Optoacoustics of the channel of high-power pulsed laser radiation propagation through the atmosphere

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Received July 19, 2003

The paper describes potentialities of the processing of optoacoustic signals with the use of the developed Atmospheric Optoacoustics software. Use of this package makes it possible to compensate in real time for the deteriorating effect of the atmosphere on the quality of the optoacoustic data on the propagation of high-power pulsed laser radiation through the atmosphere.

In the studies on high-power laser radiation (HPLR) propagation through the atmosphere, as a medium containing aerosol components, the optoacoustic effect (OA) has been used. The advantage of using this effect in such studies is that the acoustic waves are generated in the medium due to absorption the intensity-modulated radiation.[1] The parameters of optoacoustic signals generated in the high-power laser radiation channel, which are recorded with a remote receiver, are conditioned both by the characteristics of absorbed radiation and by the optical, thermal, and acoustic characteristics of the atmosphere.

Comprehensive analysis of the experiments on the propagation of high-power laser radiation through the atmosphere is of current interest since it is, first, a check up of laboratory experiments and of the theoretical models; second, new problems can be formulated in solving the problem on interaction of the high-power laser radiation and the atmosphere. It is known that with the account of the expenses, required for the field measurements, the discussion of such results is very important from the viewpoint of wide scope of problems. In particular, one of such problems is the use of an acoustic channel for prompt diagnostics of the atmospheric effect on the formation of a long laser spark at a given airway region or a highly ionized channel for a directed sink of a lightning discharge[2] or for solving an opposite problem – the transport of laser energy through the atmosphere[1] when the advent of plasma source (PS) is the least favorable factor affecting the transmission efficiency for high-power laser radiation.

In developing the method of acoustic diagnostics of a possible influence of the atmosphere on the transmission of optical radiation through the atmosphere at the instant of laser start, whatever is the cause, not only the determination of the most informative characteristics of a received acoustic response to the interaction of high-power laser radiation with the atmosphere is important, but also the methodological development of the problem of adequacy of the interpretation of sound tracks, with the account of both the knowledge of physics of the interaction of high-power laser radiation with the atmosphere in realizing different nonlinear optical effects and the physics of the optoacoustic pulse generation and propagation.

To solve this problem, there is a need in using the method of diagnostics of the optical state of the atmosphere operating in real time and the technique of predicting the efficiency of either geometric or energy parameters of high-power laser radiation for a particular optical and meteorological state of the atmosphere. One can judge on the efficiency of generation of an ionization channel of a long laser spark (LLS) type, in this case, from a received acoustic signal generated by plasma sources initiated, e.g., with a CO_2-laser pulse propagating through the atmosphere.[3]

The physical principles of the acoustic method as an indicator of the process of interaction of the high-power laser radiation with aerosol particles are described in the literature.[1] The technique of reception, recording, and interpreting of sound tracks, formed by plasma sources, initiated with high-power CO_2-laser radiation of microsecond duration propagating along extended atmospheric paths were discussed in the literature,[4] where the data on acoustic diagnostics of a long laser spark in the atmosphere were presented. This paper analyzes the measurement results on a series of parameters of acoustic response of the atmosphere.

It was noted that the formation of plasma sources occurred successfully at low humidity of the air (*RH*). The enhanced moisture content in the atmosphere results in water coating of solid phase aerosol. The water coating of such aerosols increases the time delay in the formation of plasma sources relative to the onset of the laser radiation pulse. The precipitations favor the removal of coarse-dispersed fraction of aerosol.

It is shown that the dependence of the mean pressure in a thermo-acoustic signal on the mean density of the laser radiation power or peak pressure of a compression phase on the energy density in a beam can be well approximated by a linear dependence only with the account of the energy inhomogeneity of a laser beam. By a thermoacoustic signal we mean an acoustic pulse generated due to the expansion of the

0235-6880/03/09 750-06 $02.00

atmospheric matter at its heating by the absorbed high-power laser radiation without phase transitions.

Thus, the acoustic measurements make it possible to interpret the results taking into account the laser beam energy structure.

A systematic study of spectral and energy characteristics of acoustic waves generated by a set of plasma sources was described in the literature.[5,6]

The detection of acoustic signals resolved in time from individual plasma sources[3,6,7] enabled us to connect the duration and amplitude of these signals with the dimension of plasma sources for microsecond laser pulses.

It should be noted that for energy characteristics of a laser source, used in the full-scale experiments, the beaded structure of the long laser spark was realized due to the initiation of plasma sources on the solid aerosol particles. In this case, the mechanism of plasma sources initiation is of little importance for the acoustic method of indication of the long laser spark initiation. From the data of optoacoustic measurements the critical dimensions of aerosol particles have been reconstructed, initiating plasma sources depending on the energy density of the high-power laser radiation that is of interest in the prediction of the high-power beam propagation along atmospheric paths.

In the papers published previously (Refs. 1, 3–7, 9) the processing of acoustic characteristics of the long laser spark in real time was not performed. This paper gives examples of processing the optoacoustic signals generated by long laser sparks, using the developed Atmospheric Optoacoustics software as well as the description of algorithm and the physical substantiation of the models used in the program complex.

Figure 1 shows typical shape of the time scale of an acoustic response from an isolated quasi-spherical plasma sources obtained by digital processing at a discrete frequency of 34.7 kHz.

An acoustic response of the plasma sources (curve *1* in Fig. 1*a*) in its basic part has a characteristic shape, which agrees well with the model profile (curve *2* in Fig. 1*a*) calculated by use of the software developed. The program contains a module allowing the imitation of the pulse effect on the transmission function of an emitter of zero order (the model of pulsed sphere), which is of the form:

$$K(\omega) = \frac{P_0 a}{dc\,(1 + iX)} \exp(iX) \exp[i\omega(\tau - d/c)],$$

where $X = \omega a/c$, $\omega = 2\pi f$, d is the distance from an acoustic receiver to plasma sources, τ is the time delay between the moment of transmitting the high-power laser radiation and the moment of receiving the acoustic signal, f is the frequency of sound wave; a and P_0 denote the radius of optoacoustic emitter and the pressure at its surface, respectively, c is the sound velocity.

However, in contrast to the model, a true optoacoustic response has an insignificant and extended "tail" (Fig. 1*b*). A plasma source does not "collapse" immediately after its initiation and lasts for a long time. As a sound emitter the plasma source is a resonator with its own finite quality.

An explanation of this phenomenon was theoretically predicted in the literature[3] and is as follows. In a warmed up plasma source the generation zone of acoustic waves moves away from the particle surface and the warming-up up acoustic waves move from the warmed zone not only to the outside but inward either. But the gas supersonic counterflow in the inside convective region of a plasma source prevented the acoustic wave collapse to a particle. The result of the interaction of acoustic wave of warming up with the counterflow is the constriction of the convective region, fast growth of pressure at its boundary with the heat-conducting region, and peculiar reflection (reverberation) of acoustic waves of warming up, which increases the life time at external reception.

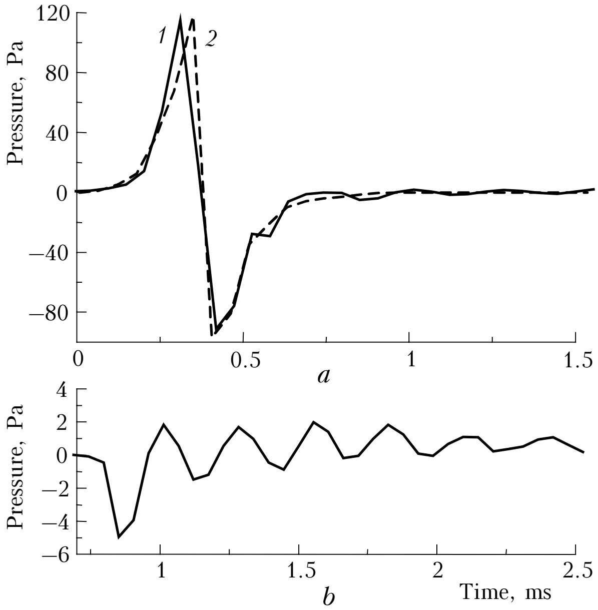

Fig. 1. An acoustic response of the quasispherical plasma source. d = 16 cm, T = 291 K, RH = 78%, experiment (*1*); model (*2*); the pulsations of a plasma source (*b*) (10 times magnification as compared to *a*).

As a rule, at remote reception of an optoacoustic signal in the atmosphere the "tail" of acoustic response from plasma sources is not detected due to the effect of external acoustic noises, which decrease substantially the signal-to-noise ratio at the input of the receiving equipment.

Acoustic receivers, located close to the Earth's surface at certain altitude can be moved from a sloping channel of high-power laser radiation to a distance of hundreds meters and more, and the recorded optoacoustic signals are distorted because of the attenuation in the atmosphere.[8] Therefore the remote optoacoustic measurements in the atmosphere call for the reconstruction of the initial amplitude-frequency characteristic of the optoacoustic signals for obtaining the reliable data on the process of high-power laser radiation propagation through the atmosphere.

The Atmospheric Optoacoustics software enables one to take into account in real time the effect of dissipative, diffraction and nonlinear distortions on the shape of optoacoustic signals. Methods of the narrow-band spectral analysis are used in the algorithms. All transformations of the signals are made in the spectral domain. The program is efficient for different types of acoustic detectors as well as enables one to use built-in amplitude calibration, rebuilt digital filters (low-pass, low-cut, narrow-band, and rejection), which make it possible to perform optimal frequency filtration of optoacoustic signals against the background of atmospheric and apparatus noise. The program is equipped with multi-window interface including the user's dialog menu.

Because the analog circuits of the receiving acoustic equipment contain differential and integrating circuits, the amplitude-frequency and phase-frequency distortions of measured signals, introduced by these circuits, must be taken into account in the subsequent processing. This is achieved by the program insertion of a digital tunable dedifferentiating and de-integrating circuits in each of the four simultaneously processed channels for reconstructing the initial optoacoustic signals and compensation for the apparatus distortions.

By introducing the initial data on the geometry of measurements (the location of high-power laser radiation channel, optoacoustic receivers, and underlying surface) the possibility exists of minimizing the effect of acoustic noise in the form of reflected pulses simultaneously for the four spaced acoustic sensors. The program algorithm compensates for spherical and cylindrical divergence of acoustic waves, classical (viscous and thermal losses) and molecular (rotational and vibrational relaxation) absorption of sound based on the initial meteorological data, turbulent extinction, and extinction due to the Earth's surface.[8] Absolute values of the sound pressure can be put for the distance of 1 m.

The location of individual plasma sources in the range of breakdown is determined by the formula

$$d = 20.067 K_{RH} \sqrt{T} \tau,$$

where T is the temperature of the air in K; K_{RH} is the correction factor for humid air. The localization of plasma sources when working at the ground path of high-power laser radiation propagation is determined by calculating the cross correlation functions that enabled us to select an arbitrary location of optoacoustic receivers relative to the high-power laser radiation channel.

When recording the sound track, containing acoustic signals from isolated plasma sources, the signals, reflected from the underlying surface, are also recorded. The amplitude of reflected signals is lower than that of the corresponding direct pulses, and the delay between the direct pulses and pulses reflected from the ground depends on the difference between path lengths of the direct and reflected sound waves. Because the speed of sound in the air is lower than that in the ground, the reflection coefficient of optoacoustic signals according to the sound pressure R_p varies from 1 at an angle of total internal reflection to the value

$$R_p = (\sin\varphi - z_1/z_2)/(\sin\varphi + z_1/z_2)$$

at normal incidence of sound wave on the surface, where φ is the angle of reflection, $z_1 = \rho c$ is the acoustic impedance of the air, ρ is the air density, z_2 is the acoustic impedance of the underlying surface (complex value).[8] The sum sound field at the point of reception is presented in the form:

$$\Phi = \frac{e^{ikr_1}}{r_1} + \frac{e^{ikr_2}}{r_2} R_p + \frac{e^{ikr_2}}{r_2} (1 - R_p) F,$$

where $k = 2\pi/\lambda$ is the wave number; λ is the sound wavelength; $r_1 = d$ and r_2 are the distances from the source to the receiver and from the imaginary source to the receiver, respectively. The first term in this equation describes the wave propagating from the source to the receiver. The second term refers to the reflected wave. The parameter F of the third term in the equation is the coefficient of the surface losses. F is as follows:

$$F = 1 + 2i\sqrt{\theta}\, e^{-\theta} \int_{-i\cdot\sqrt{\theta}}^{\infty} e^{-u^2} \mathrm{d}u$$

where θ is the "numerical distance" given by the following expression:

$$\theta = \frac{2ik_1r_2}{(1 - R_p)^2 \cos^2\varphi} \left(\frac{z_1}{z_2}\right)^2 \left(1 - \frac{k_1^2 \cos^2\varphi}{k_2^2}\right).$$

Here k_1, k_2 are the wave numbers in the air and in the ground, respectively.

The acoustic impedance of the ground is calculated in the program with the use of the known Delany–Bazley single-parameter model

$$z_2/z_1 = 1 + 9.08(\sigma/f)^{0.75} - i11.9(\sigma/f)^{0.73},$$

where σ is the specific resistance to the flow per unit of the surface thickness.

Figure 2 shows the results of the field measurements of the reflection coefficient of the underlying surface. In this case the high-power laser radiation propagation channel was horizontal at 5 m height over the Earth's surface.

The region filled with plasma sources was extended enough in order to cover the interval of measured angles from 4 to 46°. The data were obtained by averaging over several starts of high-power laser radiation over one and the same area of the underlying surface. Perceptible change of the dependence $R_p(\varphi)$ after the rain is due to the increase of the impedance of the underlying surface. The curves in the figure show the calculation made using the above-mentioned formula at $\mathrm{Re}(z_2/z_1) = \mathrm{Im}(z_2/z_1) = 1$ (curve *1*) and 1.2 (curve *2*). The point spread at angles of reflection higher than 15° is due to the inhomogeneity of underlying surface.

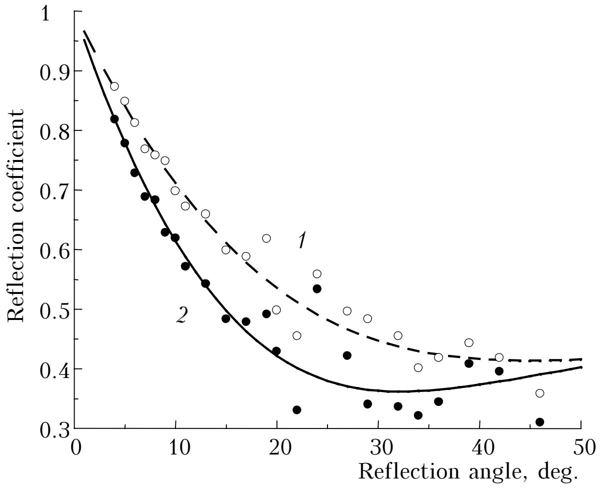

Fig. 2. The reflection coefficient of acoustic responses of the plasma source by the underlying surface based on the sound pressure: dry soil (*1*); the same region after rain (*2*). Field measurements are denoted by the points, theoretical approximation is denoted by the lines.

Based on the initial data on the impedance of underlying surface[8] and the geometry of measurements the reflection coefficient is calculated for all the acoustic sources occurred along the path of high-power laser radiation propagation. Then, the reflected noise is cut out from the sound track. As an example, Fig. 3 shows the result of such an operation of the program, with the noise having the amplitude about half of the true signal amplitude in the range of 1.5 ms (curve *1*) and after compensation less than 10% (curve *2*).

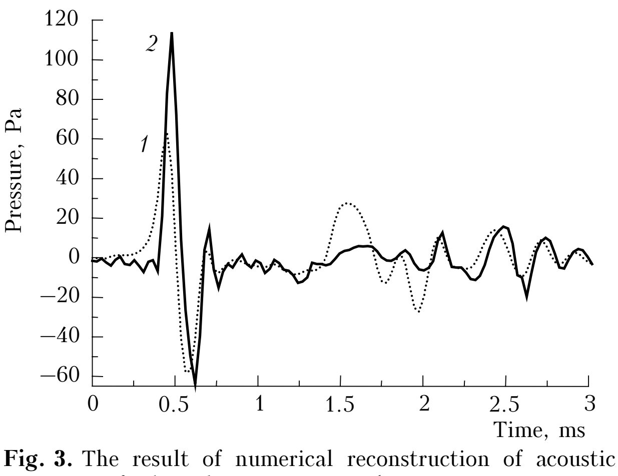

Fig. 3. The result of numerical reconstruction of acoustic response of the plasma source: d = 141 m; T = 288 K; RH = 75%. With the compensation of only spherical divergence (dashed line) (*1*) ; total compensation including the reflection noise (solid curve) (*2*).

According to literature[7] the empirical relationships have been found, by means of multiple simultaneous recording of visible dimensions of the plasma cells and generated acoustic pulse, between the diameter of the plasma cell d_{PS}, the duration τ_+, and the amplitude P_+ of the generated acoustic pulse of constriction

$$d_{\mathrm{PS}} \approx 0.71\tau_+ c;\ d_{\mathrm{PS}} \approx P_+ d/2100.$$

The program realization of the second relationship is much simpler, therefore in the program algorithm the plasma cell diameter is determined from the amplitude of the acoustic pulse generated and used to calculate nonlinear losses of high-power laser radiation energy along the propagation path. From the measured amplitudes of the acoustic responses, generated by isolated plasma cells, we determine the dimensions of all the plasma cells and their size distribution. Then the histograms are constructed illustrating the regions of nonlinear losses of high-power laser radiation along the path.

For an efficient operation of this algorithm, one should reconstruct the initial amplitudes of optoacoustic responses with high validity that is available only at digital signal processing.

Figure 3 shows that after the program compensation for sound attenuation the reconstructed amplitude of the initial signal (curve *2*) became almost twice as large (positive phase of sound pressure) than before the compensation (curve *1*).

Acoustic characteristics of a long laser spark are manifested late when plasma sources are expanded to the surrounding gas, as a rule, according to the mechanism of a light explosion wave. The spectral characteristics occurring in this case under conditions of dispersion and dissipation of fairly low frequency weakly attenuated components of acoustic waves of warming up are the main source of acoustic data on the long laser spark at a remote reception. The region of optical breakdown is characterized by different spatial scales, i.e., by the plasma cell dimension, mean distance between the adjacent plasma cells, and the total dimension of the breakdown region. These scales can be evaluated promptly by the spectral peculiarities in the frequency range. The higher the accuracy of the frequency spectra measurements, the higher is the accuracy of measurements of the spatial scales of the breakdown region.

Figure 4 shows, as an illustration of the efficiency of the program in reconstructing the reference acoustic frequency spectra of the breakdown region, the reconstructed frequency spectrum of acoustic signals generated by a region densely filled with plasma cells (PC cluster).

The cluster is at a distance of 160 m from the acoustic receiver and the transformation of the frequency spectrum by the distorting atmospheric effect is relatively noticeable, especially at high frequencies (spectral peak at f = 6 kHz).

In some papers[1,3,4,9] the authors pointed out that apart from the pressure pulses from the breakdown cells there is the so-called thermoacoustic signal in the acoustic response, which is generated at light energy distribution throughout laser beam cross section, i.e., it can serve as a factor of energy inhomogeneity. In the atmospheric optoacoustic investigations, using slant paths the single-position measurement scheme is possible when the axis of acoustic reception of a microphone located at the Earth's surface is perpendicular to the high-power laser radiation (HPLR) channel, and the extension of the monitored region of the HPLR channel equals the first Fresnel zone for the basic harmonic generated by an acoustic wave. Taking into account that the most of HPLR beams are close to the axially symmetric ones, we can estimate approximately the HPLR energy density distribution over a beam without solving the strict inverse problem of the computational reconstructive tomography (Fig. 5).

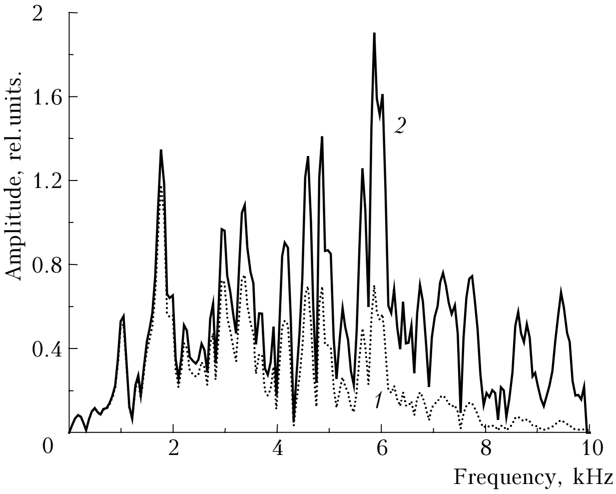

Fig. 4. The numerically reconstructed frequency spectrum of acoustic characteristics of the cluster of the plasma cells. d = 160 m, T = 288 K; RH = 75%; without the account of the frequency transformation of acoustic responses (*1*); with account for such responses (*2*).

The HPLR beam structure was ring-shaped that can be seen on the time scales. With the increasing energy density of the HPLR the principal maximum in the frequency spectrum, corresponding to the beam diameter, does not vary, and the dependence of acoustic pressure on the energy density turns out to be linear. The second maximum (high-frequency) corresponds to the dimensions of the fine beam structure, and the dependence of its amplitude on the energy density is nonlinear. At the minimum energy density, this maximum is practically insignificant, i.e., "fine structure" of a beam practically disappears. The remote measurements, used in calculating the integral in time acoustic power in the sound range, give an estimation of the HPLR beam power or the total aerosol content in the HPLR channel.

To compensate for nonlinear absorption of optoacoustic signals in the atmosphere using the starting meteorological data, in the program an individual processing module is provided fulfilled by the algorithm presented in Ref. 10. However, because of the complexity of the algorithm resulting in slow calculation, this module is used for processing of optoacoustic signals from single plasma sources.

The compensation algorithm of nonlinear absorption of optoacoustic signals should be used practically at the value of nonlinearity parameter being more than 1 (in the Khokhlov–Zabolotskaya–Kuznetsov equation). The calculations show that for plasma sources of diameter 3 cm the decrease in the acoustic response amplitude due to nonlinear absorption does not exceed several percent.

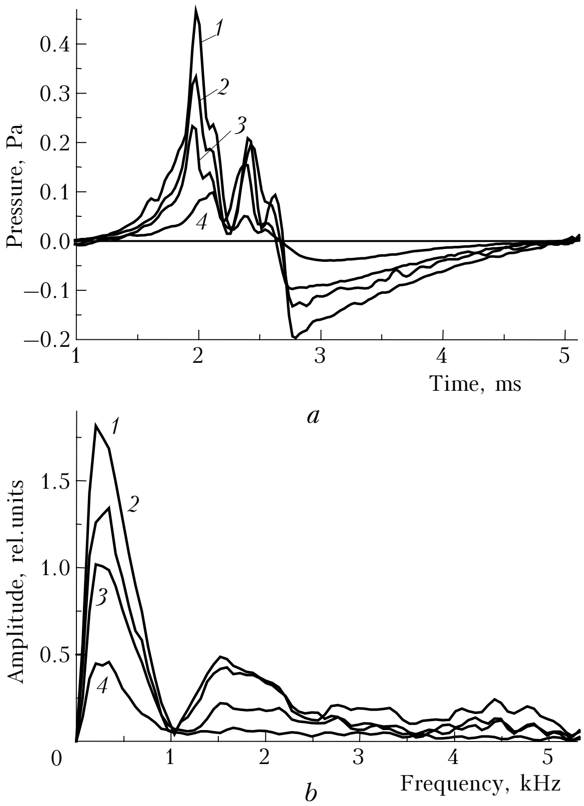

Fig. 5. The result of reconstruction of acoustic pulses generated by the HPLR channel and recorded by acoustic receiver at 30-m distance (*a*), and their frequency spectra (*b*) for different values of the laser power density: 1.7 (*1*); 1.36 (*2*); 0.87 (*3*); 0.29 J/cm^2 (*4*); d = 30 m, T = 291 K, RH = 71%.

Thus, the developed Atmospheric Optoacoustics software enables one to compensate in real time for the atmospheric distortions of the quality of the optoacoustic data on the HPLR propagation through the atmosphere.

Acknowledgments

The work has been performed under support from the Russian Foundation for Basic Research (Grant No. 03–05–64431).

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