ACOUSTIC EFFECTS OCCURRING IN OPTICAL BREAKDOWN WITH A LIQUID BY LASER RADIATION

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Researches of the acoustic effects accompanying optical breakdown in a liquid, generated by the focused laser radiation have been carried out at interaction with a liquid surface. Researches have been spent on the first and the second harmonics of Nd:YAG laser. Density of power for laser impulse was $10^{11} \text{ W/cm}^2$. Various modes of movement of plasma fronts have simultaneously been investigated at various focusings of laser radiation. Estimations of acoustic radiation power were spent and dynamics of spectral structure of acoustic radiation have been investigated at various modes of plasma fronts movement. It is shown, that two spectral maxima characterizing acoustic emission are observed. The displacement of a low-frequency maximum in area of smaller frequencies is observed at increase energy of laser impulse. As a whole the linear dependence of acoustic pressure on the energy of laser pulses is observed. Using acoustic data it is possible to reproduce function $R(t)$ which will be in accord with characteristic dependences $R(t)$, obtained from optical data that is practically important for breakdown studying in opaque environments.

1. Introduction

Optical breakdown caused by laser radiation has explosive properties$^1$. Especially large data sets have been accumulated for breakdown in gases, for which a detailed description of mechanisms was given in papers$^{1,2}$. Optical breakdown in condensed media remains poorly studied. An excellent review of recent achievements in the field of physics of bubble oscillations in liquid, and particularly in the dynamics of bubbles that form under the effect of laser radiation in liquid, was presented in papers$^3$. The authors of paper$^4$ investigated the energy balance of various mechanisms of energy transmission from the breakdown region and revealed the high efficiency of optical energy’s transformation into acoustic energy, which lay in the range of 10–49% and depended largely on the energy and duration of a laser pulse. Such a large spread in the efficiency of acoustooptical transformation in liquid was associated with the different mechanisms of generating acoustic waves upon optical breakdown caused by laser pulses with various energies and with different focusing of the laser radiation in liquid. It was therefore of interest to study the dependence of acoustic emission on the laser pulse energy and its focusing in liquid, and on the presence of an additional source of sound that could facilitate optical breakdown.

2. EQUIPMENT AND SCHEME OF EXPERIMENTS

Our experimental layout is shown in Fig. 1. To excite optical breakdown in each experiment, we used a Brilliant B Nd:YAG laser with an emission wave length of 532 nm, a pulse duration of
10 ns, and pulse energies of up to 180 mJ, with the last varied in a modulated Q-mode. The power density of the laser radiation grew in addition, due to sharp focusing of the radiation wherever needed (in the liquid’s depth, near its surface, or on its surface) using lenses (4) with different focal lengths $F = 40$, 75, and 125 mm. The distribution of the radiation in the breakdown region varied, depending on whether a short or long focus lens was used. Optical breakdown was detected using a Flame Vision PRO System optical multichannel spectral analyzer with a temporal resolution of 3 ns. As a whole the optical scheme of experiment is similar to the schemes presented in papers $5,6$.

Experiments were performed according to the scheme in Fig. 1. Acoustic radiation was controlled using a GSPF_053 digital generator of arbitrarily shaped signals $9$ and broad band amplifier $10$ with maximum amplitude at a resonance of $10^5$ Pa.

![Figure 1](image)

**Figure 1.** Experimental layout: (1) computer, (2) data input–output board, (3) laser, (4, 5) lenses, (6) monochromator coupled to a CCD camera, (7) acoustic emitter, (8) hydrophone, (9) digital signal generator, and (10) power amplifier.

The processing procedure was as follows. The first, a series of images of optical breakdown with exposures of 3 ns and different steps of temporal delay relative to the onset of breakdown were recorded in each experiment. Then we processed the images depending on the delay time in order to investigate the formation and growth dynamics of bubbles in liquid. And finally an analysis of simultaneously written acoustic information allowed us to relate the dynamics of bubbles to the parameters of acoustic emission from the optical breakdown region.

3. **Acoustical emission for different types of optical breakdown**

The most of our experimental data were based on the spectral density of acoustic emission for different types of breakdown in water: surface breakdown, breakdown in the water’s depth, and mixed breakdown. Different types of breakdown in water were achieved by focusing the laser radiation with a variety of lenses. Breakdown thus occurred either in the water’s depth, or in near_surface layers of water, or in a combination of the abovementioned types of breakdown. In the figure 2 the spectral density of acoustic emission is presented for two different types of breakdown in the water: near the surface and within the water. It was determined that the acoustic emission (spectral density of sound) differed substantially depending on the character of optical breakdown.
Figure 2. Spectral density of acoustic emission for different types of breakdown in the water: a) – within the water (lower curve) and b) – near the surface

The measurements of acoustic emission were then used to investigate the dependences of the efficiency of sound generation on the laser pulse energy \( E \). Figure 3 shows the dependence of the sound pressure \( P \) in the leading edge of the acoustic pulse on the energy \( E \). The spectral characteristics of an acoustic wave generated in liquid by optical breakdown, depending on the energy of the laser pulse, are shown in the insert in Fig. 3.

Figure 3. Dependence of the sound pressure \( P \) at the front edge of the acoustic pulse on the energy \( E \). The shift of the peak frequency of acoustic emission upon the increase in laser pulse energy \( E \) is shown in the insert.

It can be seen that the low frequency maximum shifts into the regions of lower frequencies as the pulse energy rises. The higher frequency spectral maximum, which remains the same at all laser pulse energies, is probably associated with the intrinsic resonance of the hydrophone at frequencies of \( \sim 300 \) kHz. It can be seen that the dependence of the acoustic pressure on the laser pulse energy is generally linear. Let us analyze the dependence of acoustic emission on the bubble dynamics. The total energy of an acoustic pulse \( E_{ac} \) is calculated using the formula

\[
E_{ac} = \int_{V_{ac}} \langle p(r,t)v(r,t) \rangle dV.
\] (1)
where the angle brackets for function denote averaging over time of type At great distances where acoustic emission is detected, the wave front in the area of detection can be considered planar; hence, we have a relation between the pressure and velocity of particles in the wave in the form [2] where \( \rho \) is density, \( c \) is the speed of sound,

\[
E_{ac} = \frac{2\pi r^2}{\rho c} \int_0^\tau P_r^2(t)dt.
\]  

(2)

and \( P_r(t) \) is the magnitude of the acoustic pressure in the pulse with duration \( \tau \), measured using the hydrophone at distance \( r \) from the point of breakdown. The evaluation of the acoustic emission energy indicates that the efficiency of the optoacoustic transformation in our case was \( 10\% \) \(^{7,9} \), which agrees with the data in \([4]\) at the lowest limit. Along with assessing the total energy of the emitted acoustic pulse, it was of interest to solve the inverse problem, or to reconstruct the bubble dynamics from the data on acoustic emission\(^{8,9}\). Our theoretical base was the formula for the pressure distribution in a wave emitted from a spherical bubble as a source of monopole radiation, written in the form \([3]\)

\[
P_r(t) = \rho(R\ddot{R} + 2\dot{R}^2)(R/r).
\]  

(3)

where the velocity of bubble wall motion is associated with the velocity of particles in a wave propagated on the bubble’s surface by boundary condition. In order to calculate function \( R(t) \), we must solve nonlinear differential equation (3) relative to function \( R(t) \), keeping in mind that function \( P_r(t) \) is based on the experimental data for a measured acoustic pulse. Having calculated function \( R(t) \), we can determine the velocity of bubble wall motion and the velocity of a wave on the bubble’s surface. Finally, the intensity of the acoustic wave can be calculated using the formula

\[
I = \langle P_r(t)\dot{R}(t) \rangle. \tag{4}
\]

in which the pressure on the bubble’s surface can be recalculated from the data on measuring pressure with the hydrophone at distance \( r \) from the bubble:

\[
P_r(t) = (r/R)P_r(t) \tag{5}
\]

4. Features of optical breakdown of liquid under the action of ultrasound

Further we represent results on studying of optical breakdown of liquid at additional influence of ultrasound. The main attention is concentrated on dynamics of the acoustic emission accompanying pulsations of a bubble, formed at late stages of evolution of plasma breakdown of liquid under the influence of laser radiation. The detection of breakdown thresholds and essence of acoustic emission in fresh and sea water was important.

In Figure 4 the excess of the spectrum of acoustic emission at simultaneous acoustic and laser radiation of water in comparison with the spectrum of acoustic emission without laser radiation is submitted. One can see a multiple harmonicas of the incident radiation. The difference of harmonicas levels are 0 dB with breakdown and without breakdown. Thus, one can see that the additional laser radiation with energy in the impulse 56 mJ leads to increase the acoustic emission from an interaction zone with liquid.

In Figure 5 the excess of acoustic emission at simultaneous acoustic and laser radiation of water in comparison with the spectrum of acoustic emission without acoustic emission is submitted. One can see a multiple harmonicas of the incident radiation (the main harmonica with a frequency of 29 kHz). The excess of a noise emission level in intervals between harmonicas averages 18 dB at frequencies about 100 kHz as opposed to the excess of an emissions at the separate frequencies reaching 40 dB.
Figure 4. The excess of the spectrum of acoustic emission at simultaneous acoustic and laser radiation of water in comparison with the spectrum of acoustic emission without laser radiation.

Figure 5. The excess of a spectrum of acoustic emission at simultaneous acoustic and laser radiation of water in comparison with the spectrum of acoustic emission without acoustic emission.

Thus, it is shown that the additional acoustic radiation leads to increase in an acoustic emission from a zone of interaction of laser radiation with liquid also as additional laser radiation with energy in an impulse 56 mJ leads to increase in acoustic emission from a zone of interaction of ultrasound with liquid.

One can see the contrast between the spectrum of acoustic emission at optical breakdown with acoustic radiation and without one. So in the Fig. 6 the specified spectrum of acoustic emission is presented at laser radiation of water from formation of breakdown. It is significantly lifted in comparison with the bottom curve of background noise without breakdown of water.

In the Figure 8 the difference of a spectrum of acoustic emission is presented at laser and acoustic radiation of water from formation of breakdown and a noise emission without acoustic radiation is presented. From Fig. 8 one can see the effect of laser radiation in appearing of a additional noise emission from the breakdown area which level averages about 2 dB. This effect in separate spectral sites reaches 4 dB.

Thus, the experimental results showing that joint impact of laser and ultrasonic radiation increases acoustic emission from a breakdown are received at the first time. Those results shows that development of cavitation effects in the field of interaction of ultrasound and laser radiation with environment are strong.
Figure 6. Spectrum of acoustic emission at laser radiation of water from formation of breakdown. Acoustic radiation of water wasn’t. The bottom curve marks a noise spectrum without water breakdown.

Figure 7. Difference of a spectrum of acoustic emission at laser radiation of water from formation of breakdown and a spectrum of a background of noise emission (acoustic radiation of water was absent).
Figure 8. Difference of a spectrum of acoustic emission of water by laser breakdown and ultrasonic radiation and spectrum radiation at laser breakdown without acoustic radiation.

Figure 9. The effect of huge extension of acoustic emission of water.

At last, the important effect found in experiments on registration of acoustic emission at laser breakdown of water is extension of acoustic emission of water. This effect is presented in Fig. 13. Thus, in this work the experimental result connected with acoustic emission at optical breakdown of sea water with or without ultrasound exceeds acoustic emission in fresh water is established for the first time. Acoustic emission of optical breakdown with or without ultrasound exceeds acoustic emission in fresh water was determined at the first time.
5. Conclusion

Our experimental results give us an idea of the energy redistribution with different types of optical breakdown in liquid. It was shown that two spectral maxima characterizing acoustic emission are observed, and the low frequency maximum shifts to the region of lower frequencies when the laser pulse energy is increased. The dependence of the acoustic emission pressure on the laser pulse energy is generally linear. We succeeded in reconstructing function $R(t)$ from the acoustic data; it agrees with characteristic dependences $R(t)$ found from the optical data. This is of practical importance in investigating breakdown in opaque media. It was shown that the effect of sound enhances acoustic emission from the zone of optical breakdown. Acoustic emission of optical breakdown with or without ultrasound exceeds acoustic emission in fresh water was determined at the first time. It is interesting to note that the threshold for optical breakdown in sea water was less then in fresh water and the level of acoustic emission from the region of optical breakdown in sea water was greater in comparison with fresh water. The last experimental fact is not explained yet.

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REFERENCES