applications expands - from single measurements to series production.

Existing classical non-neural network methods are also based on image analysis (including convolution computations), but they are not adapted to multi-stage measurements and require the development of complex algorithms, which is particularly difficult to implement in universal setups designed for measuring various optical systems that differ, for example, in spectral ranges or focal lengths.

With the system requirements taken into account, various families of neural network architectures were analyzed [6–12]. Modern single-stage architectures were considered for solving the problem of recognizing control points and line groups, as they provide the best ratio of speed and accuracy during computations run on a central processing unit without the use of a discrete graphics accelerator. Among them, three main directions stand out: classical detectors, modern universal models, and ultra-lightweight mobile architectures. Transformer models, being the most relevant trend in computer vision, are also distinguished. Despite their high accuracy, they were not considered for this system due to their excessive demands on processor resources.

Under limited performance conditions, such architectures operate significantly slower than their convolutional counterparts. Nevertheless, for completeness of analysis, transformer models have been included in the comparative characteristics of architectures provided in Table 1.

The conducted analysis allowed to establish that modern single-stage architectures of the YOLO family provide the best ratio of localization accuracy for small objects, computational complexity, and ease of integration. In contrast to transformer-based models, they exhibit stable real-time performance on the target hardware, which is why they were selected for the system implementation.

Table 1

Comparative table of single-stage neural network architectures

Architecture	Representatives	Accuracy for small objects	Complexity of integrating in the system	Used in real-time mode
Ultra-lightweight	PicoDet, NanoDet	Medium	Medium	Yes
Classical, single-stage	SSD, RetinaNet	Medium	Low	Limited
Modern universal	YOLO	High	Low	Yes
Transformer	RT-DETR	High	Medium	Limited

For training the neural network models, over 8,000 images were captured in the short-wave visible-to-IR (0.4–2.0 μm) and long-wave (8–14 μm) IR spectral ranges for lenses with focal lengths of 10 mm and 35 mm.

The neural network model was tested during measurements of the developed lenses with known focal lengths using of specially designed resolution targets. The line width of these targets corresponds to the magnification produced by the "lens under test – collimator lens" system, so that the image of the test objects is clearly distinguishable and readable. This is required not only for obtaining reliable measurement results, but also for the stable operation of the neural network model. These targets can also be used for testing lenses with other focal lengths, provided that the image quality is maintained.

The test objects were labeled as follows to train the neural network (see Fig. 2): red – labels for measuring focal length; blue – the center of the line target, used for positioning and for

measuring distortion; green – groups of lines for determining the resolving power limit. The coordinates of the regions of interest are calculated by finding their geometric center.

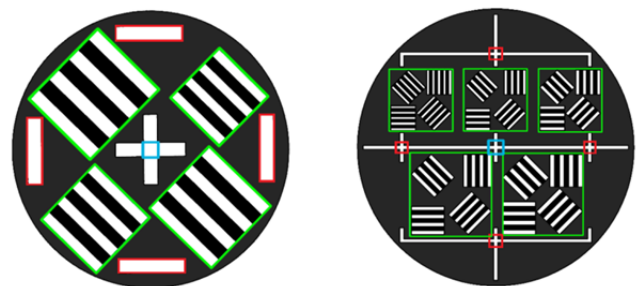


Fig. 2. Labeling of line targets (on the left – for OS with $f' = 10$ mm, on the right – $f' = 35$ mm)

Each group of lines highlighted in green has its own spatial resolution value with a step of 5 lines/mm, corresponding to the focal length of the lens under test, which is set by the operator in the software. The groups on the target in the right part of Fig. 2 are arranged in ascending order, from top to bottom. The line groups on the left

target are arranged in a “crisscross” pattern: the smallest group has the lowest spatial resolution and is followed by a group located diametrically opposite to the first one, the next group is positioned to the left of the second one, and finally, the last group is the largest and, accordingly, has the highest spatial resolution. The results are analyzed and calculated taking into account these specific arrangement features of the groups on the coordinate axes of the image matrix.

To enhance the robustness of the trained neural network models [13], augmentation techniques [14] were applied, including geometric transformations (rotation, scaling) and brightness and contrast adjustments to simulate temperature drift.

Although the neural network models trained on these data successfully prove that they are able to memorize the patterns of the resolution targets, the potential for improving the dataset and developing image preprocessing algorithms to enhance the accuracy and increase the speed of model inference has not been exhausted. In-depth modification of image preprocessing algorithms requires shall be studied individually and was not considered at this stage.

Evaluation of Model Performance

The neural network models were trained using various YOLO modifications ranging from the 8th to the 26th generation, in different configurations: from the most compact and fast (Nano) to the large-scale (Large) versions. Training was performed by varying hyperparameters and environmental conditions. The best results were achieved with medium-sized models: YOLOv8m for the control point detection task, and YOLO26m for recognizing line groups on the resolution targets.

The performance quality of the models was evaluated using a set of metrics that allows evaluating both the correctness of object recognition and the accuracy of their placement in a frame. To interpret these metrics, it is necessary to understand the four possible scenarios of neural network performance:

1. True Positive (TP) – the neural network correctly detected an object where one exists;

2. False Positive (FP) – “false alarm”, the neural network mistook an empty area or noise for an object;

3. False Negative (FN) – a miss of a target, where the neural network failed to detect an existing object;

4. True Negative (TN) – the neural network correctly determined that an empty area contains no object (this parameter is usually not considered in object detection tasks, because the number of empty “areas” in a frame is infinitely large).

Based on these scenarios, the key metrics presented in Table 2 are calculated:

– Precision is the proportion of actual objects among all those that the neural network labeled as detected. High precision means that the system produces very few false alarms. It is calculated by the formula:

$$P = \frac{TP}{TP + EP}; \quad (4)$$

– Recall is the proportion of detected objects out of the total actual number of objects. High recall indicates that the system finds almost all objects and minimizes misses. It is calculated by the formula:

$$R = \frac{TP}{TP + FN}; \quad (5)$$

To evaluate the localization quality, the IoU (Intersection over Union) metric is used, which is the ratio of the intersection area of the predicted and reference frames to their union area (0 = no overlap, 1 = perfect match).

The central performance indicator is mAP (mean Average Precision), which combines the precision and recall metrics. Depending on the strictness of localization requirements (frame overlap), two modifications are distinguished:

– mAP@0.5: calculated under the condition that an object is considered detected (TP) if the overlap area of the predicted and reference frames is at least 50%. This metric characterizes the overall ability of the model to recognize objects;

– mAP@0.5:0.95: represents the average value at different IoU thresholds (from 50% to 95% with 5% increments). This metric is stricter

and more critical in terms of the fitting quality of the bounding box boundaries and allows evaluating the model's robustness to geometric inaccuracies and the precision of object coordinate determination.

Thus, the YOLOv8m model demonstrated high detection quality for control points ($\text{mAP}@0.5 = 0.975$), providing high precision and recall values. This means that in 97.5% of cases, the system correctly finds, classifies, and determines the location of the control point in the

image, allowing only a minimal percentage of errors in the form of misses or false positives. At the same time, the $\text{mAP}@0.5:0.95$ metric was lower, which means lower localization accuracy under strict IoU thresholds. It should be noted that system performance could be further improved by developing and integrating additional algorithms for control point analysis and center finding, but the investigation of this possibility remains beyond the scope of this paper.

Table 2

Results of training neural networks models

Task	Model	Precision	Recall	$\text{mAP}@0.5$	$\text{mAP}@0.5:0.95$
Recognition of test object's control points	YOLOv8m	0.956	0.955	0.975	0.598
Recognition of test object's target lines	YOLO26m	0.813	0.932	0.874	0.737

The YOLO26m model demonstrated lower classification precision when recognizing line groups ($\text{mAP}@0.5 = 0.874$), but it provided better localization stability, as confirmed by a higher $\text{mAP}@0.5:0.95$ value. In other words, the model correctly detects and classifies line groups in 87.4% of cases.

Thus, the combined use of these models effectively addresses the comprehensive task of optical system parameter control. Despite differences in error characteristics, the achieved precision for each subtask provides a sufficient basis for the correct operation of the entire system, ensuring the necessary balance between key point detection and the stability of line group recognition.

Conclusion

The developed automated system for controlling lens parameters, which is based on two neural network models (YOLOv8 m – for measuring focal length and distortion; YOLO26 m – for measuring resolving power), allows controlling optical systems across various spectral ranges (0.4–2.0 and 8–14 μm).

The advantages of this system include speed, precision, and independence from the human factor, making its application particularly

relevant in the mass production of optical systems. The system has demonstrated a reduction in labor efforts during measurements: checking all lens parameters (focal length, distortion, and resolving power) with this intelligent system takes less than 15 minutes, whereas manual measurement by a human operator can require over 60 minutes.

The first neural network model, based on YOLOv8m, detects control points almost perfectly: they are recognized absolutely correctly in 97.5% of cases. This is a high figure, which indicates that errors in point detection are nearly eliminated.

When recognizing the test object's lines, the second model, based on YOLO26m, shows a slightly lower accuracy of 87.4%. This means that when the system encounters a group of lines, it correctly identifies it and accurately isolates it in 87.4% of cases. At the same time, the final measurement error does not exceed the values established by the measurement procedure.

The system was tuned and tested on a computer without a discrete graphics accelerator. All neural network computations were performed using the central processing unit. Despite this, the system enables fast measurements with the required precision, thus confirming the correct selection of models and approaches.

REFERENCES

1. Kreopalova G. V., Lazareva N. L., and Puryaev D. T. Optical Measurements: A Textbook for Universities / Ed. Puryaev D. T. Moscow: Mashinostroenie, 1987.
2. Sun Y., Duthaler S., and Nelson B. J., Microscopy Research and Technique **65** (3), 139–149 (2004).
3. Gashnikov M. V. Methods of Computer Image Processing / Ed. Soifer V. A., 2nd ed. Moscow: FIZMATLIT, 2003.
4. Liu H.-I., et al., ACM Computing Surveys **57** (6), 1–42 (2024). <https://doi.org/10.1145/3657282>.
5. Bouguettaya A., Kechida A., and Taberkit A. M., International Journal of Informatics and Applied Mathematics **2** (2), 28–44 (2019).
6. Redmon J., Divvala S., Girshick R., and Farhadi A. Proceedings of the IEEE Conference on Computer Vision and Pattern Recognition (CVPR), 779–788 (2016). <https://doi.org/10.1109/CVPR.2016.91>.
7. Yaseen M. What is YOLOv8: An In-Depth Exploration of the Internal Features of the Next-Generation Object Detector, 2024. arXiv preprint. arXiv:2408.15857.
8. Liu W., et al. Computer Vision – ECCV 2016. Lecture Notes in Computer Science **9905**. Cham: Springer, 21–37 (2016). https://doi.org/10.1007/978-3-319-46448-0_2.
9. Mittal P., Artificial Intelligence Review **57**, Art. 242 (2024). <https://doi.org/10.1007/s10462-024-10877-1>.
10. Lin T.-Y., et al. Proceedings of the IEEE International Conference on Computer Vision (ICCV), 2980–2988 (2017). <https://doi.org/10.1109/ICCV.2017.324>.
11. Andriyanov N. A., Dementiev V. E., and Tashlinskiy A. G., Journal of Communications Technology and Electronics **67** (10), 1015–1034 (2022).
12. Zhao Y., et al., Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR), 16965–16974 (2024). arXiv:2304.08069.
13. GOST R 70462.1-2022. Information technology. Artificial intelligence. Assessment of neural network robustness. Part 1. Overview. Moscow: Standartinform, 2022.
14. Emelyanov S. O., Ivanova A. A., Shvets E. A., and Nikolaev D. P., Sensory Systems **32** (3), 236–245 (2018). <https://doi.org/10.1134/S0235009218030058>.
15. Padilla R., Netto S. L., and da Silva E. A. B., International Conference on Systems, Signals and Image Processing (IWSSIP), 237–242 (2020). <https://doi.org/10.1109/IWSSIP48289.2020.9145130>.

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Bactericidal properties of two-dimensional ordered linear-chain carbon

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Laboratory tests of the bactericidal properties of stainless steel samples with a protective nanolayer of linear-chain carbon of various modifications were carried out in a closed volume of air at atmospheric pressure, 100 % humidity and room temperature. After testing, it was shown that with respect to spore-forming gram-positive bacteria of the *Bacillus pumilus* species, the coatings showed bacteriostatic activity, which did not allow these microorganisms to multiply, and with respect to vegetative forms of Gram-negative bacteria *Pseudomonas aeruginosa*, all tested samples showed bactericidal activity, expressed in almost complete suppression of their viability on all types of coatings. For fungi, only one type of coating doped with lithium atoms had antifungal properties when there was a complete absence of fungal growth and the absence of viable micromycete units. For the remaining samples, there was a slight growth of fungi compared to the control samples.

Keywords: stainless steel, two-dimensionally ordered linear-chain carbon, protective nanolayer, micromycetes, bacteria.

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Introduction

Currently, carbon and new carbon-based composite materials are of great practical and scientific interest in all branches of human activity. For a long time, only two allotropic modifications of carbon – graphite and diamond – were actively studied. At present, the polytypes of diamond and graphite have been thoroughly investigated and described [1–3]. If we consider diamond (a three-dimensional carbon polymer) as the limiting case of the paraffin series, and graphite (a planar polymer) as the limiting case of the aromatic series, then it is logical to assume that the next form will be the limiting case of the unsaturated series, which can be represented as a linear polymer whose molecules are built from polyynes or cumulene chains [4]. The possibility

of the existence of linear carbon polymers with *sp*-hybridization was considered as early as 1885 by Baeyer. He attempted to synthesize a chain carbon – polyyne. Attempts to obtain one-dimensional polyyne chains from tetraacetylene were unsuccessful due to the instability of tetraacetylene [5]. As a result of long-term research, Baeyer postulated the impossibility of obtaining linear chain carbon. This work ceased for a long time. However, in 1960, the A. N. Nesmeyanov Institute of Organoelement Compounds of the Russian Academy of Sciences (INEOS), discovered the third crystalline allotropic form of carbon and named it carbyne [6]. Subsequently, various methods for obtaining carbyne were developed [5, 7, 8, 9]. The next step was the modification of surface properties by creating thin carbon films or layered

film structures on them, with thicknesses ranging from microns to fractions of a micron. The orientation of carbon molecular chains can be controlled while the structures are growing [10–12]. Such film structures serve as the basis for building the elemental base of modern micro- and nanoelectronics. Thin films can also perform functional tasks such as surface hardening or changing wettability and the friction coefficient. When deposited onto a solid surface, carbon atoms can form various allotropic modifications differing in hybridization type: sp^3 and sp^2 , which correspond to the stable modifications of diamond and graphite, sp^1 and sp^0 , which are these are metastable modifications of linear chain carbon (LCC) and face-centered (FC) carbon. Upon condensation on the surface, the chains cross-link to form a graphite-like condensate. Under certain condensation conditions of carbon vapor on the surface, films of two-dimensionally ordered linear chain carbon (2DO LCC), which consist of linear carbon chains oriented normal to the surface and forming ordered ensembles can be formed [10–12]. 2DO LCC films are ordered ensembles of quantum wires spaced $0.4\div 0.5$ nm apart, and therefore weakly interacting with each other and possessing unique electrophysical properties. Integration of additional atoms into carbon chains or the cross-linking of polymer chains of linear carbon allows modifying both their physical properties and biological activity.

Biomedical studies of implants coated with linear chain carbon have shown the absence of protein denaturation on their surfaces and an extremely low blood coagulation potential. The application of 2DO LCC coatings on the surface imparts exceptional thromboresistance and improves the biocompatibility of medical implants and devices, reducing the risk of thrombosis, implant rejection, and inflammation [13]. According to prior studies, carbyne in the form of nanopowders exhibits biocidal activity against microorganisms of various species, in particular against representatives of human automicroflora and opportunistic pathogenic microorganisms [14].

The aim of this paper is to obtain experimental data on the effect of coatings made from various modifications of 2DO LCC on the viability of airborne microorganisms at atmospheric pressure, 100% humidity, and room temperature.

Experimental Section

For the purpose of the research, sixteen samples of 12X18H10T stainless steel, each measuring $50\times 25\times 1$ mm, were produced. On the surface of 12 samples, a layer of two-dimensionally ordered linear chain carbon (2DO LCC) approximately 200 nm thick was synthesized by ion-beam deposition [10]. On the surface of 4 samples, the layer was deposited in the presence of hydrogen in the residual atmosphere (2DO LCC + H); on 4 samples, the layer was deposited in the presence of nitrogen (2DO LCC + N); on 4 samples, the layer was doped with lithium atoms in an inert atmosphere (2DO LCC + Li); and 4 samples were used as controls without coating. The biocidal properties of the fabricated samples were tested using representatives of bacterial and fungal flora. The bacterial test cultures used were representatives of Gram-negative flora – bacteria of the species *Pseudomonas aeruginosa* and spore-forming Gram-positive bacilli of the species *Bacillus pumilus*. As micromycete cultures, the following fungal species from the All-Russian Collection of Microorganisms (VKM) were used:

Aspergillus niger van Tieghem – VKM F – 1119;
Aspergillus terreus Thom VKM F-1025;
Aspergillus oryzae (Ahlburg) Cohn VKM F – 55;
Chaetomium globosum Kunze VKM F – 109;
Paecilomyces varioti Bainier VKM F – 378;
Penicillium funiculosum Thom VKM F – 1115;
Penicillium chrysogenum Thom VKM F – 245;
Penicillium cyclopium Westling VKM F – 265;
Trichoderma viride Pers. ex Fr. VKM F – 426.

On two samples from each group, microdroplets of the prepared bacterial suspension with a bacterial count ranging from 1×10^6 to 4×10^6 CFU were applied. On two samples from each group, droplets of a fungal spore suspension were applied. The suspension was prepared by mixing equal parts of the suspensions of each fungal species. After that, all samples with the applied suspension were placed in a closed sealed volume at atmospheric air pressure, room temperature, and 100% humidity. A stainless steel chamber with an inner radius of 60 mm and a height of 140 mm was used to create the sealed volume (Fig. 1). The test samples were placed inside the chamber on an aluminum rack-type holder. To achieve the required humidity of the gas environment, a recess with a volume of 2 cm^3 was made in the upper part of the holder and filled with distilled

water (Fig. 1). The test duration was 14 days for bacterial cultures and 28 days for fungal cultures.

After the bacterial tests were finished, the samples were subjected to microbiological analysis to identify differences in the quantitative level of viable microorganisms on the test and control samples. The analyses were carried out by standard methods [15]. The results of the antimicrobial property tests for samples with different coating types are presented in Table 1.

As shown in Table 1, on unprotected stainless steel samples, approximately 4×10^2 CFU/sample of *Pseudomonas aeruginosa* were found, while on the protected samples, only single cells (0 to 9) were detected, corresponding

to 97.75% to 100% protection efficiency. Comparative tests of protected and unprotected steel samples show that spore-forming microorganisms of the species *Bacillus pumilus* remain viable, but their quantitative level was not found to increase above that on the control samples in any case.

After the mycological tests were finished, the material samples were inspected in diffuse light at $10\times$ magnification using a Stemi 2000 stereomicroscope. Fungal resistance was evaluated by the intensity of fungal growth on the samples using a 6-point scale as per GOST 9.048-75 [16], as shown in Table 2. Table 3 shows the sample surface inspection results in points.

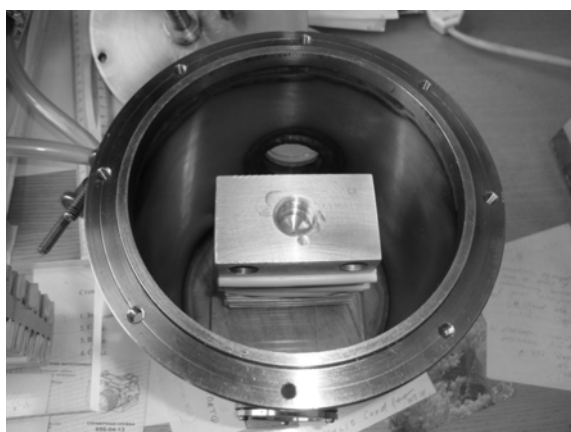


Fig. 1. Chamber with the holder installed Top view

Table 1

**Test results of antimicrobial properties of the coatings against Gram-negative microorganisms
Pseudomonas aeruginosa and *Bacillus pumilus***

Sample and coating type	<i>Pseudomonas aeruginosa</i> , CFU/sample	<i>Bacillus pumilus</i> , CFU/sample
Stainless steel (control)	4.0×10^2	6.0×10^4
Stainless steel + 2DO LCC + H	0–9	3.6×10^4
Stainless steel + 2DO LCC + N	0–8	3.0×10^4
Stainless steel + 2DO LCC + Li	0	4.5×10^4

Table 2

Fungal growth evaluation

Point	Point description
0	No fungal growth is visible under a microscope.
1	Germinated spores and a slightly developed mycelium in the form of unbranched hyphae are visible under a microscope.
2	A mycelium in the form of branched hyphae and sporulation structures are visible under a microscope.
3	Fungal growth is barely visible to the naked eye, but is clearly visible under a microscope.
4	Fungal growth is clearly visible to the naked eye, with the fungi covering less than 25% of the tested surface.
5	Fungal growth is clearly visible to the naked eye, with the fungi covering more than 25% of the tested surface.

Table 3

Evaluation of fungal growth on sample surfaces after exposure

Material	Fungal growth score (points)	Evaluation results
Stainless steel (control)	2	The gas environment contains chemical compounds used by fungi for slight growth.
Stainless steel + 2DO LCC + H	2–3	The gas environment and the coating contain chemical compounds used by fungi for greater growth than in the control.
Stainless steel + 2DO LCC + N	2–3	The gas environment and the coating contain chemical compounds used by fungi for greater growth than in the control.
Stainless steel + 2DO LCC + Li	0	The material surface has a coating that prevents fungal growth.

As can be seen from the presented data, the air environment contains compounds that micromycetes are able to use for their anabolism. This is confirmed by the growth of micromycetes on the control samples. On the test coatings, fungal growth in the form of branched hyphae and weak sporulation was observed (Fig. 2). The exception was the stainless steel samples with the 2DO LCC + Li coating, on which no fungal growth was detected (Fig. 3). After culturing the washings from these samples, no viable micromycete CFU were found. Thus, according to the results of the microbiological tests conducted, only the coating deposited on the stainless steel substrate and consisting of 2DO LCC doped with lithium atoms exhibited antifungal properties.

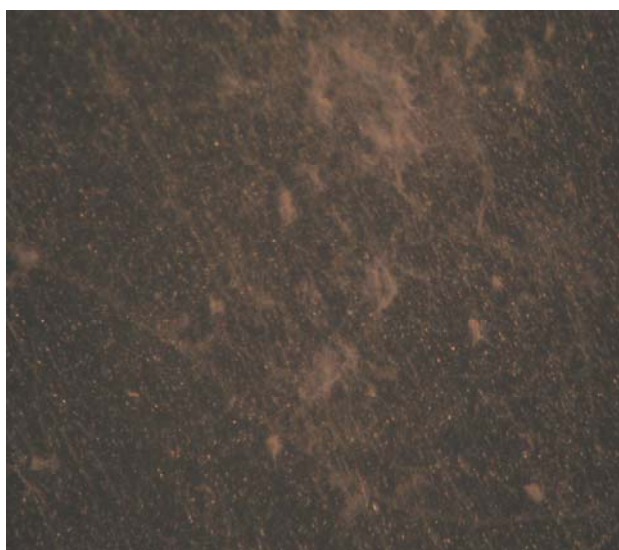


Fig. 2. Surface of the sample with the deposited 2DO LCC + N layer after testing. Fungal growth is observed. Magnification – $\times 10$



Fig. 3. Surface of the sample with the deposited 2DO LCC + Li layer after testing. No fungal growth is observed. Magnification – $\times 10$

Conclusion

All tested 2DO LCC nanocoatings exhibited bactericidal activity against vegetative forms of Gram-negative microorganisms *Pseudomonas aeruginosa*, which was expressed in the almost complete suppression of their viability. Against spore-forming Gram-positive bacteria of the species *Bacillus pumilus*, the coatings exhibited bacteriostatic activity that prevents these microorganisms from reproducing and increasing in number on the protected samples. According to the results of the microbiological tests against fungi, one type of coating, 2DO LCC + Li, exhibited antifungal properties, with a complete absence of fungal growth and no viable micromycete CFU

observed. For the remaining samples, slight fungal growth was observed compared to the control samples.

2DO LCC nanocoatings are promising for preventing fungal growth and suppressing bacterial viability. The differences in the biological properties of the protective nanocoatings of two-dimensionally ordered linear chain carbon require further investigation of their

surface properties and the mechanisms of microbial growth suppression.

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REFERENCES

1. Shumilova T. G. Diamond, graphite, carbene, fullerene and other carbon modifications. Yekaterinburg: Ural Branch of the Russian Academy of Sciences, 2002.
2. Romanenko A. V. and Simonov P. A. Carbon materials and their physico-chemical properties, Under the general editorship of Dr. of Technical Sciences, professor A. S. Noskova. Moscow: Kalvis, 2007.
3. Sladkova T. A. Carbon research – successes and problems / Ed. by Yu. N. Bubnov. In-t elementorgan. A. N. Nesmeyanov Compounds of the Russian Academy of Sciences. Moscow: Nauka Publ., 2007.
4. Sladkov A. M. Carbene is the third allotropic form of carbon / Ed. by Yu. M. Bubnov. Moscow: Nauka, 2003.
5. Kulakova I. I., Chemistry, No. 13, 731 (2007) [in Russian].
6. Sladkov A. M., Kasatochkin V. I., Korshak V. V., and Kudryavtsev Yu. P., Byull. invent., No. 6, (1972) [in Russian].
7. Bitao Pan, Jun Xiao, Jiling Li, Pu Liu, Chengxin Wang, and Guowei Yang, Sci. Adv. **1** (9), 1:e1500857 (2015).
8. Babaev V. G., Guseva M. B., Novikov N. D., Savchenko N. F., and Khvostov V. V., Nanotechnology: Development, application **2** (1), 88–95 (2010) [in Russian].
9. Garnov S. V., Abramov D. V., Bukharov D. N., Khudaiberganov T. A., Khor'kov K. S., Osipov A. V., Zhirnova S. V., Kucherik A. O., and Arakelyan S. M., Physics Uspekhi, **67** (2), 109 (2024).
10. Kochakov V. D., Novikov N. D., Yablokov M. Yu., Eremkin A. V., and Vasiliev A. I., Actual problems of humanities and natural sciences, No. 12, 11 (2009) [in Russian].
11. Babaev V. G., Novikov N. D., Guseva M. B., Khvostov V. V., Savchenko N. F., Korobova Yu. G., and Alexandrov A. F., Nanotechnology: development, application – XXI century **2** (1), 53 (2010) [in Russian].
12. Novikov N. D., Vasilyak S. L., Barkova M. I., and Yanenko Yu. B., Usp. Prikl. Fiz. (Advances in Applied Physics) **8** (3), 167–175 (2020) [in Russian].
13. Babaev V. G., Guseva M. B., Savchenko N. F., Novikov N. D., Khvostov V. V., and Flood P., Surface. X-ray, synchrotron, and neutron studies, No. 3, 16 (2004) [in Russian].
14. Polikarpov N. A., Novikova N. D., Vallano G. E., Vasilyak L. M., Klimovsky I. I., Pecherkin V. Ya., Dobrinsky E. K., and Malashin S. I., Aerospace and environmental medicine, No. 6, 53 (2010) [in Russian].
15. A guide to medical microbiology. Book 1: General sanitary microbiology / ed. by A. S. Labinskaya, E. G. Volina. Moscow: BINOM, 2008.
16. GOST 9.048-75. Materials and products. Methods of testing for microbiological resistance. Moscow: Publishing House of Standards, 1978.

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Investigation of the ring laser perimeter stability to vibration overloads

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The paper presents an experimental study of the perimeter sensitivity of a helium-neon ring laser to external dynamic impacts. The laser under investigation had a generation wavelength of 633 nm and a resonator perimeter of 28 cm. A quantitative dependence of perimeter detuning on the overload along the axis of the movable piezo-mirror was experimentally established. It was determined that the operational stability threshold of the laser corresponds to an overload of 56g, at which the critical detuning of 222 nm is reached. Exceeding this threshold disrupts the single-mode generation regime in the laser, leading to a significant error in the output signal. The sensitivity of the laser perimeter to dynamic impacts was calculated to be 3.75 nm/g. The obtained results define the applicability limits of this type of ring laser under vibration load conditions.

Keywords: ring laser, perimeter detuning, dynamic effect, vibration, overload.

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Introduction

Ring lasers have found wide application as high-precision angular rate sensors in modern navigation and control systems [1]. Their operating principle is based on the Sagnac effect, which results in a frequency difference Δf between counter-propagating waves that is proportional to the rotation rate of the device Ω : $\Delta f = K\Omega$, where K is the scale factor of the ring laser [2, 3]. Excluding the active medium, this factor is determined by the resonator geometry: the optical path length L , the area S enclosed by the contour, and the generation wavelength λ . A key condition for the stable and accurate operation of a ring laser is maintaining the resonator length (perimeter) with an accuracy of a few nanometers [3, 4]. During operation, external impacts (temperature, vibrational accelerations) can cause mechanical deformations of the resonator, leading to its detuning ξ – a change in

the effective perimeter ΔL [5, 6]. This phenomenon causes a shift of the generation frequency from the center of the gain line of the active medium, which impairs key laser parameters, resulting in a decrease in radiation intensity, an increase in the lock-in threshold, and the instability of the scale factor.

To compensate for thermal deformations, the ring laser is equipped with a perimeter control system (PCS) that actuates movable piezomirrors [6, 7]. However, rapid oscillations of the piezomirrors caused by vibration may not be compensated by the system in time [8]. In this case, perimeter detuning ξ causes the laser to exit the optimal generation mode. Moreover, changes in the optical path of the resonator caused by mirror movement can induce an error signal interpreted as rotation [4].

The problem of dynamic impacts becomes particularly relevant when ring lasers are used under conditions of increased mechanical loads,

for example, in the geophysical equipment or control systems for moving objects [1, 9]. As shown in prior studies [10, 11], the ring laser design has its own resonant frequencies (up to 2000 Hz), at which vibration accelerations on the resonator housing can reach tens of g. The element most sensitive to overloads is the movable piezomirror, whose displacement directly affects the resonator perimeter. Thus, a quantitative assessment of the stability of the ring laser perimeter against vibrations is an important task that determines the reliability and application range of these high-precision devices.

The aim of this paper is to experimentally study of the ring laser perimeter's sensitivity to external dynamic impacts and to determine the physical mechanisms behind the vibration influence on its output characteristics.

Theoretical part

The operation of the ring laser as an angular rate sensor is based on maintaining a stable single-mode generation regime at the center of the gain line of the active medium. As noted in the introduction, external dynamic impacts cause perimeter detuning ξ , which leads to a change in the resonator's optical length ΔL and a shift in the natural frequency of the longitudinal mode, as determined by the expression [2, 12]:

$$v = q \frac{c}{L + l(n_a - 1)}, \quad (1)$$

where q is an integer (mode order); c is the speed of light; l , n_a are the length and refractive index of the active medium, respectively.

The dependences of generation intensity I on the resonator length L have been well studied [5, 2]. When the perimeter changes by ΔL , the intensity I will change, and it is convenient to choose the perimeter change (detuning) ξ as the argument of the intensity function, which is defined as $\xi = \Delta L = L - L_0$, where L_0 is the resonator length corresponding to the maximum intensity ($I = I_0$). The relationship between the perimeter detuning ξ and the generated radiation intensity I is key to understanding the stability of device operation. Near L_0 , the dependence $I(\xi)$ is approximated by a parabola [5, 11]:

$$I_\xi = I_0 (1 - a \cdot \xi^2), \quad \text{with } |\xi| \leq \pm \xi_f, \quad (2)$$

where a is a constant coefficient; ξ_f is the boundary of the stable single-mode regime region. As detuning continues to increase, a transition to the mode competition zone occurs.

$$\begin{aligned} -I_\xi &= I_0 \left[1 - a \cdot (\xi \pm 1)^2 \right], \\ \text{with } -\xi_f \pm 1 &\leq |\xi| \leq \pm \xi_f \pm 1, \end{aligned} \quad (3)$$

followed by a transition to the irregular regime described by the random function $SQR(\xi)$ [11]. Thus, the threshold detuning value ξ_f is a critical parameter that defines the boundaries of the ring laser operating mode.

Under vibrational impact conditions, the overload P_g arising at the structure's resonant frequencies f_B causes a force applied to the piezomirror, leading to its displacement and perimeter modulation. This process can be described by the dependence:

$$\xi(t) = P_g(f_B) \cdot \xi_g \cdot \sin(2\pi f_B t), \quad (4)$$

where ξ_g is the sensitivity of the perimeter detuning to the projection of vibrational acceleration onto the normal to the piezomirror surface. The overload coefficient P_g , which depends on the impact frequency f_B can be expressed in a linear approximation through the natural frequencies of the resonant modes f_{Bi} with excitation amplitudes a_{Pi} and quality factors Q_{Pi} [8]:

$$P_g(f_B) = \frac{a_{Pi}}{\sqrt{(f_B^2 - f_{Bi}^2)^2 + \left(\frac{f_B \cdot f_{Pi}}{Q_{Pi}}\right)^2}}. \quad (5)$$

Thus, the theoretical model establishes a direct relationship between the external vibrational impact described by the frequency f_B , the overload P_g , and the resulting perimeter detuning ξ , which directly determines the radiation intensity I_ξ and, consequently, the stability of the ring laser output characteristics. Experimental verification of these dependences allows for a quantitative assessment of the laser stability threshold.

Experimental Study and Results

The object of study was a helium-neon ring laser with a four-mirror resonator, a perimeter of 28 cm, and a lasing wavelength of $\lambda = 633$ nm [9]. The schematic of the experimental setup is shown in Fig. 1. The laser resonator consists of two movable (3) and two fixed mirrors (4). Thermal deformations of the ring laser housing were controlled and compensated by a perimeter control system acting on the piezocorrectors (5) of the movable mirrors via a control voltage U_{PC} . Information on the resonator state was recorded by two intensity monitoring

photodiodes (1), whose signals I_{M1} , I_{M2} carried data on the intensity of the counter-propagating waves. The measurement of the difference frequency Δf of signals $U_{\sin}$ and $U_{\cos}$, proportional to the angular velocity Ω , was performed using an information photodiode (2). The laser housing (6) was mounted on a mechanical dither (7) fixed by screws to a movable plate (8) of a vibration shaker to ensure the rigid transmission of mechanical impacts in the specified direction (9). Accelerometers were mounted on the housing (6) to record the overloads P_g along three axes of external impacts.

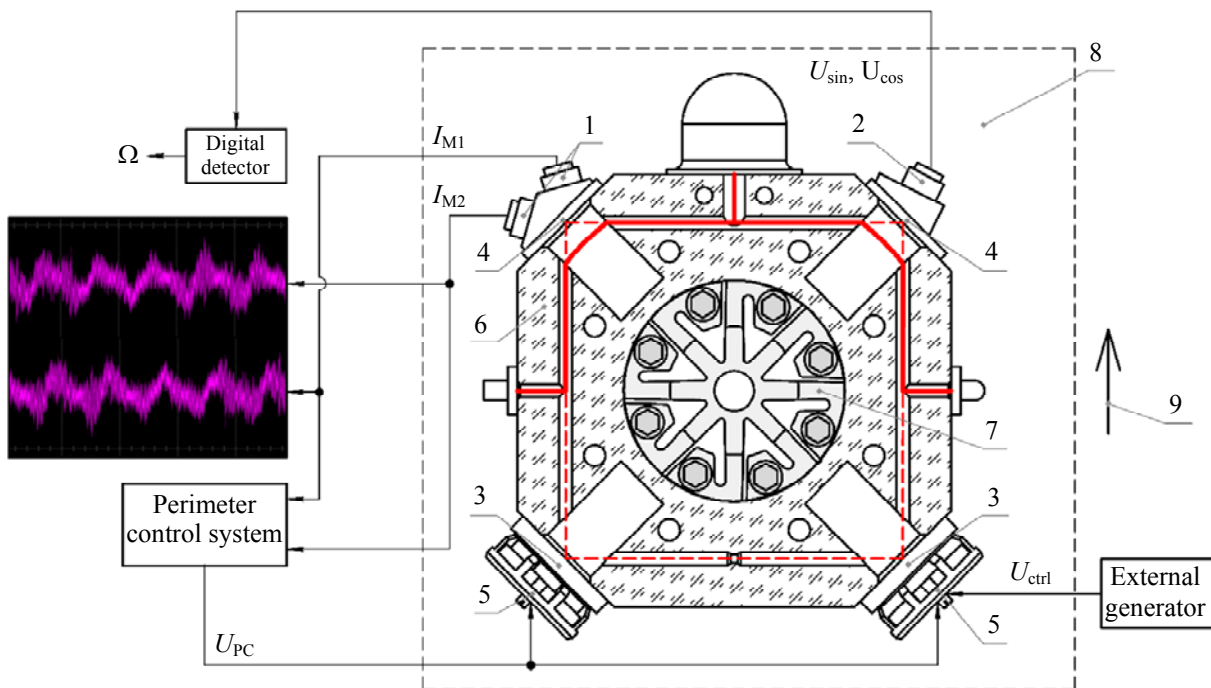


Fig. 1. Experimental setup schematic: 1 – intensity monitoring photodiodes; 2 – information photodiode; 3 – movable mirrors; 4 – fixed mirrors; 5 – piezocorrectors; 6 – ring laser housing; 7 – mechanical dither; 8 – vibration shaker plate; 9 – external dynamic impact direction

The first stage of the experiment studied the dependence of the output signal Ω on the controlled perimeter detuning ξ created by applying a voltage U_{ctrl} to the piezocorrector, with the PCS disabled. The signal Ω was found to remain stable in the range of ξ from 0 to 222 nm and to correspond to the projection of the Earth's diurnal rotation rate (~ 12.45 deg/h). When the threshold of 222 nm was exceeded, a sharp, fivefold increase in the readings was observed, indicating that the ring laser had exited the operating single-mode regime. Additionally, the

intensity modulation I_M under a sinusoidal detuning at a frequency of 2 kHz was investigated. The amplitude of the signal modulation was recorded to grow linearly with ξ increasing up to 222 nm, after which characteristic nonlinear distortions appeared in the signal. The second stage was devoted to the impact of an external harmonic vibration in the frequency range f_B from 20 to 2000 Hz at an acceleration amplitude $P = 4g$. The ring laser with the mechanical dither was mounted on a dynamic shaker. After a preliminary warm-up of

the laser, the PCS was switched to manual mode (the voltage across the piezocorrectors was fixed) to exclude its influence on the modulation of signal I_M and to enable the recording of the detuning ξ caused exclusively by external vibration. A significant increase in the modulation amplitude of the intensity signal I_M was observed only in narrow frequency bands (675–690 Hz, 720–750 Hz, 1010–1045 Hz) that correspond to the regions of mechanical

resonances of the ring laser structure. Figure 2 shows a fragment of the signal I_M at a vibration frequency f_B of 920–1120 Hz.

The accelerometer readings recorded along three axes (in the direction of impact, the ring laser sensitivity axis, and the movable piezomirror axis) confirmed the occurrence in these spectral frequency ranges of significant overloads P_g directed primarily along the axis normal to the movable piezomirror surface (Fig. 3).

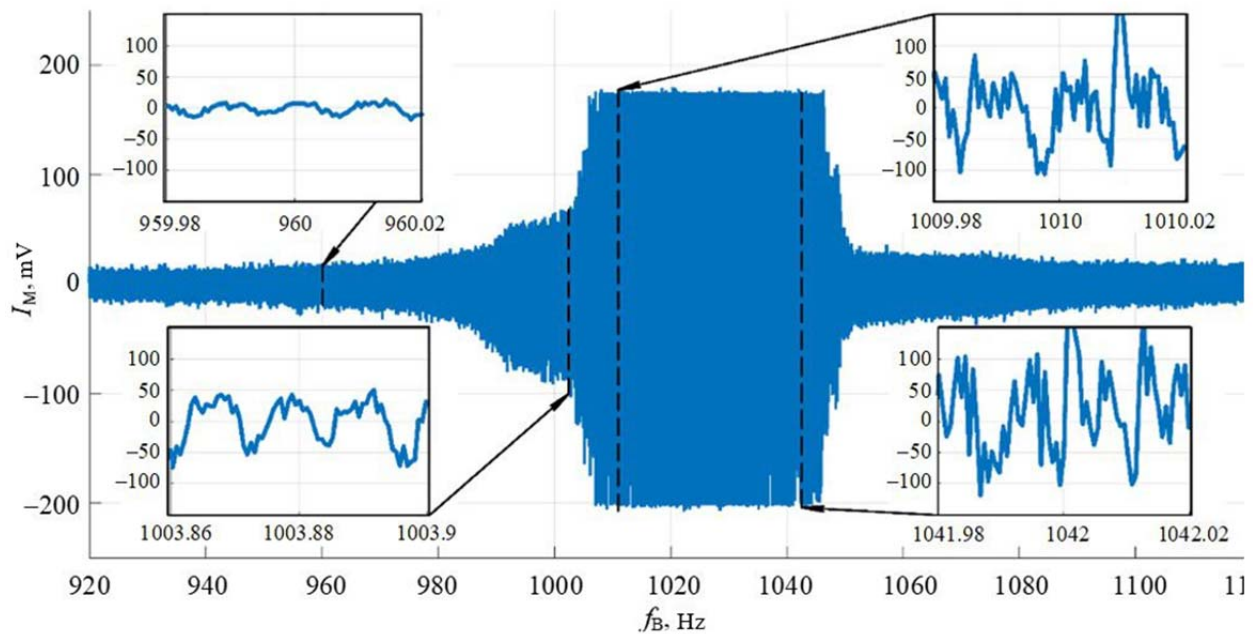


Fig. 2. Modulation of the intensity signal under an external dynamic impact

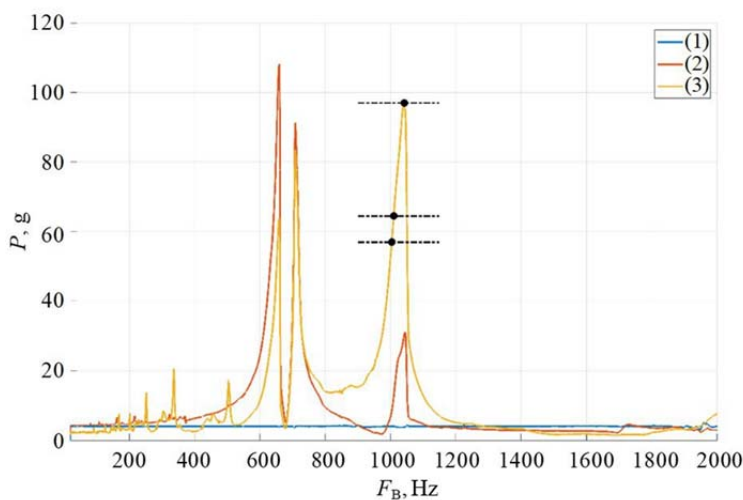


Fig. 3. Overloads along the ring laser axes: (1) – along the impact axis (driving action), (2) – along the ring laser sensitivity axis, (3) – along the ring laser piezomirror axis

A comparison of the modulation pattern of the optical signal I_M under vibration with the calibration dependence obtained at the first stage

of the experiment allowed establishing a quantitative relationship between the overload P_g along the mirror axis and the induced perimeter

detuning ξ . An approximation of the experimental data (Fig. 4) yielded the following dependence:

$$\xi(P) = 0.057P^2 + 0.789P. \quad (6)$$

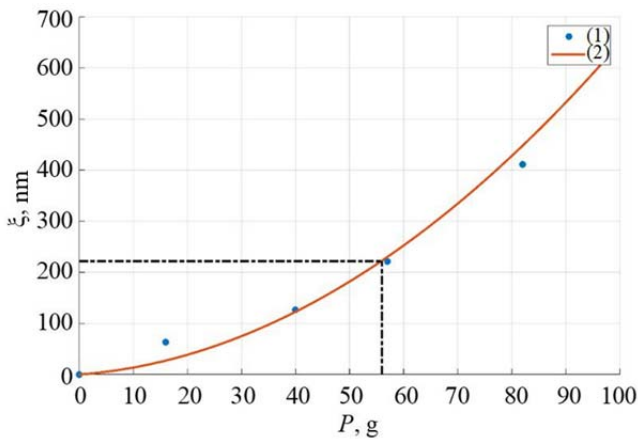


Fig. 4. Dependence of the ring laser perimeter detuning on the overload along the movable mirror axis

It follows from this dependence that the critical detuning value $\xi \approx 222$ nm is reached at an overload $P \approx 56$ g. A linear approximation in the operating range determines the sensitivity of the perimeter of the investigated ring laser to dynamic impacts as equal to 3.75 nm/g.

Discussion of the Results

The obtained experimental data allow concluding that the investigated ring laser exhibits high dynamic stability and establishing a quantitative correlation between mechanical impacts and changes in its optical parameters. The critical threshold established for the perimeter detuning, which is equal to 222 nm, corresponds to the theoretical boundary of the stable single-mode lasing regime. Exceeding this value leads to a transition to the zone of longitudinal mode competition, which fully explains the fivefold increase observed in the output signal error of the device. This result confirms the basic principle that the stability of the ring laser scale factor is determined by maintaining the condition $\xi < \xi_f$.

The revealed selectivity of the laser output signal response to vibration, which is expressed as a significant modulation of the radiation intensity only in narrow frequency ranges, indicates the resonant nature of the impact. This agrees with the data on the intrinsic resonances of the ring laser structure existing within the

frequency range up to 2000 Hz. The prevailing overload specifically along the axis normal to the surface of the movable piezomirror experimentally proves that this element is the main channel for transmitting dynamic perturbations to the optical path of the resonator.

The quadratic nature of dependence (7) likely reflects the nonlinearity of the elastic properties of the piezomirror mount to the laser housing at large deflection amplitudes. The calculated perimeter sensitivity of 3.75 nm/g and the determined stable operation threshold of 56g are key quantitative characteristics for assessing the applicability of the device. These values indicate that at overloads below 56g, the PCS is potentially capable of compensating for the resulting detuning, as it remains within its operating range and does not exceed the critical value ξ_f .

A comparison with known studies [8, 10] confirms the general mechanism of vibration influence through the excitation of structural resonances. At the same time, the obtained specific numerical characteristics (3.75 nm/g, 56g) for a laser with a perimeter of 28 cm contribute new insights into the operational limitations of such devices as part of inertial measurement systems and expand the understanding of their applicability under moderate vibrational loads.

Conclusion

An experimental study of the influence of external dynamic impacts on the stability of the ring laser perimeter has been conducted in this paper. Quantitative estimates of the device stability have been derived from the analysis of the relationship between vibrational overloads, perimeter detuning, and the output characteristics of the device.

The results confirm the theoretical model, according to which the stability of the single-mode lasing regime critically depends on the perimeter detuning value. The experimentally established detuning threshold of 222 nm corresponds to the boundary of the stable single-mode lasing zone. Exceeding this threshold results in a transition to the mode competition regime and a significant increase in the measurement error.

A direct relationship has been established between the overload acting along the axis of the movable piezomirror and the induced perimeter detuning. It has been found that the critical detuning is reached at an overload of 56g, which sets a clear operational limit for devices of this type. The calculated sensitivity of the perimeter to dynamic impacts is 3.75 nm/g.

The obtained results are of practical significance for the development and application

of ring laser gyroscopes under vibrational loading conditions. They show that as long as overloads remain below the specified threshold, the perimeter control system can ensure the normal operation mode of the device, thereby expanding its potential applicability. This study contributes to the understanding of vibration influence mechanisms on the accuracy of inertial measurement systems and provides specific quantitative criteria for assessing their stability.

REFERENCES

1. Sinelnikov A. O., Tikhmenev N. V., Ushanov A. A., and Medvedev V. M., *Photonics of Russia* **18** (6), 450–466 (2024). <https://doi.org/10.22184/1993-7296.FRos.2024.18.6.450.466>.
2. Lukyanov D. P., Raspopov V. Ya., and Filatov Yu. V. *Applied Theory of Gyroscopes*, St. Petersburg: GSC RF OJSC Concern TsNII Elektropribor, 2015 [in Russian].
3. Aronowitz F. *Optical Gyroscopes and Their Applications*, **339**, (1999).
4. Lee J. I., *International Journal of Precision Engineering and Manufacturing* **13** (8), 1439–1443 (2012).
5. Grushin M. E., Kolbas Yu. Yu., and Medvedev A. A., *Photonics* **14** (2), 150–159 (2020) [in Russian]. <https://doi.org/10.22184/1993-7296.Ot.2020.14.2.150.157>
6. Fenercioglu T. O. and Yalçinkaya T., *International Journal of Applied Electromagnetics and Mechanics* **61** (3), 429–443 (2019). <https://doi.org/10.3233/JAE-190019>
7. Lee S. H., Shon W. H., Suh S. W., Yu S. N., and Han C. S., *International Journal of Precision Engineering and Manufacturing* **12** (1), 91–96 (2011). <https://doi.org/10.1007/s12541-011-0011-1>
8. Bolotnov S. A., Nazarov S. I., Sinelnikov A. O., Tikhmenev N. V., and Ushanov A. A., *Gyroscopy and Navigation* **15** (3), 215–225 (2024). <https://doi.org/10.1134/S2075108724700317>
9. Kuznetsov A. G., Molchanov A. V., Izmailov E. A., and Chirkin M. V., *Quantum Electronics* **45** (1), 78–88 (2015). <https://doi.org/10.1070/QE2015v045n01ABEH015420>.
10. Tikhmenev N. V., Nazarov S. I., Ushanov A. A., and Sinelnikov A. O., *Management of Large Systems: Collection of Papers*, № 109, 293–309 (2024) [in Russian]. <https://doi.org/10.25728/ubs.2024.109.13>.
11. Sinelnikov A. O., Tikhmenev N. V., Ushanov A. A., and Nazarov S. I., *Nanoindustry* **18** (S11–1 (135)), 380–387 (2025) [in Russian]. <https://doi.org/10.22184/1993-8578.2025.18.11s.380.387>
12. Liu J., Guo L., Weng J., Liu W., Yang Y., Zhao K., and Zheng Y., *Optics Express* **31** (22), 36314 (2023). <https://doi.org/10.1364/oe.503255>.

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Study of changes in the adsorption properties of L-asparaginase on mica under thermal action for the development of a nanopore-based detector

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Atomic force microscopy (AFM) is used to study the adsorption of L-asparaginase (L-ASNase) E. carotovora enzyme on mica within 25 °C to 60 °C temperature range. Thermally induced changes in the oligomeric state of L-ASNase and its adsorbability on mica are revealed. Maximum adsorption of L-ASNase in the form of individual globules is observed at 45 °C. At 55 °C, the enzyme adsorbs in the form of filamentous structures, and at 60 °C it loses its adsorbability. The results obtained are fundamentally important for the development of electrical molecular detectors based on solid-state nanopores (SSN-EDs) intended for studies of the mechanism and kinetics of enzymatic catalysis, and may also be of interest for the development of anti-cancer drugs.

Keywords: L-asparaginase, atomic force microscopy, enzyme adsorption, thermal denaturation, solid-state nanopore.

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Introduction

The enzyme L-asparaginase (L-ASNase) belongs to hydrolases and catalyzes the conversion of L-asparagine to L-aspartate [1]. L-ASNase (type II) has found application in the therapy of oncological diseases – in particular, acute lymphoblastic leukemia [2]. This enzyme is also used in the food industry to prevent or reduce the formation of acrylamide in food products during thermal processing [3]. The

latter has attracted great interest to investigating the effects of elevated temperatures on the physicochemical properties of L-ASNase [3, 4].

Currently, the thermal stability of bacterial type II L-asparaginases is widely studied by spectroscopic methods [4, 5], which do not allow obtaining a signal from single molecules of the enzyme under study [6]. The study of the physicochemical properties of single enzyme molecules, in turn, allows a deeper insight into the kinetics and mechanism of enzymatic

catalysis [6]. This is done by using molecular detectors: the atomic force microscope and solid-state nanopore-based electrical detectors (SSN-ED). SSN-EDs allow recording the catalytic activity of single enzyme macromolecules [7], which is essential for studying the kinetics and mechanism of enzymatic catalysis [6, 8]. It should be noted that the key element of an SSN-ED is an inorganic membrane, which is often fabricated on the basis of silicon compounds [9] with a solid-state nanopore [7]. The adsorption of the enzyme under study onto the surface of this membrane and the enzyme behavior on this surface can fundamentally affect the results of studying its functioning with the use of an SSN-ED. Thus, an essential task is to investigate the adsorption of enzymes onto inorganic silicon-containing surfaces. Atomic force microscopy (AFM) allows the visualization of single enzyme macromolecules [10, 11] and the registration of the slightest changes in their adsorption properties. Mica, a silicon compound whose surface chemical properties are similar to those of the membrane material of the SSN-ED - silicon nitride Si_3N_4 , is often used as a substrate in AFM [12, 13].

The aim of this study is to investigate the adsorption of type II L-ASNase onto mica under conditions of thermal exposure on the enzyme.

Materials and Methods

Experimental design. Temperature-related changes in the adsorption properties of the enzyme were studied by AFM within the temperature range from 25 to 60 °C.

Reagents and enzyme. The enzyme L-asparaginase from *E. carotovora* was obtained and purified at the Laboratory of Medical Biotechnology of the Institute of Biomedical Chemistry (IBMC) in accordance with previously published protocols [14]. The lyophilized enzyme powder was dissolved in 2 mmol/l Dulbecco's phosphate-buffered saline (PBS-D) and diluted to reach the required concentration for the experiment. PBS-D (pH 7.4; 2 mmol/l phosphate, 30 mmol/l NaCl) was prepared from a salt mixture purchased from Pierce (USA). All solutions used in the experiments were prepared using deionized ultrapure water (18.2 M Ω ·cm) obtained with a Simplicity UV system (Millipore, France).

Atomic force microscopy. Samples of the enzyme solution were first heated in a microcentrifuge tube to the required temperature, and then the enzyme was adsorbed from this solution onto mica substrates for AFM as follows.

First, a 0.1 $\mu\text{mol/l}$ solution of L-ASNase in 2 mmol/l PBS-D (pH 7.4) was placed in a thermostatted shaker Thermomixer Comfort (Eppendorf, Germany) and sequentially heated to the required temperatures (25 °C, 30 °C, 45 °C, 55 °C and 60 °C). At each of these temperatures, two 1 ml samples of the solution were taken, and heating was continued up to 60 °C. The enzyme from the samples treated as described above was then adsorbed by direct adsorption [15] onto freshly cleaved mica AFM substrates. Each 1 ml sample of the enzyme solution was pipetted into a 1.7 ml Eppendorf tube, and a rectangular muscovite mica plate (SPI, USA) sized 7×15 mm was immersed into the solution. The tube was continuously shaken at 600 rpm at room temperature (25 °C) for 10 min. After that, the AFM substrate was removed from the enzyme solution, placed in another tube with 1 ml of water, and shaken again at 600 rpm at room temperature (25 °C) for 10 min to remove buffer salts from its surface. All AFM measurements were performed using an NTEGRA PRIMA instrument (NT-MDT, Zelenograd, Russia) in the intermittent-contact mode in air under controlled conditions (temperature 25 °C, air humidity 55%). At least 25 scans sized 2 $\mu\text{m} \times 2 \mu\text{m}$ with a resolution of 256×256 points were obtained for each substrate.

AFM data analysis (including the calculation of height distributions of the AFM images of enzyme molecules $\rho(h)$ and the number of enzyme molecules normalized to an AFM substrate area 400 μm^2 , denoted as N_{400}) was performed as described previously [16].

Results and Discussion

Figure 1 shows typical AFM images of L-ASNase adsorbed onto mica from solutions incubated at temperatures of 25 °C, 30 °C, 45 °C and 55 °C, as well as typical distribution curves $\rho(h)$ obtained for enzyme samples treated at 25 °C, 30 °C, 45 °C or 55 °C. At 60 °C, no enzyme adsorption was observed.

According to the presented AFM images, in the temperature range from 25 to 45 °C, the enzyme adsorbed onto mica in the form of individual globules, whereas heating the enzyme

solution to 55 °C resulted in its adsorption in the form of filamentous structures. The latter fact indicates significant denaturation of the enzyme at 55 °C.

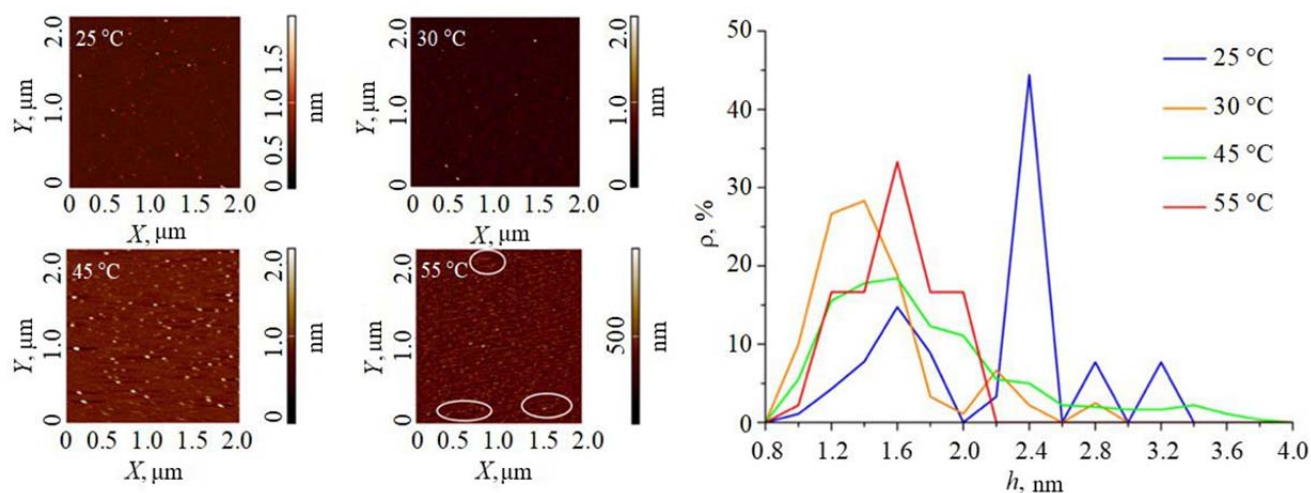


Fig. 1. Typical AFM images and height distribution curves $\rho(h)$ of L-ASNase adsorbed onto mica from solutions incubated at 25 °C, 30 °C, 45 °C or 55 °C. Ellipses mark the images of denatured enzyme structures. AFM image size: $2\ \mu\text{m} \times 2\ \mu\text{m}$. Experimental conditions: enzyme solution concentration $0.1\ \mu\text{mol/l}$, pH 7.4

The blue curve in Fig. 1 shows that the maximum of the height distribution $\rho(h)$ for the L-ASNase sample adsorbed onto mica at 25 °C corresponds to a height value of $h_{\text{max}} = 2.4\ \text{nm}$. Previous studies of another enzyme – horseradish peroxidase (HRP), whose molecular weight (44 kDa [17]) is comparable to that of L-ASNase (which is 36 kDa [18]) showed that the maximum height of AFM images of the monomeric form of HRP on mica is 1.0 to 1.2 nm [10, 11]; while the height of AFM images of higher-order aggregates of HRP on mica is $\geq 2.4\ \text{nm}$ [11]. Based on these considerations, we conclude that after being treated at 25 °C, L-ASNase adsorbs onto mica in the form of aggregates with AFM image heights of about 2.4 nm.

Upon incubation of L-ASNase at higher temperatures (from 30 to 45 °C), h_{max} values can be observed to decrease to 1.6 and 1.4 nm (Fig. 1, orange and green curves). This fact indicates the disaggregation of L-ASNase with an increase in the relative content of the monomeric form of the enzyme as compared to the total number of particles adsorbed onto mica.

AFM images of individual L-ASNase molecules are quite distinguishable at all investigated temperatures up to 45 °C, but at a

higher temperature (55 °C), compact objects are practically not observed (Fig. 1). The absence of compact objects in the AFM images obtained in the experiments involving the enzyme incubated at 55 °C indicates that the enzyme molecules undergo significant structural changes at this elevated temperature. These changes lead to the formation of filamentous structures on mica (Fig. 1), while adsorption of the enzyme in its “normal” form is not observed. During experiments conducted at 55 °C, only filamentous structures of the denatured enzyme are visualized. The height of the AFM images of these structures ranges from 0.5 to 0.8 nm. A further increase in temperature to 60 °C leads to the complete disappearance of enzyme adsorption on mica: after enzyme treatment at such a high temperature, neither compact objects nor filamentous structures are observed. It should be noted that the count of enzyme particles N_{400} adsorbed onto mica at temperatures of 25, 30, 45, and 55 °C was 1003, 540, 1605, and 159 particles/400 μm^2 , respectively.

Thus, the study of the thermal denaturation of L-ASNase by AFM showed that the enzyme adsorbs on mica in an aggregated form at 25 °C. An increase in temperature to 30 °C led to a

twofold decrease in the number N_{400} of enzyme particles adsorbed on mica. The latter fact indicates temperature-induced changes in the conformation of enzyme globules, which resulted in reduced enzyme adsorption. Based on N_{400} values and $\rho(h)$ curves (Fig. 1), it can be concluded that an elevated temperature promotes the disaggregation of the enzyme and the adsorption of a greater number of enzyme particles in the monomeric form. These phenomena are likely associated with the processes of thermal denaturation of the enzyme. A further increase in temperature to 45 °C promotes enzyme adsorption, which indicates that denaturation processes continue and lead to changes in the conformation of enzyme globules. This latter fact contributes to stronger binding of the enzyme to the mica surface. It should be

emphasized once again that the maximum adsorption of L-ASNase on mica is observed at 45 °C. However, a further increase in temperature to 55 °C leads to a sharp decrease in enzyme adsorption, which is accompanied by the development of filamentous structures of the denatured enzyme. At 60 °C, the enzyme completely loses its adsorption capacity, as neither compact objects nor filamentous structures are observed on mica.

Our results are critically important for the development of solid-state nanopore-based electrical detectors (SSN-ED). The pilot experiments involving L-ASNase on an SSN-ED (whose organization was described previously [7]) derived the dependence of the ionic current (I) flowing through the nanopore vs. time (t) at 25 °C (Fig. 2).

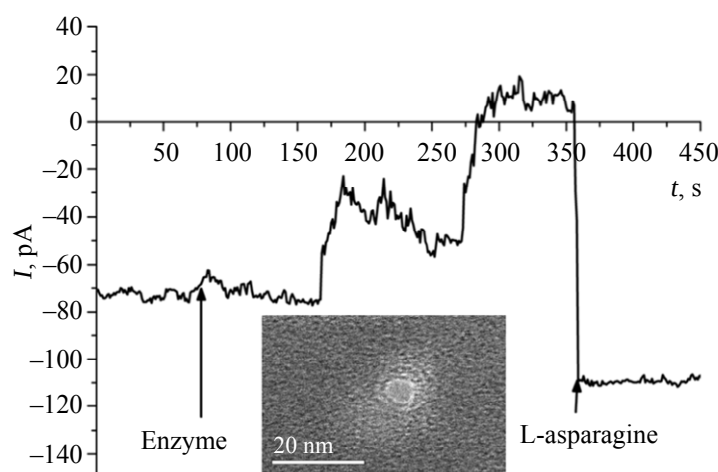


Fig. 2. Typical dependence $I(t)$ derived using an SSN-ED with an L-ASNase macromolecule embedded in the solid-state nanopore, and an image of a 6 nm nanopore formed in an inorganic membrane, obtained by transmission electron microscopy (inset)

Before the enzyme was added, a base level of I was recorded in 1 mmol/l of PBS-D (pH 7.6). After 0.1 $\mu\text{mol/l}$ was added to L-ASNase into the cis chamber of the SSN-ED measurement cell, the absolute value of I decreased, indicating partial blocking of the nanopore by the enzyme molecule. The subsequent addition of 10 $\mu\text{mol/l}$ L-asparagine solution, in turn, led to a significant increase in I , indicating the unblocking of the nanopore. In blank experiments performed using a pure buffer instead of the enzyme solution, no significant changes in I were observed. Given the substantial changes in the adsorption properties of L-ASNase under thermal exposure conditions, a detailed investigation of the kinetics of functioning of this enzyme's single molecules using an SSN-ED requires further studies.

Conclusion

The AFM method was applied to investigate the dependence of the L-ASNase adsorption properties on the thermal exposure of the enzyme solution. The height of the AFM images of L-ASNase adsorbed on mica was found to decrease from 2.4 nm at 25 °C to 1.6 and 1.4 nm in the temperature range from 35 to 45 °C. At the same time, the count of enzyme particles adsorbed on mica increases significantly, with the maximum reached at 45 °C. This fact indicates that changes in the enzyme globule structure caused by thermal denaturation in this temperature range promote its adsorption onto mica. A further increase of temperature to 55 °C leads to a sharp decrease in the adsorption

capacity of the enzyme, which is accompanied by the formation of filamentous structures on the mica surface. At 60 °C, the enzyme completely loses its ability to adsorb on mica. The obtained results are essential for the development of electrical molecular detectors based on solid-state nanopores required for an in-depth study and understanding of the mechanism and kinetics of enzymatic catalysis, and may also be useful in the development of anti -cancer drugs.

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REFERENCES

1. Batool T., Makky E.A., Jalal M., Yusoff M.M. Appl Biochem Biotechnol. **178**, 900–923 (2016).
2. Aguayo A., Cortes J., Thomas D., Pierce S., Keating M., Kantarjian H. Cancer **86** (7), 1203–1209 (1999).
3. Jia R., Wan X., Geng X., Xue D., Xie Z., Chen C. Microorganisms **9**, 1659 (2021).
4. Dobryakova N., Zhdanov D., Dumina M. et al. Catalysts **13** (5), 832 (2023).
5. Upadhyay A.K., Singh A., Mukherjee K.J., Panda A.K. Front. Microbiol. **5**, 486 (2014).
6. Xie X.S., Lu H.P. J. Biol. Chem. **274** (23), 15967–15970 (1999).
7. Ivanov Y.D., Vinogradova A.V., Nevedrova E.D. et al. Int J Mol Sci. **25**, 10864 (2024).
8. Galenkamp N.S., van den Noort M., Maglia G. RSC Chem. Biol. **6**, 1686 (2025).
9. Dekker C. Nature Nanotech. **2**, 209–215 (2007).
10. Ivanov Y.D., Pleshakova T.O., Shumov I.D. et al. Sci Rep. **10**, 9022 (2020).
11. Ivanov Y.D., Shumov, I.D., Kozlov A.F. et al. Micromachines **14**, 1024 (2023).
12. Shinohara K., Makida Y. Sci. Rep. **8**, 13982 (2018).
13. Antoniou M., Tsounidi D., Petrou P.S., Beltsios K.G., Kakabakos S.E. Med. Devices Sens. **3**, e10072 (2020).
14. Papageorgiou A.C., Posypanova G.A., Andersson C.S., Sokolov N.S., Krasotkina J. FEBS J. **275** (17), 4306–4316 (2008).
15. Kiselyova O.I., Yaminsky I.V., Ivanov Yu.D., Kanaeva I.P., Kuznetsov, V.Y., Archakov A.I. Arch Biochem Biophys. **371** (1), 1–7 (1999).
16. Pleshakova T.O., Kaysheva A.L., Shumov I.D. et al. Micromachines **10**, 129 (2019).
17. Welinder K.G. Eur J Biochem. **96**, 483-502 (1979).
18. Michalska K., Jaskolski M. Acta Biochim Pol. **53** (4), 627–640 (2006).

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- article title;
- initials and surnames of authors;
- abstract of the article (10–15 lines describing the purpose of the paper and its main findings);
- keywords;
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The bottom of the first page of the text shall accommodate a separate paragraph (in bold) containing contact information about the author (or authors) (**mandatory section**): surname, first name, patronymic (in full), **e-mail (of all authors)**, profiles and registration numbers in scientometric databases (SPIN code, RINTS Author ID, ArXiv Author ID, Orcid ID, Scopus Author ID), academic degree, title, position, postal address of the enterprise).

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Ivanov I. I. / *Applied Physics*. 2022. No. 1. P. 12–18.

Lang D. V. / *J. Appl. Phys.* 1974. Vol. 45. No. 7. R. 3023–3034.

Reference to **books**: Surname, initials, book title, city, publisher, year. (When a specific chapter or page in a book is referred to, the page number is placed after the year.)

Korn G., Korn E. *Mathematical Handbook*. – Moscow: Nauka, 1974.

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Ultraviolet technologies in the modern world / edited by Karmazinov F.V. Kostyuchenko S.V., Kudryavtsev N.N. – Dolgoprudny: Intellekt, 2012.

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Reference to **patents**: Surname, initials, title, type, number, year.

Davydov S. G., Dolgov A. N., Yakubov R. H. *Vacuum spark gap*. Patent of invention No. 2654494 (RF). 2018.

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Grechikhin V. A. *Development and analysis of computer algorithms for processing single-particle signals of laser Doppler anemometers*: Abstract from diss. by Candidate of technical sciences. – Moscow: MPEI, 1996.

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Lang D. V., *J. Appl. Phys.* **45** (7), 3023–3034 (1974).

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Conference proceedings:

Romanov A. V., Stepovich M. A., and Filippov M. N. *Proc. XVII Intern. Meeting on Radiation Physics of Solid State*. Sevastopol, 2007, pp. 592–599.

Patents:

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Dissertations and Abstracts:

Grechikhin V. A. *Development and analysis of computer algorithms for processing single-particle signals of laser Doppler anemometers*: Abstract. Diss. Candidate of Technical Sciences. M., MEI, 1996.

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