GENERATION OF ACOUSTIC PERTURBATIONS IN AIR AT OPTICAL BREAKDOWN BY RADIATION OF A NEODYMIUM LASER

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Received May 5, 1997

We have detected low-frequency acoustic waves generated by the plasma of optical breakdown in air at the intensity of incident radiation of the order of 10^6 W·cm^{-2}. *Using fast Fourier transform analysis we estimated the spectrum of the acoustic signal detected. The acoustic frequency is from* 10^3 *to* 10^4 Hz. *Measurements made with an electric probe showed that in plasma there occur oscillations of the electron density at a rate of* 10^5 *to* 10^6 Hz, *with the electron density that corresponds to the acoustic signal maximum being* 10^{16} cm^{-3}.

In recent years optical breakdown attracts much attention[1–3] in connection with the development of new methods for remote sensing of the atmosphere. It was found that the plasma occurring due to the optical breakdown can generate acoustic waves that may be useful for diagnostics of the breakdown region. For example, in Ref. 4 it was established that the plasma cell generates a sound pulse with approximately equal amplitudes of positive and negative half periods. However, the data from Ref. 4 are insufficient for characterizing the acoustic wave generation processes occurring at the optical breakdown.

In this paper we present some results of experimental studies of the acoustic perturbations generated at optical breakdown on a soot particle. To acquire information on plasma we have used an electric probe that provides for a possibility of tracing the dynamics of electron density oscillations that earlier have been observed in Ref. 5 using a spectral method.

Block-diagram of the experimental setup we used for studying dynamics of the acoustic perturbations and electron density in the breakdown plasma is depicted in Fig. 1. In order to initiate the breakdown we used spherical soot particles with the diameter d = 600–800 μm as seeds. To do this we placed an isolated soot particle in the focal region of a beam condensing lens using a glass thread of 0.1 mm in diameter. In that case the heat losses from such a particle were minimized and the process of the breakdown initiation could be considered spherically symmetric. Pulsed radiation from a neodymium glass laser (GOS–1001) delivering 500 J per pulse at 1.06 μm wavelength was focused with a lens having 15-cm focal length onto the particle. The focal spot had the diameter $2R$ = 5mm that provided power density in the focal region up to 0.63·10^6 W·cm^{-2}. The breakdown threshold estimated experimentally was 0.59·10^6 W·cm^{-2} at a pulse energy of 470 J. The laser was operated in a free generation mode with the pulse duration at half maximum level being 0.75 to 1 ms. To monitor the position of a seeding particle we used the beam of an auxiliary He–Ne laser with the radiation wavelength λ = 0.63 μm that made a focal spot of 0.1 mm in diameter on the particle. This auxiliary beam was directed along the optical axis of the main beam with a system of mirrors. In the discharge gap we have inserted a double Langmuir electric probe for measuring the breakdown plasma parameters. Acoustic signals from the breakdown were recorded with a piezoelectric sensor TsTS–19 (zirconium-titanium lead) with the transmission band up to 1 MHz and a commercially available acoustic sensor KD–45 with the pass band of 20 kHz. The acoustic sensors were installed at 10 cm distance from the focal spot center. The responses from the sensors were recorded with a memorizing oscilloscope C9–8 at a 20 MHz rate and with a dual channel oscilloscope C1–74. Then the signals were digitized and processed using a Fourier analysis algorithm. The oscilloscopes were synchronized by a trigger pulse from the main laser.

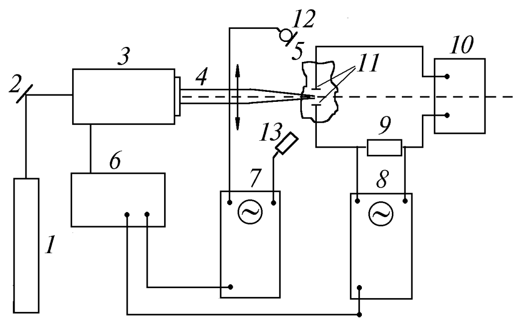

FIG. 1. Arrangement of the experimental setup for studying the dynamics of acoustic perturbations. 1 is a He-Ne *laser; 2 is a beam splitter; 3 is a* Nd-*glass laser; 4 is a lens; 5 is the optical breakdown plasma cell; 6 is a* Nd-*glass laser power supply; 7 is a dual channel oscilloscope; 8 is memorizing oscilloscope; 9 is the load resister of* 61.9 kOhm*; 10 is the power supply of the electrical probe; 11 is a probe; 12 is a microphone; 13 is an acoustic sensor.*

The origin of signals from the acoustic sensors was establish to be due to the processes in the breakdown region may be confirmed by the following facts.

First, no signals were recorded from the electric and acoustic sensors without a seed particle in the focal spot.

Second, the experimental arrangement excluded the possibility of detecting echoes either from the laser flash lamps or the laser installation itself since the travel time for sound to reach the focal spot from the laser was about 10 ms, while full time of the oscilloscope trace was only 2 ms.

Typical oscillogram of signals from the electric probe is shown in Fig. 2. The peak that is observed at about 1.2 ms time shows the start of the power supply capacitor discharge through the laser flash lamps. Then in approximately 400 μs the process of plasma formation begins. As seen from Fig. 2, the breakdown plasma lasts during about 1.5 ms. The electric conductivity of plasma that was experimentally measured at the moment corresponding to the maximum of signals from electrodes is $\sigma = 0.2\ \text{Ohm}^{-1}\cdot\text{cm}^{-1}$. Such a high conductivity value in the discharge gap well confirms the formation and existence of plasma here since, for instance, in Ref. 6 the conductivity measured with no laser irradiation equaled only $3\cdot10^{-17}\ \text{Ohm}^{-1}\cdot\text{cm}^{-1}$. The electron density in the plasma peak was estimated to be $n_e = 10^{16}\ \text{cm}^{-3}$.

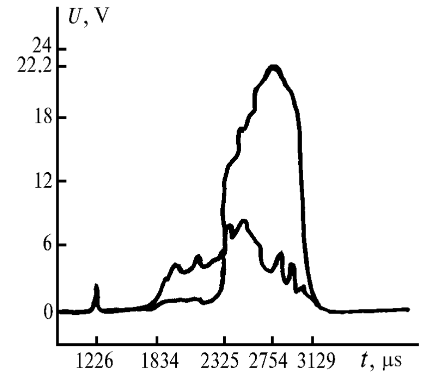

FIG. 2. The oscillogram of signals from the probe.

Figure 3 presents the oscillogram of acoustic signals from plasma recorded with a KD–45 sensor. The acoustic perturbations were recorded in this experiment in 3.38 ms after a trigger pulse, i.e., 2.1 ms after a laser pulse delivery. The acoustic impulse clearly exhibits the initial phase of compression that is followed by the rarefaction phase. The maximum pressure recorded in the sound wave was $P \approx 0.05\cdot10^5$ Pa. The duration of rarefaction phase in the acoustic response is about 300 μs that corresponds to the sound travel time at a speed of 300 m/s through the plasma cell region of 1 cm size. Assuming spherical symmetry off the process one may calculate the acoustic energy by the following formula:

$$W_a = 4\pi d^2 P_p^2\, \tau/(\rho_{air}\, c),$$

where d is the distance from the center of the lens focal plane; ρ_{air} is the air density; c is the speed of sound; P_p is the maximum pressure recorded with the sensor; τ is the duration of the compression and rarefaction phases in the acoustic impulse.

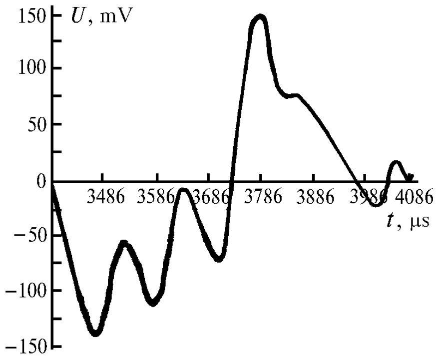

FIG. 3. The acoustic perturbation generated by the optical breakdown plasma.

If we have $d = 0.1$ m, $\rho_{air} = 1.29\ \text{kg/m}^3$, $c = 331$ m/s, $P = 0.05\cdot10^5$ Pa, and $\tau = 0.7$ ms then the estimate of the acoustic energy is $W_a = 2\cdot10^{-5}$ J.

The rate of the plasma cell expansion may be estimated by the following formula:

$$v \approx R/\tau,$$

where R is the characteristic size of the plasma cell and τ is the plasma cell lifetime.

The size R of a plasma cell has been determined from a discharge photo and it appeared that the length of plasma cell was about 2 cm while the transverse size being about 1 cm. The lifetime of the breakdown plasma formation may be taken to be 1 ms as it follows from the data of electric sounding. Correspondingly the speed values of breakdown front propagation were 20 and 10 m/s. These values show that the breakdown wave propagates in the slow burning mode.

The experimental error is mainly due to 15% accuracy of the sensor calibration and the error of oscillographing. The error of timing with the memorizing oscilloscope C9–8 doesn't exceed the estimate $\pm(0.5T_0/\Delta t_x)\%$, where T_0 is the duration of the storage time interval displayed on the screen and Δt_x is the time interval measured. In our case corresponding error is about 1%.

When estimating the acoustic response spectrum (see Fig. 4) the error essentially depends on the number of the discretization points. Calculations of the fluctuation variance have been carried out over 64 readouts at the discretization rate on the frequency scale being $9\cdot10^5$ Hz. Since the normalized random error in calculations of the variance is

$$\varepsilon\left(\sigma_T^2\right) \approx 1/\sqrt{N},$$

the resulting error was 12% at $N = 64$, where N is the number of readouts of the spectral curve.

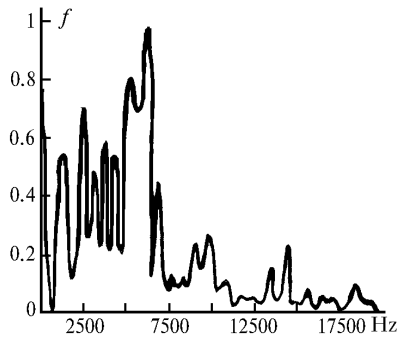

FIG. 4. Frequency spectrum of the plasma acoustic response.

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