

Assessment of the influence of the manufacturing quality of a reflective coating on the angular distribution function of the reflected radiation intensity of laser signaling systems

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ABSTRACT

The paper substantiates the prospects of using diffraction-reflecting coatings as part of laser signaling systems to improve reliability. An increase in the such alarm systems reliability occurs due to a power increase of reflected laser radiation and the possibility of forming a certain number of "laser barriers" in different directions. In general, laser signaling systems with diffractively reflecting coatings, in contrast to existing laser signaling systems, allow solving additional tasks of assessing the movement speed of objects in the protected area and determining their movement directions.

Key words :diffraction reflective coating, laser alarm systems, scattering chart.

1. INTRODUCTION

Promising automatic systems for protecting objects and perimeters of the area from all kinds of intruders are being developed based on the use of laser alarm systems [1– 7]. This is due to the advantages of laser systems: the absence of physical and electronic contacts between the components, the accuracy of laser devices; light weight and small dimensions of lasers; high noise immunity and ease of installation and alignment of laser devices [1].

Laser alarm systems allow simultaneous blocking of the terrain area perimeter and of the protected object and conduct optical-electronic reconnaissance [2]. Thus, the use of laser signaling systems for solving the problems of protecting the area perimeters and objects and conducting reconnaissance is promising.

Laser alarm systems usually consist of a transmitter and receiver, which are located in a line of sight. In this case, the sensor of such an alarm generates an alarm signal when the laser beam is interrupted, falling on the receiving unit[3, 4].

At the same time, laser alarm systems have a number of disadvantages. The main disadvantage is false alarms in difficult weather conditions, which reduce the transparency of the environment (eg fog, rain, snow). In this case, the reliability of laser alarm systems can be ensured by using multiple excess of the laser radiation energy over the minimum threshold value necessary for the system to operate.

2. LITERATURE REVIEW

In practice, when using laser signaling systems, it is necessary to take into account the cumulative effect of the radiation interaction with the atmosphere, which is simultaneously an absorbing, scattering and randomly inhomogeneous medium [8 – 14]. This influence can occur in a very wide range. Therefore, in order to ensure the required level of laser signaling systems reliability at a given distance, it is proposed to obtain a sufficient power reserve with the possibility of forming several "laser barriers".

One of the promising solutions to this problem is the use of diffractively reflecting coatings (as a reflective element) as part of a laser signaling system. Such coatings make it possible to redistribute the energy of the reflected laser radiation in space. This allows, when calculating the characteristics of a laser alarm system, to make the transition from uniform reflection, which is described by Lambert's law, to a substantially non-uniform distribution, which is characteristic of laser radiation reflection on diffraction gratings [15, 16].

The use of diffractively reflecting coatings as part of a laser signaling system makes it possible to provide[1, 17–21]: multiple increase in the power of the reflected laser radiation; the possibility of forming a certain number of "laser barriers" along the diffraction maxima propagation directions of the scattering diagram of the diffractively reflected coating.

3. MAIN MATERIAL

In practice, it is impossible to take into account absolutely all the factors affecting the quality of the fabrication of a

reflecting coating diffractively (for example, the uniformity of the washout of the photoresist during the production of coatings by photolithography). With the same surface material and the same technology for its processing, each time the laser radiation reflection occurs from diffractively reflecting coatings that have the required surface profile, but not identical, but only similar to each other. Such coatings have the same statistical properties, but their surfaces are specifically described by different equations. The degree of their difference largely depends on the perfection of the modern technology for the manufacture of diffractive phase coatings.

Taken together, diffractively reflecting coatings obtained with the same technological processing form a single statistical ensemble, the full description of which is given by the density functional probability. This theoretic-probability approach to describing the statistical properties of a surface has been extensively developed [1,4]. In practice, when describing errors, they are limited to the approximation of their fluctuations by some normal random process, the parameters of which are set by analyzing the effect of coating production conditions on the statistical characteristics of the errors that appear. Such an approximation turns out to be quite satisfactory, which is a consequence of the joint and additive influence of a large number of factors independent of each other on the process of manufacturing diffraction-reflecting coatings.

In the presence of errors in the manufacture of diffractively reflecting coatings (roughness), the radiation power corresponding to the weakening of the coherent component of the illumination signal is scattered in directions that do not correspond to the directions of the diffraction maxima formation of the angular of the radiation intensity distribution function reflected from the coating. The total power of laser radiation reflected from a diffractively reflecting coating has two components: specular (coherent) and diffuse (incoherent). The specular component is due to the reflection of the optical wave from the coating. The diffuse component is due to scattering by roughness. These components of the reflected radiation power are characterized by the corresponding intensities.

Let us consider the influence of errors on the intensity of the coherent component of the reflected optical radiation, which in the presence of the diffractively reflecting coating roughness can be represented as

$$I_{KOO}(\theta_i, \theta_s) = |P_K(\theta_i, \theta_s)|^2, \quad (1)$$

where $P_K(\theta_i, \theta_s) = \chi P_V(\theta_i, \theta_s)$ is a function that describes the coherent component of the complex amplitude of an optical wave reflected from a diffractively reflecting coating; χ is characteristic function of a random variable of roughness given by the dependence $\varphi(x)$, which according to [2] is defined as follows:

$$\chi = \langle \exp[-ik \cos \theta_i \cos \theta_s \varphi(x)] \rangle. \quad (2)$$

The averaging of the characteristic function of phase errors should be carried out in the general case over the area of the diffractively reflecting coating illuminated by the backlight laser. Expression (2) is valid for the cases when the averaged phase incursion due to the presence of roughness does not exceed 2π , when the change in the optical path length due to roughness is less than the wavelength of the illuminating laser.

To analyze the effect of roughness caused by the peculiarities of the manufacturing diffractively reflecting coatings technology, the function χ is advisable to express through the probability density function $W_0[\varphi(x)]$ as [2]

$$\chi = \int_{-\infty}^{\infty} \exp[-ik \cos \theta_i \cos \theta_s \varphi(x)] W_0[\varphi(x)] d\varphi, \quad (3)$$

where, in the presence of roughness, the phase modulation according to [3] is defined as

$$\varphi(x) = 2\Delta d_T(x), \quad (4)$$

where $\Delta d_T(x)$ is a random function of the heights of the diffractively reflecting coating surface roughness.

Provided that the height of the roughness caused by the production technology of the diffractively reflecting coating is distributed normally with dispersion σ_0^2 , then according to [1, 3, 14]

$$W_0(f) = \frac{1}{(2\pi)^{\frac{1}{2}} \sigma_0} \cdot \exp\left(-\frac{\varphi^2}{2\sigma_0^2}\right) \quad (5)$$

and on the basis of expressions (2) – (4), it is possible to determine the characteristic function of the errors magnitude introduced by roughness on the surface of the diffractively reflecting coating.

On the Figure 1 the results of the angular distribution calculations of the coherent component intensity of the reflected radiation under conditions of normal laser radiation incidence on the diffractively reflecting coating surface are presented. A diffractively reflecting coating of the "echelette" type has the following parameters: $d = 3\lambda$, $i = 0.17$ radian, $a = 3.14\lambda$, $M = 10$. These parameters were obtained using expression (1) at various values of the root-mean-square of the surface profile deviation under normal illumination conditions of the coating by laser $\lambda = 1.06$ mkm. This takes into account the presence of technological errors, characterized by the mean square deviation of the surface profile: $\sigma_0 = \lambda / 20$, $\lambda / 10$. The Figure 1 also shows a graph of the distribution function of the radiation intensity reflected from diffractively reflecting coatings without roughness (ideal surface).

Based on the analysis of the results obtained, the requirements for the manufacturing accuracy of reflective coatings are formulated. No significant distortion of the angular distribution function form of the reflected radiation intensity

is observed if the distribution of the roughness heights is characterized in the standard deviation $\approx \lambda / 20$. It is technically possible to recreate such parameters on the illumination laser wavelength $\lambda = 1.06$ mkm, which is characterized in the arithmetic mean deviation of the order ≈ 0.23 mkm. This statement is confirmed in works [1, 3, 14]. Thus, the intensity of the coherent component of the reflected laser radiation at the working diffraction maximum under conditions of such roughness decreases on $\approx 20\%$ in comparison with the case of the complete absence of errors in the manufacture of diffraction-reflecting coatings. In turn, the distribution of roughness heights with an arithmetic mean deviation of the order of ≈ 0.33 mkm is advisable to consider the limiting from the point of view of the satisfactory quality of the form of the coatings production. So, in the presence of such manufacturing errors, the intensity of the coherent component of radiation reflected from the coating in the working diffraction maximum decreases on 50% compared to a perfectly manufactured diffractively reflective coating.

At this stage of technology development for the production of diffractive elements, the production of diffractively reflecting coatings for lasers with a radiation wavelength $\lambda = 1.06$ mkm has been mastered with the required accuracy, which allows us to conclude that it is possible to produce high-quality diffraction-reflecting coatings using existing industrial methods.

A decrease in the intensity of the radiation coherent component reflected from the coating leads to an increase in the intensity of the incoherent (diffuse) component of the reflected optical signal. Assuming that the incoherent component of the optical radiation power, caused by technological errors in the manufacture of diffractively reflecting coatings, is determined by a smooth function of the object illumination and observation angles (for example, Lambert's law), the smoothing of the angular distribution function of the radiation intensity reflected from the diffractively reflecting coating will be observed. Therefore, there will be a slight increase in the intensity of radiation reflected from the coating in directions different from the directions of working maximum propagation of the scattering pattern of the diffractively reflecting coating.

In general, the estimates made indicate that for the high-quality diffractive-reflecting coatings manufacture, during production it is necessary to ensure the distribution of roughness heights with a mean square deviation of the order of $\approx \lambda / 20$ and less. Along with this, coatings characterized in a mean square deviation of the order of $\approx \lambda / 10$.

Let us consider a method for evaluating the divergence of the illumination laser radiation influence on the angular distribution function of the radiation intensity reflected from a diffractively reflecting coating.

The relationships that determine the angular distribution function of the radiation intensity reflected from the diffractively reflecting coating do not take into account the

divergence of laser radiation generated by the laser of the illumination station. However, in practice, the angle of radiation incidence on the coating surface takes on the values $\theta_i = \theta_i - \Delta\omega/2 \dots \theta_i = \theta_i + \Delta\omega/2$, where $\Delta\omega$ is the value of the optical radiation divergence. In this case, it will be true that the function of the angular redistribution of the reflected optical intensity radiation in space, determined by these expressions, will be distorted in some way. In this case, the degree of distortion will depend on the value $\Delta\omega$.

To assess the effect of the divergence of the illuminating laser radiation on the angular distribution function of the radiation intensity reflected from the diffractively reflecting coating, we use the following assumption. Coherent optical radiation incident on the coating surface with a certain divergence should be represented as a set of coherent radiation with zero divergence. Thus, each of such coherent radiation illuminates the coating surface at a certain angle determined on $\Delta\omega$. Then the expression that determines the angular distribution function of the radiation intensity reflected from the diffractively reflecting coating, and does not take into account the divergence of the illuminating coherent optical radiation, for the illuminating beam with the divergence $\Delta\omega$ should be written as follows:

$$P_V(\theta_i, \theta_s) = \frac{1}{(n+1)^2} \left(\sum_{j=-\frac{n}{2}}^{\frac{n}{2}} \left(q_j I_j(\theta_i + j \frac{\Delta\omega}{n}, \theta_s) \right)^{\frac{1}{2}} \right)^2, \quad (6)$$

where $n + 1$ is the number of sampling intervals that determines the accuracy of the calculations;

q_j is weighting factor determined by the distribution of the radiation intensity in the cross section of the laser illumination beam.

Calculated of expression(6), the angular distribution functions of the radiation intensity reflected from a diffractively reflecting coating of the "echelette" type at different values of the laser radiation divergence ($\Delta\omega = 10^{-0.75}$; 10^{-1} ; $10^{-1.25}$; $10^{-1.5}$; $10^{-1.75}$ radian) presented on the Figure 2 and Figure 3 respectively for the number of illuminated coverage periods $M = 10$ and $M = 100$. While calculating, it was suggested that the laser radiation with the wave length of $\lambda = 1.06$ mkm normal to the surface, illuminates a diffractively reflecting coating with parameters: $d = 3.18$ mkm, $i = 0.17$ radian and $a = 2.54$ mkm. The number of sampling intervals was taken $n = 10$, and the values of the weight coefficients $q_j = 1$ (uniform intensity distribution over the laser beam cross section).

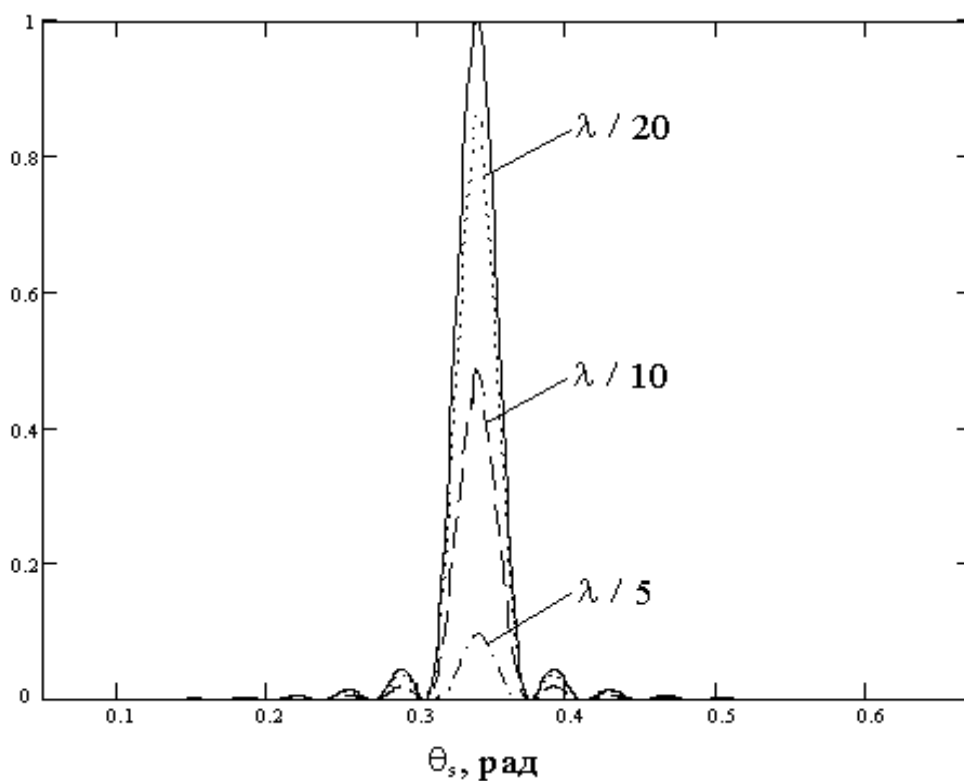


Figure 1: Form of normalized angular distribution functions intensity of the radiation coherent component reflected by a diffractively reflecting coating of the "echelette" type

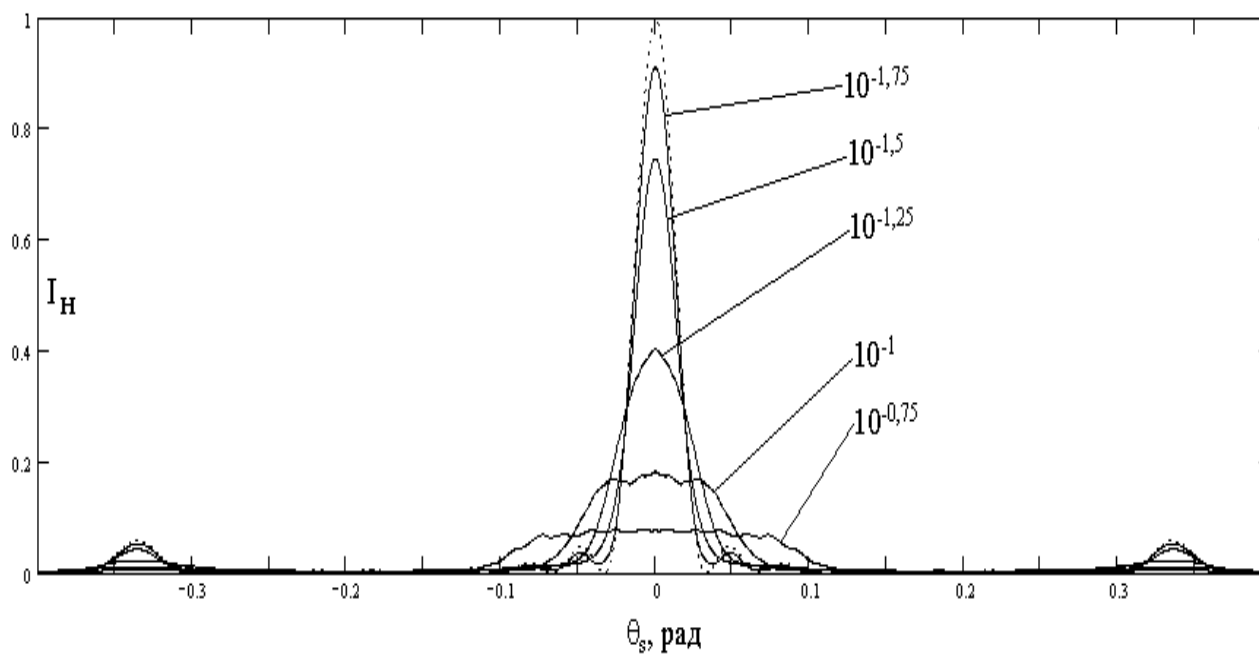


Figure 2: Normalized functions of the angular distribution of the laser radiation intensity reflected from a diffractively reflecting coating of the "echelette" type in $M = 10$ for different values $\Delta\omega$

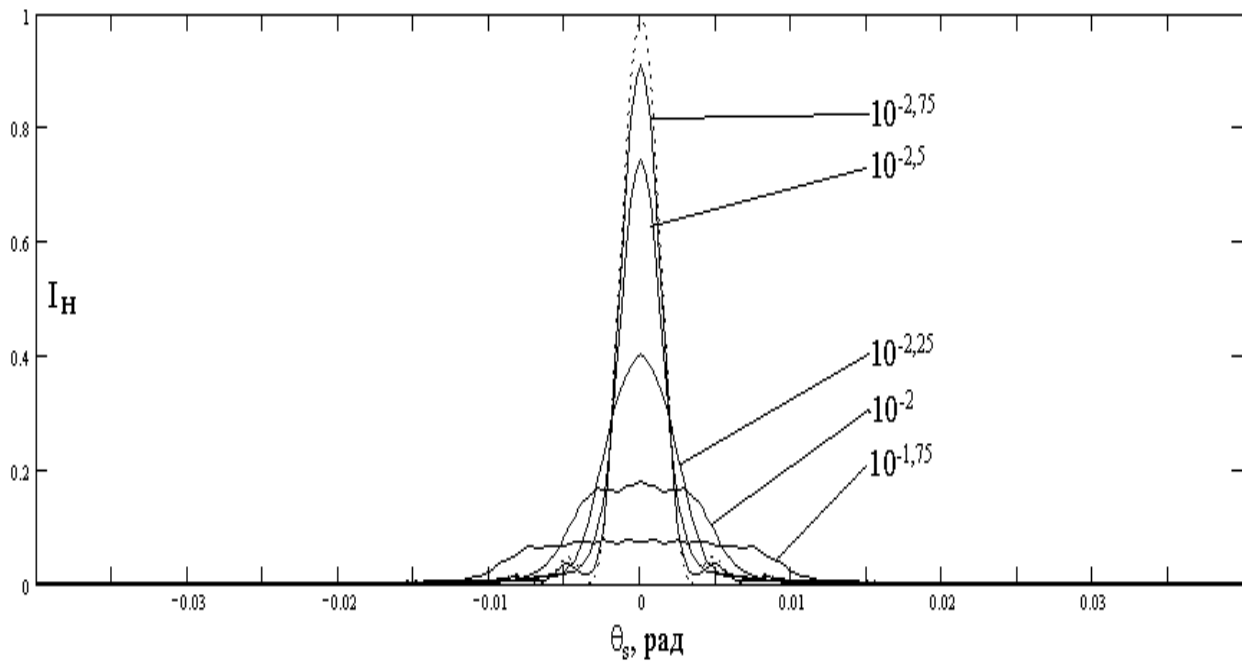


Figure 3: Normalized functions of the angular distribution of the laser radiation intensity reflected from a diffractively reflecting coating of the "echelette" type in $M = 100$ for different values $\Delta\omega$

4. RESULTS AND DISCUSSIONS

An analysis of the angular distribution functions of the coherent radiation intensity reflected from a diffractively reflecting coating of the "echelette" type, presented in the figures, allows us to draw the following conclusions:

the form of the distribution function of the reflected radiation intensities substantially depends on the relationship between the values $\Delta\omega$ and $1/M_2$;

in $\Delta\omega \gg 1/M_2$ the width of the diffraction maximum of the intensity distribution function is determined by the divergence of the illuminating laser radiation $\Delta\omega$;

in $\Delta\omega \ll 1/M_2$ the width of the main diffraction maximum of the intensity distribution function is determined on the value $1/M_2$ the angular size of the main diffraction maximum of the coating scattering pattern under laser illumination with $\Delta\omega \approx 0$.

In practice, as a rule, lasers are used in laser signaling systems, which are characterized on wavelengths $\lambda = (0.63 \dots 10.6)$ mkm and the laser radiation divergence $\Delta\omega = (10^{-3} \dots 10^{-4})$ radian in distances $(3 \dots 10)$ km. Under such conditions, the angular width of the main diffraction maximum of the distribution function of the coherent radiation intensity reflected from a coating with a constant $d = (1 \dots 10) \lambda$, will be largely determined by the value of the divergence $\Delta\omega$ illuminating laser beam. Then this coating should be considered as a coating that re-reflects the laser radiation illumination into the angular sector determined

by the blaze angle.

5. CONCLUSIONS

The paper substantiates the prospects of using diffraction-reflecting coatings as part of laser signaling systems to improve reliability. An increase in the such alarm systems reliability occurs due to a power increase of reflected laser radiation and the possibility of forming a certain number of "laser barriers" in different directions.

A power increase of the reflected laser radiation as a result of the diffractively reflecting coatings use will lead to an expansion of these alarm systems of the range of diffractively reflecting coatings in $(3 \dots 5)$ times in comparison with existing laser alarm systems.

The formation of $(5 \dots 7)$ "laser barriers" will allow effective control over a certain area not only in one direction, as in the existing laser signaling systems, but in the whole sector of $(40 \dots 700)$ directions. In this case, the sector width is determined only by the parameters of the diffractively reflecting coatings, but additional sources of laser radiation are not required.

In general, laser signaling systems with diffractively reflecting coatings, in contrast to existing laser signaling systems, allow solving additional tasks of assessing the movement speed of objects in the protected area and determining their movement directions.

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REFERENCES

1. S. Herasimov, Y. Kozhushko, E. Roshchupkin, V. Dekadin, V. Djus, and Y. Melenti, **Evaluation of surface profile of holographic diffraction reflective coatings on scattering chart using in laser alarm systems**, *International Journal of Emerging Trends in Engineering Research*, vol.8, is. 8, 2020, p.p. 4502-4507, <https://doi.org/10.30534/ijeter/2020/74882020>.
2. A. Katunin, R. Sidorenko, Y. Kozhushko, and G. Rybalka, **Expansion of security functions of laser alarm systems**, *Information processing systems*, № 2(100), 2012, p.p. 54-57.
3. S. Herasimov, O. Tymochko, O. Kolomiitsev, G. Aloshin, O. Kriukov, O. Morozov, and V. Alekseyev, **Formation Analysis Of Multi-Frequency Signals Of Laser Information Measuring System**, *EUREKA: Physics and Engineering*, vol. 5, 2019, p.p. 19-28, <https://doi.org/10.21303/2461-4262.2019.00984>.
4. A. Katunin, V. Bzot, O. Kolodiy, and O. Lukovsky, The use of radiant infrared systems to protect the perimeters of objects in difficult weather conditions, *Weapons systems and military equipment*, № 2(22), 2010, p.p. 192-195.
5. S. Herasimov, E. Roshchupkin, V. Kutsenko, S. Riazantsev, and Yu. Nastishin, **Statistical analysis of harmonic signals for testing of Electronic Devices**, *International Journal of Emerging Trends in Engineering Research*, vol.8, is. 7, 2020, p.p. 3791-3798, <https://doi.org/10.30534/ijeter/2020/143872020>.
6. P. Ayswarya, S. Pournami, and Ravi Nambiar, **A Survey on Ring Laser Gyroscope Technology**, *International Journal of Computer Applications*, vol. 116, is. 2, 2015, p.p. 25-27.
7. Y. Kozhushko, **Improvement of laser alarm systems based on the use of diffraction reflective coatings**, *Weapons systems and military equipment*, № 2(42), 2015, p.p. 106-108.
8. S. Herasimov, M. Pavlenko, E. Roshchupkin, M. Lytvynenko, O. Pukhovyi, and A. Salii, **Aircraft flight route search method with the use of cellular automata**, *International Journal of Advanced Trends in Computer Science and Engineering*, vol. 9, is. 4, 2020, p.p. 5077-5082, <https://doi.org/10.30534/ijatcse/2020/129942020>.
9. S. Herasimov, V. Pavlii, O. Tymoshchuk, M. Yakovlev, D. Ye. Khaustov, Ye. Ryzhov, L. Sakovych, and Yu. A. Nastishin, **Testing Signals for Electronics: Criteria for Synthesis**, *Journal of Electronic Testing*, vol. 35, is. 148, 2019, p.p. 1-9, <https://doi.org/10.1007/s10836-019-05798-9>.
10. A. Goncharsky, V. Popov, and V. Stepanov, **Introduction to Computer Optics**, Moscow, MGU, 163 p., 1991.
11. N. Vukainovi, and J. Duhovnik, **Optical 3D Geometry Measurements Based on Laser Triangulation**, *Advanced CAD Modeling*, 2018, p.p. 191-216, https://doi.org/10.1007/978-3-030-02399-7_9.
12. S. Herasimov, Y. Belevshchuk, I. Ryapolov, O. Tymochko, M. Pavlenko, O. Dmitriiev, M. Zhyvytskyi, and N. Goncharenko, **Characteristics of radiolocation scattering of the SU-25T attack aircraft model at different wavelength ranges**, *Information and controlling systems*, *Eastern-European Journal of Enterprise Technologies*, № 6/9 (96), 2018, p.p. 22-29, <https://doi.org/10.15587/1729-4061.2018.152740>.
13. S. Herasimov, Y. Belevshchuk, I. Ryapolov, A. Volkov, M. Borysenko, and O. Tokar, **Modeling technology of radar scattering of the fourth generation EF-2000 Typhoon multipurpose aircraft model**, *International Journal of Emerging Trends in Engineering Research*, vol.8, is. 9, 2020, p.p. 5075-5082, <https://doi.org/10.30534/ijeter/2020/30892020>.
14. Y. Kozhushko, D. Karlov, O. Klimishen, M. Bortsova, S. Herasimov, O. Hrichanuk, and V. Bykov, **Comparison of the Efficiency of Some Images Superposition Algorithms Used in Aircraft Map-Matching Navigation Systems**, *2018 IEEE International Conference on Mathematical Methods in Electromagnetic Theory*, 2018, p.p. 282-285.
15. O. Katz, and I. Spevak, **Diffraction of electromagnetic waves**, Kharkiv, KhVU, 178 p., 1998.
16. O.S. Makarenko, D.A. Krushinskii, and O.S. Makarenko, **Modelling of pedestrians movement on the base of cellular automata**, *System research and information technologies*, № 1, 2010, p.p. 100-109.
17. M.A. Facas Vicente, **Design, Modelation and Numerical Simulation of a Novel Artefact for Coordinate Measuring Machines Calibration Based on Laser Trilateration**, *Arabian Journal for Science and Engineering*, vol. 38, is.6, 2013, p.p. 1519-1528, <https://doi.org/10.1007/s13369-013-0537-x>.
18. Hong-e Ren, and Wei Yan, **The Test Principle and Algorithm of Laser Measuring Tree Height**, *Informatics in Control, Automation and Robotics*, 2012, p.p. 381-387, https://doi.org/10.1007/978-3-642-25899-2_51.
19. S. Menzel, L. Diehl, and C. Pflügel, **Quantum cascade laser master-oscillator power-amplifier with 1,5 W output power at 300 K**, *Optics Express*, vol. 19, is. 17, 2011, p.p. 16229-16235.
20. W.H. Cheng, M.T. Sheen, G.L. Wang, S.C. Wang, and J.H. Kuang, **Fiber alignment shift formation mechanisms of fiber-solder-ferrule joints in laser module packaging**, *Technol*, vol. 19, is. 8, 2001, p.p. 1177-1184.
21. Y. Kozhushko, D. Kolomiets, I. Tabakova, I. Hannoshyna, N. Serdiuk, and T. Voichenko, **Determination of accuracy of low-altitude navigation of dynamic objects equipped with correlation-extreme systems**, *International Journal of Advanced Trends in Computer Science and Engineering*, vol.9, is.3, 2020, p.p. 2981-2986, <https://doi.org/10.30534/ijatcse/2020/75932020>.