EXPERIMENTAL DETECTION OF THERMAL BLOOMING OF AN OPTICAL BEAM IN AN OUTDOOR ATMOSPHERE

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The extinction of CW optical radiation in an outdoor clear atmosphere free of any aerosol burden along a near–ground path has been measured. Analysis of the data obtained indicated additional extinction of the beam in excess of the molecular absorption, which could be explained by thermal blooming of the beam.

1. INTRODUCTION

The first paper devoted to experimental study of thermal blooming of a laser beam propagating in an absorbing medium was published in *Applied Physics Letters*[1] in October of 1964, thirty–one years ago. It was the experiment with a He–Ne laser beam. Cells with various liquids were inserted into a laser cavity. Leite et al.[1] used this phenomenon for measurements of small values of the radiation absorption indices in liquids. It was demonstration of a possible practical application of this phenomenon. In succeeding years this effect, among many other self–action effects, was primarily studied in connection with its adverse effect on the characteristics of laser beam propagating along extended atmospheric paths.

Most experiments studying thermal blooming of optical beams were done under laboratory conditions.[1–4] In Refs. 5–7, experiments were performed with laser beam propagating through outdoor atmosphere. In Ref. 5, a beam propagating along 195 m path was transmitted through a special chamber modeling a windless section of the path. Almost simultaneously the average intensity in the focal plane of the beam was measured without chamber. The obtained results reveal thermal distortions of the beam, because the average intensity in the beam focus with windless zone was twice less than that without this zone. Rudash et al.[6] observed ellipsoid distribution of the intensity over the focal plane of a CO_2–laser beam on 760 m path. However, results of this experiment can hardly be explained by thermal blooming of the beam, because experiment was performed with the beam power being equal to ~1 kW at a low water vapor content in air being equal to 5 g/m^3. Banakh et al.[7] studied the effects of the atmospheric path and its section between a source and optical system on defocusing of optical beam under conditions of thermal blooming.

The present paper studies the extinction of cw optical radiation with a wavelength of 10.6 μm along 1500 m near–ground path in an outdoor atmosphere for wide variety of meteorological conditions. Results obtained allow us to draw a conclusion that the thermal blooming of laser beam is experimentally observed.

2. EXPERIMENTAL PROCEDURE AND RESULTS

The experimental procedure employed for determination of the extinction coefficient of optical radiation in the atmosphere was based on measurement and comparison of maximum intensity in the focal plane of beams propagating along the measurement and reference paths.[8] Measurement path 1500 m long was located above a flat underlying surface at an altitude of about 10 m. As a reference path, a short path 275 m long or the same measurement path under meteorological conditions corresponding to maximum transparency of the atmosphere was used.

An experimental stand included a source, a system of beam shaping, and devices for measuring the characteristics of radiation and the atmospheric meteorological parameters. A commercial CO_2 laser was used as a source. It generated single pulses with duration of several seconds. A laser beam was shaped and focused with a telescope whose focal length was adjusted in the range 200–2000 m. The annular beam had a screening factor being equal to ~ 0.4.

Upon entering the atmosphere the beam power was measured by a power meter of bolometric type. At the end of the propagation path, the distribution of a power density over the beam cross section was measured in the focal plane of the beam with a 42×42 cm matrix meter having 49 6×6 cm sensitive elements. Mathematical processing of these data allowed us to reconstruct the power distribution over the beam cross section with required accuracy within the solid angle at which the measurement matrix was seen from an observation post, and to measure the maximum intensity in the focal plane of the beam.

The data were processed only for laser shots under most controllable conditions and reliable operation of optical quantum generator and means of measuring.

Simultaneously with measurements of the radiation parameters, we measured the standard atmospheric parameters: the wind speed and direction, meteorological visibility range, and structural characteristic of the refractive index of air.

Two parameters were determined experimentally: molecular absorption coefficient in the atmosphere α_M and total extinction coefficient α_t.

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The molecular absorption coefficient was determined by the indirect method: it was calculated on the basis of the measured meteorological parameters with the use of relation[9,10]

$$\alpha_M = 0.86\cdot 10^{-3}\exp(1800(1/T-1/296)) \times$$
$$\times\ (P_{H_2O}+2.3)P_{H_2O}+0.0757(296/T)^{3/2}\times$$
$$\times\ \exp(2233(1/T-1/296))\ , \qquad (1)$$

where T is the air temperature, K; P_{H_2O} is the water vapor partial pressure, Torr. In the experiments, the ranges of variations of the air temperature and mass concentration of water vapor were 3–21° C and 5–19 g/m^3, respectively.

By measuring maximum intensity in the focal plane of beams propagating along measurement and reference paths, we determined α_t based on the relation:

$$\alpha_t = \frac{1}{Z_m}\left[\ \ln\left(\frac{I_r\,P_m}{I_m\,P_r}\right) - 2\,\ln\left(\frac{Z_m}{Z_r}\right) + \alpha_r\,Z_r\right], \qquad (2)$$

where I, P and Z are the maximum radiation intensity in the focal plane, output power density, and path length, respectively, for measurement and reference paths specified by the subscripts “mB and “rB The value of α_r was assumed to be equal to α_M determined from formula (1).

Estimates of aerosol and turbulent components of the atmospheric transparency carried out with the use of standard methods[4] from the known meteorological parameters have shown that we may neglect these components in comparison with the molecular absorption. Meteorological visibility range was 10–30 km and the structural characteristic of the air refractive index was within the range $(0.3–8.0)\cdot 10^{-16}$ cm$^{-2/3}$.

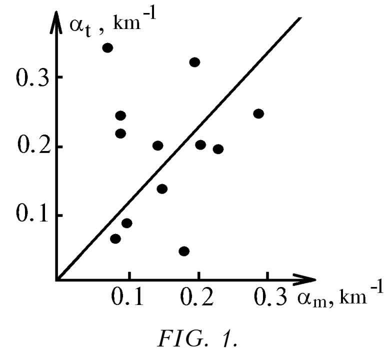

FIG. 1.

In Fig. 1 the measured total extinction coefficient of the beam intensity is shown as a function of the molecular absorption coefficient. The solid straight line shown in the figure is for the regression equation connecting these values. The slope of the regression line is equal to 1.1. Thus, the total extinction coefficient is in excess of the molecular one. The excess extinction can be attributed primarily to thermal blooming of the beam, as analysis and estimates of possible reasons for the difference between the total extinction and molecular absorption coefficient has shown.

3. COMPARISON OF EXPERIMENTAL RESULTS WITH A THEORY

For comparison of the experimental results with a theory, the model of thermal blooming of a focused Gaussian beam propagating under conditions of uniform constant horizontal wind was chosen, which describes conditions of our experiments in the steppes at the seaside. In the model, relative variations of the extinction coefficient of a beam in the regime of long laser pulse are described by the expression[10,11]

$$\frac{\alpha_t - \alpha_M}{\alpha_M} = \tilde{N}_0 G_0\left(1 + \frac{\pi\sqrt{\pi}\ r_0\ \mathrm{t}_{\ \mathrm{st}}}{3\ \ln\,3\ t\ v_\perp\sqrt{1+3\ F^2}\ \mathrm{t}_{\ \mathrm{nst}}}\right)^{-1}, \qquad (3)$$

where t is the duration of laser pulse, r_0 is the beam radius at 1/e, $V_\perp$ is the transverse component of the wind velocity, $F=kr_0^2\,/z_F$ is the Fresnel number, z_F is the focal length, k is the wave number, and the parameters $\tilde{N}_0$ and G_0 characterize the dependence of thermal blooming on meteorological conditions and beam parameters upon entering the atmosphere:

$$\tilde{N}_0 = \frac{(n_0-1)\ (\gamma-1)\ P_0\ z_F}{2\sqrt{\pi}\ n_0\ \gamma\ p\ v_\perp r_0^3}; \qquad (4)$$

$$G_0 = \frac{\pi\ F^2}{3\sqrt{1+3\ F^2}}\times$$
$$\times\left(1 - \frac{6\ F}{\pi\ (1+3\ F^2)}\ \ln\frac{1+3\ F^2}{e\ F}\right)\exp\left(-\frac{\tau\ F}{0.6+F}\right).$$

In these formulae, n_0 and γ are the refractive index and adiabatic exponent, respectively, p is the atmospheric pressure, P_0 is the output beam power, and $\tau = \alpha_M z_F$ is the optical thickness. The functions $\Phi_{st}(F,\tau)$ and $\Phi_{nst}(F,\tau)$ have been determined in Ref. 12, and their values are close to unity for the parameters F and τ realized in our experiments. Therefore, to compare the theory with the experiment we have chosen expression (3) with $\Phi_{st}/\Phi_{nst}=1$.

In addition, it was necessary to adjust the parameters of the beam used in our experiments and the model beam parameters. This adjustment was made by choice of two parameters of the model beam, namely, the beam radius and the effective Fresnel number, which characterizes the real angular beam divergence.

The radius of the model beam was chosen to be equal to the average radius of a real beam calculated from the condition of their equal average power. This means the fulfillment of the equality

$$\iint_S \mathrm{d}x\ \mathrm{d}y\ (x^2+y^2)\ I\ (x,y) =$$

$$= \int_{-\infty}^{\infty}\!\!\int \mathrm{d}x\ \mathrm{d}y\ (x^2+y^2)\ \exp\left(\frac{x^2+y^2}{r_0^2}\right),$$

in which the integral in the left-hand side is taken over the output aperture of the beam. It then follows that $r_0 = R\sqrt{(1+\varepsilon^2)/2}$, where R is the external radius of the angular aperture, ε is the screening factor of the aperture.

The real beam divergence caused by partial coherence was calculated by substituting in Eqs. (3) and (4) the Fresnel number for the effective Fresnel number determined experimentally for laser shots along the reference path.

Statistical processing of the results of calculations of the total extinction coefficient on the basis of experimental data with the use of Eq. (3) leads to the following regression relation: $\alpha_t = 1.35\alpha_M$. This result refines analogous relation presented in Refs. 13 and 14 and, like these papers, shows that to suit the theory and experiment one needs to refine relation (3) by entering the additional coefficient $\gamma_f < 1$, which is equal to 0.28, namely,

$$\frac{\alpha_t - \alpha_M}{\alpha_M} = \gamma_f\, \tilde{N}_0 G_0 \left(1 + \frac{\pi\sqrt{\pi}\ r_0}{3\ln 3\ t\, v_\perp \sqrt{1 + 3F^2}}\right)^{-1} .$$

The need of entering this coefficient can be explained by additional focusing of the beam, whose initial profile of the intensity has a dip on the beam axis.[11]

4. CONCLUSION

The distinctive feature of this work lies in the fact that the experiments were conducted under natural conditions, corresponding to the strongest manifestation of the effect under study – beam thermal blooming, namely, at high air humidity and for high value of the meteorological visibility range. The methods of scaling of this effect, such as addition of strongly absorbing admixtures, formation of stagnant zones, etc. were not applied.

To detect the beam thermal blooming under these conditions, it was necessary to increase 2–3 times beam power, aperture, and range in comparison with the beam used in Ref. 1. In general, the results obtained characterize the progress in development of atmospheric optics during the elapsed three decades.

REFERENCES

1. R.C.C. Leite, R.S. Moore, and J.R. Whinnery, Appl. Phys. Lett. **5**, No. 7, 141–143 (1964).
2. D.C. Smith, TIIER **65**, 59–103 (1977).
3. M.P. Gordin, et al., Itogi Nauki Tekhn., Ser. Radiotekhn. **20**, 206–289 (1980).
4. V.E. Zuev, *Propagation of Laser Radiation in the Atmosphere* (Radio i Svyaz', Moscow, 1981).
5. T.G. Miller, et al., J. Opt. Soc. Am. **65**, 1191 (1975).
6. V.K. Rudash, et al., in: *Abstracts of Reports at the First All-Union Symposium on Propagation of Laser Radiation in the Atmosphere,* Tomsk (1977), pp. 169–172.
7. V.A. Banakh, V.V. Karasev, Yu.A. Konyaev, et al., Atmos. Oceanic Opt. **6**, No. 12, 881–883 (1993).
8. L.V. Gustov and M.A. Fedorov, Sudostroitel'naya Promyshlennost', Ser. Obshchetekhnich., No. 35, 62–66 (1991).
9. R.E. Robert, et al., Appl. Opt. **15**, 2085–2089 (1976).
10. E.L. Breig, J. Opt. Soc. Am. **62,** 518–524 (1972).
11. M.A. Fedorov, Pis'ma Zh. Eksp. Teor. Fiz., No. 9, 455–460 (1992).
12. M.A. Fedorov, Atmos. Oceanic Opt. **7**, No. 3, 172–173 (1994).
13. L.V. Gustov and M.A. Fedorov, Sudostroitel'naya Promyshlennost', Ser. Obshchetekhnich. **35**, 66–72 (1991).
14. L.V. Gustov, D.Ya. Kovalevskii, and M.A. Fedorov, in: *Abstracts of Reports at the XIIth Interrepublic Symposium on Propagation of Laser Radiation in the Atmosphere and Water Media*, Tomsk (1993), p. 128.