# TRANSMITTANCE OF THE NEAR–GROUND ATMOSPHERE FOR A PULSED $CO_2$ LASER

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*Data of field investigations of a high–power laser radiation in different optical and meteorological situations is analyzed. An essential influence of the molecular–to–aerosol components ratio of the atmospheric extinction coefficient on the extinction itself has been revealed.*

First experimental studies of propagation of intense $CO_2$–laser beams through a near–ground path showed that initial parameters of the beams suffer significant distortions[1–4] caused by interaction of an intense laser radiation (ILR) with the components of a propagation medium, by the change of their optical properties, and, as a consequence, by the effect of the changed optical properties of the medium on the conditions of the laser beam propagation.[5] The variety of processes of the ILR interaction with different atmospheric components depending on the radiation parameters, their multiplicative character,[6,7] dependence of a medium extinction on weather conditions and strong variability[8] of the extinction, different contributions coming to the extinction from the gaseous and aerosol components of the atmosphere at one and the same value of the total extinction coefficient, significant spread of the experimental data on the ILR transmission factor at the wavelength $\lambda = 10.6$ μm obtained in field conditions – all these factors make the interpretation of experimental results very hard.

Atmospheric transmission for radiation at the wavelength under study is simultaneously governed by water vapor and aerosol, i.e., by two most variable components of the atmosphere. Moreover, it is difficult to separate the contributions from these two components into the transmission because, on the one hand, the contributions into the total extinction are comparable and, on the other hand, the aerosol component of the extinction depends on the atmospheric humidity.

In this paper we discuss an attempt undertaken to find some characteristics of the interaction between ILR and the ground atmospheric layer that could be informative when estimating the effects of aerosol and molecular components of the extinction on the atmospheric transmission for ILR at the initial parameters (type of radiation, its energy parameters, optical and meteorological conditions) being fixed. It is of practical interest to analyze a combined influence of the atmospheric characteristic $\eta = \alpha_m/\alpha_a$, the beam energy and geometric parameters on the atmospheric transmission for ILR. Here $\alpha_m = \alpha_{H_2O} + \alpha_{CO_2}$ ($\alpha_{H_2O}$ is the extinction coefficient due to water vapor absorption at $\lambda = 10.6$ μm and $\alpha_{CO_2}$ is the extinction coefficient due to carbon dioxide absorption at the same wavelength), $\alpha_a$ is the aerosol extinction coefficient.

The component of the atmospheric extinction due to interactions of radiation with gas components of the atmosphere has a known dependence on temperature, pressure, and contents of gases and therefore we have calculated it following the technique from Ref. 9. The aerosol component of the volume extinction coefficient of the atmosphere was determined according to Ref. 8. In addition, the values of $\alpha_{H_2O}$, $\alpha_{CO_2}$, and $\alpha_a$ were calculated using standard meteorological parameters of the atmosphere measured for each ILR shot.

An example of the dependence of the atmospheric transmission $T_{exp}$ for an intense $CO_2$–laser radiation of microsecond duration on the aerosol and gas components of the extinction coefficient is given in Table I. The data presented in this table were chosen so that they correspond to approximately one and the same energy density of ILR at the beginning of the propagation path at close values of the transmission coefficient $T_{cal}$ of the atmosphere calculated assuming linear propagation of the radiation at $\lambda = 10.6$ μm through the atmosphere (see Refs. 8 and 9). The measurements were carried out in different seasons though for one and the same type of optical weather (spring and fall hazes) but for different η ratios. Some meteorological parameters measured in the experiments are given in Table I. They are: $f$ is the relative humidity of air, ρ is the absolute air humidity, $t$ is the temperature, and $S_m$ is the meteorological visual range. Geometry of the laser beam is characterized by the ratio $F/R_1$, where $F$ is the focal length of a transmitting telescope and $R_1$ is the initial radius of a collimated laser beam, has been kept constant ($F/R_1 \sim 9\cdot10^2$). It can be seen from Table I that the atmospheric transmissions for ILR in winter and summer are different, with the summer conditions characterized by an enhanced water vapor content are more favorable for ILR propagation.

The ranges of η variations occurred in our measurements in different seasons are given in Table II for some types of aerosol situations.

Analysis of contributions coming from the gas and aerosol components of the atmosphere to the atmospheric extinction of ILR ($\alpha_n$) has been carried out based on the results of field experiments.[1,3,7] Some results of this analysis are shown in Fig. 1. One can easily separate out the influence of a beam geometry on the atmospheric extinction from the curves shown in this figure, that is caused by an increase of the beam power density for a shorter focused beam. Thus, at $F/R_1 \sim 9\cdot10^2$ and $E_0 = 0.1$ J/cm$^2$ the optical breakdown occurs along a sufficiently long portion of a beam propagation path, what strongly affects the transmission of the atmospheric propagation channel.[1,3,7] At the same time, for $F/R_1 \sim 2.4\cdot10^3$ no optical breakdown is observed along the propagation path at all. In the latter case the view of $\alpha_n(E_0)$ function is much more complicated. The function $\alpha_n(\eta)$ at a constant $E_0$ value is nonmonotonic.

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*TABLE I. The effect of the relation for the molecular–to–aerosol components of the volume atmospheric extinction coefficient on the ILR transmission coefficient.*

| Parameters | | Season | |
|---|---|---|---|
| | | Winter | Summer |
| $f$, | % | 88 | 93 |
| $\rho$, | g/cm$^3$ | 2.2 | 9.74 |
| $t$, | °C | – 8.8 | 11.7 |
| $S_m$, | km | 4.9 | 5.1 |
| $\alpha_{H_2O}$, | km$^{-1}$ | 0.022 | 0.164 |
| $\alpha_{CO_2}$, | km$^{-1}$ | 0.039 | 0.065 |
| $\alpha_m$, | km$^{-1}$ | 0.061 | 0.229 |
| $\alpha_a$, | km$^{-1}$ | 0.322 | 0.133 |
| $\alpha$, | km$^{-1}$ | 0.383 | 0.362 |
| $T_{cal}$ | | 0.81 | 0.82 |
| $E_0$, | J/cm$^2$ | 0.19 | 0.2 |
| $\eta$ | | 0.19 | 1.72 |
| $T_{exp}$ | | 0.61 | 0.75 |

*TABLE II. The ranges of $\eta$ variations under different season conditions.*

| Type of optical weather | Season | | | |
|---|---|---|---|---|
| | Winter | Spring | Summer | Fall |
| Haze | 0.19–0.98 | 0.69–1.95 | 3.0–10.43 | 0.31–9.65 |
| Mist | 0.07–0.08 | | 0.42–0.84 | 0.06–0.65 |
| Advective fog | | 0.01–0.10 | 0.03–0.05 | 0.02–0.04 |
| Drizzle | | 0.08–0.18 | | 0.6 |

An interesting result of the above analysis is that the dependence $\alpha_n(E_0)$ at $\eta \sim 1$ and $F/R_1 \sim 2.4{\cdot}10^3$ is weak. It can also be seen from the figure that $\eta = 1$, the function $\alpha_n(E)$ is only weakly nonmonotonic while starting from $\eta = 1.2$ to $\eta = 1.5$ the extinction coefficient $\alpha_n$ is a linear function of both $E_0$ and $\eta$. Such a narrow range of the $\eta$ value variations is indicative of a high $\alpha_n$ sensitivity to variations of $\alpha_m$ and $\alpha_a$.

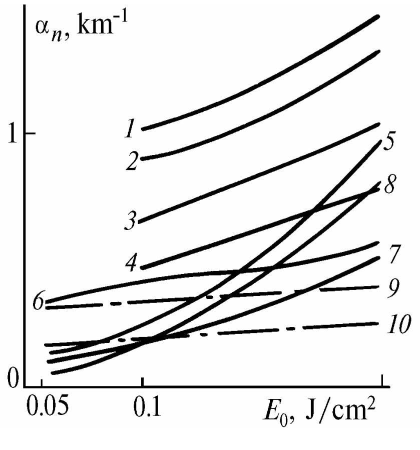

*FIG. 1. The extinction coefficient of the near–ground path for different ILR beam geometry as a function of the initial energy density and of the values* $\eta = 0.5$ *(curves 1 and 5),* 1.0 *(2 and 6),* 2.0 *(3 and 7),* 3.0 *(4 and 8),* 1.2 *(9), and* 1.5 *(10),* $F/R_1 \sim 9 \cdot 10^2$ *(1–4), and* $2.4 \cdot 10^3$ *(5–10). Optical weather conditions: a spring and fall haze.*

Let us now consider the function $\alpha_n(E_0)$ at $F/R_1 \sim 9{\cdot}10^2$ when the contribution from the aerosol atmospheric component into the extinction of radiation dominates. The view of $\alpha_n(E_0)$ function is shown in Fig. 2. At a constant value $\alpha_m \approx 0.08$ km$^{-1}$ the propagation conditions that took place in the experiments are characterized by a great variety of aerosol formations, i.e., rain, snow, winter haze, and mist. The difference observed between the $\alpha_n(E_0)$ functions shown in Figs. 1 and 2 is caused by the fact that the data in Fig. 1 were obtained by averaging $\alpha_n$ values over all the $\alpha_m$ and $\alpha_a$ values occurred in the experiments at a constant $\eta$ value and certain type of optical weather.

Basic mechanisms of interaction between ILR and a medium of propagation that regulate the atmospheric transmission for laser radiation are: absorption of radiation by gases and aerosol particles providing the vaporization and explosion of water droplets, which, as a result's change their optical properties, as well as the heating and melting of solid particles and, as a consequence, the modification of their optical properties and the properties of ambient air. These processes result in destruction of agglomerations of solid aerosol particles into a great number of secondary particles of a small size.[10] The optical and meteorological situations observed during the experiments determined the main processes taking place due to interaction between ILR and aerosol particles. When conditions necessary for a rain droplet explosion[11] are created on a long enough portion of a propagation path, the droplets are divided into a great number of optically active secondary particles whose size and, as a consequence, their influence on $T_{exp}$ decrease with increasing ILR energy per pulse.[4] In the meteorological situation of a snowfall certain time is required for flakes to transform into water droplets with their following fragmentation what decreases the resulting (occurring during the ILR pulse) nonlinear atmospheric extinction of radiation. Under conditions of the above–described experiments (radiation parameters and air humidity) the contribution coming from the extinction of ILR by the cells of optical breakdown to the total extinction coefficient $\alpha_n$ is from 0.6 to 0.8 km$^{-1}$.

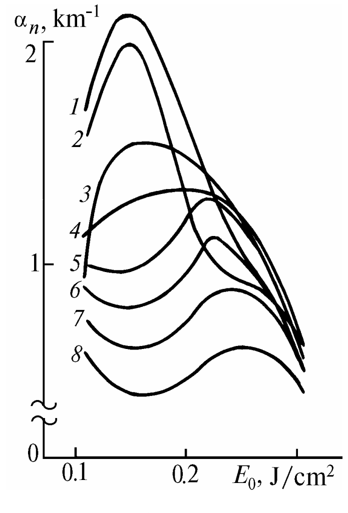

*FIG. 2. The effect of the aerosol situation along the propagation path on the function* $\alpha_n(E_0)$: $F/R_1 \sim 9{\cdot}10^2$, $\alpha_m = 0.08$ km$^{-1}$, *curves 1 and 2 – rain,* $\eta \sim 0.1$ *and* 0.11, *respectively, 3 and 4 – snow,* $\eta \approx 0.13$ *and* 0.15, *5 and 6 – winter dry haze,* $\eta = 0.19$ *and* 0.25, *and 7 and 8 –mist,* $\eta \approx 0.36$ *and* 0.67.

The absence of large particles on the propagation path can explain the shift of maximum of the curves (see Fig. 2, curves *5–8*) towards higher energies. The drop of the $\alpha_n$ value with increasing $E_0$ occurs due to vaporization of the particulate matter in the liquid phase. Our calculations have shown that the growth of $E_0$ up to 0.15 J/cm$^2$ results in an increase of the near ground atmosphere channel of ILR propagation by approximately 10%. These calculations are in a good agreement with the experimental data. After vaporization of the water shield of a particle there appear plasma cells of solid cores of aerosol particles. Simultaneously, the growth of energy provides the explosion which takes place in the regime of fragmentation of small particles and aerosol agglomerations covered with water what is clearly seen as the maximum in $\alpha_n$ ($E_0$) curves.

A decrease in the extinction of ILR by the atmosphere can also be caused by the dependence of $\alpha_{CO_2}$ and $\alpha_{H_2O}$ values on the energy of incident radiation. Such a decrease of the extinction can be a result of two effects[6]:

– saturation of light absorption by the vibrational–rotational transitions of $CO_2$ molecule taking place at a threshold intensity $I \sim 0.2–0.5 \cdot 10^6$ W/cm$^2$;

– saturation of the light absorption with the far wing of 010 absorption band of $H_2O$ molecule at a threshold intensity of radiation $I \sim 2–3 \cdot 10^6$ W/cm$^2$.

As our estimations showed the contributions from these two effects into the $E_0$ behavior of $\alpha_n$ under the optical and meteorological conditions under study were negligible.

Thus the above analysis allows us to arrive at the following conclusions:

1. An essential dependence of $\alpha_n$ on $\eta$ at a fixed set of ILR parameters shows that a development of models of ILR transfer through the real atmosphere cannot be restricted by an assumption that its interactions with the gas and aerosol components of the atmosphere are additive. In fact the interaction processes take place simultaneously, influence on each other, and complete.

2. In the case of weakly focused beams with $E_0$ = 0.1–0.2 J/cm$^2$ under conditions of spring or fall hazes the most stable and reliable forecast of the atmospheric transmission for ILR is only possible for equal gas and aerosol components of the extinction. A prevalence of a contribution from one of these components into the initial extinction coefficient of the atmosphere results in a noticeable ambiguity of estimations of an ILR extinction along an atmospheric path. In the case of sharply focused beams of the same initial energy density the extinction of radiation by the atmosphere is much higher and depends on the $\eta$ value with the main contribution into the extinction coming from the aerosol component.

3. In order to make a detailed analysis of the correlated processes of interactions between ILR and gas and aerosol components of the atmosphere one should carry out experiments on ILR propagation in the atmosphere accompanied with a rapid analysis of the gas composition and aerosol microstructure directly within the atmosphere channel of ILR propagation.

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