INVESTIGATION OF THE INTRACAVITY METHOD FOR MEASURING ATMOSPHERICTRANSMISSION NEAR 10 μm ON REAL PATHS

S.D. Burakov, A.P. Godlevskiĭ, and S.A. Ostanin

Institute of Atmospheric Optics,
Siberian Branch of the Academy of Sciences of the USSR, Tomsk
and
Special Design Office of Scientific Instrument Building "Optika",
Siberian Branch of of the Academy of Sciences of the USSR, Tomsk

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The results of measurements of the extinction coefficient on the atmospheric path using devices based on a laser with a long cavity are presented. It is shown that inserting an additional mirror in the cavity makes it possible to extend the measurable range of extinction coefficient up to ~ 50 km. Estimates of the variance of fluctuations in the intensity of the laser radiation with two- and three-mirror cavities are evaluated.

In Refs. 1–3 it is shown that laser systems based on coherent intracavity detectors can be used to solve different problems in atmospheric optics. In Refs. 3 and 4 a CO_2-laser with an external mirror and a cavity length exceeding 100 m in a turbulent atmosphere was studied and it was shown that the extinction coefficient can in principle be measured with a high sensitivity near 10 μm. In this paper we examine the results of further studies of an apparatus for measuring the extinction coefficient of the real atmosphere based on a CO_2 laser with an external reflector at the end of the path. The purpose of these investigation was to determine the absolute values of the recorded extinction coefficients and to extend the range of the measurements up to large optical thicknesses.

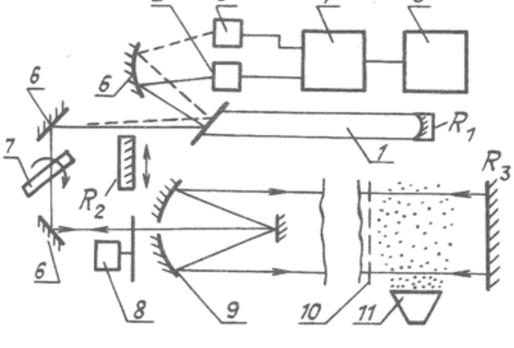

FIG. 1. Diagram of the experimental arrangement: 1) GL-501 gas-discharge tube; 2, 3) photodetectors; 4) ADC; 5) MERA-660 computer; 6) mirrors; 7) ZnSe plate; 8) obturator; 9) telescope; 10) film; 11) aerosol generator; R_1, R_2, and R_3 are cavity mirrors.

Figure 1 shows the optical arrangement of the apparatus. In contrast to Ref. 4, we employed a GL-501 gas-discharge tube, which had a higher gain than the GL-502 tube and a highly stabilized power supply for the tube. This made it possible to obtain continuous lasing with a cavity length greater than 100 m and the structure constant of the index of refraction C_n^2 of ~ 10^{-4} $cm^{-2/3}$.

This arrangement was distinguished by the fact that it employed a calibrated attenuator (ZnSe plate oriented at an angle close to Brewster's angle). The plate was inserted between the end of the gas-discharge tube and the collimator. A mirror with a different reflection coefficient, which was also a cavity mirror (R_2), was inserted between the end of the tube and the calibrated attenuator. The signal was recorded on a magnetic tape and then processed on the MERA-660 computer.

As shown in Ref. 4, the minimum absorption coefficient recorded using a CO_2 laser with a long two-mirror cavity was equal to ~ 10^{-7} cm^{-1}. In this paper we present the results of experiments whose purpose was to determine the range of variation of the optical thickness of inserted in the laser cavity. In these experiments an artificial water aerosol with the most probable diameter of 1–2 μm and with known concentration was employed. The measurements showed that lasing stops for a water aerosol with an optical thickness of the order of ~ 0.083. In this case the particle concentration in the beam was equal to ~ 10^4 cm^{-3}.

Using the relations derived in Ref. 4 for the variance of the displacement of the center of gravity of the beam, we obtained the following expression for the variance σ_2 of the fluctuations in the laser power in the case of a two-mirror cavity:

$$\sigma_2 = \frac{2}{\pi} \langle P \rangle \left[\arccos\sqrt{1 - \frac{\langle R_c^2 \rangle}{4A^2}} + \frac{\langle R_c^2 \rangle}{4\ A^2} \sqrt{1 - \frac{\langle R_c^2 \rangle}{4A^2}} \right], \tag{1}$$

where <*P*> is the measured average lasing power. A is the output aperture of the collimator: the mean-square displacement

$\langle R_c^2 \rangle = 2.72\ L^3 C_\varepsilon^2\ (A/2)^{-1/3}\ (1 - b^{-1/6})$,

where L is the path length; C_ε^2 is the structure characteristic of the dielectric constant; $b = \hat{k}h\sqrt{2}/\pi A$, where $\hat{\kappa}$ is Karman's constant; and, h is the distance from the earth's surface to the center of the beam.

We shall derive an analogous relation for a three-mirror cavity. Starting from the relation derived in Ref. 5 for the lasing power as a function of the external signal strength we obtain for σ_3

$$\sigma_3 = \frac{GW_\upsilon \langle \beta \rangle}{\tau\ (Q - \langle \beta \rangle)}, \tag{2}$$

where $\beta = 1/2\ (L_p \ln (1 + \langle \Delta I \rangle)$, G is the excess of the pump power above its threshold value; W is the excitation cross section; υ is the velocity of light in the active element; τ is the spontaneous deactivation time of the active centers; L_c is the length of the laser cavity; Q is the Q-factor of the cavity; and, $\langle \Delta I \rangle$ is the average intensity corresponding to the contribution of the interference term.

Consider the result of the interaction of the reference field, $E_0 = A_0 \exp\ (i\omega_0 t + \varphi_0)$, and the signal field $E_s = A_s \exp\ (i\omega_0 t + \varphi_s)$, whose phase and amplitude are perturbed. For interference on a half-transmission mirror with transmission R

$$I = R \int_s (E_0 + E_s)(E_0^* + E_s^*)\ ds.$$

The integration extends over the cross section S of the capillary of the gas-discharge tube with diameter D. If $A_0 \gg A_s$, which condition is always satisfied in practice, the quadratic term A_s^2 can be neglected. The term proportional to A_0^2 determines the average constant component of the intensity of the field on the mirror. Averaging over an ensemble of realizations of the random field of the dielectric constant ε gives (analogously to Ref. 6):

$$\langle \Delta I(t) \rangle = R^{1/2} \pi D^2 \langle A_0 A_s \rangle \int_0^D \left[\arccos \frac{r}{D} - \frac{r}{D} \sqrt{1 - \frac{r^2}{D^2}} \right] \times$$
$$\times \Gamma_2(x, r)\, r dr. \tag{3}$$

The spatial coherence function is

$$\Gamma_2\ (x,\ r) = \exp\ (-\ A^{5/3} 0.365 C_\varepsilon^2 k^2 L), \tag{4}$$

where L is the length of the additional cavity and κ is the wave number.

One can see from Eqs. (3)–(4) that an increase in C_n^2 results in a decrease of the average lasing power. This result is confirmed by the experimentally obtained amplitude spectra of the lasing power with different values of C_n^2.

Thus from Eqs. (2)–(4) we obtain the variance of the fluctuations in the laser power for the case when the coherence radius of the signal field is greater than the diameter of the capillary.

We performed a series of experimental measurements in order to study the spectrum of the fluctuations and the amplitude of the lasing power with a two- and three-mirror cavity on a path near the ground under different meteorological conditions.

As we pointed out above, using a gas-discharge tube with a large gain (approximately by an order of magnitude) made it possible to achieve continuous-wave lasing with a laser with a two-mirror cavity for atmospheric turbulence of almost any strength.

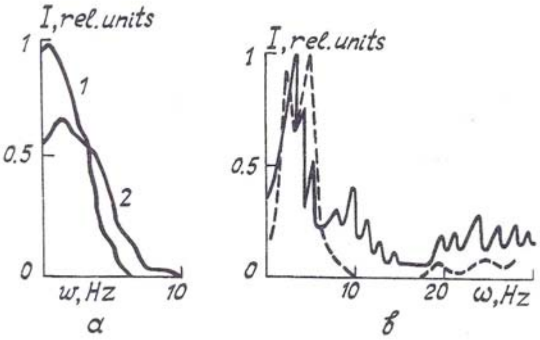

FIG. 2. The spectrum of fluctuations of the lasing intensity of the laser: a) two-mirror cavity, weak (1) and strong (2) turbulence; b) R_2 is a ZnSe plate (solid line) or a Ge plate (broken line).

Figure 2a shows an example of the frequency spectrum of the fluctuations in the intensity of lasing with weak (1) and strong (2) turbulence. A low frequency of the fluctuations in the intensity of lasing was observed under different meteorological conditions. The maximum frequency reached 5–8 Hz and the most probable frequency was equal to 2–3 Hz. The low frequency of the intensity fluctuations is connected with the rocking of the beam owing to refraction, while because of the complete interception of the beam the redistribution in the intensity and phase over the cross-section of the capillary of the discharge tube has no effect on the lasing characteristics of the laser.

In many practical problems measurements must be performed in a wide range of optical thickness, and in particular, for large optical thicknesses (fogs, precipitation, smoke, etc.). To this end we studied a CO_2 laser with a three-mirror cavity, in which the sensitivity to extinction on the path can be varied. The passive part of the cavity was placed in the real atmosphere and it was 110 m long.

When a third cavity mirror (R_2) is inserted between the tube and the telescope the frequency spectrum of fluctuations of the lasing intensity of the laser changes substantially. A second maximum, formed by the interference phenomena on the mirror R_2, is observed at high frequencies near 20 Hz. In addition, the magnitude of this maximum depends both on the turbulent characteristics of the atmosphere and on the value of reflection coefficient R of the mirror R_2, i.e., the ratio of the intensities of the radiation in the passive and active parts of the cavities. In these experiments the structure constant of the fluctuations in the index of refraction of the atmosphere C_n^2 was measured occasionally from the spectrum of fluctuations of the intensity of a He-Ne laser, which was measured with a point photodetector.

Figure 2b shows an example of the frequency spectrum of fluctuations of the intensity of a laser with a three-mirror cavity for $C_n^2 \sim 10^{-15}$ cm$^{-2/3}$ and for different values of the reflection coefficient of the mirror R_2. Plates consisting of ZnSe coated with a reflective coating and Ge plates were used for the mirror R_2. As one can see from the figures, the magnitude of the high-frequency maximum depends on the intensity of the radiation in the passive part of the cavity, in this case, on the reflection coefficient of the mirror R_2.

The form of the frequency spectrum of the laser with a three-mirror cavity can be explained as follows. The first, low-frequency, maximum is determined by fluctuation in the phase of the radiation owing to optical nonuniformities in the atmosphere along the path, that is, a high-frequency component connected with the rapidly oscillating interference term $A_0 A_s \cdot \cos \Delta\varphi$, where $\Delta\varphi$ is the phase increment integrated over the path, appears in the spectrum of the lasing power. The magnitude of the second maximum with turbulence of the same strength will be highest in the case when the fields in the active and passive parts of the cavity are equal $A_0 = A_s$. The magnitude of the high-frequency maximum also depends on the turbulent characteristics of the atmosphere and its highest value was observed with strong turbulence $C_n^2 \sim 5 \cdot 10^{-1}4$ cm$^{-2/3}$ (wind, change in temperature). As pointed out in Ref. 4, the maximum value of the amplitude of the radiation was practically identical for different values of C_n^2 and depend solely on the power sampling time. This situation was realized for both two- and three-mirror cavities.

The experimental determination of the transmission of the atmosphere using a laser with a two- and three-mirror cavity in absolute units was determined experimentally by several methods. First the change in the lasing power and its dynamic range when calibration losses, whose magnitude was varied smoothly, were introduced into the two-mirror cavity. For these purposes the thin ZnSe plate was rotated around an axis perpendicular to the cavity axis. The losses due to reflection from the two surfaces of the plate are minimum when the plate is tilted at Brewster's angle θ_B. It is well known that the reflection coefficient of the plate as a function of the angle of inclinition $\Delta\theta$ is given by the expression

$$R(\Delta\theta) = \frac{\mathrm{tg}^2\left[\theta_B + \Delta\theta - \arcsin\dfrac{\sin(\theta_B + \Delta\theta)}{n}\right]}{\mathrm{tg}^2\left[\theta_B + \Delta\theta + \arcsin\dfrac{\sin(\theta_B + \Delta\theta)}{n}\right]}. \quad (5)$$

Once the angle of inclinition of the plate $\Delta\theta$ has been measured the insertion losses in the cavity can be determined right up to termination of lasing. Figure 3a and b show the calibration curve of the lasing intensity I/I_0 (I_0 is the intensity of the radiation at $\theta = \theta_B$) versus the angle of rotation of the plate (Fig. 3a) and in this connection the attenuation of the radiation in the cavity (Fig. 3b). It is virtually impossible to realize controllable conditions on a 100 m path for the background aerosol extinction based on existing absorption methods. As one can see from the graph in Fig. 3b lasing stops when particles from the water aerosol generator with a most likely diameter of 1–2 μm and a concentration of 10^4 cm^{-3}, which corresponded to an optical thickness of ~ 1.0 km^{-1}, were placed in the cavity. It is obvious that in this case the dynamic range can be expanded by increasing the gain of the active medium of the laser, which, in its turn, will require increasing the dimensions and power consumption of the system. This makes it difficult to use this method in a number of practical problems, for example, in the mobile variant. In working with a three-mirror cavity, when the additional cavity mirror R_2 placed in front of the telescope contributes to the lasing, the sensitivity of the apparatus to the extinction of radiation along the path can be reduced. In this case, because of the high sensitivity of the laser to the weak radiation (down to 10^{-12} W/Hz) returning into the cavity[2] large optical thicknesses can be measured.

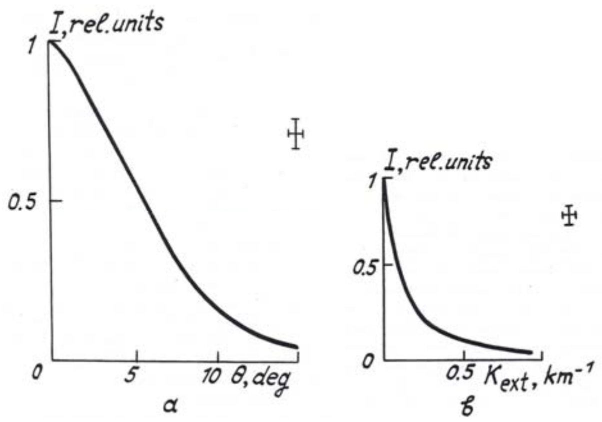

FIG. 3. Calibration curves: a) lasing intensity versus the angle of rotation of the plate; b) lasing intensity versus extinction coefficient ($k_{\rm ext}$).

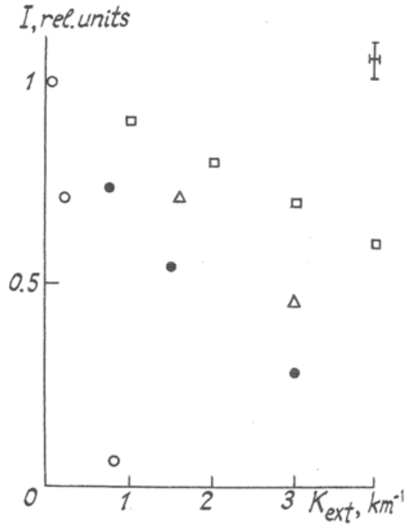

FIG. 4. The results of measurements of the extinction coefficient k_{ext}: light-colored circles — no mirror R_2; dark-colored circles — R_2 = 20% (KBr); triangles — R_2 = 40% (ZnSe); squares — R_2 = 70% (CGe).207.

In experiments with a three-mirror cavity a water-aerosol generator was inserted into the passive part of the cavity; the aerosol concentration could be changed in steps by changing the diameter of the intake nozzle. A tiacetran film 50 μm thick was also used. In addition, measurements were also performed in natural fog. The optical thicknesses created were measured by the standard absorption method. To eliminate random errors in the measurements performed by this method the extinction was determined on the same apparatus, i.e., the same optoelectronic apparatus and the same beam parameters were employed, and in so doing the external mirror was turned by a small angle and the radiation was directed onto a second photodetector. The ratio I/I_0, were I and I_0 are the intensities measured by the photodetectors 2 and 3, respectively, was measured. The extinction coefficients were then calculated from Bouguer's law. In the case when the measurements of the extinction coefficients by the intracavity method are impossible to perform by the absorption method in the region of weak absorption, we increased the optical thickness by several times and we made the corresponding conversion after the measurements. From the measurements of k_{ext} performed with the help of a laser with a two-mirror cavity and a three-mirror cavity with different reflection coefficients of the mirror R_2 and the same atmospheric parameters (Fig. 4) one can see that based on the intracavity method it is impossible to cover continuously the entire range of measurements of k_{ext} by the Q-factor of the passive and active parts of the cavities. Measurements were also performed in natural fog, using a germanium mirror for R_2. It should be noted that on a 110-meter path with a visibility range of 30–40 m the signal was recorded reliably from the external mirror with k_{ext} ~ 50 km^{-1}. Approximately the same value was obtained by inserting a film in the path in the cavity.

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