INTENSITY FLUCTUATIONS OF LASER RADIATION REFLECTED FROM A DISC OF FINITE SIZE

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Results of experimental study of the dependence of the intensity fluctuations of laser radiation reflected in a turbulent medium on the reflector size are presented. It is shown that for reflectors with diffraction size equal to the integer number of Fresnel zones, the intensity variance of a reflected spherical wave far (several times) exceeds that for reflectors with diffraction size equal to the noninteger number of Fresnel zones. For the same propagation conditions, the intensity fluctuations of the reflected wave on correlated paths, when incident and return waves pass through the same inhomogeneities of the medium, are always stronger than that on uncorrelated paths.

Predicted theoretically[1,2] the effect of enhancement of the intensity fluctuations in the turbulent atmosphere after reflection of a spherical wave in strictly backward direction from a specular disc of large size was experimentally tested in Ref. 3. However, in practice reflectors of finite size are of principal interest. In this case after reflection an optical beam with diffraction cross-section intensity distribution propagates in the medium rather than the initial wave. Mean intensity and intensity fluctuations of the reflected wave in the receiving plane are determined not only by the interference of random rays but also by wandering of the diffraction pattern distorted by the turbulence about a receiving diaphragm. In Ref. 4 it was shown theoretically for such propagation conditions that due to correlation between oncoming waves, the mean intensity on the reflected beam axis may increase or decrease as compared with that of a wave that has passed the uncorrelated path of the same length.

We carried out an experimental study of the mean intensity and intensity fluctuations of a spherical wave reflected from a reflector of diffraction-limited size for different strength of the optical turbulence. The mean intensity behavior on the axis of a beam on correlated and uncorrelated paths was analyzed in Refs. 5 and 6. The effect of the reflector size and turbulence strength on the intensity fluctuations of the reflected wave is under study in this paper. Our measurements were carried out in an artificial turbulent medium. The test conditions, experimental procedure, and method of data processing were described in Refs. 5 and 6 in detail. Here we note only that the mean intensity and the variance of the intensity fluctuations were measured simultaneously on the correlated path, when incident and return waves were passing through the same inhomogeneities of a medium, and on the uncorrelated path, when segments of wave propagation in direct and reverse directions were considerably spaced apart. The reflector size was determined by the diameter of a diaphragm placed immediately adjacent to the reflector and varied between 0.27 and 5 Fresnel zones. The generalized turbulence parameter $\beta_0^2 = 1.23\, C_n^2 k^{7/6} L^{11/6}$ (here $k = 2\pi/\lambda$, λ is the wavelength, and L is the path length between the source and the reflector) was calculated for a beam that has passed once through the turbulent medium. The structure constant C_n^2 was determined from the fluctuations of the angles of arrival of a plane wave.

The behavior of the variance of the intensity fluctuations as a function of the reflector size and turbulence strength differs considerably from that of the mean intensity.[5,6] These distinctions are illustrated by the results of experimental data processing shown in Figs. 1, 2, and 3. In Figs.1 and 2 shown are the experimental and theoretical dependences of the mean intensity on the reflector size and turbulence parameter β_0^2 for correlated and uncorrelated paths, respectively. The mean intensity on the reflected beam axis, plotted on the vertical axis in these figures, is scaled to quadruple spherical wave intensity $4\langle I_{\text{sph}}\rangle$. The variance of the intensity fluctuations is shown in Fig. 3. From these data it follows:

– in accordance with the diffraction theory, in our experiments the mean intensity on the beam axis is maximum for reflector size equal to the odd number of Fresnel zones and is minimum for reflector size equal to the even number of zones. For the same propagation conditions, the diffraction pattern becomes more smeared on the correlated path than that on uncorrelated one. Thus, on the correlated path the dependence practically disappears already for $\beta_0^2 > 0.2$ and $n > 2$ (n is the reflector size in Fresnel zones),

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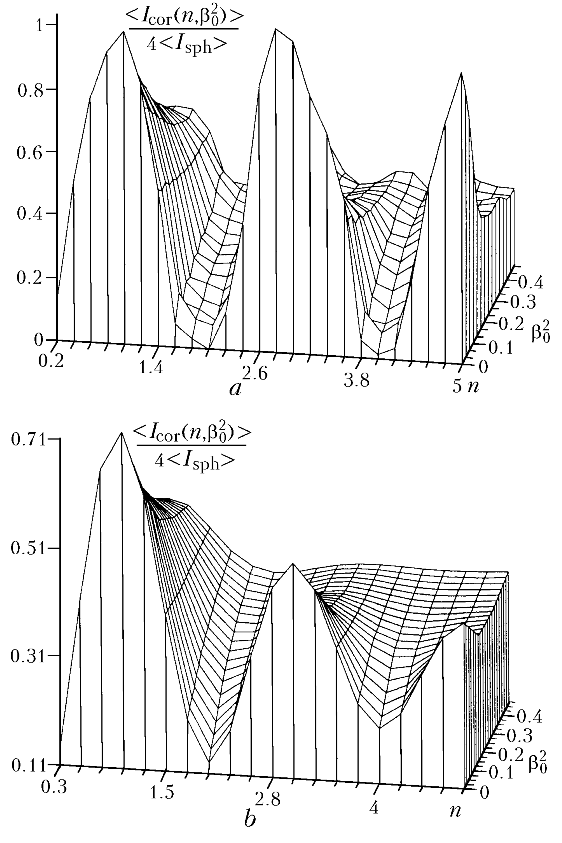

FIG. 1. Mean intensity on the reflected beam axis as a function of the reflector size in Fresnel zones (n) and optical turbulence parameter (β_0^2) on the correlated path: a) experiment, b) theory.

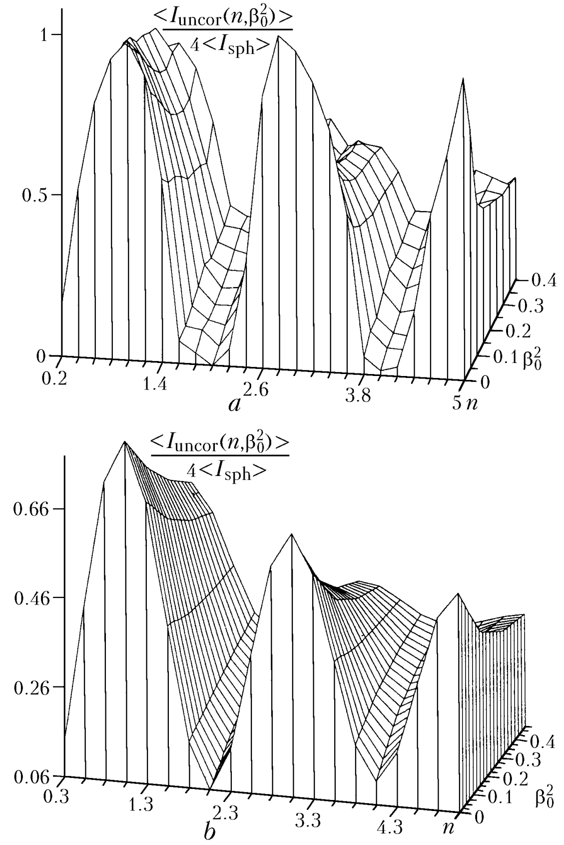

FIG. 2. Mean intensity on the reflected beam axis as a function of the reflector size in Fresnel zones (n) and optical turbulence parameter (β_0^2) on the uncorrelated path: a) experiment, b) theory.

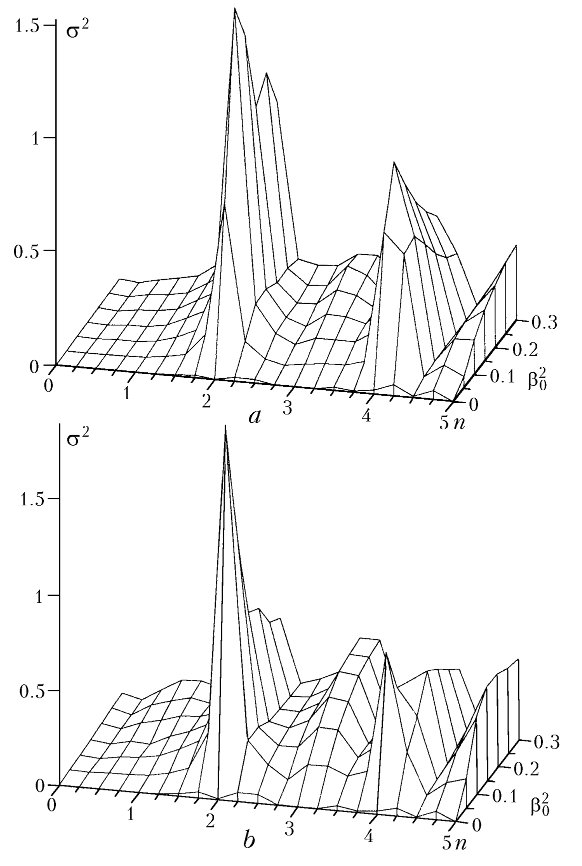

FIG. 3. Variance of the intensity fluctuations as a function of the reflected size (n) and turbulence parameter (β_0^2): a) the correlated path, b) the uncorrelated path.

as Fig. 1 shows, whereas on the uncorrelated path it is still pronounced;

– the mean intensity tends to that of a spherical wave with increasing turbulence strength;

– theoretical and experimental results agree qualitatively and are close quantitatively;

– the variance of the intensity fluctuations peaks for the reflector diffraction size equal to the integer number of Fresnel zones. It is minimum for the reflector size equal to $(n + 0.5)$;

– the variance of the intensity fluctuations tends to saturation with increasing β_0^2. The level of saturation and β_0^2 value at which that saturation occurs depend on the reflector size and type of the propagation path (correlated or uncorrelated);

– regardless of the reflector size, the variance of the intensity fluctuations in the reflected wave exceeds the variance in the spherical wave after it has passed through the same path without reflection.

The β_0^2–dependences of the variance of the intensity fluctuations for different reflector size are shown in Figs. 4 and 5. From Figs. 4 and 5 it follows:

– for the reflector size equal to the even number of Fresnel zones, the variance of the intensity fluctuations peaks when $0.05 \le \beta_0^2 \le 0.1$ on both correlated and uncorrelated paths. The rate of the variance increase before it reaches its maximum and the rate of its subsequent decrease are faster on the correlated path than on uncorrelated one ($\sigma_{\text{cor}}^2 < \sigma_{\text{uncor}}^2$ at $\beta_0^2 > 0.1$). As the reflector size increases, the maximum intensity variance decreases. Thus, $\sigma^2 \sim 2$ when $n = 2$ and $\sigma^2 \sim 1$ when $n = 3.92$

– for the reflector size equal to the odd number of Fresnel zones, the intensity variance increases with increasing parameter β_0^2 and reflector size ($n = 1$; 2.95; 5). The magnitude of the variance on the correlated path exceeds the variance on the uncorrelated path. With increasing β_0^2 the variance tends to saturation. The level of saturation and the value of the parameter β_0^2, at which this saturation occurs, depend on the reflector size. The larger is the reflector size, the higher is the saturation level and the smaller is β_0^2 at which the saturation occurs. Thus, for $n = 5$ the saturation occurs at $\beta_0^2 \ge 0.15 - 0.2$ on correlated ($\sigma_{\text{sat}}^2 = 0.5$) and on uncorrelated ($\sigma_{\text{sat}}^2 = 0.35$) paths, for $n = 2.95$ the saturation is observed only at $\beta_0^2 \sim 0.25 - 0.3$ ($\sigma_{\text{sat}}^2 = 0.46$ on the correlated path and $\sigma_{\text{sat}}^2 = 0.24$ on the uncorrelated path), whereas for $n = 1$ only a trend to saturation is evident for the conditions of our experiment. These results contradict the data of numerical simulation carried out in Ref. 7 for similar conditions;

– for the reflector size equal to the noninteger number of Fresnel zones, the variance may increase with increasing β_0^2 at small reflector size ($n = 0.27$, 0.74) or may saturate ($n = 1.43$, 4.55) or reach the maximum ($n = 3.7$). In this case intensity fluctuations on the correlated path exceed the intensity fluctuations on the uncorrelated path.

It is worthwhile to consider the variance of the intensity fluctuations as a function of the phase structure function $D_{\text{s}} \sim C_n^2\, k^2\, L(2a_{\text{r}})^{5/3}$, calculated for the reflector size $2a_{\text{r}}$. The point is that the spherical wave propagates on the direct segment of the path from the source to the reflector, and fluctuations of its intensity are sufficiently small ($\sigma^2 \sim 0.01$). On the reverse segment of the path (from the reflector to the receiver), the diffracted beam propagates which has complex cross-section distribution of the intensity. It is well known that the intensity fluctuations in a beam are determined not only by random redistribution of the intensity in the beam cross section, but also by beam random displacement (wandering) as a whole. As for reflector size equal to the odd (even) number of Fresnel zones a sharp maximum of $4\ I_{\text{sph}}$ occurs at the center of the diffraction pattern, the effect of beam wandering plays a significant role. Wandering effect is most pronounced when the amplitude of beam displacements is comparable to the size of central (light or dark) spot of the diffraction pattern and become less pronounced with a further increase in the amplitude of beam displacements. These effects are seen from the data shown in Fig. 5. Parameter D_{s} suits better than β_0^2 for an analysis of the intensity fluctuations in spatially limited beams, and we hope that its use will be advantageous for systematization of the obtained experimental data.

As function of the parameter D_{s}, the measured variance of the intensity fluctuations is shown in Figs. 6 and 7. It follows from these figures that for reflector size equal to the integer number of Fresnel zones (or close to that) the intensity variance saturates at the level 0.3, regardless of the reflector size, when D_{s} exceeds 20 ($D_{\text{s}} > 20$). For smaller values of the parameter D_{s} ($D_{\text{s}} < 20$), the behavior of the variance depends strongly on the reflector size. For intermediate reflector size, on the contrary, at small values of the parameter D_{s} ($D_{\text{s}} < 3$) the intensity variance is proportional to D_{s} both on correlated and uncorrelated paths. For large values of D_{s}, the variance behavior depends on specific reflector size.

Thus, our experiments have shown that the mean intensity and the variance of the intensity fluctuations on the axis of the beam, which is formed after reflection of a spherical wave by a mirror of finite size, are determined by the optical turbulence strength and the diffraction reflector size. The maximum variance of the intensity fluctuations is observed under conditions of weak turbulence ($\beta_0^2 = 0.05$–0.1) after reflection from a disc with diffraction size equal to the even number of Fresnel zones when diffraction minimum occurs at the beam axis. In the case of the reflector with diffraction size equal to the odd number of Fresnel zones, when diffraction maximum occurs at the beam axis, the amplitude of fluctuations increases with turbulence strength and fast saturates. For reflector size equal to the noninteger

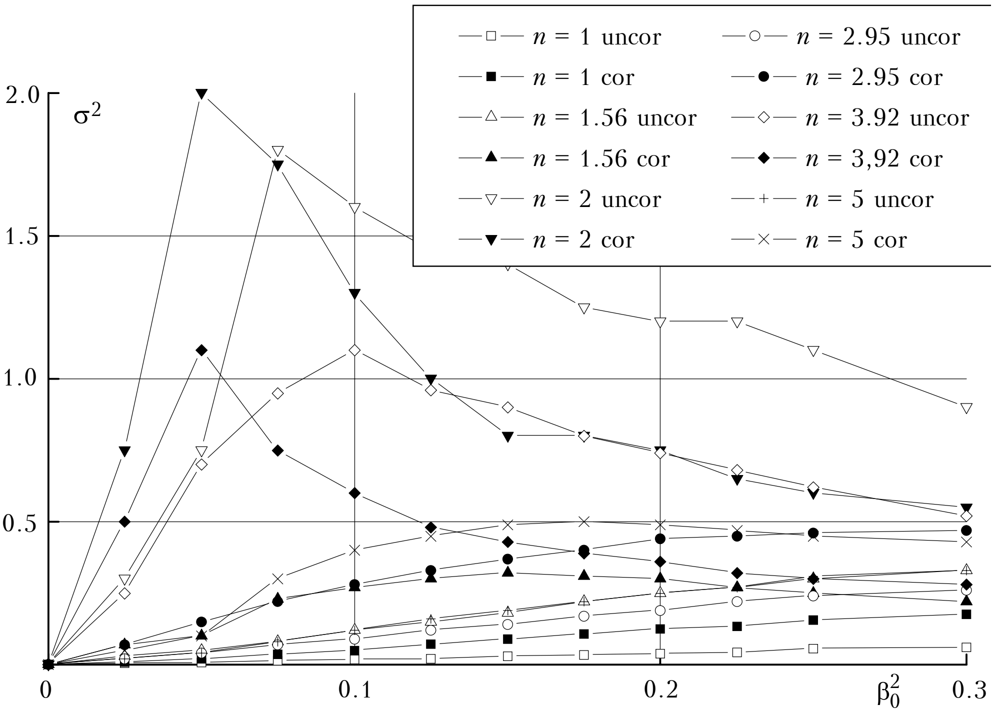

FIG. 4. Dependence of the variance of the intensity fluctuations on turbulence parameter β_0^2 on correlated (labeled by cor) and uncorrelated (labeled by uncor) paths.

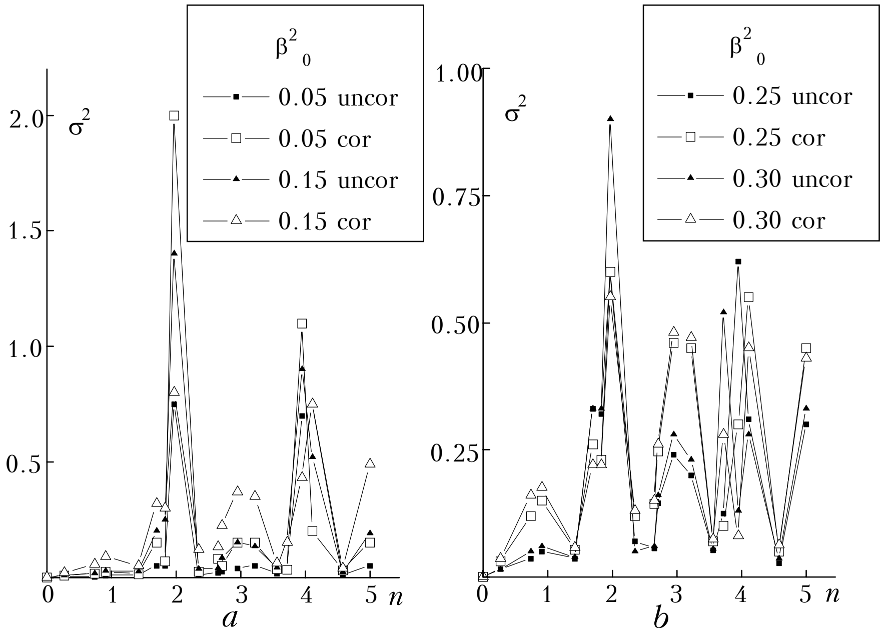

FIG. 5. Dependence of the variance of the intensity fluctuations on the reflector size on correlated (labeled by cor) and uncorrelated (labeled by uncor) paths.

number of Fresnel zones the intensity distribution of the reflected beam does not contain sharply pronounced diffraction maxima and minima, and the variance of the intensity fluctuations

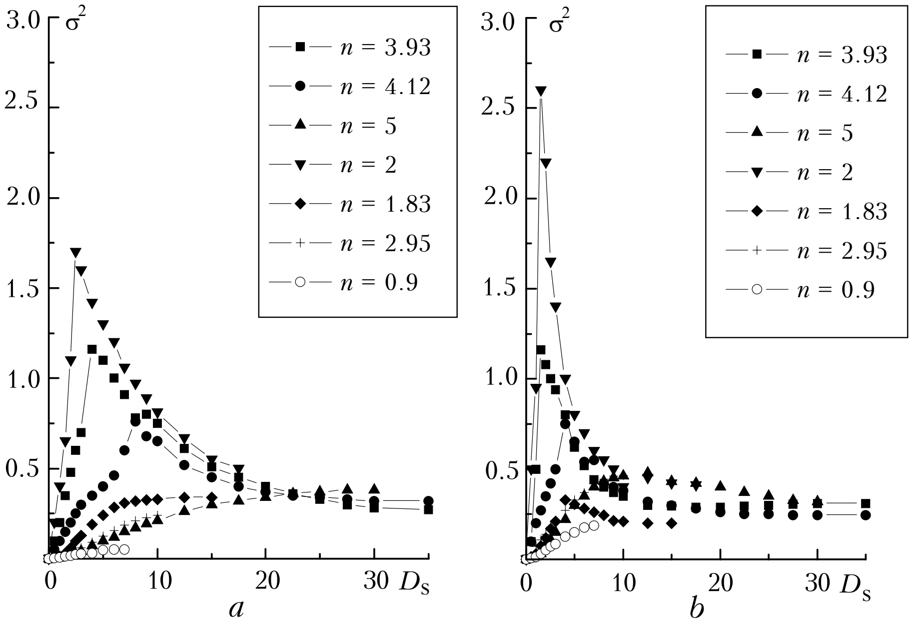

FIG. 6. The variance of the intensity fluctuations σ^2 as a function of the structure phase function D_s for reflector size equal to the integer number of Fresnel zones: a) the uncorrelated path, b) the correlated path.

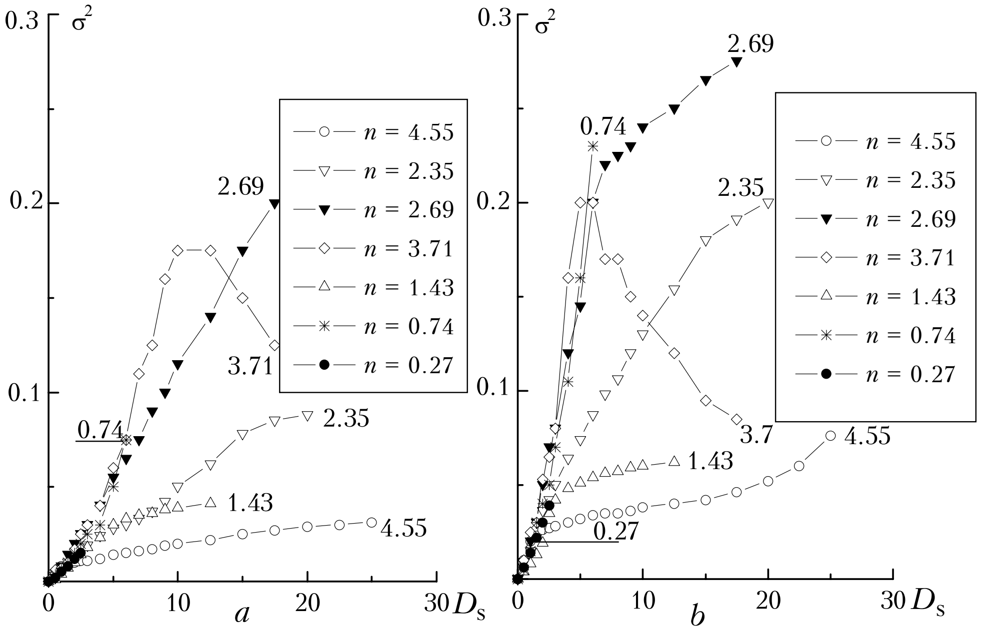

FIG. 7. The intensity variance as a function of the structure phase function D_s for reflector size equal to the noninteger number of Fresnel zones: a) the uncorrelated path, b) the correlated path.

is found much smaller than in the above cases. In all measurements the variance of the intensity fluctuations on the correlated path exceeds the variance on the uncorrelated path, that is, the correlation of oncoming waves leads to enhancement of the intensity fluctuations in the reflected beam.

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REFERENCES

1. A.G. Vinogradov, Yu.A. Kravtsov, and V.I. Tatarskii, Izv. Vyssh. Uchebn. Zaved., ser. Radiofizika **16**, No. 7, 1064–1070 (1973).

2. V.A. Banakh and V.L. Mironov, *Lidar in a Turbulent Atmosphere* (Artech House, Boston–London, 1987), 185 pp.

3. A.S. Gurvich, A.P. Ivanov, S.S. Kashkarov, G.Ya. Patrushev, and A.P. Rostov, Atmos. Oceanic Opt. **5**, No. 1, 29–32 (1992).

4. V.A. Banakh, Atmos. Oceanic Opt. **6**, No. 4, 229–233(1993).

5. V.A. Banakh, V.M. Sazanovich, and R.Sh. Tsvyk, Atmos. Oceanic Opt. **7**, Nos. 11–12, 831–833 (1994).

6. V.A. Banakh, V.M. Sazanovich, and R.Sh. Tsvyk, Atmos. Oceanic Opt. **8**, No. 10, 794–797 (1995).

7. P.A. Konyaev, V.P. Lukin, G.Ya. Patrushev, and S.Yu. Tabakaev, Atmos. Oceanic Opt. **3**, No. 12, 1194–1197 (1990).