Analysis of the Requirements to the Accuracy of Diffractively Reflecting Coatings Manufacturing

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***Abstract*—One of the main problems of modern laser alarm systems is appearance of false alarms in difficult weather conditions (fog, rain, snow) because of reduction of the environment transparency. A promising solution is creation of "laser barriers" with the help of diffractively reflecting coatings as reflective elements. But the properties of those coatings depend considerably on the manufacturing process. If a coating was produced with errors, the coherent component of the total power reflected from a diffractively reflecting coating could decrease and the diffuse component (arising due to scattering by roughness) increase. Besides, the coating could scatter power in directions that do not correspond to the directions of the diffraction maxima. The presented paper substantiates the requirements to the accuracy of diffractively reflecting coatings manufacturing on the basis of analysis of the angular distribution functions of the reflected power.**

Keywords—diffraction reflective coating, laser alarm system, angular distribution function

I. 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. Laser alarm systems allow simultaneous blocking of the terrain area perimeter and of the protected object and conduct optical-electronic reconnaissance. 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 [1-7]. 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 (e.g. 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.

II. Description of the Method

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 [2, 8-13]. 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.

The use of diffractively reflecting coatings as part of a laser signaling system makes it possible to provide:

– 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.

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) [14, 15]. 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 probability density function. This theoretic-probability approach to describing the statistical properties of a surface has been extensively developed [12].

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 [12]. 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 [14, 15].

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 (DRC) 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 DRC roughness can be represented as [10, 12]

$$\mathrm{I}_{\mathrm{KO\Gamma}}(\theta_i,\theta_s) = \left|P_K(\theta_i,\theta_s)\right|^2, \qquad (1)$$

where $\mathrm{P_K}(\theta_i,\theta_s) = \chi \mathrm{P_V}(\theta_i,\theta_s)$ 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 [6] is defined as follows:

$$\chi = \left\langle \exp\left[-ik\cos\theta_i \cos\theta_s \phi(x)\right]\right\rangle. \qquad (2)$$

The averaging of the characteristic function of phase errors should be carried out in the general case over the area of the DRC 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 [12]

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

where, in the presence of roughness, the phase modulation according to [6] is defined as

$$\phi(x) = 2\Delta d_T(x), \qquad (4)$$

where $\Delta \mathrm{dT}(x)$ is a random function of the heights of the DRC surface roughness.

Provided that the height of the roughness caused by the production technology of the DRC is distributed normally with dispersion σ_0^2, then according to [10, 12]

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

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.

In Fig. 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 DRC surface are presented. A DRC of the "echelette" type has the following parameters: $d = 3\lambda$, $i = 0.17$ rad., $a = 3.14\lambda$, $M = 10$. 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 $\lambda = 1.06$ μm. This takes into account the presence of technological errors, characterized by the mean square deviation of the surface profile: $\sigma_0 = \lambda / 20$, $\lambda / 10$. Fig. 1 also shows a curve of the distribution function of the radiation intensity reflected from diffractively reflecting coatings without roughness (ideal surface).

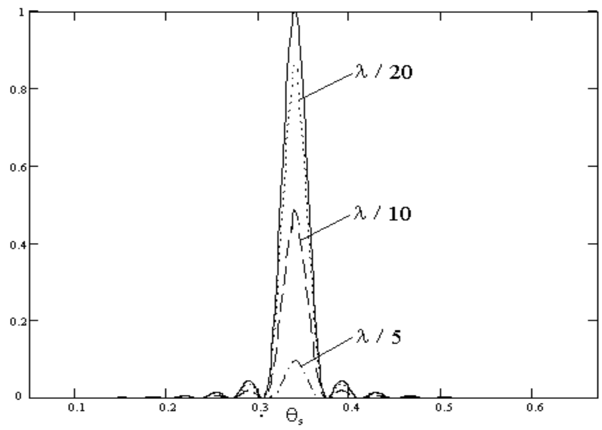

Fig. 1. Normalized angular distribution functions for the coherent component of the power reflected by a DRC of the "echelette" type

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 ≈ λ / 20. It is technically possible to recreate such parameters on the illumination laser wavelength λ = 1.06 μm, which is characterized in the arithmetic mean deviation of the order ≈ 0.23 μm. Thus, the intensity of the coherent component of the reflected laser radiation at the working diffraction maximum under conditions of such roughness decreases on ≈ 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 μm 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 λ = 1.06 μm 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 DRC 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 ≈ λ / 20 and less. Along with this, coatings are characterized by a mean square deviation of the order of ≈ λ / 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 DRC 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 $\theta_i = \theta_i - \Delta\omega / 2 \ldots \theta_i = \ = \theta_i + \Delta\omega / 2$, where Δω 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 Δω .

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 Δω . 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 Δω should be written as follows:

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

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 DRC of the "echelette" type at different values of the laser radiation divergence (Δω = $10^{-0.75}$; 10^{-1}; $10^{-1.25}$; $10^{-1.5}$; $10^{-1.75}$ radian) are presented in the Fig. 2 and Fig. 3 respectively for the number of illuminated coverage periods M = 10 and M = 100. While calculating, it was supposed that the laser radiation with the wave length of λ = 1.06 μm normal to the surface illuminates a DRC with parameters: d = 3.18 μm, i = 0.17 rad. and a = 2.54 μm. 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).

An analysis of the angular distribution functions of the coherent radiation intensity reflected from a DRC 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 Δω and $1/M_2$;

– in Δω >> $1/M_2$ the width of the diffraction maximum of the intensity distribution function is determined by the divergence of the illuminating laser radiation Δω ;

– in Δω << $1/M_2$ 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 Δω ≈ 0.

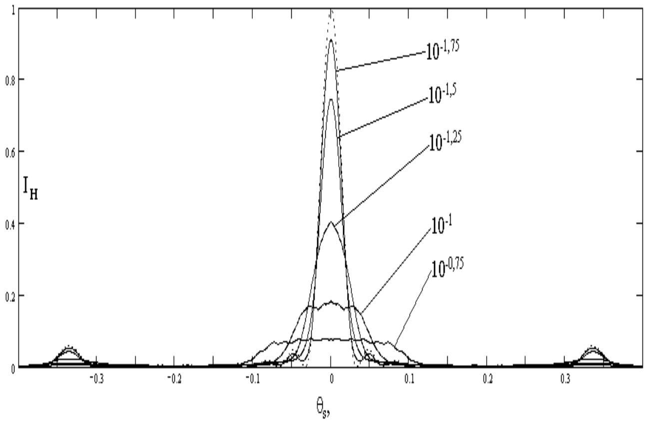

Fig. 2. Normalized functions of the angular distribution of the laser radiation intensity reflected from a DRC of the "echelette" type in M = 10 for different values Δω

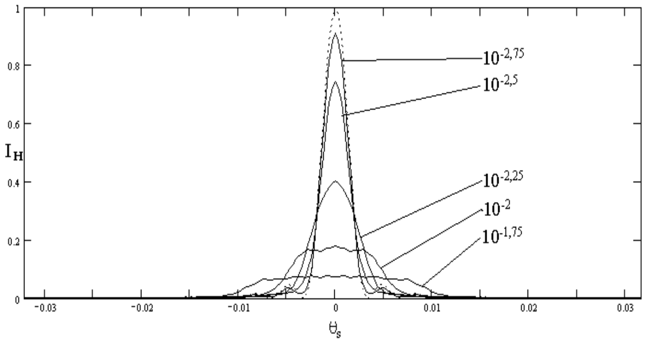

Fig. 3. Normalized functions of the angular distribution of the laser radiation intensity reflected from a DRC of the "echelette" type in M = 100 for different values Δω

In practice, as a rule, lasers are used in laser signaling systems, which are characterized on wavelengths $\lambda = (0.63\ldots10.6)$ μm and the laser radiation divergence $\Delta\omega = (10^{-3} \ldots 10^{-4})$ rad. in distances from 3 km to 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 $d = (1 \ldots 10)\,\lambda$, will be largely determined by the value of the divergence Δω 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.

III. Conclusions

The paper substantiates the prospects of using diffraction-reflecting coatings in laser signaling systems to improve their reliability. An increase in 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.

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 $\approx \lambda / 20$.

Thus, the intensity of the coherent component of the reflected laser radiation at the working diffraction maximum under conditions of such roughness decreases on ≈ 20 % in comparison with the case of the complete absence of errors in the manufacture of diffraction-reflecting coatings.

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.

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," in *International Journal of Emerging Trends in Engineering Research*, vol. 8, is. 8, 2020, pp. 4502–4507.

[2] M. Szustakowski, W. Ciurapinski, M. Zyczkowski, N. Palka, M. Kastek, R. Dulski, G. Bieszczad, and T. Sosnowski, "Multispectral system for perimeter protection of stationary and moving objects," in *Proc. SPIE*, *Electro-Optical and Infrared Systems: Technology and Applications VI*, 74810D (23 September 2009).

[3] R. Kakkar, *Atomic and molecular spectroscopy. Basic concepts and applications*. Delhi, India: Cambridge University Press, 2015.

[4] J. Hecht, *Understanding lasers: an entry-level guide*. Hoboken, New Jersey, US: John Wiley & Sons, 2018.

[5] V. Tarshyn, A. Tantsiura, V. Mosharenkov, Y. Kozhushko, and Y. Tarshyna, "The objects detection increasing probability method on integrated images of the sight surface in difficult observation conditions", in *International Journal of Emerging Trends in Engineering Research*, no. 8, 2020, pp. 4659–4665.

[6] A. Jaber, Y. Platon, A. Hervé, G. Peres, B. Pasquier, L. Evain, G. Cambon, F. Harly, H. Lenquette, B. Sinigaglia, and B. Spitz, "Thin diffraction grating technology," in *9th European Conference on Antennas and Propagation (EuCAP)*, 13-17 April 2015, Lisbon, Portugal.

[7] 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, pp. 2981–2986.

[8] C.B. Park and Ch.H. Lee, "ACA lidar system for continuous monitoring of aerosols, dust and cloud in troposphere at Suwon, Korea," in *Proc of the 5th Pacific Rim Conference on Lasers and Electro-Optics*, Taipei, Taiwan, 2003, pp. 729–733.

[9] S. Herasimov, O. Tymochko, O. Kolomiitsev, G. Aloshin, O. Kriukov, O. Morozov, and V. Aleksiyev, "Formation analysis of multi-frequency signals of laser information measuring system," in *EUREKA: Physics and Engineering,* no. 5, 2019, pp. 19–28.

[10] Swift C.T. (Ed.), Special Joint Issue on Radio Oceanography, *IEEE Trans., Antennas Propagat* , OE-2(1), 1977, pp. 1–159.

[11] A. Farah, D.D. Venable, A.N. Thorpe, P. Misra, and W.S. Heaps, "An excimer laser-based lidar system for tropospheric ozone measurements," in *Proc. of Conference on Lasers and Electro-Optics (CLEO'2000)*. Technical Digest. Postconference Edition, San Francisco, CA, USA, vol. 39, 2000, pp. 510–511.

[12] A. Ishimaru, *Wave propagation and scattering in random media*. IEEE/OUP series on electromagnetic wave theory, 1997.

[13] O. Kulakov, A. Katunin, Y. Kozhushko, O. Roianov, and T. Gorbach, "Usage of lidar systems for detection of hazardous substances in various weather conditions," in *2020 IEEE Ukrainian Microwave Week, UkrMW 2020*, 2020, pp. 360–363.

[14] Xin Liu, Changchang Gong, Bin Fan Jiang, Bian High, and "Precision fabrication method of fresnel diffractive lenses on ultrathin membrane for imaging application," in *IEEE Photonics Journal*, vol. 12, no. 4, August 2020.

[15] Qi Zheng, Jinyun Zhou, Qiming Chen, Liang Lei, Kunhua Wen, and Yiming Hu, "Rapid prototyping of a Dammann grating in DMD-based maskless lithography," in *IEEE Photonics Journal,* vol. 11, no. 6, 2019.