NONLINEAR PROPAGATION OF LASER BEAMS THROUGH THE ATMOSPHERE

A.A. Zemlyanov

*Institute of Atmospheric Optics,
Siberian Branch of the Russian Academy of Sciences, Tomsk*
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The results of investigations into laser–radiation nonlinear propagation through the atmosphere, performed at the Institute of Atmospheric Optics of Siberian Branch of the Russian Academy of Sciences, are presented in the paper. They cover nonlinear optical phenomena, propagation of an intense radiation through turbid media, and laser beams thermal blooming.

INTRODUCTION

The problem of nonlinear propagation of laser radiation through the atmosphere is among the problems of nonlinear optics of the atmosphere that is a branch of modern atmospheric optics. The research work on this problem is carried out at the Institute of Atmospheric Optics (IAO) under supervision of Academician V.E. Zuev already more than 20 years. During these years the problem has been well studied because of integrated character of the investigations. Various theories of nonlinear optical interactions in the atmosphere as well as laboratory and field experiments have been elaborated to establish the principal regularities of the propagation of an intense optical radiation in the atmosphere. These studies were connected with such problems of practical importance as applications of high–power lasers to communication, laser detection and ranging, laser sounding and energy transmission for long distances that were under investigation at IAO.[1]

Some results of the scientific activity on nonlinear light propagation were reported in numerous papers, reviews, and monographs prepared by researchers at IAO.[1,2,6–8,10–13]

Of course, many studies were conducted in this area in other scientific institutions.[3–5,9,14–19,22,58]

In this paper, the most appreciable results on the key points of the above–mentioned problem that were obtained at IAO are considered. The goal of this paper is to discuss the principal aspects of the problem and recently results obtained.

1. NONLINEAR OPTICAL EFFECTS IN THE ATMOSPHERE

A kind of classification of the principal nonlinear optical effects in the atmosphere is presented in Table I. The effects are systematized according to their physical characteristics (resonance and nonresonance effects) as well as according to their influence on wave parameters (frequency, amplitude, phase, temporal characteristics).

TABLE I.

Beam conversion	Effects			
	Resonance		Nonresonance	
	Type of medium			
	Gases	Aerosols	Gases	Aerosols
Frequency	Stimulated Raman scattering Stimulated Brillouin scattering	Stimulated Raman scattering Stimulated Brillouin scattering Laser oscillation	Stimulated temperature scattering	Scattering by capillar waves
Spatial (thermal blooming)	Kinetic effects Laser chemical effects		Thermal refractive effects Kerr effect, striction	
Amplitude	Absorption saturation clearing up		Breakdown	Vaporization Explosion Combustion Sublimation Breakdown
Temporal	Phase modulation	Stimulated Raman scattering		

Nonlinear optical effects in the atmosphere are analogous to the processes occurring in gaseous and condensed media, which are the subject matter of traditional nonlinear optics,[20,21,23] though they have certain peculiarities as well. They are related to inhomogeneity, randomness and multicomponent composition of the medium (i.e. the atmosphere) where nonlinear interaction occurs. These peculiarities along with linear effects (such as

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refraction, gas and aerosol absorption and scattering, turbulence) manifest themselves in the beam behavior.[1,13]

Much attention has been paid, at IAO, to the investigation into nonlinear effects occurring in the atmospheric aerosol. This is of practical importance since aerosol influence on the energy of a laser beam when its spectrum falls within atmospheric transmission windows. A large number of aerosol nonlinear optical effects were studied including thermal effects, optical breakdown, optoacoustic effects, and effects in transparent particles.[1,2,6,7,10–13]

Nonlinear effects in gases are very detrimental to the propagation of laser beam through unturbid atmosphere. These effects have been analyzed in detail in several monographs,[1,11,65] hence we will not consider such interactions at length in this paper.

As to the nonlinear optical effects in aerosols, we would like to call attention to the differences of these phenomena from the similar processes that are examined in nonlinear optics of continuous condensed media.

The conditions for such unique thermodynamic states of the matter as the deep metastable overheating of liquid and supercritical states are created in absorbing aerosol particles owing to small interaction volume with a high rate of electromagnetic energy pump.

A droplet serves as an optical element (a lens or a resonator) for short–wave radiation. This fact results in occurrence of various nonlinear optical processes such as stimulated fluorescence, stimulated Raman scattering, and stimulated Brillouin scattering as well as frequency mixing and optical breakdown. Figure 1 shows the electromagnetic field distribution inside transparent particles (with the refractive index $n_i = 1.33$) under resonance and nonresonance conditions.

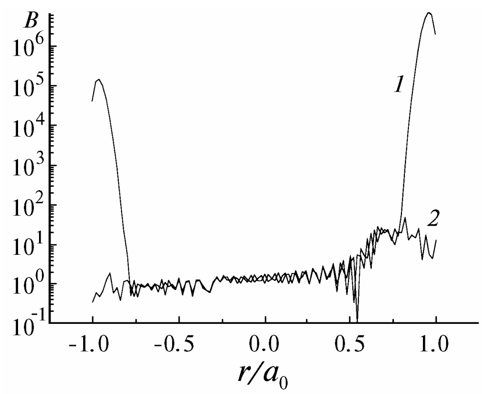


FIG. 1. Inhomogeneity factor profiles for the optical field inside a droplet along the principal water–droplet diameter ($|n_i| = 1.33$). The droplet is of 6 μm *radius. Data were obtained under resonance (1) and nonresonance (2) conditions.*

Laser vaporization of the droplets

The works performed at IAO[2,25,28,29] form the basis for the study of laser vaporization of aerosols. This problem was of interest for a long time since creation of channels of enhanced transmission in clouds and fogs and clearing the atmosphere over the runways using laser beams seemed to be a promising application of high–power lasers.[24,76,78] The asymptotic regimes of water–drop vaporization in the laser field were established in Ref. 29. Different regimes of vaporization with diffusion, convective, or kinetic vapor transfer from the drop surface were found to be dependent on radiation intensity, absorbility of the substance, and size of particles.

Pioneering experimental studies of surface regimes of drop vaporization have been also performed at IAO.[29] Despite the fact that large drops suspended on threads were used, the experiments demonstrated satisfactory agreement with the theory developed for the case of uniformly absorbing particles.

Numerous experimental and theoretical papers[4,14–16,19,27,86] were devoted to a more accurate consideration of all physical processes involved in the drop vaporization and the temperature field inhomogeneity resulting from inhomogeneity of the optical field as well as to examination of aerosol–size drop behavior.

A theory developed in Ref. 18 based on balance mass and energy equations showed it to be a promising one. The "effective" regime of the drop vaporization was demonstrated to be a good approximation for practical calculations.[4] According to this approximation, vaporization of the drops with radius a can be simply described by the following equation:

$$\frac{d\,a}{d\,t} = -\,\beta_T\,\frac{K_a\,I}{4\,Q}\,. \qquad (1)$$

Here β_T is the differential efficiency of the vaporization process, Q is the heat consumed by the drop vaporization, K_a is the efficiency of absorption of radiation by a drop, I is the radiation intensity, and t is time.

Laser destruction of aerosols

The explosive regime of the drop vaporization was firstly observed at IAO.[25,30] The drop explosion was shown to be related to the fast processes of appearance and growth in the vapor phase inside the particle with boiling up centers located at the points of laser field maxima.[26,32] Unlike the surface vaporization, the explosion of particles is essentially the threshold process. The energy threshold of the explosion depends on both the absorbility and size of the drop and temporal behavior of the laser radiation.

The problem of laser destruction of liquid aerosol particles, especially its experimental aspects, was of great interest for a long time. Data on explosion of particles 1–100 μm in diameter irradiated by both pulsed and cw laser beams with intensity ranging from 10^4 to 10^9 W/cm^2 are summarized in Refs. 6, 7, 11, and 31.

The richest experience was gained on the destruction of water drops under CO_2–laser irradiation. Let us briefly consider the most appreciable results obtained earlier and during recent time.

Different types of explosion with respect to the character of phase transition and with respect to dynamics of destruction occur depending on absorbility of the substance, drop size, and energy of radiation.[31]

The explosion of a particle occurs when the temperature inside it is close to the spinodal temperature that is equal to 593 K at the normal pressure of 1 bar. Under such an overheating, the vapor bubbles rapidly appear and grow in zones of energy generation. These bubbles cause the drop destruction or destruction of its surface layer into smaller particles and vapor. In increasing the rate of heating, the growth in pressure is possible in zones of energy generation inside the drops. As it takes place, the spinodal temperature increases. Under certain conditions a monophase liquid–vapor transition is possible under irradiation with short high–energy laser pulses. The explosion of these regions adjacent to the drop surface is a flow of quasi–continuous medium.[31] Let us then consider two–phase liquid–vapor transition such that the fragmentation of aerosol particles takes place.

The explosion of particles can be either a single–stage or a multi–stage process depending on the size of a particle and laser energy. In the first case, the explosive boiling up occurs when the vapor escapes from the regions of the initial metastable overheating. This leads to the distruction of particle as a whole in case of small particles ($2\alpha_a a_0 < 1$, where α_a is the volume absorption factor). Similar process is observed for larger particles under conditions of "slow" heating up to the explosion temperature. Thermal conduction and convection equalize the temperature inside the drops and the boiling up process is similar to that in the case of homogeneous absorption. For large drops and "rapid" heating regimes, the boiling up process begins in the regions of energy generation adjacent to the illuminated and shaded surfaces.

The initial escape of the vapor–condensate results only in the drop deformation. As it was demonstrated in experiments,[37] the complete decomposition of a particle occurs later.

Theoretical estimation of the threshold of a drop explosive boiling up resides in the determination of energy conditions under which the excess temperature T_{ex} (see Ref. 31) is reached in certain particle zones. This temperature is defined as the temperature at which vapor bubbles appear that can survive.

An estimation of optical–energy density level that leads to boiling up initiation can be obtained from the following expression:

$$w_{ex} = \rho_L C_p (T_{ex} - T_0)/B_m \alpha_a, \qquad (2)$$

where B_m is the maximum value of inhomogeneity factor B for the intensity of optical field inside the particle, ρ_L is the density of liquid, and C_p is the liquid heat capacity per unit mass at constant pressure.[5]

A number of experiments dealt with the investigations into thresholds of laser boiling up and particle complete decomposition processes. The thresholds of boiling up was found to depend slightly on drop size within size range typical for real clouds and fogs. The threshold of complete decomposition was measured for some particle size. The results obtained were found to be different for short and long laser pulses. In particular, the decomposition threshold was nearly independent of particle size when microsecond laser pulses with energy density of 2–4 J/cm² were used.[42] At the same time, the threshold of complete decomposition was determined by particle size in the case of pulses of higher energy and cw radiation. As it took place, the threshold value of energy density increased with increasing pulse duration.[41,43,85]

Figure 2 presents experimental data on the boiling up threshold and the threshold of complete decomposition as a function of particles size for CO_2–laser pulses of different durations. The theoretical values of the above–mentioned thresholds are shown in Fig. 2 as well. Table II summarizes the data on threshold laser intensity I_{ex} for explosive boiling up of water droplets.

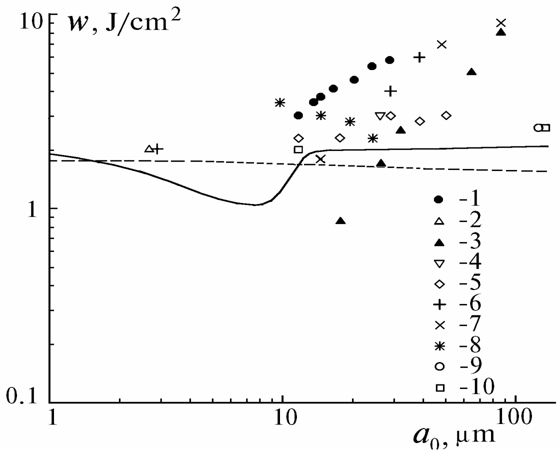


FIG. 2. Experimental data on explosive boiling up and decomposition thresholds for water–droplet aerosol in the field of a CO_2–laser radiation (λ = 10.6 μm) as a function of initial particle radius. Depicted in the figure are results from Refs. 32 (1), 33 (2), 42 (3), 41 (4), 34 (5), 36 (6), 39 (8), 40 (9), and 43 (10). Dashed line corresponds to numerical calculation (Ref. 88), solid line is the estimation from expression (2).

TABLE II. Threshold values for radiation intensity necessary for occurrence of nonresonance nonlinear effects in aerosols.

Nonlinear effect	Threshold, W/cm²		Note
	λ = 1.06 μm	λ = 10.6 μm	
Explosion	$5\cdot10^6 - 10^8$	$5\cdot10^3 - 10^6$	Water, $a_0 = 1 - 10$ μm
	$2\cdot10^6 - 10^8$	$2\cdot10^4 - 10^7$	Volcanic aerosol
	$10^{10} - 10^{12}$	$10^8 - 10^{10}$	H_2SO_4– droplets
Combustion	$10^5 - 10^6$	$3\cdot10^4 - 10^5$	Carbon, $a_0 = 0.1 - 1$ μm
Sublimation	$5\cdot10^5 - 2\cdot10^6$	$5\cdot10^4 - 4\cdot10^5$	Al_2O_3, $a_0 = 0.1 - 1$ μm
Optical breakdown	$5\cdot10^6$	$3\cdot10^6$	$t_p > 10^{-5}$ s
	$10^7 - 10^{11}$	$10^7 - 10^9$	$t_p = 10^{-6} - 10^{-8}$ s

In experiments the dynamic characteristics of explosion[37,40] and the size of the secondary particles formed due to decomposition[36,38,53] were examined. It was found that the characteristics of explosion were essentially determined by the rate of heating of the liquid under irradiation. This rate may be described by a parameter $J_h = (\alpha_a/\rho_L C_p)\,\bar{I}$. In this expression $\bar{I} = w_p/t_p$ is the mean intensity of radiation and w_p is the energy density per laser pulse of duration t_p. For a continuous laser radiation $\bar{I} = I_0$.

As an example, the experimental and theoretical data on characteristic size of fragments of the initial drops of various size as a function of the rate of heating are shown in Fig. 3.

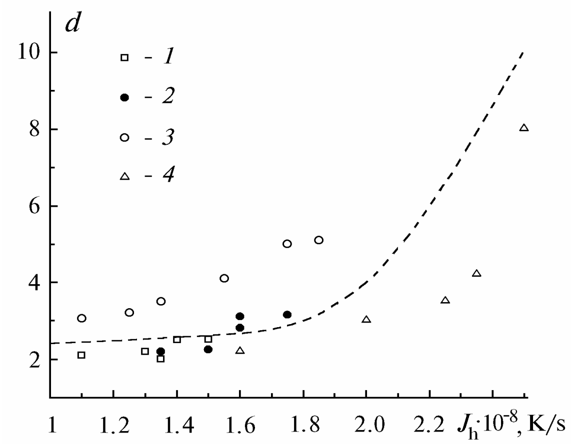


FIG. 3. Experimental dependence of the degree of particle decomposition $d = a_0/a_d$ (here a_0 is the initial radius of particle and a_d is the average fragment radius) as a function of heating rate parameter J_h. Depicted correspond to initial radii of 10 *(1),* 15 *(2),* 20 *(3), and* 25 μm *(4). Dashed line shows theoretical result.*

When analyzing the theoretical investigations into the problem of explosive decomposition of particles, we would like to attract attention to the researchers at IAO and other institutes of former USSR pioneering the studies of this problem. Thus, in Ref. 25 the first formulation of energy conditions for explosion in the case of uniformly absorbing drops has been presented. The prediction and theoretical study of supercritical (monophase) mode of the drop explosion have been done in Refs. 60 and 61. The conditions of explosive drop decomposition for inhomogeneous energy generation were first obtained in Ref. 5. The explosion thresholds for continuous laser radiation under conditions of homogeneous temperature field inside the droplet were established in Refs. 4, 18, and 33. Development of semiempirical models of explosion process based on data of special experiments was a noticeable part of the work that was carried out at IAO in recent years.

Optical characteristics of the turbid media in the field of high–power laser radiation

Though the study of surface and volume droplet vaporization is of interest for physics of nonresonance interactions between radiation and matter, these investigations were mainly stimulated by the interest in characteristics of turbid media exposed to laser radiation. A great variety of experimental and theoretical studies were devoted to this problem. The main results obtained are summarized in monographs and reviews of researchers from IAO,[1,2,6,7,10,11] Scientific–Production Union "Taifun",[4] Institute of Radioelectronics (IRE) of the Russian Academy of Sciences.[14–16,18]

The central point of these studies was the establishment of the functional form for polydisperse extinction coefficient $\alpha = \alpha_0\, e^{-\beta w}$ under conditions of regular droplet vaporization mode. In this expression w is the energy density in medium, β is the factor depending on droplet vaporization.[2,4,18] This functional form leads to the following expression for the fog transmittance T_e in the field of a collimated laser beam:

$$T_e = e^{-\tau_0}\,\{1 + e^{-\tau_0}\,(e^{-\beta\, w_0} - 1)\}^{-1}. \tag{3}$$

Here $\tau_0 = \alpha_0\, z$ is the optical thickness of the aerosol layer, $w_0 = w(z = 0)$ is the initial value of laser energy density. This formula is the main relation in the theory of laser clearing up of vaporizing aerosols. It is called the Glickler approximation.

Theoretical calculations of the nonlinear extinction coefficient for uniformly absorbing water–droplet aerosol under conditions of particle explosion were carried out based on various phase–explosion models.

The state–of–the–art of the investigations demonstrates a possibility of using two models for extinction coefficient and, as a result, two models of nonlinear transfer.

The first model considers propagation of cw or long–pulse CO_2–laser radiation with the intensity of 10^4–10^5 W/cm^2 ($J_h \sim 10^6$–10^7 K/s) through the droplet media with variation of particle size over a wide range.[4,63] A substantial feature of the model is the concept of threshold of droplet explosion. Here it is defined based on instantaneous intensity. Such a definition is possible for moderate energy generation in the droplet when the thermal outflow caused by surface vaporization contributes to the total energy balance, and redistribution of the heat sources due to thermal conduction and thermal capillary convection inside the droplet occurs.[4,18] The latter process equalizes distribution of the heat sources inside large droplets and makes it possible to use the relations derived for the case of uniformly absorbing large particles. For the case of continuous radiation, the models of polydisperse extinction coefficients and medium transmittance have been developed in Ref. 63 based on the drop explosion considered as successive breaks down of the initial particles into smaller fragments. Propagation of the high–power radiation leads to nonstationary processes ($J_h > 10^7$ K/s), and the threshold is determined not by the instantaneous intensity, but by energy density.[11] Just these situations are considered below.

It has been established for such a mode that extinction coefficient at λ = 10.6 μm in case of fogs depends on w:

$$\alpha = \alpha(w). \tag{4}$$

This relation indicates that this is a type of nonlinearity called storing nonlinearity, typical for thermal modes of droplet vaporization.

The expression for aerosol extinction coefficient in phase explosion of the particles of small–droplet fog ($2\alpha_a\, a_0 < 1$) can be written as

$$\alpha = \alpha_0, \qquad w \le w_{ex};$$

$$\alpha = \alpha_0\, \varphi(1 - X_{ex})\, \exp\,(-\,\beta_e\,(J_h, w)\,(w - w_{ex})),\ w > w_{ex}\,. \tag{5}$$

Here φ is the factor determining the contribution of light scattering to the total radiation extinction in the droplet; β_e is the integral (over aerosol ensemble) efficiency of vaporization; X_{ex} is the explosive vaporization degree, that is, the relative mass of liquid converted to vapor under explosion; and, w_{ex} is the laser energy density that is necessary for initiation of explosive boiling up of the particle ($w_{ex} \sim 1.5$–2 J/cm^2). The value of β_e varies from 0.2 cm^2/J for regular vaporization to 0.1 cm^2/J for huge explosions. This decrease in value of β_e is connected with the increase in the energy losses due to fragments vaporization. The average size of the fragments decreases with increasing rate of heating.

Parameters β_e and X_{ex} that characterize the explosion process change continuously along the beam propagation path in connection with change in $w(z)$ and in the instantaneous value of the parameter of rate of heating $J_h(z)$.

The expression for transmittance of small–droplet fog was derived in Ref. 11. Similar expressions can be derived also for the fogs consisting of the particles of a medium size when the local decomposition of a droplet is followed by its deformation and total decomposition.

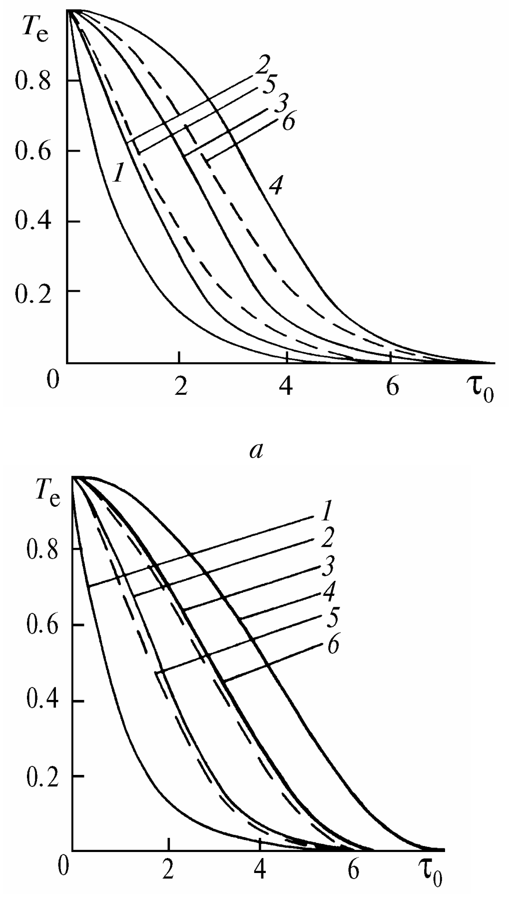


FIG. 4. Influence of optical thickness on transmittance (λ = 10.6 μm) of clearing–up zone of small–droplet fog (φ = 1) (a) and medium–size particle aerosol (a_m = 7μm, φ = 0.75) (b) in explosive regime at various w_0: 1 (1), 10 (2 and 5), 20 (3b), and 30 J/cm^2 (4). Dashed line corresponds to regular droplet vaporization.

Figure 4*a* presents the channel transmittance versus τ_0 at various w_0 values. Data for the case of high–efficiency regular stationary droplet–vaporization modes ($\beta_T \approx 1$) are presented as well. In this case the transmittance is determined by the Glickler expression.

Analysis of Fig. 4*a* shows that the smallest–droplet aerosol ($2\alpha_a\, a_0 \ll 1$, $\varphi \approx 1$) has somewhat lower transmittance as compared to the regular droplet–vaporization mode. The transmittance of larger–size aerosol ($2\alpha_a\, a_0 \lesssim 1$, $\varphi < 1$) was calculated to be higher than in the case of regular vaporization regime. However, no substantial differences in the shape of transmittance curves were observed in different regimes of decomposition of uniformly absorbing droplet aerosol of different microstructure.

The computed transmittance of the medium–size droplet fog as a function of the initial optical thickness value at different laser–energy density is presented in Fig. 4*b*. The dashed curves present the same function for the high–efficiency regular stationary droplet vaporization regime when the β_T value is close to unity. Figure 4*a* demonstrates that efficiency of clearing up of the fog is somewhat higher in explosive regime than in the regular one, but this excess is not significant.

Such a behavior of the transmittance of the medium–size droplet fog in different regimes of the initial particle decomposition is related to the specific features of the extinction of the medium–wave IR–laser radiation by the droplets of the size considered, to explosive boiling up of the droplets as well as to specific features of the vaporization when particle splitting and strong heating are involved. It should be noted that this result is difficult to predict, because of reliable data on decomposition process dynamics are absent.

Indeed, approximation that is valid for stationary heating regime applied to consideration of the unsteady–state processes under conditions of high–power irradiation of the medium–size particles results in the appreciably higher clearing up in explosive regime than in regular one.

Action of laser radiation on solid–phase absorbing aerosol under pre–threshold conditions of optical breakdown

Action by high–power laser radiation on aerosol particles that can be involved in the thermochemical reactions in the atmosphere can lead to their inflammation. This results in a change of their optical parameters due to combustion of the substance and formation of thermal–mass halo in the reaction region.

An estimation of threshold intensity for solid–particle inflammation I_{bu} can be made by the following expression:

$$I_{bu} = \frac{4\,(T_{bu} - T_0)}{a_0\, K_{ab}(a_0)} \left[\frac{\lambda_g^*}{a_0} + \frac{\rho_c\, C_p\, a_0}{3} \right]. \tag{6}$$

Here ρ_c and C_p are density and specific heat of the particle; T_{bu} is the inflammation temperature of the substance; and, λ_g^* is thermal conductivity of air within the temperature range form T_0 to T_{bu}. Typical I_{bu} values for carbon particles (T_{bu} = 1240 K) are presented in Table II.

Under high–power laser irradiation, the solid particles can convert to vapor without melting. For incombustible particle, sublimation precedes melting, whereas for combustible particles, sublimation and combustion occur simultaneously. The threshold intensity for sublimation of a combustible particle at a certain temperature T_s can be written as

$$I_s = \frac{1}{K_{ab}(a_0)} \left[\frac{\lambda_g^*\,(T_s - T_0)}{a_0} - \frac{Q\,\rho_c}{d\,a\,/\,d\,t^*} \right]. \tag{7}$$

Here Q is the heat of exothermal reaction of particle substance oxidation (for carbon $Q = 10^4$ J/g, T_s = 5000 K) and $|da/dt|^*$ is typical combustion rate. For incombustible particles, I_s is obtained like I_{bu} (equation (6)). The sublimation threshold for carbon and corundum (Al_2O_3) particles are presented in Table II as well.

Optical breakdown of aerosols

The appreciable contribution to investigation into this process was made by researchers from IAO, Union "Taifun", IRE, Research Institute of Physical and Chemical Investigations, Nizhny Novgorod State University, and Altai State University. The main results obtained are presented in monographs and reviews.[6,7,10,12,13]

Aerosol particles are of great importance as centers of ionization and development of optical breakdown wave in surrounding air. High–power laser radiation initiates vaporization of solid particles and optical breakdown in the vapor produced.[7,11,12] The energy breakdown threshold in aerosol is much lower (by 1–2 orders of magnitude) than in pure air.[80] In liquid–droplet aerosol the breakdown threshold is lower due to focusing of incident laser beam into the inner regions of droplets.[29]

Theoretical estimation of the optical breakdown threshold value in the aerodisperse medium is based on solution of the equation for cascade ionization in aerosol vapor. It was established that threshold value I_{br} depends strongly on laser pulse duration t_p. It decreases by more than four orders of magnitude (from 10^{11} to 10^7 W/cm^2) with the increase of t_p from 10^{-8} to 10^{-6} s (see Ref. 11). When $t_p \ge 10^{-5}$, the threshold intensity I_{br} is nearly independent of t_p, keeping constant at a level $I_{br} \approx 5\cdot10^6$ W/cm^2 (Table II). The dependence of I_{br} on the altitude is mainly connected with the decrease in natural electron number density that serves as origin for the discharge avalanches. This factor is important for altitudes higher than 20 km.[10]

In literature there are also experimental data on optical breakdown threshold intensity as a function of particle size in an aerodisperse medium.[6,10,12,13,80] Generally I_{br} tends to drop with an increase in a_0. In solid–phase aerosol this fact is attributed to the favorable conditions for vaporization of large particles with respect to the energy deposition and to the increase of vapor number density near the particle surface as compared to the vaporization of small particles. In the liquid aerosol this regularity is related to the increase in the initial breakdown probability in the regions of diffraction maxima of optical field inside transparent droplets with an increase in their radius. At the further stage of breakdown, the plasma front reaches the particle–air boundary. It was found that for large water droplets ($a_0 \ge 10^{-2}$ cm) the threshold intensity, that provides conditions when the breakdown wave escape the particle, is higher than the initial breakdown threshold.

SRS in transparent droplets

In weakly absorbing droplets of atmospheric aerosol, a large number of nonlinear optical effects are observed such as effects related to the ponderomotive force,[6] stimulated Raman scattering,[44,47] stimulated Brillouin scattering,[48] emission at laser transitions,[49,50] and other effects.[51]

Let us consider specific features of SRS in transparent aerosol particles since this problem was under investigation in a large number of experimental papers. It was discovered that SRS signal in a transparent droplet had multi–peak shape, it occurred in a time lag with respect to the pumping pulses, if short, and lower SRS threshold was fixed in aerosol medium as compared to that in the solid one. A quantitative picture of SRS in droplets can be drawn based on idea of a droplet as a high–Q dielectric resonator.

As known,[52] such a resonator has the highest Q–value for modes of "whispering gallery" type, which are localized near its surface. In transparent particles, focusing of incident beam occurs also. This leads to appearance of two maxima of electromagnetic field near shaded and illuminated surfaces, respectively (Fig. 1). These regions are powerful sources of spontaneous Raman scattering. If a frequency from Raman spectrum corresponds to the free frequency of the resonator, the amplification of Raman wave is quite probable. Thus the SRS field in a droplet is a standing light wave with Stokes frequency w_s and with space configuration corresponding to the optical resonator mode with frequency ω_{ln}.

An expression for estimation of the radiation intensity at which the amplification in the Stokes mode volume occurs can be written as[53]

$$I_{SRS} = 2\pi \,/\, g_s\, \lambda_s\, Q_n^l\, \bar{B}\ .$$

Here g_s is the Raman gain; λ_s is the Stokes wavelength; Q_n^l is the quality of a resonator for a corresponding mode; and, $\bar{B}$ is the factor of inhomogeneity of the optical field inside the droplet averaged over the volume.

In Fig. 5, the closed circles present the radiation intensity values that initiate SRS in droplets with the diffraction parameter $x = 2\pi\, a_0 \,/\, \lambda$. Solid lines indicate SRS threshold low–order (high Q values) and high–order (low Q values) resonance conditions that are equally probable in a droplet. As it follows from these data, the dependence of SRS threshold on diffraction parameter is described by multiple valued function even under additions of certain mode excitation.

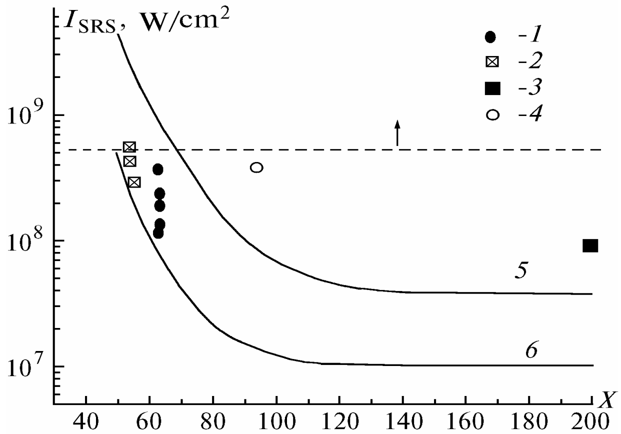


FIG. 5. SRS threshold intensity for transparent droplets. Experimental data: ethanol droplets[49] (1), water droplets[64] (2), water droplet[73] (3), and water–droplet aerosol[74] (4). Theoretical data: calculation for high–order resonances (5), calculation for low–order resonances (6). Dashed line presents the threshold of optical breakdown in a droplet.[49]

2. NONLINEAR PROPAGATION OF LASER RADIATION ALONG NEAR–GROUND ATMOSPHERIC PATHS.

The study of propagation of high–power laser radiation along near–surface paths under real conditions allowed us to obtain rich experimental material on transmittance of corresponding optical channels in the atmosphere depending on laser parameters and optical weather. The contribution of researchers from IAO to obtaining these data should be mentioned especially. The most important results concerning propagation of laser beams along a path in the presence of optical breakdown are summarized in monographs.[6,7,10–13] So, it was established for pulsed CO_2–laser beam that transmittance of the atmosphere reduced by 75% when the laser energy density increased from 2 to 20 J/cm^2. It was found also that in the atmosphere with the background aerosol content a long laser spark of the length of 70–100 m occurred when the laser beam was softly focused. This spark consisted of a number of separate regions of optical breakdown.

In the later papers of researchers from IAO, the data not only on optical breakdown but also on propagation of high–energy laser beam through fog, rain, drizzle, and snow in presence of all aerosol nonlinear effects were analyzed and interpreted.

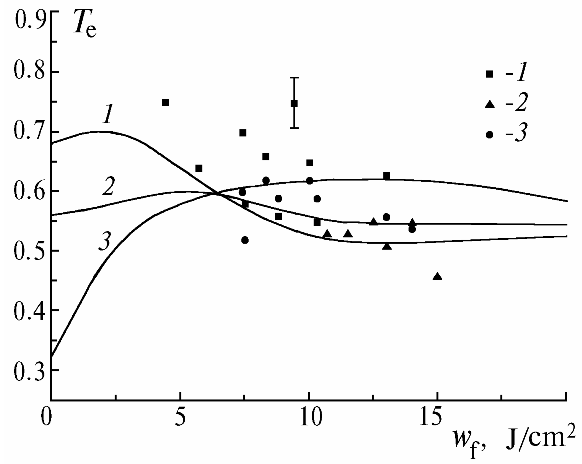
Let us consider these results. The radiation energy parameters and meteorological conditions were monitored during the experiments. Physical processes occurred in the atmosphere were monitored using spectral, photographic, and optoacoustic instruments. Laser energy parameters exceeded threshold values for different nonlinear processes including vaporization and explosion of water droplets as well as optical breakdown of the medium.

The interpretation of experimental data was performed based on original theory of propagation of focused laser beams through aerodisperse media.[11] The model function of aerosol extinction coefficient that is important for interpretation of experimental data was selected according to a specific meteorological situation. The focusing conditions and initial dimensions of laser beam were varied too.

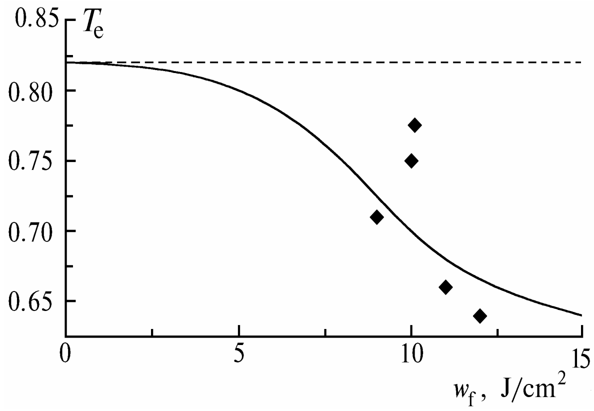
When studying propagation of focused laser radiation through the real meteorological formations, it is essential to take into account the solid–phase background aerosol, since it determines the probability of optical breakdown. When the physical situation on the path is set, it is also important to know how long certain atmospheric state that is observed at the moment of measurements exists. Both aquation of the solid–phase fraction and its washing–out occur in the steady–state fog. Experiments showed that aquation only slightly influences the optical breakdown in high–power laser beam. The number density of the coarse–disperse fraction N_{cf} affects the optical breakdown to a much higher degree. It is known that the longer is the time period of existence of one or another meteorological formation, the less is the background aerosol number density, especially for $a_0 \geq 1$ μm. Hence, in the calculations, the number density of coarse–disperse fraction of background aerosol was varied together with parameters of distribution function of water–droplet aerosol.

Figure 6*a* presents results of calculations at different initial optical thickness of the fog: τ_0 = 1.2, 0.6, and 0.4 as well as results obtained in different experiments.[54, 55] The extinction of the radiation by optical breakdown plasma that is initiated by background aerosol particles was taken into account according to the model from Ref. 56. The threshold intensity was taken to be $I_{br} = 10^8$ J/cm^2. The calculations were carried out at coarse–disperse aerosol number densities $N_{cf} = 10^{-1}$ (*1*), $5{\cdot}10^{-3}$ (*2*), and 10^{-3} cm^{-3} (*3*).

Figure 6*a* demonstrates that the final level of integral fog transmittance mainly caused by coarse–disperse fraction number density that determines the concentration of plasma initiation cores. When the radiation energy increases from 5 to 15 J/cm^2 (τ_0 = 0.4), no essential decrease in the transmission is observed, since, on the one hand, all possible breakdown centers associated with coarse–disperse particles already occur and, on the other hand, the energy is lower than the breakdown threshold for the fine–disperse fraction of background aerosol (a_0 < 1 μm).



a



b

FIG. 6. Experimental data on transfer factor for the fog (a) with τ_0 = 1.2 (1), 0.6 (2), and 0.4 (3) and for the rain (b) with τ_0 = 0.2 as a function of the energy density in the detection plane of a focused laser beam. Solid lines present theoretical calculations. Dashed line corresponds to linear propagation.

The function $T_e(w)$ calculated for rain conditions is plotted in Fig. 6*b*. A γ–distribution with a_m= 700 μm and μ = 1 was employed to model the rain–droplet ensemble. The coarse–disperse fraction number density of background aerosol was assumed to be equal to 0. A comparison of Figs. 6*a* and 6*b* shows that in any case of a steady–state fog ($N_{cf} \to 0$), increase in laser energy results in an increase in the atmospheric transmission. It is attributed to a decrease in the extinction cross section with a decrease in particle size due to fragmentation. When the explosion threshold is exceeded under rain conditions, the decrease in transmission coefficient value is observed due to the increase in the total geometric cross section of the droplets due to fragmentation.

Consider the problem on propagation of laser pulse series through a turbid medium. There is experimental evidence that the energy losses of a laser pulse tandem are significantly lower then those of a single pulse with the same energy when the optical breakdown on the solid–phase aerosol particles is involved.[37] This fact is related to effects of vaporization and escape of solid particles initiating the optical breakdown under high–power irradiation. However, the same regularity is observed for lower laser intensity in the droplet media in the presence of solid fraction. It is evidenced by calculation of $T_e(w)$ function for a fog ($\tau_0 = 1.6$). This function is plotted in Fig. 7. Two types of interaction is considered: propagation of a single pulse with peak intensity $I_{max} = 2{\cdot}10^7$ W/cm and of a pulse tandem with $I_{max1} = I_{max2} = 6{\cdot}10^6$ W/cm^2. N_{cf} value is 10^{-3} cm^{-3}. However, higher transmittance of the fog for the pulse tandem as compared to single pulse of the same energy is caused by the fact that the energy of an individual pulse is insufficient for maintenance of the optical breakdown, while the single pulse activates all centers of plasma initiation.

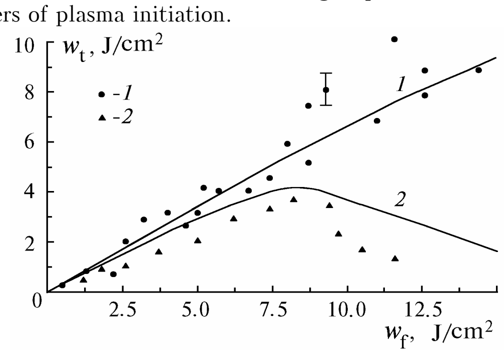


FIG. 7. Energy density of the beam passed through the fog ($\tau_0 = 1.6$) versus energy density in the detection plane for different types of laser irradiation: CO_2–laser pulse tandem (1); single pulse (2). Solid lines depict theoretical calculations.

Analysis of the large volume of experimental data showed that at certain critical values of the energy density, the substantial nonlinear extinction of the incident radiation occurs. Figure 8 presents some functions of this type for different optical weather. The critical value is caused by optical breakdown in coarse–disperse fraction of background aerosol. The larger is the optical thickness of the medium, the higher is the critical energy density. This critical value reaches maxima for fogs and drops, downs to minima for the weak rain and in the haze.

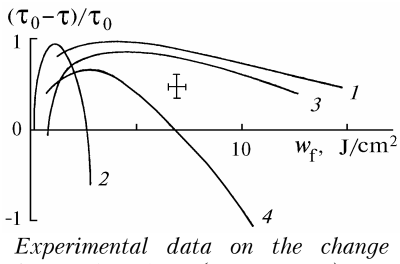


FIG. 8. Experimental data on the change in optical thickness of aerosol medium (λ = 10.6 μm) as a function of laser energy in the focal detection plane w_f for different optical weather: fog (1); haze (2); drizzle (3); and, rain (4).

3. THERMAL BLOOMING OF LASER BEAMS IN THE ATMOSPHERE

Nonlinear effects in gases, which change their dielectric susceptibility, lead to self–action of laser beams. Slight variations of phase in elementary volume, due to change in the refractive index, result in appreciable distortions of the wave phase and amplitude. Generally speaking, the self–action of beam causes conversion of its angular spectrum with corresponding bend of trajectory, or the occurrence of self–focusing and self–defocusing effects. Self–action of spatially modulated waves in the atmosphere causes thermal effects of laser radiation (heating, kinetic cooling) and resonance effects of variation of the medium polarizability.[71]

In the clear atmosphere, the efficiency of laser energy transmission over long distances decreases mainly due to thermal blooming since this process has the lowest energy threshold. Below we consider only this phenomenon.

Thermal blooming of the laser radiation attracted great attention of researchers. Results of both theoretical and experimental investigations into thermal distortion of laser beams in model media were summarized in Refs. 3, 9–11, 16–23. The effect in real atmosphere has been investigated not so good.

It should be noted that laser experiments in real atmosphere are very expensive. This stimulated performance of extremely precise and reliable analytical and numerical calculations of laser parameters to predict behavior of high–power beams in the atmosphere. So, numerous theoretical approaches and methods for description of this process were developed as well as a lot of algorithms of their performance were suggested (see Refs. 9–11, 16–23, 62, 66, 67, 70, 72, 81–84, and 89).

This problem was solved at the Institute of Atmospheric Optics based on complete consideration of the atmospheric influence on light wave parameters. Such an approach includes the idea that the atmospheric turbulence should be taken into account together with the self–action of the beam. Indeed, on the one hand, it disturbs the coherence of the beam and, on the other hand, it serves as a randomizer of the temperature field in the beam channel. It was of great importance to consider the partially coherent laser sources and other specific features of propagation of the real high–power laser beams through the atmosphere.

A characteristic feature of thermal blooming of laser beams in the atmosphere is also mutual effect of different types of beam conversion (spatial, amplitude, frequency, temporal) on each other. This is caused by the influence of both linear (speckle structure of the beam due to scattering by turbulent and local inhomogeneities of the atmosphere) and nonlinear effects on the beam conversion. So, amplitude nonlinear conversion of the beam results in change of diffraction characteristics of the channel,[70] stimulated Raman scattering causes change in radiation divergence.[90]

Two approaches to theoretical study of complex atmospheric influence on the beam parameters were developed at IAO. One of them is based on the field description of atmospheric effects.

In this case, a parabolic equation is numerically solved. At IAO an efficient method of solution of multidimensional stochastic diffraction problems was developed based on the method of splitting over physical factors together with the method of the fast Fourier transformation.[62] Using this method, a study of nonlinear beam propagation was performed.[8]

Together with the method of solution of parabolic equation, an original theory of radiation transfer as a ray method in the theory of waves was suggested by scientists from IAO. Below we shall characterize this method in general and illustrate its usefulness with specific examples.

A large number of applied problems in nonlinear atmospheric optics are related to thermal blooming of wide–aperture laser beams under conditions of substantial nonlinear distortions. It indicates that the main interaction in a nonlinear medium occurs in the zone of geometric shadow. This problem is quite difficult for solution when using the procedure based on quasioptical equation. It is rather a complicated problem to examine the self–action of partially coherent beams. Hence, the development of new approaches in this area seems to be natural.

The ray approximation is one of possible new approaches. It is a method of constructing the short–wave asymptotics for the wave equation providing solution of diffraction problems by means of geometric optics.[67]

Solution of the equation for radiation brightness transfer enables one to expand the area of application of the ray methods to appreciable degree and to study the problem of self–action at different parameters of interaction process.

A set of equations for computation of the intensity of a narrow laser beam propagating through a medium with smooth variation of parameters and low losses, by using the equation of radiation brightness transfer, can be written as

$$\left[\frac{\partial}{\partial z} + \mathbf{n}\,\nabla_{\mathbf{R}} + \frac{1}{2}\nabla_{\mathbf{R}}\,\tilde{\varepsilon}(I)\,\nabla_{\mathbf{n}}\right] J(\mathbf{R},\,\mathbf{n},\,z,\,t) = 0; \tag{8}$$

$$J(\mathbf{R},\,\mathbf{n},\,z = 0,\,t) = J_0(\mathbf{R},\,\mathbf{n},\,t); \tag{9}$$

$$I(\mathbf{R},\,z,\,t) = \int\!\!\int_{-\infty}^{\infty} J(\mathbf{R},\,\mathbf{n},\,z,\,t)\,\mathrm{d}^2 n\,. \tag{10}$$

Here J is the radiation brightness; $\mathbf{R}$ is transverse vector of a point in the beam; z is coordinate in the direction of propagation; $\mathbf{n}$ is the transverse vector of the tangent to the ray trajectory; and, $\tilde{\varepsilon}$ is the change in dielectric constant.

In a specific case this set is replenished by an equation that determines the $\tilde{\varepsilon}(I)$ function. The method of characteristics is the classic one for integration of the transfer equation (8) with the initial condition (9). According to this method, the intensity is related to the brightness at the input aperture by the following integral equation:

$$I(\mathbf{R},\,z,\,t) = \int\!\!\int_{-\infty}^{\infty} J_0(\mathbf{R}'(0),\,\mathbf{n}'(0),\,z,\,t)\,\mathrm{d}^2 n, \tag{11}$$

$$\frac{d\,\mathbf{R}'}{d\,z'} = \mathbf{n}', \qquad \frac{d\,\mathbf{n}'}{d\,z'} = \frac{1}{2}\nabla_{\mathbf{R}}\,\tilde{\varepsilon}(\mathbf{R},\,z',\,t) \tag{12}$$

with the following initial conditions in the plane of observations:

$$\mathbf{R}'\,(z' = z) = \mathbf{R}', \quad \mathbf{n}'\,(z' = z) = \mathbf{n}', \quad z' = 0,\,\dots\,,\,z. \tag{13}$$

In the method of characteristics the integral (11) is written for characteristic rays emitted from a point $(\mathbf{R},\,z)$ into the initial plane $z = 0$ in the direction $\mathbf{n}$. These rays intersect the initial plane at the point $\mathbf{R}^0 = \mathbf{R}'\,(z' = 0)$, their direction is along the vector $\mathbf{n}^0 = \mathbf{n}'\,(z' = 0)$. The behavior of characteristic rays obeys the equations of geometric optics.

The characteristic rays reveal specific features of the solution integrated. The trajectories become dense at focuses and thin when the beam is blooming. In geometric optics the beam intensity is established from the energy conservation law for an elementary ray tube whose cross section is calculated using trajectory of only one central beam. In the method of solution of transfer equation, trajectories of the great number of rays are used for intensity calculations. This removes the waist problem and provides correct consideration of diffraction on the beam aperture.

The method of characteristics was employed in different versions for solution of problems of propagation of coherent and partially coherent laser beams in the atmosphere within a wide range of parameters of the process and for paths of different length.[66,70,81,82,89] Based on this method, we studied the problems of thermal blooming of the laser beams that were not solved. In particular, the problems of self–induced waist,[66] conversion of coherent properties of radiation in a nonlinear medium,[81] nonlinear refraction of wide–aperture beams,[81] fluctuations in nonlinear medium[89] were under examination. Below some illustrations of application of this method to the problem of propagation of high–power laser beam in the atmosphere are presented.

In Ref. 91 numerical experiments on the effect of the initial beam divergence Θ_0 on optimal focusing of cw laser radiation on the long high–altitude paths at the level of tropopause and in the stratosphere are presented. Figure 9 shows spatial distribution of the intensity of cw CO_2 laser with different initial diffraction–limited divergence. Results obtained demonstrate that to obtain the highest intensity of a beam, with a given initial divergence, it is necessary to focus laser radiation behind the detection plane since beam diffusion caused by gas absorption in tropopause and by aerosol in the stratosphere occurs. A beam with the lowest divergence has the smallest size in the detection plane, despite the fact that nonlinear distortions are most pronounced in this case.

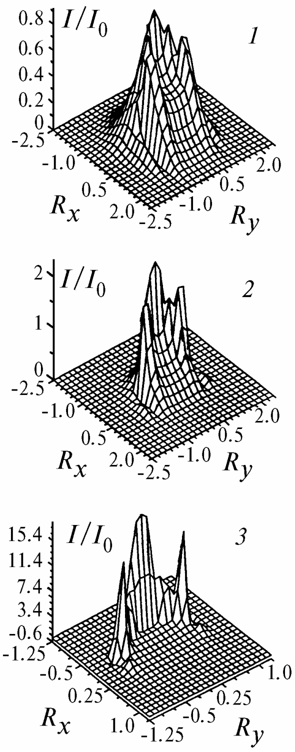


FIG. 9. Influence of the initial diffraction divergence on focusing of high–power laser beam at a long high–altitude atmospheric path: for $\Theta_0 = 2{\cdot}10^{-6}$, $F/L = 1.37$ (1); $\Theta_0 = 10^{-6}$, $F/L = 1.48$ (2); and, $\Theta_0 = 2{\cdot}10^{-7}$, $F/L = 1.49$ (3). Here F is the focus length of transmitting aperture and L is the path length.

Results obtained in Ref. 81 show some specific features of thermal blooming of a partially coherent radiation on a vertical path under conditions of kinetic cooling of the medium. The self–defocusing effect is observed with a partially coherent beam since it has high initial divergence, whereas coherent beam of the same parameters and dimensions exhibits self–focusing effect (Fig. 10). The effective beam radius versus dimensionless distance for laser beams with different degree of spatial coherence is presented

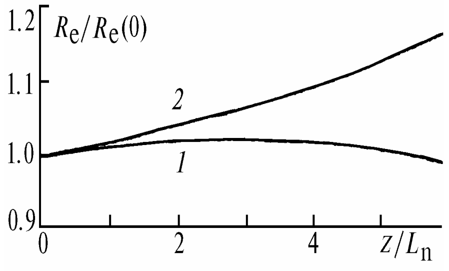


FIG. 10. Effective beam radius as a function of dimensionless distance. Atmospheric model is a summer in middle latitudes model.

in Fig. 10 for $t = t_p$ and $\delta = t_{VT}/t_p = 0.5$ (t_p is the pulse duration and t_{VT} is VT relaxation time of nitrogen molecules). Curve *1* presents the case when the initial divergence $\Theta_0^c = 1.69\cdot 10^{-6}$ and the parameter of nonlinearity $P = L_0^c/L_n = 123$; curve *2* corresponds to the case of partially coherent radiation, $\Theta_d^{pc} = 1.69\cdot 10^{-5}$, $P = L_d^{pc}/L_n = 12.3$. Together with the approaches to solution of self–action problem for homogeneous and inhomogeneous nonlinear refractive media, some methods are being developed at IAO that allow one to estimate *a priori* the influence of different nonlinear processes on the beams with different spatial profiles.[83] Moreover, it is possible for a number of cases to obtain precise solutions for effective integral beam parameters.[84] When using these methods, the quality of energy transfer is determined by an effective beam intensity. The initial value of this intensity as the main factor that influences on the degree of nonlinear distortions of the beams with the different profiles is taken as a criterion of the energy transfer quality. The effective beam intensity can be expressed as

$$I_e(z) = P_0 \exp\left(-\int_0^z \alpha_g(z')\, dz'\right) [\pi (R_e^2(z) - R_c^2(z))]^{-1}. \quad (14)$$

The variables R_e (effective beam radius) and $\mathbf{R}_c$ (center of gravity–vector shift) are obtained from the following equations[11,83]:

$$\frac{d^2 \mathbf{R}_c}{d z^2} = \frac{1}{2 P(z)} \int\!\!\int_{-\infty}^{\infty} \nabla_{\mathbf{R}}\, \varepsilon(\mathbf{R}, z, t)\, I(\mathbf{R}, z, t)\, d^2 R\,; \quad (15)$$

$$\frac{d R_e^2}{d z} = 2 \frac{R_e^2}{F_{e1}}\,; \quad (16)$$

$$\frac{d}{d z} \frac{R_e^2}{F_{e1}} = Q_e^2 + \frac{1}{2 P(z)} \int\!\!\int_{-\infty}^{\infty} \mathbf{R} \nabla_{\mathbf{R}}\, \varepsilon(\mathbf{R}, z, t)\, I(\mathbf{R}, z, t)\, d^2 R; \quad (17)$$

$$\frac{d Q_e^2}{d z} = \frac{k^{-1}}{2 P(z)} \int\!\!\int_{-\infty}^{\infty} \nabla_{\mathbf{R}}\, \varepsilon(\mathbf{R}, z, t) \nabla_{\mathbf{R}}\, \varphi(\mathbf{R}, z, t)\, I(\mathbf{R}, z, t)\, d^2 R; \quad (18)$$

$$\frac{d P}{d z} = -\alpha_g P(z, t)\,. \quad (19)$$

Here P is the beam power; φ is the wave phase; k is the wave number; and, Θ_e is the effective width of the angular spectrum (polar diagram) that is written as:

$$Q_e^2 = \frac{1}{k^2 r_{de}^2(z, t)} + \frac{R_e^2(z, t)}{F_e^2(z, t)}\,. \quad (20)$$

Here ρ_{de} scale characterizes diffraction features of the beam and F_e is the effective radius of wave–front curvature.

Behavior of the effective parameters of different collimated beams is found to be similar under conditions of strong nonlinear distortions. Indeed, the form of the function $I_e(z)/I_e(z{=}0)$ of (z/L_n^2) is approximately the same for different beams (Fig. 11). This effect occurs near the emitter, where a nonlinear layer forms the limiting polar diagram of the beam. In this case, the nonlinear component of the minimum beam divergence is determined by the expression $\Theta_{n\infty} = R_{e0}/L_n$.

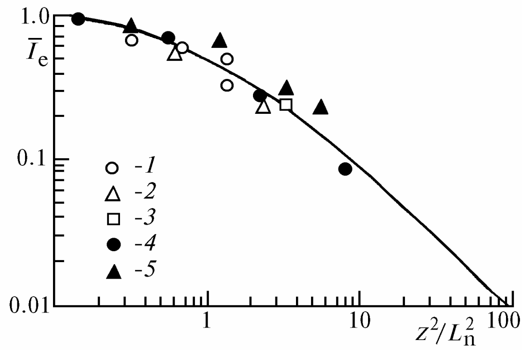


FIG. 11. Relative effective beam intensity near the center of gravity versus z/L_n parameter in a nonlinear medium with a stationary wind nonlinearity. Different dots correspond to beams with different initial profiles.[83]

The versatile form of the longitudinal scale of the nonlinearity was found as

$$L_n = R_e(0) \left[\frac{1}{2 P(0)} \int\!\!\int_{-\infty}^{\infty} \mathbf{R} \nabla_{\mathbf{R}}\, \varepsilon(\mathbf{R}, 0, t) I(\mathbf{R}, 0, t)\, d^2 R \right]^{-1/2}. \quad (21)$$

This equation eliminates the known problem of understating the thresholds for nonlinear effects in aberration–free and geometric optics approximations.

Formation of the minimum divergence was studied with the initially homogeneous and inhomogeneous refractive medium.

The solution for effective beam parameters in presence of nonlinear layer can be written as

$$R_e^2(z) = R_e^{*2} \left[\left(1 + \frac{z - z^*}{F_{e1}^*}\right)^2 + \frac{(z - z^*)^2}{k^2 \rho_{de}^{*2} R_e^{*2}} + \beta^* (z - z^*)^2 \right]; \quad (22)$$

$$\mathbf{R}_c(z) = \mathbf{R}_c^* + Q_c^* (z - z^*); \quad (23)$$

$$Q_c^* = \frac{1}{R_e^*} \int_0^{z^*} \frac{d z}{P(z)} \int\!\!\int_{-\infty}^{\infty} \nabla_{\mathbf{R}}\, \varepsilon(z)\, I(z, \mathbf{R})\, d^2 R\,. \quad (24)$$

Here $\beta = (F_e^*)^{-2} - (F_{e1}^*)^{-2}$ is the factor of beam distortions caused by aberrations; $(F_{e1}^*)^{-1} = (F)^{-1} + (F_n^*)^{-1}$; F_n^* is nonlinear component of the effective curvature radius of the phase front F_{e_1}; and, * indicates the variables calculated on the boundary of the region where nonlinear effects are observed. This boundary is determined by the equation for saturation of angular divergence

$$Q_\infty^2(z^*) = Q_e^2(0) + k^{-1} \times$$

$$\times \int_0^{z^*} \frac{d\,z}{P(z)} \int\int_{-\infty}^{\infty} \nabla_{\mathbf{R}}\, \varepsilon(z)\, \nabla_{\mathbf{R}}\, \varphi(z)\, I(z, \mathbf{R})\, \mathrm{d}^2 R = \mathrm{const.} \quad (25)$$

In the general case, following the definitions of F_e and F_{e1}, $F_e \le F_{e_1}$. Hence, the structure of solution will be different in aberration–free case and in the presence of aberrations. The scale F_e may be both positive (self–defocusing) and negative (self–focusing) being the most sensitive indicator of the medium refractive properties. Therefore, it is reasonable to establish the thresholds of nonlinear effects for an inhomogeneous path from analysis of F_n^*. Self–defocusing (self–focusing) occurs at a distance z when $|F_n^*| \le z$. If the beam is focused onto detection plane $F = z$, nonlinear effects would take place on the background of the diffraction ones at $|F_n^*| \le L_d$ and if the characteristic refraction angle $\tilde{Q}_n^* = R_{e_0}/|F_n^*|$ is larger then the diffraction–limited beam divergence: $\tilde{Q}_n \ge \Theta_0$.

Expression for F_n^* and nonlinear component of the minimum divergence can be written for weak nonlinear distortions on an inhomogeneous path in the following way ($\tilde{\varepsilon} = \tilde{\varepsilon}_{max}(z)\bar{\varepsilon}(\mathbf{R})$):

$$F_n^* \cong k\, R_{e0}^2 \left(\int_0^{z^*} \tilde{\varepsilon}_{max}(z')\, \mathrm{d}\, z' \right)^{-1} \times$$

$$\times \left(\int\int_{-\infty}^{\infty} \mathbf{R}\, \nabla_{\mathbf{R}}\, \bar{\varepsilon}(\mathbf{R}, 0)\, I(\mathbf{R}, 0)\, \mathrm{d}^2 R \right)^{-1} = L_n^2 \,/\, L_{ef}\,;$$

$$\Theta_{n\infty} = R_0\, L_{ef} \,/\, L_n^2; \quad (26)$$

$$L_{ef} = \int_0^{z^*} \tilde{\varepsilon}_{max}(z')\, \mathrm{d}\, z' \,/\, \tilde{\varepsilon}_{max}(0)\,. \quad (27)$$

Here L_{ef} is the scale of inhomogeneity of the atmospheric path parameters. If $L_n \le L_{ef}$, strong nonlinear distortions of the beam occur. In this case, the inhomogeneity of the path does not substantially affect the integral beam parameters. The main influence is introduced by the nonlinear lens created near the source. It is obvious that an intermediate region exists where $L_n = L_{ef}$. In this case, the beam parameters that determine the effective intensity out of the nonlinear layer can be computed only numerically.

Figure 12 illustrates the minimum angular beam divergence versus scale of nonlinearity that is obtained from numerical solution of self–action problem for a pulsed beam on a vertical path by the method of solution of equation of brightness transfer. This function has two asymptotics: strong distortions $\Theta_{n\infty} = R_0/L_n$ and weak distortions $\Theta_{n\infty} = R_0 L_{ef}/L_n^2$. Since the solutions that correspond to strong distortions $L_n < L_{ef}$ were not obtained in Ref. 81, an extrapolation of the data from the boundary of the region to conditions that cause this situation was made. The calculated function $\Theta_{n\infty}(L_n)$ was found to be satisfactorily described by an approximate expression $\Theta_{n\infty} = R_0 L_{ef}/(L_n(L_n + L_{ef}))$.

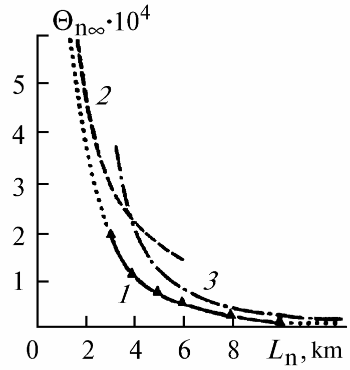


FIG. 12. Nonlinear component of the minimum beam divergence as a function of length of nonlinearity (self–action of a long laser pulse on a vertical atmospheric path): calculation by the method of solution of transfer equation (solid curve) and extrapolated function (dashed curve) (1); asymptotic of the strong (2) and weak (3) nonlinear distortions; approximate function (▲).

The method of estimation of the efficiency of the laser energy transfer in nonlinear refractive media developed at IAO enables one to perform qualitative and quantitative analysis of a number of important multi–parametric problems of atmospheric nonlinear optics based on equations for integral beam parameters.

CONCLUSION

When analyzing tendencies of development of the problem of nonlinear spatially and amplitude modulated wave propagation through the atmosphere, it should be noted that optical sounding of physical and chemical parameters of different substances using nonlinear optical interaction has attracted great interest.[7,11,12,13,77] It is obvious that wide use of advanced methods of investigation of nonlinear wave processes in the atmosphere will always have great potentials for modern atmospheric optics and laser physics.

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