MEAN INTENSITY OF A REFLECTED WAVE IN A TURBULENT MEDIUM

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The results of experimental investigation of the mean intensity of a spherical wave reflected from a reflector of diffraction limited size are presented. The measurements have been carried out on a correlated path (when incident and reflected waves pass through the same inhomogeneities of a medium) and on a path with segments of wave propagation in direct and reverse directions being considerably spaced apart. The experimental results obtained have been compared with the theoretical ones, and it has been found that due to correlation of the oncoming waves, amplification or attenuation of the mean intensity on the reflected beam axis may occur as compared with that on the uncorrelated path depending on the reflector size.

Distinguishing features of wave propagation along paths with reflection in random media are determined by the correlation between the oncoming waves passing through the same inhomogeneities of the refractive index. This leads to redistribution of energy in a reflected wave and can be manifested through the increase of the mean intensity of the reflected wave in strictly backward direction as compared with that on a path of the same length without reflection (backscatter amplification effect), as well as through the increase of the intensity fluctuations, retention of the intensity correlation in the reflected wave for arbitrary separation of observation points, and so on.

The effects of correlation between the oncoming waves have been studied in sufficient detail[1-3] in the case of reflectors with smooth boundaries when reflectance amplitude falls smoothly with the distance from the center to the edges of reflector according to the Gaussian law and in the cases of point and infinite reflectors. At the same time in practice, as a rule, reflectors of finite size with constant reflectance over the entire reflector surface are used. For such reflectors the diffraction by their edges becomes essential factor. As a result, an annular beam propagates through a medium after reflection, the intensity distribution over the beam cross section varies as the beam propagates along the path with alternate maxima and minima of the axial intensity. For this reason, the intensity fluctuations in such situation are determined not only by the interference of random rays, but also to a greater extent by nonuniformity of the beam intensity distribution over its cross section and by beam wandering as a whole. Theoretical study of this problem was performed by Banakh[4] who has shown that diffraction by the reflector edges changes the character of manifestation of the effect of backscatter amplification. The mean intensity on the beam axis may increase or decrease as compared with that of a beam that has passed once the path of double length depending on the reflector size.

In the given paper, the results are presented of experimental study of the backscatter amplification effect depending on conditions of diffraction of incident wave by reflector edges. In comparison with Ref. 5, in this experiment the range of the reflector size was extended, and reflector diameters were carefully sized to compare the experimental results with calculations of Ref. 4.

For quantitative estimation of the backscatter amplification effect, it is convenient to introduce the factor

$$N(R) = \langle I^R(x_0, R)\rangle / \langle I^R(x_0, R)\rangle_{\rm uncor}$$

where $\langle I^R(x_0, R)\rangle$ is the mean intensity of a reflected wave at the point R in the source plane $x' = x_0$, and $\langle I^R(x_0, R)\rangle_{\rm uncor}$ is the mean intensity of the same wave passed from a source to a reflector in the plane $x' = x$ and back along uncorrelated segments of a path. In the experiment, the intensities $\langle I^R(x_0, R)\rangle$ and $\langle I^R(x_0, R)\rangle_{\rm uncor}$ were measured simultaneously as functions of the diffraction parameter $\Omega_{\rm r} = ka_{\rm r}^2/L$, where $a_{\rm r}$ is the reflector radius, $k = 2\pi/\lambda$ is the wave number, λ is the wavelength, $L = x - x_0$ is the path length, $\Omega_{\rm r} = 3.14n$, and n is the reflector size measured in Fresnel zones.

Let us briefly outline the test conditions and experimental procedure described in Ref. 5 in detail. The measurements were carried out in an artificial turbulent medium modeling the condition of developed convection.[6] The laser radiation with $\lambda = 0.63$ μm was used to produce a quasispherical wave that after passage of a turbulent inhomogeneous layer reflected

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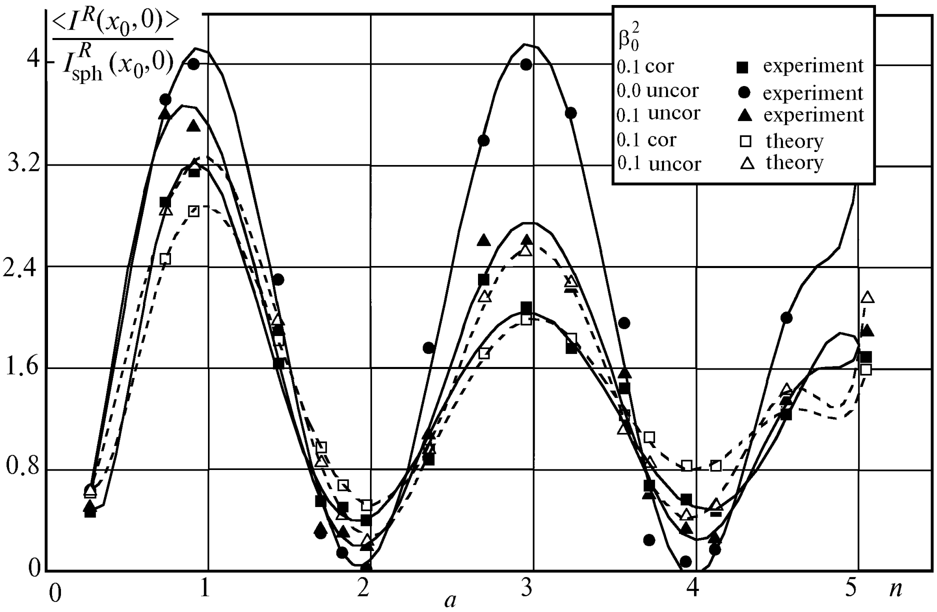
from the front face of an optical cube and returned strictly backward to the source plane, to the receiver. A part of radiation reflected from a diagonal of the cube returned to another receiver along the section of the path parallel to the incident wave in such a way as to avoid the correlation between the incident and return waves. Signals were detected with PMTs and after amplification were processed using a computer.

The mean intensity and the variance of the intensity fluctuations were calculated simultaneously in both channels. The mean intensity was analyzed as a function of the reflector size and strength of optical turbulence. The reflector size was determined by the diameter of an aperture stop placed directly against the reflector and was varied in the range $1 < \Omega_r < 16$ or between 0.27 and 5 Fresnel zones. The generalized turbulence parameter $\beta_0^2 = 1.23\, C_n^2\, k^{7/6}\, L^{11/6}$ was calculated for a beam that has passed once through the inhomogeneous medium. The structure constant C_n^2 was calculated from the fluctuations of angles of arrival of a plane wave emitted by an additional laser source. In contrast with Ref. 5, in this paper, when estimating C_n^2, we took into account the contribution from small-scale inhomogeneities of the refractive index resulting in the double decrease of the measured values of C_n^2.



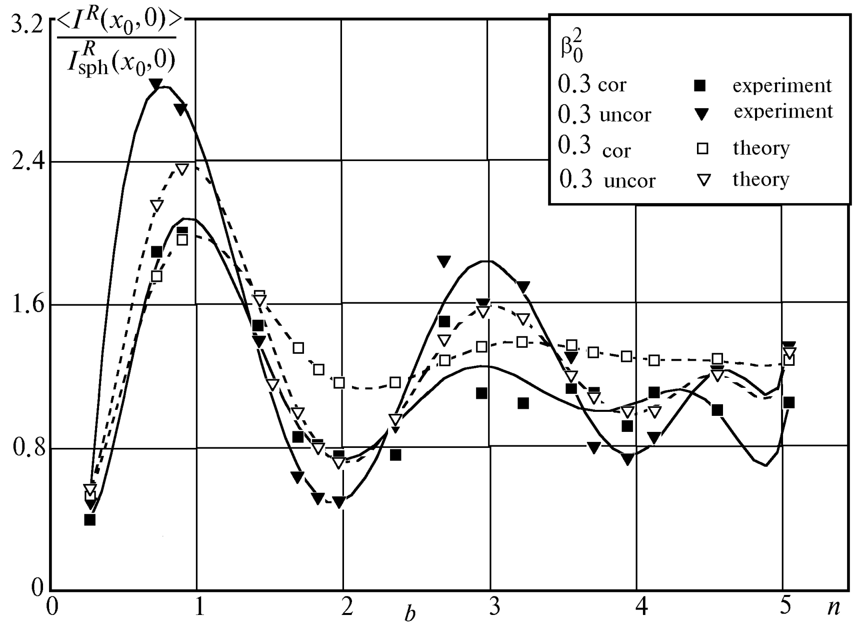


FIG. 1. Mean intensity as a function of the reflector size for $\beta_0^2 = 0$ and 0.1 (a) and 0.3 (b).

In Fig. 1, the mean intensity of the reflected wave is shown as a function of the reflector size for $\beta_0^2 = 0$, 0.1, and 0.3. The measured values of the mean intensity were scaled to the intensity of a spherical wave reflected from an infinite reflector in a homogeneous medium. It is seen that diffraction pattern sharply defined in the homogeneous medium ($\beta_0^2 = 0$) is blurred by the turbulence. The correlation between the incident and reflected waves gives rise to greater blurring of the diffraction pattern as compared with the passage of the incident and return waves along the uncorrelated paths.

Thus, when the reflector size is multiple of the even number of the Fresnel zones (in this case, there is a dark spot at the center of the intensity distribution over the receiver), the absolute amplification of the mean intensity is observed at the reflected beam axis with increasing turbulence strength and the increase of the mean intensity on correlated path as compared with uncorrelated one (relative amplification). For reflectors with the size multiple of the odd number of the Fresnel zones (there is a light spot at the axis in the receiving plane), the decrease of the mean intensity on the beam axis is observed, and the intensity values on the correlated path are less than that on the uncorrelated path (relative attenuation). In intermediate cases of fractional n, amplification or attenuation of the mean intensity is possible depending on the reflector size. Figure 1 demonstrates good agreement between experimental and theoretical data.

We can estimate the absolute and relative variations of the intensity from realization of the mean intensity on correlated and uncorrelated paths shown in Fig. 2 as a function of turbulence strength for reflector with size of one Fresnel zone ($n \approx 1$). The measured intensity values are scaled to the axial intensity in a homogeneous medium ($\beta_0^2 = 0$). Thus, the coefficients of absolute variation of the intensity on correlated and uncorrelated paths are plotted as ordinates in Fig. 2. The ratio of the coefficients for the same values of β_0^2 determines the relative intensity variation. The solid curves in Fig. 2 show the results of data processing using the least-square technique. From Fig. 2, it is seen that for reflector with the size of about one Fresnel zone the rate of decrease of the axial mean intensity on the correlated path exceeds that on the uncorrelated path with turbulence increase.

In Fig. 3, the mean intensity as a function of the parameter β_0^2 is shown for six reflectors whose size covered the limiting cases of the experiment. The measured intensity values were scaled to the same quantity as the data in Fig. 1. The numbers adjacent to the curves, indicate the reflector size measured in Fresnel zones. It is seen from Fig. 3 that beginning with a certain value of the parameter β_0^2, the mean intensity saturates on correlated and uncorrelated paths. The intensity saturation at a constant level occurs at higher values of β_0^2 for the reflector size multiple of the integer number of the Fresnel zones than for the reflector size multiple of the fractional number of the Fresnel zones. It seems likely that in the first case the difference between the maximum and minimum intensities of the diffraction pattern in the receiver plane for homogeneous medium ($\beta_0^2 = 0$) is less than in the second case. With increasing reflector size and strengthening optical turbulence, the levels of the intensity saturation tend to the mean intensity of a spherical wave reflected from an infinite reflector.

The comparison of the calculated and measured values of the mean intensity on correlated and uncorrelated paths at $\beta_0^2 = 0.1$ and 0.3 for all reflector size is shown in Fig. 4. The solid curves in Fig. 4 are the regression ones. The calculated correlation coefficient equals 0.9. Experimental and calculated data differ by a constant factor, that is, the dependence on turbulence strength observed in the experiment is weaker than it follows from calculation results. This may be caused by overestimation of the measured values of β_0^2 or by the other factors that were ignored.

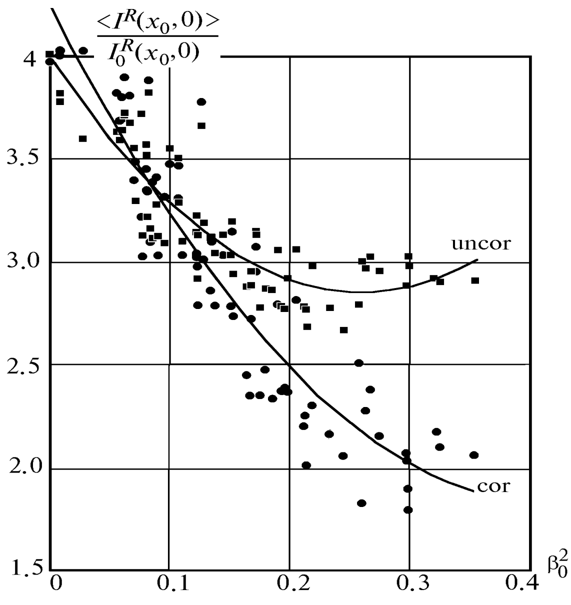


FIG. 2 Absolute intensity variations on correlated and uncorrelated paths for the reflector size of one Fresnel zone.

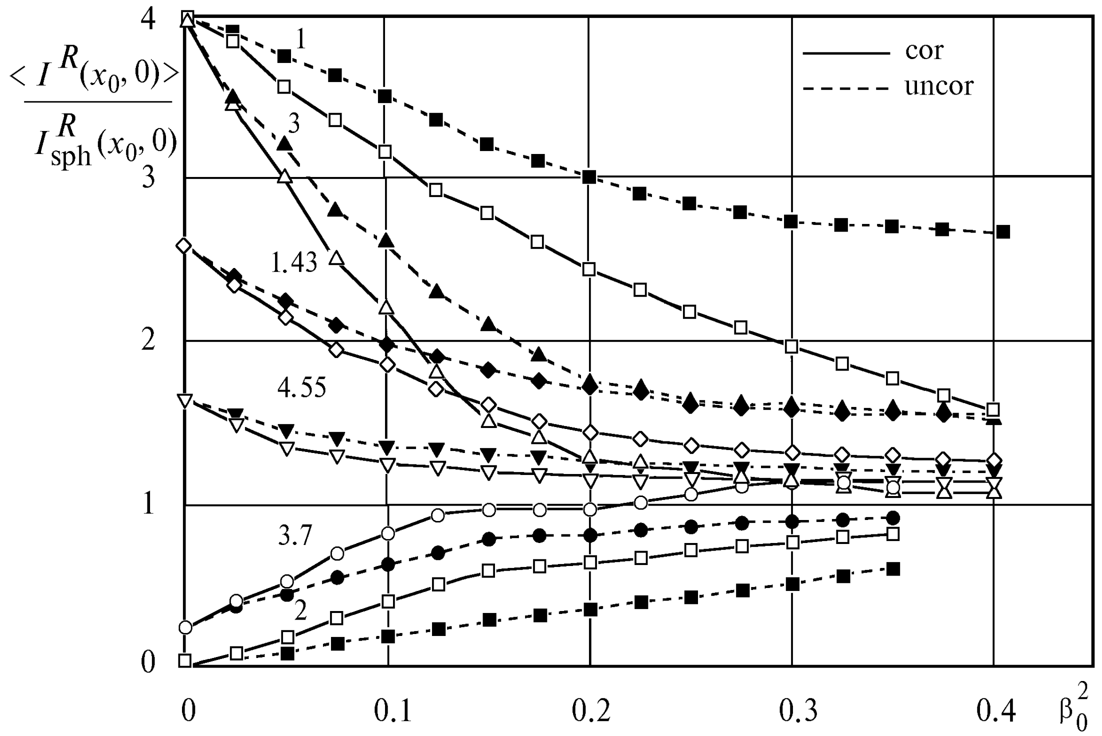


FIG. 3. Dependence of the mean intensity on the optical turbulence strength.

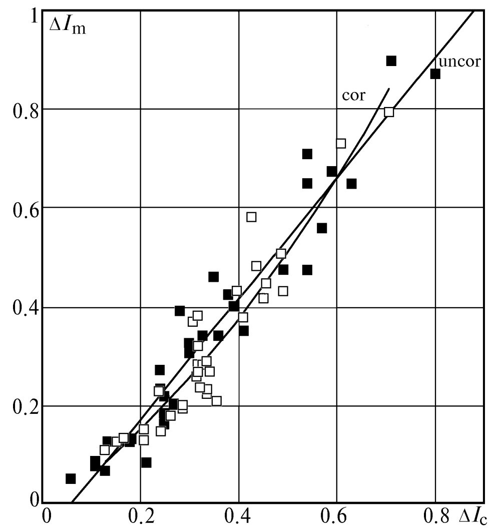


FIG. 4 Comparison of the measured and calculated values of the mean intensity.

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