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APPLIED OPTOACOUSTICS OF FEMTOSECOND LASER RADIATION

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The modern level of development atmospheric optoacoustics allows to use it achievements in the decision of various physical tasks, including, for complex researches of distribution of supershort laser pulses in an atmosphere. In the report the results of experimental optico-acoustic researches of interaction of intense femtosecond laser pulses with air, by liquid-dropled aerosols and biotissues are discussed. These researches have allowed to find out and to investigate a number of the new physical phenomena.

The efficiency of application optico-acoustic (OA) of a method in a problem of research of distribution supershort of femtosecond laser pulses is considered in the report on an example of experimental results executed in laboratory conditions at interaction of supershort laser pulses with aerosols, by air by separate drops and biotissues [1-6].

1. Interaction of femtosecond laser pulses with aerosols

In experimental researches the source the Ti:Sa-laser was used [7], which generated pulses on length of a wave 0,8 μm, duration 80 fs and 9 ns at energy in a pulse up to 17 mJ and width of a laser beam of 8 mm.

As modelling medium the particles of clean water by the size 2,5 μm with addition of silver nanoparticles were used. The aerosol medium with the number density to 10^7 cm^{-3} was formed by an ultrasonic generator. The acoustic part of the setup included two recording channels with the linear frequency range of 20 Hz÷100 kHz. The technique of the executed experiments is in detail submitted in [1, 2]. OA-diagnostics in air along the femtosecond laser pulse at different distances from the lens focus has shown that, in the case of sharp focusing by mirrors with length of focus 86 and 120 cm, for on distance 0,1÷4,2 m the significant «extinction» of a filament is observed. The amplitude of the generated OA-response indirectly corresponde to concentration free electrons in the plasma which has arisen as a result of influence of femtosecond radiation. Is received, that at a small distance from the focus the filament energy decreases by orders of magnitude. The filament energy is understood here as an energy part, which forms the weakly ionized plasma and then dissipates into the thermal energy of the medium due to the electron and ion recombination. Thus, the acoustic signal records the thermal losses of the laser radiation associated with the filamentation of the beam. The observed decrease of these losses indicates that, behind the focus, the filament, defined as a self-sustained formation, already does not exist. The divergent beam does not feed the filament with the energy sufficient for balance of two effects: Kerr nonlinearity and plasma formation.

The dependence of the peak pressure in the acoustic signal on the relative transmittance, which is connected with the particle number density in the aerosol medium by an obvious relation, shows that as we pass from the femtosecond pulse to the nanosecond one with the pulse energy kept the same, the amplitude of the acoustic response decreases by two orders of magnitude. Two scenarios are possible. The first one is that, because the action differs only in the intensity, the multiphoton absorption realizes in the particulate matter for the case of the femtopulse. In the second scenario, for the femtosecond pulse, the heat outflux from silver nanoparticles, doped into an aerosol particle, can be neglected, then the conditions of liquid overheating and explosive boiling take place in local areas of the droplet, and the acoustic response is higher than in the case of the thermal and evaporative mechanisms of generation of the acoustic response. However, the interpretation of the obtained result with the use of some or other mechanism requires detailed evaluation. In addition, these mechanisms are not mutually exclusive.

The optical transmittance of the aqueous aerosol at the wavelength of the sensing cw radiation does not change during the propagation of femtosecond laser pulses in the aerosol, which indicates that the aerosol microstructure does not change and, consequently, the thermal effects of evaporation and explosive boiling of the particulate matter do not take place. In the case of an optical breakdown in the aerosol, observed in some cases by the acoustic method, the optical thickness of a fog also does not change, thus indicating that the breakdown centers are formed inside a small number of aerosol particles and, receiving no energy from the short laser pulse, they do not develop.

The registration of a OA-signal in longitudinal concerning a laser beam a direction has allowed in air to restore the geometrical sizes of area with the raised ionization (area filamenta), on what for the first time is specified in [1].

Executed in [1] the experimental researches of distribution of femtosecond laser pulses in water aeroashes have shown, that the easing of energy of pulses by an aerosol layer is close to the law Bugera with factor of easing poorly distinguished from linear. Besides aerosol environment is capable not only to reduce energy of femtosecond pulse, but also to increase his duration for the account dispersion in water particles.

The monodispersion water aerosol does not bring in essential features to transformation of a laser beam at his spatial focusion, that allows to recommend such an aerosol for use as linear neutral relaxation at management of a rule of nonlinear focus and spatial situation of area filamentation.

2. Nonlinear OA-effect at propagation femtosecond laser pulses in air

In work [4] the results of an experimental research of the nonlinear effect which has been found out at distribution intensive of femtosecond laser radiation are resulted: nonlinear absorption of energy of laser pulses in air.

The experiments were carried out with use linearly - is polarized radiations femtosecond of a laser complex [7]. The energy in a laser pulse changed with the help polarizing relaxation and was measured by the calibrated photo diode. The radiation from an output of the laser was focused by a spherical mirror with a focal length 86 cm.

The investigation of absorption of laser radiation was performed using a OA-method. For this purpose on distance 42 cm from a focusing mirror about an axis of a beam the microphone with frequency by a strip 100 kHz was placed, distance from a microphone up to an axis of a beam made 1,5 cm.

Oscilogramma of a signal from a microphone for registered of femtosecond a laser pulse represented a wave of compression and underpressure. The dependence of amplitude of the first peak of a OA-signal on energy in femtosecond laser pulse received from measurements with atmospheric air $P(E) \sim E^{2,756}$, cardinally differs from similar dependence $P(E) \sim E$ at distribution of laser radiation of micro- and nanosecond duration (thermooptical generation of acoustic waves) and illustrates the nontrivial changes in the air absorptance.

When instead of femtosecond of a pulse the pulse of nanosecond duration was used, the OA-signal became much less on amplitude, and the dependence of amplitude of a OA-signal on energy in a laser pulse was linear.

The received experimental results testify that the absorption of energy of femtosecond laser pulses in atmospheric air carries nonlinear character and size of absorption much more linear absorption of laser pulses of nanosecond duration.

The theoretical explanation of the received results is given in work [4]. It is well known that homonuclear molecules of nitrogen and oxygen, the main components of atmospheric air, have no electron dipole moments. But in the strong electromagnetic field of a femtosecond laser pulse an induced dipole moment is produced, being predominantly oriented along the molecule axis. The interaction of this induced dipole moment with the electric field of a laser pulse leads to the rotational excitation of molecules and, consequently, to the absorption of laser radiation. The rotational energy of the molecules transfers, through collisions, into heating, which is the source of OA-wave excitation.

The quantitative description of the stated above mechanism was executed in view of the mentioned above mechanism and is specified in view of the mechanism self-channeling of a laser beam.

As is known, for a case of weak linear absorption of laser radiation in gases the task was solved in work [8].

The proposed model of nonlinear absorption of femtosecond laser pulses in air due to rotational excitation of nitrogen and oxygen molecules with the induced dipole moment works only for linear polarization of electromagnetic radiation. For circular polarization, because of averaging over the angle the molecule's rotational energy averaged over the electromagnetic field period is zero and this mechanism, offered in work [4], is not valid.

In atomic gases, the mechanism of high intensity radiation absorption considered above is also not valid. Really, in the experiments [9] the injection of atomic Ar in a OA-cell leads to the disappearance of the OA-signal.

3. Interaction of femtosecond laser pulses with solutions of dye separate drops

Technique and the results of research of the spectral and power characteristics twofotons of the exited fluorescence of dye R6G in form the individual liquid-droplet particles at an irradiation by laser pulses of femtosecond duration are considered in [3].

It is necessary to emphasize, that the above mentioned objects of influence of femtosecond radiation – dispersion of environment - in themselves are specific physical systems. The specificity them is, that the spherical particles have focusing action and, besides are highqualitative microresonators, in which the morphological resonances are realized or style of whispering gallery [10]. It results in sharp increase in their volume intensions of influencing optical fields and, as a consequence, downturn of power thresholds of display in them of nonlinear-optical processes.

The spectra of a luminescence of a drop of dye show, that the picture of a luminescence of a drop strongly varies at change of size of energy of irradiating pulses, namely at power more than 0,5 mJ the spectrum has precisely expressed twohumped structure. Thus second the longwave peak at first prevails above first short-wave, but at increase of power disappears, and in a spectrum of radiation of a drop there is only short-wave peak, and it gets lance structure.

The change of the recorded OA-signal from the droplets of pure ethanol and the solution of R6G in ethanol with the concentration of 10^{-3} mol/liter looks roughly identically. This indicates that the processes of formation of acoustic responses from such droplets upon the femtosecond excitation are the same or very similar.

However, a the concentration of luminescent molecules increases up to 10^{-2} mol/liter, the pattern changes drastically. First, the recorded pressure in this case is much lower (roughly by an order of magnitude). Second, in the energy range of the exciting radiation from 2 to 4 mJ, no increase of the OA-signal is observed, but then the OA-signal increases approximately by the same law as in the cases of the pure solvent or the low dye concentration.

Possible explanation of observable distinctions given in work [3], following. It is known, that at influence on environment of laser radiation the size of a OA-signal is connected to the energy, absorbed in environment, and than more size of the absorbed energy, the more OA-signal. The reduction of size of a OA-signal from drops with concentration RG 10^{-2} mol/liter in comparison with feeblyconcentrate by dye and pure solvent is connected to reduction of absorption of laser radiation in a drop at increase of concentration of dye. The absorption of optical radiation in a drop is caused by absorption by molecules of the solvent and multiphoton by absorption by molecules of dye. Process competing to process multiphoton of absorption in dye, is the fluorescence of the exited molecules of dye. It is necessary to recognize, that received in work [3] experimental result yet has not found the strict theoretical substantiation.

4. Interaction of femtosecond laser pulses with biotissues

The results of experimental OA-research of easing femto- and nanosecond of pulses by some biological tissues (muscular tissue, adipose tissue, cutaneous covering, milk), and also thresholds optical breakdown on these tessues are below submitted. The technique of the executed researches is in detail given in works [2, 6, 11]. Samples of biofabrics of various thickness were placed on a piezoceramic plate, and at influence the laser pulse fixed the maximal amplitude of a OA-signal.

It is known, that for real biological tessues the reception of the pressure, normalized on size, of a OA-signal represents significant difficulties, as thermophysical parameters of researched biological environment, as a rule, are not known.

The results of the executed measurements show, that for a laser pulse of femtosecond duration the thresholds breakdown for muscular and adipose tessues practically coincide and make ~ 10 mJ (170 mJ/cm^2). For a skin cover the threshold optical breakdown is lower - ~ 5 mJ (83 mJ/cm^2).

The threshold for nanosecond of a pulse has appeared much above. The sizes of relative amplitude of the OA-response observed in experiments for nanosecond of pulses, approximately in 5 times are lower, than for femtosecond of pulses.

During performance of measurements [6] the luminescence of the examinees of objects in dark blue area of a spectrum ~ 0,4 µm was noticed at their irradiation by femtosecond pulses. At an irradiation by nanosecond pulses of the same energy of a luminescence was not observed. This effect to the authors of work [6] to explain it was not possible, that requires continuation of similar experiments.

The carried out researches show, that the weakening properties of the chosen biological objects for laser pulses of femtosecond duration do not differ from their optical properties for long pulses of the same energy and spectral structure. Hence, depth of penetration of radiation of short pulses in objects same, as well as for long. At the same time measured power thresholds optical breakdown and formation of the plasma centers on biotessures are much lower for short pulses, than for long.

The registered increase of amplitude of the OA-response at influence of femtosecond a pulse in comparison with nanosecond by a pulse is connected to downturn of a threshold optical breakdown on tessures and formation of the ionized plasma center, as the capacity in a femtosecond pulse reaches a threshold multiphoton of the mechanism of ionization, while at influence by a nanosecond pulse the ionization is realized only at the expense of the avalanche mechanism of isolation electrons.

5. Optoacoustics of area filamentation focused femtosecond laser radiation in air

The results and technique of experimental researches filamentation of the focused powerful laser beam at it self-channeling in air are submitted in [5].

Propagation of ultrashort laser pulses in atmosphere is accompanied by effects leading to transformation of spatial and temporal characteristics of laser beam. The most interesting effect for applied atmospheric optical problems is laser beam filamentation, i.e., forming of high-intensity waveguide channel, filament, in laser beam. This structure has diameter of 70÷100 µm, peak intensity 10^{14} W/cm^2, and length in range of several centimeters to hundred meters, that depends on propagation conditions and laser beam characteristics. The problem of control of spatial localization of filament path zone thereupon is rather relevant and demands of issue investigations connected with influence of optical system focal length upon filamentation process under condition of focusing effect of Kerr nonlinearity and defocusing plasma effect that appears during multiphoton ionization of medium in high-power laser beam.

There are many experimental and theoretical works dealing with investigation of spatial localization of filamentation region, location of nonlinear focus, and self-channeling beginning (collapse). The very beginning work is presented in [12] where it should be predicted for intensity laser beam propagating during focusing Kerr effect that a location of light beam focus (nonlinear focus) has spatial scale, proportional to power in a degree 0,5, if its power exceeds critical power for collapse. Nonlinear focus is always lower than geometric focus and is the most important characteristic in description of laser beam propagation in nonlinear media.

As the exact analytical formula for the description of length of nonlinear focus does not exist, the decision of this problem will usually be carried out by numerical modeling. Therefore is received, that the instability of the decision of the nonlinear equation Schrödinger for flat waves at self-modulation of a phase results in linear dependence of a situation of nonlinear focus on capacity, on what for the first time is specified in [13].

In work [14] the empirical ratio received by results of experimental researches and allowing with acceptable accuracy to determine a spatial situation of nonlinear focus for of collimated laser beams is given.

The extent of area filamentation, including distance from focusing system before nonlinear focus, is reduced with increase of an fine focus. For this case in [14] the ratio allowing to determine a situation of nonlinear focus is given.

It is necessary to notice, that in received in work [14] a ratio the initial capacity of a beam enters. This restriction for of collimated beams or beams with length focusing, close to Rayleigh length of a beam, can give the satisfactory consent of the theory with experiment. However dependence of Kerr effect from intensity of laser radiation puts under doubt validity received in [14] of ratio at fine focusing, as the intensity in this case depends on longitudinal coordinate.

For research of dynamics of a rule of nonlinear focus and length of a filamented site of a laser beam in [5] the OA-method was used which allows non destructive testing by a way with acceptable accuracy to determine borders of area filamentation, that was marked in work [1].

We used three approaches in our measurements. The first was for focusing mirror with focal length 86 cm. Acoustic signal was recorded in longitudinal direction relative on filamentation zone. For this purpose microphone was placed in alignment with laser beam at the distance of 61 cm from focusing mirror and at 2 cm from laser beam. At that forming of time scanning of OA-signal took place by summarize of signals generated by filamentation volume elements on durations: from the beginning of zone, i.e., nonlinear focus, to remote relatively microphone zone, i.e., geometric focus.

Spindle-shaped OA-source, as filament is, emits heteropolar OA-pulses in longitudinal direction, which correspond to near and far basis of «spindle» relative to receiver. At that spatial signal location corresponding to far basis of «spindle» stably localized closed to geometric focus. This signal corresponds to OA-response from optical breakdown plasma formed in geometric focus of mirror at different laser pulse energy in the experiment owing to that beam part that intensity is not enough for Kerr self-focusing.

Using a mirror with focal length 130 cm for determination of size of filamentation zone we applied another approach. Microphones were placed normally to laser beam at distance of 1.5 cm from it in areas approximately corresponding to filament forming beginning and its disappearance. Microphones were scanned equidistantly to laser beam axis. Pulse repetition frequency is 10 Hz. Points of filament beginning and ending were determined on sharp increase of OA-response (to two times) in the microphone output from filamentation zone.

From the received results it is followed that with increased of pulse energy beginning from about 1 mJ filament beginning is closing to focusing mirror (away from geometric mirror focus), i.e., with energy or radiation intensity increase nonlinear focusing of radiation begins to contribute. At that a location of far (respectively to mirror) boundary of filament does not practically change. Near to focusing mirror a fiament boundary at energy range of 1÷14 mJ closes to mirror from geometric focus on linear low: on about 25 cm for mirror with focal length 130 cm and on about 12 cm for mirror with focal length 86 cm.

Thus it was experimentally shown that under sharp focusing of laser beam an increase of initial power of laser pulse leaded to shifting of nonlinear focus from geometric one to source and directly proportional to increase of initial laser pulse power.

In summary it is necessary to note, that increase of width of a spectrum of a supershort laser pulse in a filamentation zone of a beam to proportionally effective length of existence filamenta [15]. According to the submitted above results length filamenta is proportional to initial capacity of laser radiation. Hence, increase of width of a spectrum of laser radiation of proportionally entrance capacity at its moderate sizes for self-channeling and focal length of optical system, is significant smaller of Rayleigh length of a beam.

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