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Experimental evaluation of laser radiation quality in the differential scattering method

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The influence of the lens and mirror optical circuits of the channel illuminating a prototype of an optical-electronic system for measuring the parameters of angstrom-level roughness of optical surfaces on the quality of laser radiation was researched and experimentally analyzed. Based on the prototype developed using lens and mirror optical circuits, a quantitative assessment was given of such laser radiation quality indicators as the M^2 parameter and the contrast function of the speckle structure in the cross-section of its energy profile. Based on the findings of the described comparative analysis of the influence of two optical circuits of the prototype illumination channel on the target indicators of the laser radiation quality, recommendations were made whether it is advisable to use a lens optical system in the illumination channel in terms of the minimum measurement error.

Keywords: lens and mirror optical systems; M^2 parameter; speckle structure contrast; laser beam energy profile; laser radiation; differential scattering method.

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Introduction

The scientific papers previously published [1–4] describe the main scientific principles of the differential scattering method for quality control of optical surfaces. Papers [1, 2] have demonstrated the influence of limiting factors in the differential scattering method on the monitoring of angstrom-level optical surfaces. It is also worth noting the necessity of producing the high-quality laser radiation [5], primarily in the plane of the controlled optical surface, since additional intensity fluctuations occurring in the energy profile of the laser beam can lead to the formation of the speckle pattern in the recorded scattering indicatrix [1–8]. Thus, in development of a method for monitoring the roughness of angstrom-level optical surfaces, aspects related to the quality of the laser radiation illuminated spot formed in the plane of a part under control (lateral region) are of importance and relevance.

Main part

The following quantitative indicators were analyzed as the output characteristics of the laser radiation formed by lens and mirror optical systems in the plane of the optical surface under study [1, 5] (see Table 1).

Table 1

List of the main analyzed characteristics of the laser radiation formed by the illumination channel based on the lens and mirror optical systems of the developed prototype

No.	Parameter	Best values of the characteristics
1	Contrast function of speckle structure in the cross-section of the laser beam energy profile – C_S, p. u. $C_S = \frac{\sigma_I}{I}$, σ_I – RMS value of intensity fluctuations in the video image showing the distribution of the laser beam energy profile, I – average value of intensity in the video image showing the distribution of the laser beam energy profile	< 0.5
2	Laser beam quality parameter, p. u. $M^2 = \frac{\pi \cdot \theta_{real} \cdot D_{real}}{4 \cdot \lambda} = \frac{\pi \cdot D_{real}^2}{4 \cdot \lambda \cdot z_c}$ θ_{real} – divergence of a real laser beam; D_{real} – diameter in the cross-section of the real laser beam waist; z_c – laser beam confocality parameter (near-zone length); λ– laser radiation wavelength	$1 \le M^2 \le 1,2$

To evaluate the characteristics of the optical radiation formed by the illumination channel in the differential scattering method (see Table 1), a prototype was developed with an option of modifying the illumination channel when installing both lens and mirror optical systems that were preliminarily calculated in the Zemax automated design system.

The functional diagrams developed for two versions of the prototype illumination channel based on lens and mirror optical systems are shown in Figures 1 and 2, respectively.

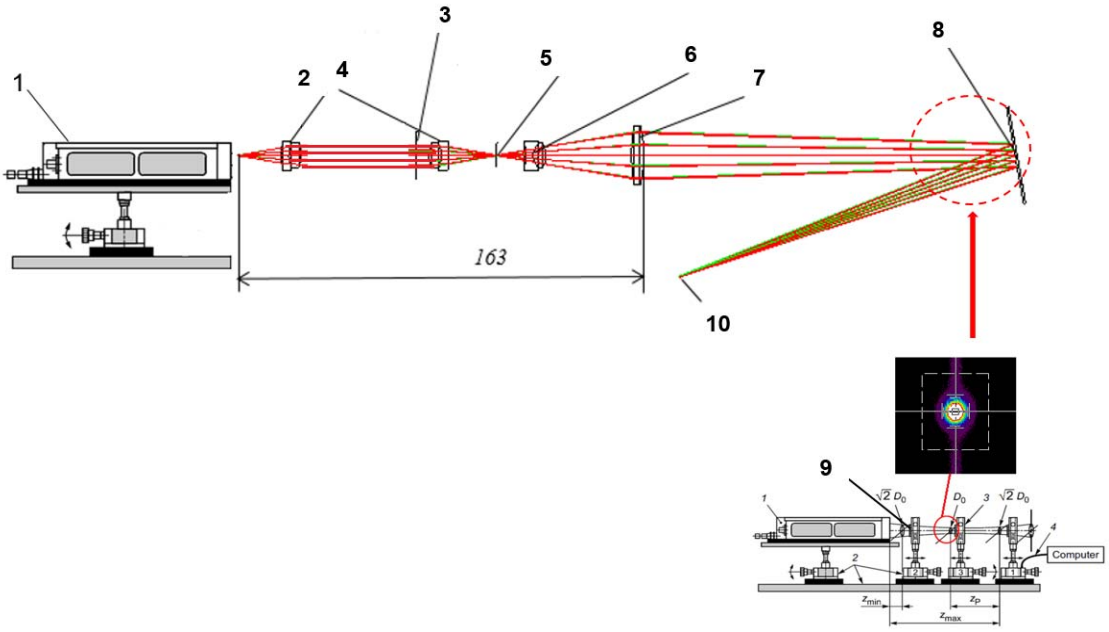


Fig. 1. Functional optical diagram for the prototype of an optical-electronic device comprising an illumination channel based on a lens optical system: 1 – laser radiation source; 2, 4, 6, 7 – lens optical system objectives; 3 – diaphragm; 4 – microdiaphragm; 8 – surface of an optical part under control; 9 – M^2sensor using the confocality measuring method; 10 – plane of analyzing the scattered laser radiation (plane of the photoreceiver – photomultiplier)

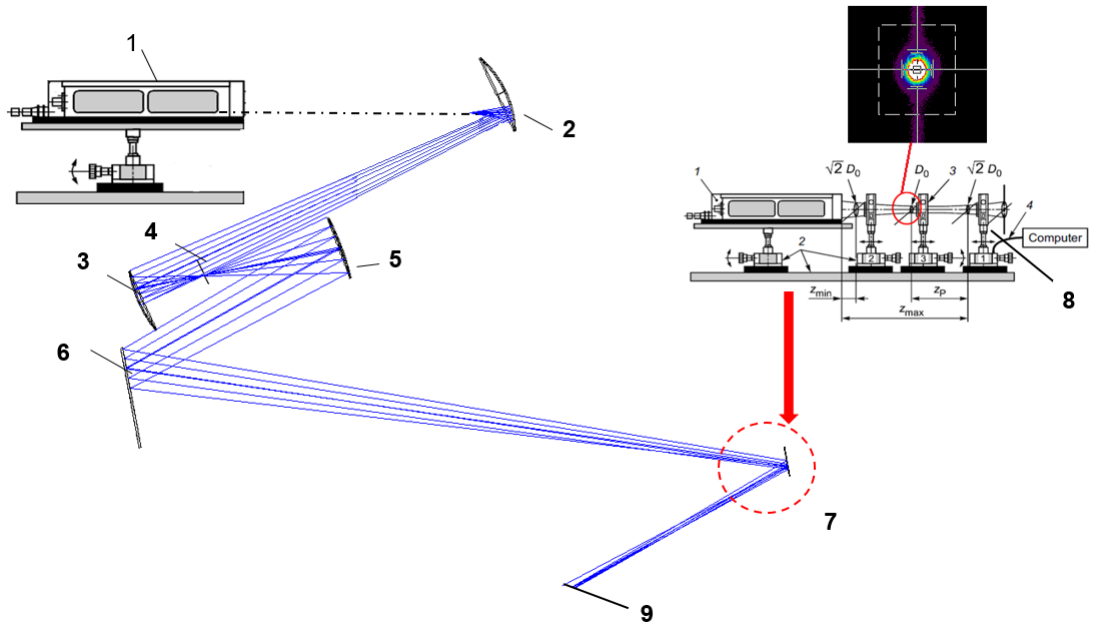


Fig. 2. Functional optical diagram for the prototype of an optical-electronic device comprising an illumination channel based on a mirror optical system: 1 – laser radiation source; 2 (R_3 = 40 mm; D_3 = 32 mm) – spherical mirror; 3 (R_3 = 50 mm; D_3 = 25.4 mm) – spherical mirror, 4 – microdiaphragm, 5 (R_3 = 100; D_3 = 25.4) – spherical mirror, 6 ($R_3 = \infty$; D_3 = 25.4) – flat mirror; 7 – surface of an optical part under control; 8 – M^2-sensor using the confocality measuring method; 19 – plane of analyzing the scattered laser radiation (plane of the photoreceiver – photomultiplier)

In the course of the prototype development, according to the functional optical schemes shown in Figures 1 and 2, five lasers were analyzed as laser radiation sources. These included gas lasers based on the He-Ne active medium having the following main generation lines: 6328 nm, 6120 nm, 543.5 nm, 632 nm, as well as a solid-state laser based on YAG-Nd at the generation wavelength of 473 nm.

Upon a comparative analysis of the steady state of quantitative energy indicators and characteristics, a laser with a generation wavelength of 473 nm was chosen as a radiation source for the comparative analysis of optical circuits, since it provides the maximum stability, on the one hand, and generates at the shortest wavelength, on the other hand, which is important for evaluation of intensity fluctuations in the energy profile.

At first the initial quality of the laser beam of a solid-state laser source based on the active medium and matrix – YAG:Nd – was measured according to the method presented in the author's paper published previously using the M^2 sensor [5].

According to the European standard ISO 11146-1-2005, such evaluation parameters as the propagation factor K and M^2 factor, have been introduced to evaluate the quality of laser radiation generated by a stable resonator. The latter describes the difference between the real laser beam's structure and the ideal mode structure TEM_{00} [5] and is defined as the ratio of angular divergence of a real laser beam and the angular divergence of an ideal (or diffraction) laser beam. According to the method described [5], the quality of the original laser beam prior to the optical system was measured. For this purpose, the minimum cross-section of the laser source beam was measured using the M^2 sensor. As the experiment showed, this cross-section for a given laser is located on the output partially transparent mirror, which is indicative of a plane-spherical, i.e. stable, resonator. After that the M^2 sensor was moved relative to the recorded minimum

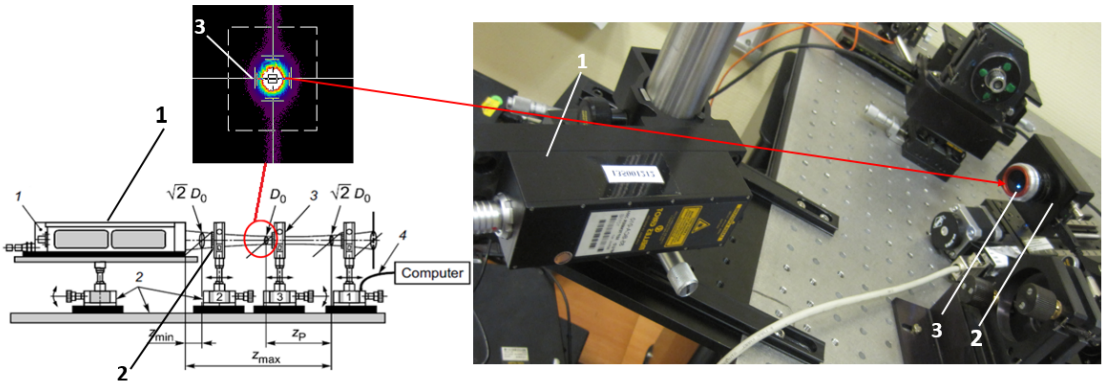
cross-section of the laser beam through the distance, at which this cross-section increased by $\sqrt{2}$, which corresponds to the mirror position of the equivalent confocal resonator [5]. The measured distance was recorded and assumed as the laser beam confocality parameter or the value describing its near zone or the Rayleigh parameter (see Fig. 3).

Analysis of the original laser beam and beams passed through the lens and mirror optical systems registered distributions of the laser beam's energy profile, including typical intensity fluctuations determined by statistical values (see Table 1):

σ_I – RMS value of intensity fluctuations in the video image showing the distribution of the laser beam's energy profile, W;

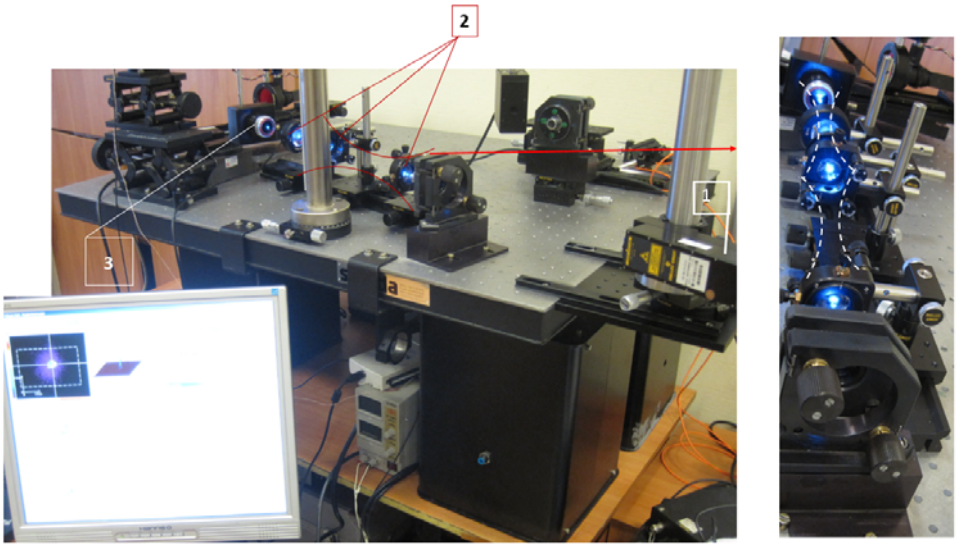
I – average value of intensity in the video image showing the distribution of the laser beam's energy profile, W;

$C_S = \frac{\sigma_I}{I}$ – contrast function of speckle structure in the cross-section of the laser beam energy profile – C_S, p. u.



a) *b*)

Fig. 3. Concerning the method of measuring the initial intensity distribution in the energy profile of the Gaussian laser beam: 1 – solid-state laser source at the wavelength of 473 nm; 2 – M^2 sensor; 3 – registered intensity distribution in the laser beam energy profile. a) – sequence of iterative measurements of the quality parameter of the Gaussian laser beam; b) – photo of the overall view of the stand for measuring initial parameters of the Gaussian laser beam



a) *b*)

Fig. 4. Photo of the overall view of the stand for measuring the quality parameter and statistical values describing fluctuations of the intensity of laser radiation passed through the lens optical system: 1 – laser radiation source; 2 – objectives of the lens optical system; 3 – M^2 sensor using the confocality measuring method; a) – photo of the entire measuring stand; b) – photo of the lens optical system and conditional transformation of the laser beam through its optical elements prior to the M^2sensor

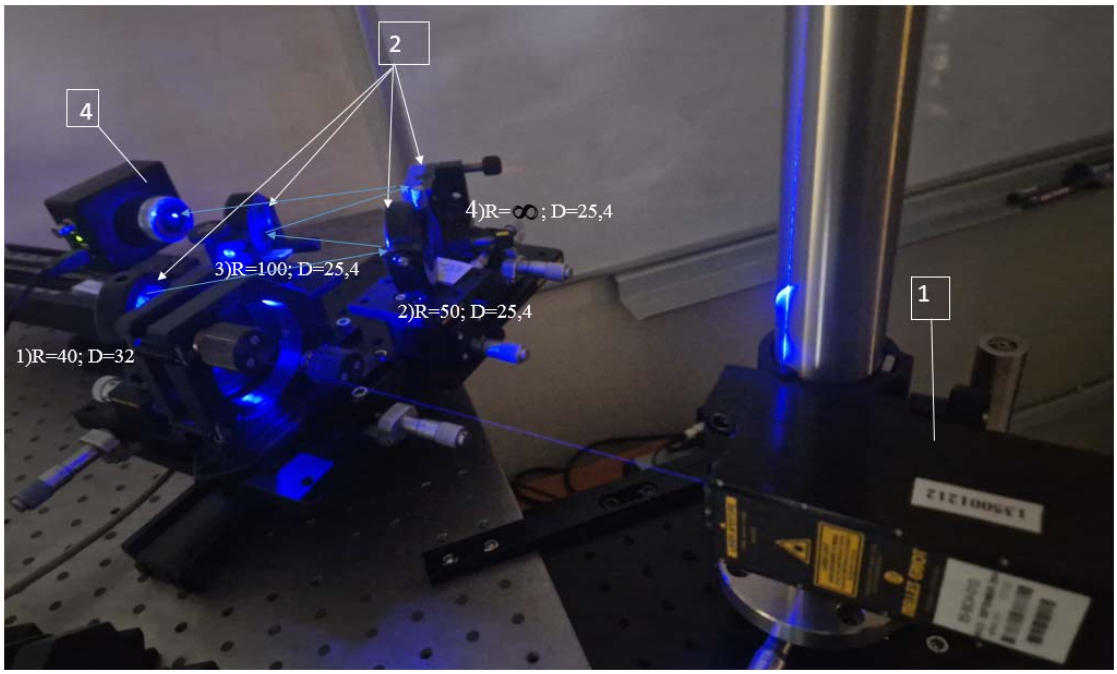


Fig. 5. Photo of the overall view of the stand for measuring the quality parameter and statistical values describing fluctuations of the intensity of laser radiation passed through the mirror optical system: 1 – laser radiation source; 2 – optical system mirrors; 3 – M^2 sensor using the confocality parameter measuring method

Based on the developed functional optical systems for the prototype comprising an illumination channel based on lens (see Fig. 1) and mirror (see Fig. 2) optical circuits, corresponding measuring stands were developed (see Fig. 4, 5).

Figure 4 shows the overall view of the stand for measuring the quality parameter and statistical values describing fluctuations of the intensity of laser radiation passed through the lens optical system.

Figure 5 shows the overall view of the stand for measuring the quality parameter and statistical values describing fluctuations of the intensity of laser radiation passed through the mirror optical system.

Conclusion

During the experimental studies of passing the optical path of the lens and mirror optical systems shown in Figures 4 and 5, the intensity distribution in the laser beam's energy profile was measured and its quality was evaluated, according to the parameters given in Table 1. Results of the experimental studies are presented in Figure 6 and Table 2.

Based on the obtained experimental data, a comparative analysis of the characteristics of laser radiation that passed through lens and mirror optical systems is presented (see Table 2).

Thus, the completed experimental comparative analysis of the characteristics of laser radiation generated by optical systems (see Table 2) shows that the lens optical system is more preferable because the contrast level of the speckle structure (speckle pattern) in the cross-section of the laser beam's energy profile is minimum. This argument is important when laser radiation interacts with a scattering optical surface having the angstrom-level roughness, which forms low-intensity scattered informative laser radiation. The second key criterion determining the feasibility of using a lens optical system is the laser beam quality parameter, which ensures the required dimensions of the lateral region (illuminated region) of the optical part under control and the specified energy in the illuminated spot.

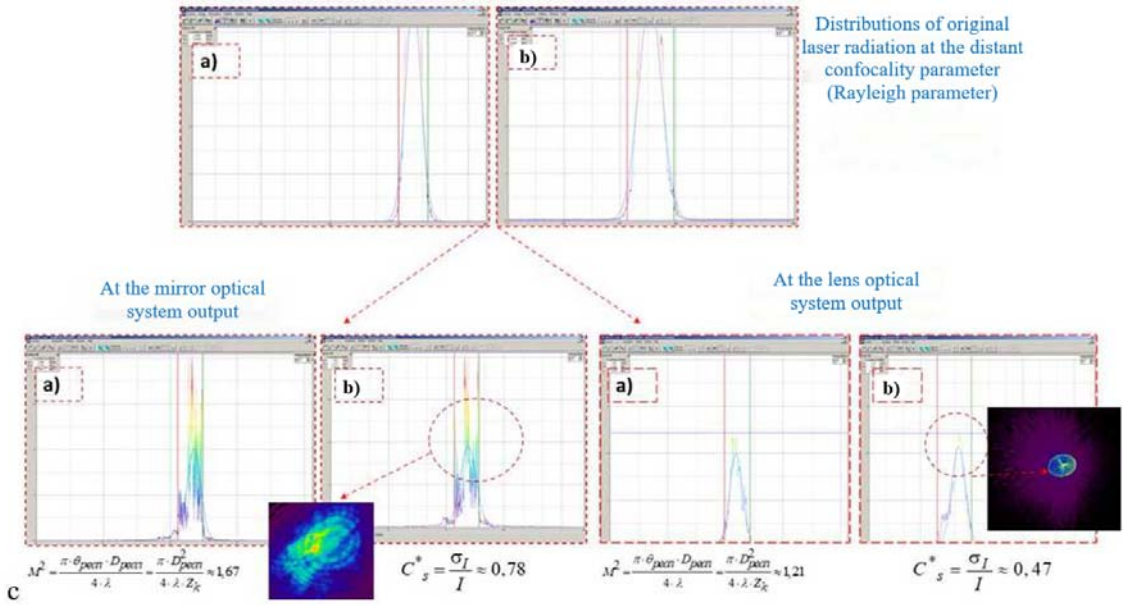


Fig. 6. Concerning the definition and research of the laser beam quality parameter and speckle structure contrast formed in the plane of the optical part under control for mirror and lens optical systems: a) – cross-section of the Gaussian beam profile along axis x; b) – cross-section of the Gaussian beam profile along axis y

Table 2

Comparison of the main characteristics of laser radiation that has passed through lens and mirror optical systems

No.	Parameter	Characteristic values (ideal case)	Characteristic values after passing the lens optical system	Characteristic values after passing the mirror optical system
1*	Contrast function of speckle structure in the cross-section of the laser beam energy profile – C_S, p. u. $C_S = \frac{\sigma_I}{I}$, σ_I – RMS value of intensity fluctuations in the video image showing the distribution of the laser beam energy profile, I – average value of intensity in the video image showing the distribution of the laser beam energy profile	< 0.5	0.47	0.78
2	Laser beam quality parameter, p. u. $M^2 = \frac{\pi \cdot \theta_{real} \cdot D_{real}}{4 \cdot \lambda} = \frac{\pi \cdot D^2_{real}}{4 \cdot \lambda \cdot z_c}$ θ_{real} – divergence of a real laser beam; D_{real} – diameter in the cross-section of the real laser beam waist; z_c – laser beam confocality parameter (near-zone length); λ – laser radiation wavelength	$1 \le M^2 \le 1{,}2$	1.21	1.67

* – abnormal emissions resulting from instability of laser radiation intensity fluctuations were filtered off during calculation.

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