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Spectrum of shock waves produced by an optical discharge at a high laser-pulse repetition rate

V.N.Tishchenko, G.N.Grachev, V.I.Zapryagaev, A.L.Smirnov, A.V.Sobolev

***Abstract*. The acceleration of a plasma jet by an optical pulsating discharge is studied. The optical discharge generated periodic shock waves or shock waves combined in periodic trains. For a pulse repetition rate $f > 50$ kHz, the line at frequency f dominated in the spectrum of periodic waves. The spectrum of trains following with the frequency $F_0 \ll f$ contained an ultrasonic component and a low-frequency component. The trains produces a strong acoustic effect. The average power of the waves amounted to 160 W, and the conversion efficiency of laser radiation to shock waves was $\sim 10\,\% - 25\,\%$.**

Keywords: *shock waves, optical discharge, plasma jet.*

1. Introduction

The shock waves (SWs) produced by single laser sparks have been studied in detail [1 – 8]. The sound excitation in a liquid at a high laser-pulse repetition rate, which was not accompanied by phase transitions, was studied in Refs [9 – 16]. An optical pulsating discharge (OPD) initiated by the repetitively pulsed laser radiation with a repetition frequency up to ~ 100 kHz was obtained in a supersonic gas flow [17]. The OPD produces a high-temperature trace with a low gas density as well as SWs [3, 7, 18 – 20]. Under certain conditions, the OPD produces a plasma jet [21] (calculations) and SWs with a controllable structure [22] (calculations and a preliminary experiment).

The aim of our experiment was to investigate the effect of the amplitude modulation of laser radiation on the structure and spectrum of periodic SWs and also of the SWs combined in trains or train packets. We also studied the spectrum control during the OPD and determined the conversion efficiency of laser radiation to SWs. For a high pulse repetition rate f inside the trains, periodic SWs interact with each other, and their spectrum is qualitatively different from the spectrum of waves with a low repetition rate, when the pulse duration is far shorter than $1/f$. Periodic trains of laser pulses convert to SWs, whose spectrum contains ultrasonic and low frequencies $F_0 \ll f$ (here, F_0 is the train repetition rate). The sound at frequency F_0 caused strong acoustic feelings, it was displayed with a video camera, recorded with a spectrometer, and was revealed in the spectrum by mathematical processing of the pressure signals measured in the SWs. Similar effects were earlier observed upon modulation of an ultrasonic beam. In Ref. [23], the ultrasonic beam produced acoustic feelings at its modulation frequency. Ultrasonic and low-frequency components were simultaneously present in the spectrum when employing a parametric radiator – an ultrasonic beam which was modulated in amplitude with the frequency $F_0 \ll f$ and was radiating at the frequency F_0. In this case, the efficiency of ultrasonic beam conversion to the low-frequency acoustic wave was very low ($\sim (F_0/f)^2 \sim 10^{-4} - 10^{-3}$, see review [24]).

V.N.Tishchenko, G.N.Grachev, A.L.Smirnov Institute of Laser Physics, Siberian Branch, Russian Academy of Sciences, prosp. akad. Lavrent'eva 13/3, 630090 Novosibirsk, Russia;
e-mail: tischenko@plasma.nsk.ru
V.I.Zapryagaev, A.V.Sobolev Institute of Theoretic and Applied Mechanics, Siberian Branch, Russian Academy of Sciences, Institutskaya ul. 4/1, 630090 Novosibirsk, Russia

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2. Experimental

The OPD in a gas was produced employing a CO_2 laser [25] which generated repetitively pulsed radiation with the following parameters: an average power of ~ 0.7– 1.5 kW, a pulse duration of ~ 1 μs, and a repetition frequency $f \sim 7 - 117$ kHz. The laser resonator could provide both repetitively pulsed radiation and periodic trains of laser pulses with no radiation between the trains. The trains contained a given number of pulses ($N \sim 10$– 30) following with the repetition rate f.

The OPD was produced at the focus of a lens on the axis of an argon jet issuing in the atmospheric air, which was required to stabilise the OPD. The energy of laser pulses was low and amounted to 0.02 – 0.1 J (depending on f), but it was high enough for the optical breakdown of Ar in the OPD. The radiation and jet axes were made coincident. Each radiation pulse produced a laser spark, which initially had a length $L \sim 3 - 5$ mm, a radius of 0.3 – 0.5 mm, and a pressure of tens of atmospheres. About 75 % of laser radiation was absorbed in the OPD.

The thermal expansion of the laser sparks produced SWs, which escaped from the jet into the immobile air to carry away $\sim 10\,\% - 25\,\%$ of the laser radiation power absorbed in the OPD. At a distance of ~ 3 cm from the OPD, the SWs were nearly spherical in shape. The pressure $p(t)$ in the SW was measured with a piezoelectric sensor. The sensor was shifted along the line which was perpendicular to the jet axis and intersected it near the beam focus. The pressure in the SW at a distance of 140 cm from the OPD was measured with a microphone possessing, like the sensor, a linearity band of no less than 100 kHz.

The signal from the sensor or the microphone was fed to the data recording system, where 4096 values with a discreteness of 1 μs were stored in a computer (the first point in time was given the value $t = 0$). The above number of points was sufficient for storing several trains of SWs (for $F_0 \sim 1$ kHz). The spectrum of $p(t)$ obtained by the Fourier transform had a discreteness of ~ 244 Hz. Experiments showed that to obtain a more detailed spectrum, the sampling should contain more than 2×10^4 data points with a discreteness of ~ 0.5 μs. For a low train repetition rate, the spectrum of the waves was measured with a spectrometer. The average power carried away by the SWs was determined from the measured average intensity of the waves under the assumption that they were spherically symmetric. The video camera recorded the sound and emission of the OPD plasma at a distance of ~ 30 cm from the OPD.

The following parameters were measured in experiments: the laser pulse repetition rate, the jet diameter (3 – 6 mm) and velocity V (100 – 400 m s^{-1}), the duration of the trains (0.0001 – 0.03 s) and their repetition rate (0.036 – 10 kHz), and the position of the piezoelectric sensor relative to the OPD ($R = 5 - 40$ cm). Two OPD modes were investigated: the repetitively pulsed mode and emission of pulse trains. In the former case, the OPD generated 'noiseless' SWs, because the spectrum of the waves in the frequency range above 10 kHz, where the human auditory system has a low sensitivity. In the train mode there appeared strong acoustic feelings. The reflected waves and the background acoustic field had only a slight effect on the results of measurements because the intensity of waves in the measurement region exceeded the background by 40 – 60 dB; the reflecting surfaces located close to the OPD were covered with a soundproof material.

3. Experimental results

3.1 Periodic SWs

Figs 1 and 2 show the pressure in the shock waves and their spectrum, which corresponds both to a low laser-pulse repetition rate [the SWs do not interact with each other, because the duration of the pause between them $\sim 1/f$ is significantly longer than the compression (t_+) and low-pressure (t_-) SW phases] and to a high repetition rate ($1/f < t_+ + t_-$). The low-frequency component of the spectrum $F < 1$ kHz was produced by the argon jet. The spectra of measured signals $p(t)$ were obtained employing the Fourier transform. The centre of the first line in the spectrum coincides with the laser-pulse repetition rate, and hence with the SW repetition rate. One can see from Fig. 2a that the spectrum of the signal for a low laser-spark repetition rate f contains a line at the pulse repetition rate $F \approx f$ and higher harmonics.

Fig. 2 shows the dependence of the ratio S between the SW power in the $0 - F$ spectral range and the total power of waves on F. For $f = 7.6$ kHz, the major part of the energy of waves is radiated in the high-frequency domain and only ~ 3 % correspond to the $F < 10$ kHz range, and therefore a low-intensity sound was produced during the OPD. As f was

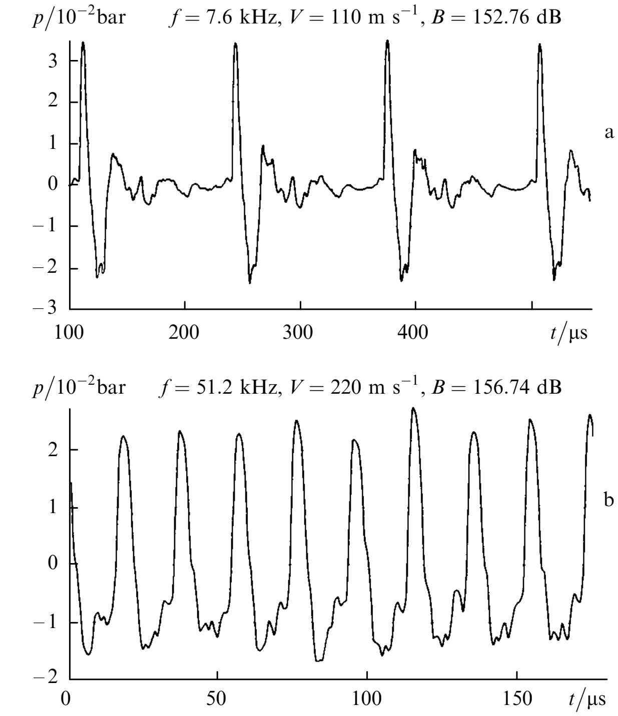

Figure 1. Time dependence of the pressure in the SW at a distance $R = 5$ cm from the OPD with a repetition rate f produced in an argon jet 6 mm in diameter issuing into the air with a velocity V for an average absorbed laser radiation power W = 535 (a) and 1290 W (b) and an average of the SWs radiated by the OPD $W_a = 58$ (a) and 147 W (b); B is the spectrum-integrated wave intensity.

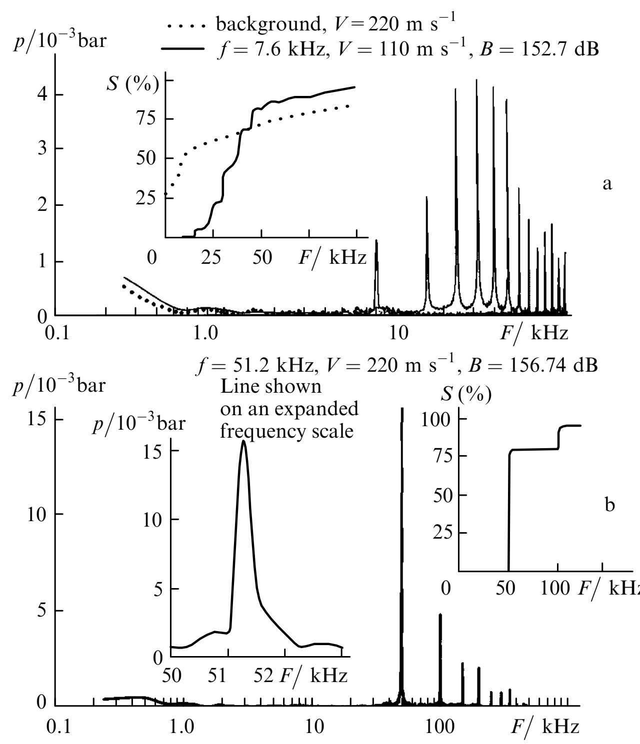

Figure 2. Spectrum of the SWs presented in Fig. 1 (solid lines) and spectrum of the background produced by the jet and the laser facility for $R = 5$ cm. The inserts show the $S(F)$ dependences for the SWs (solid curves) and the background (the dashed line) and also the profile of the strongest line.

increased, the number of intense harmonics in the spectrum decreased. Figs 1b and 2b show the pressure $p(t)$ in the waves and their spectrum for $f = 51.2$ kHz. For a high repetition rate of laser pulses (and hence of SWs), the interaction of waves takes place [22]. As a result, the pressure profile in the wave proves to be severely distorted compared to the profile of the SW of a point-like explosion. The narrow spectral range near the first harmonic $F = f$ accounts for the major part of the power of waves $S_1 \sim 80\,\%$. As f was further increased, the value of S_1 approached unity.

Fig. 2b shows the profile of the strongest line on an expanded frequency scale. In this case, as in other experiments, the characteristic line width is $\Delta F \sim 400$ kHz. This value is supposedly overestimated because the spectrum discreteness (~ 244 Hz) is comparable with ΔF. From the

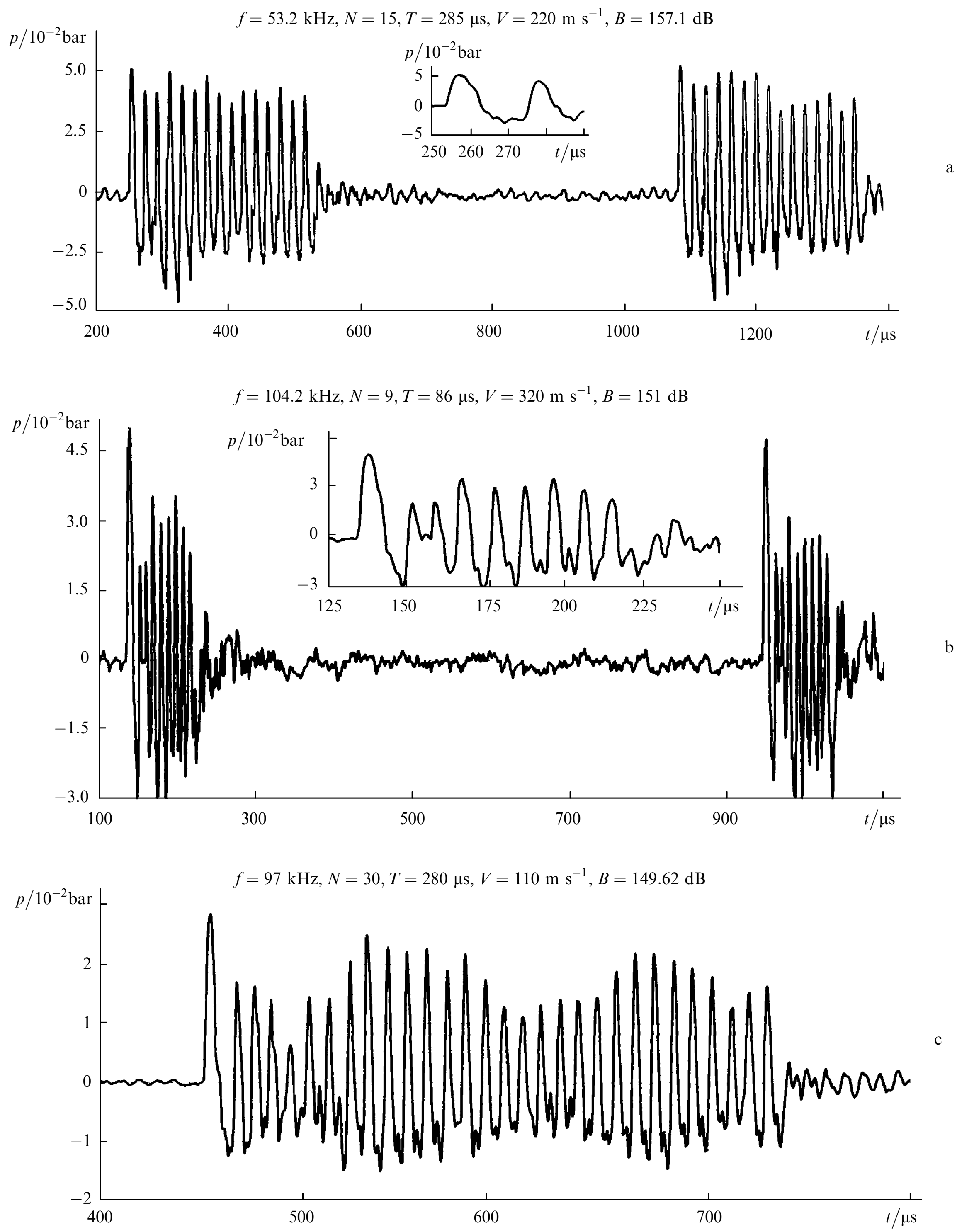

Figure 3. Pressure in the SWs produced by trains of laser pulses for $R = 5$ cm, $F_0 = 1.2$ kHz, $W = 677$ (a), 363 (b), and 536 W (c), $W_a = 161$ (a), 39.2 (b), and 28.6 W (c) ($T \sim N/f$ is the train duration).

measurements performed with a piezoelectric sensor it follows that the pressure in the SWs lowers with increasing distance to the OPD, and their average power, shape, and spectrum remain almost invariable. At a distance of 1.4 m from the OPD, the microphone recorded a harmonic signal of the form $p(t) \sim \sin(2\pi f t)$, whose spectrum contained a single line with $F = f \sim 51.2$ kHz and the power of waves was ~ 8 times lower than that obtained with a piezoelectric sensor. The measurement error was supposedly introduced by the mesh which covered the sensitive element of the microphone (and was responsible for the reflection of SWs).

3.2 Trains of shock waves

Fig. 3 shows the trains of SWs produced with the use of periodic trains of laser pulses. Figs 3 and 4 illustrate the effect of the repetition rate f and the number of pulses N in

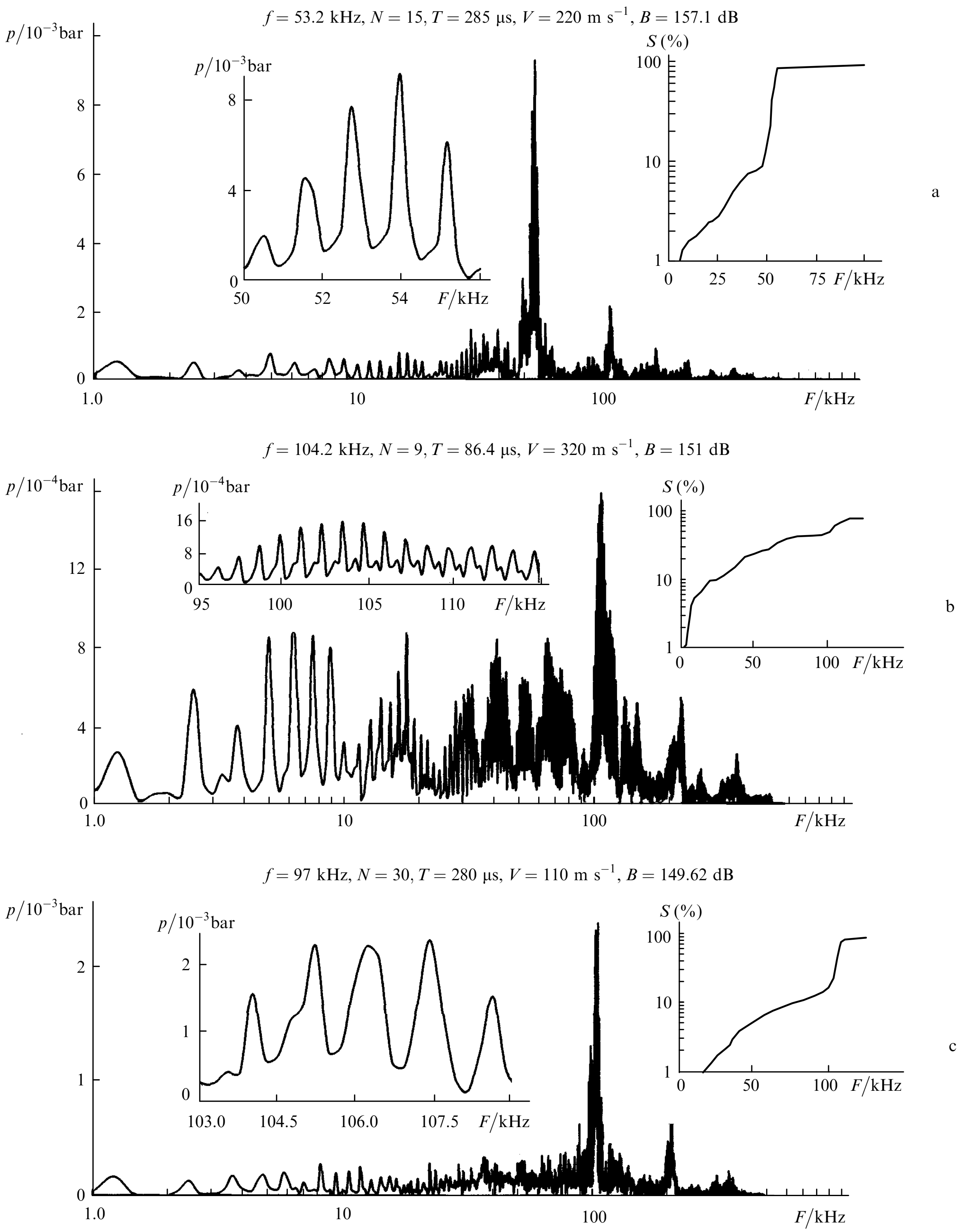

Figure 4. Spectrum of the SWs shown in Fig. 3 and dependences $S(F)$. Portions of the spectrum near the laser-pulse repetition rate in the trains is shown on an expanded frequency scale.

the train on the shape and spectrum of the SWs. During the OPD, the trains $p(t)$ repeat themselves with a good accuracy. Within a train, the SWs may substantially differ in shape, especially so for high $f \sim 100$ kHz. This is due to the nonuniformity of the conditions for laser spark production in the gas jet. The recurrence of trains is better for higher laser pulse energies and also when the jet manages to pull the spark plasma downstream during the pause between the pulses.

During the pause between the trains, the piezoelectric sensor records the pressure pulsations produced by the jet with the laser plasma decaying in it. Fig. 4 shows the spectra of pressure signals obtained employing the Fourier transform. The greatest difference from the regime of periodic wave production consists in the following: a low-frequency component appears in the spectrum, a group of closely spaced narrow lines forms at a frequency $F \approx f$ instead of a single line, and a low-frequency sound is produced at a frequency $F_0 \ll f$ and at higher harmonics. The background with an intensity $B \approx 80$ dB (summed over the entire spectrum) was perceived like a weak noise compared to the sound generated by the OPD (see Fig. 5 below).

Acoustic effects were observed both near the OPD, where the microphone of the video camera or the human auditory system experience the action of SWs, and far away from the OPD, where the influence of reflected signals is insignificant. The piezoelectric sensor was used to measure the pressure at a distance $R = 5 - 40$ cm from the OPD. The amplitude of the signals decreased with increasing distance to the source, while their shape (the trains of SWs) and spectrum changed insignificantly. Measurements at a large distance assisted with a microphone ($R = 140$ cm) showed that the pauses between the trains were filled with waves, and the structure of waves and trains was strongly smoothed out. The spectrum remained qualitatively the same: the major fraction of the power of waves is concentrated in the ultrasonic wave at a frequency $F \sim f$, the low-frequency component is also present.

To study the feasibility of controlling the spectrum of waves in a broad frequency range, we performed an experiment in which the sound was produced at a low frequency of 36 Hz or simultaneously at two frequencies of 36 and 1200 Hz. Fig. 5 shows the spectra recorded with a spectrometer which measured the average intensity in the $F_i \pm F_i/2$ frequency ranges (F_i are the centres of the ranges). Fig. 5a displays the spectrum of the background produced by the laser during operation in combination with the jet and the modulator of laser radiation (the microphone did not introduce errors in the measurements in the absence of SWs).

Fig. 5b shows the spectra of waves produced by the OPD for several train repetition rates F_0 and repetition rates f of SWs inside the trains. The sound at a frequency $F \approx 36$ Hz (curve *5*) was produced by the OPD which generated SW trains with a repetition rate $F_0 = 36$ Hz. The durations of the trains and of the pauses between them were equal to $0.5/F_0 \approx 0.027$ s. The low-frequency sound at two frequencies simultaneously (curves *3* and *4*) was produced with the use of triple modulation of laser radiation. The laser generated packets with a repetition rate $F_0 = 36$ Hz each of which contained ~ 30 trains, the radiation between the packets was missing for period of time of $\sim 0.5/F_0$. Inside each packet, the trains followed with a repetition rate $F_0 = 1.2$ kHz. Inside the trains, the laser pulses followed

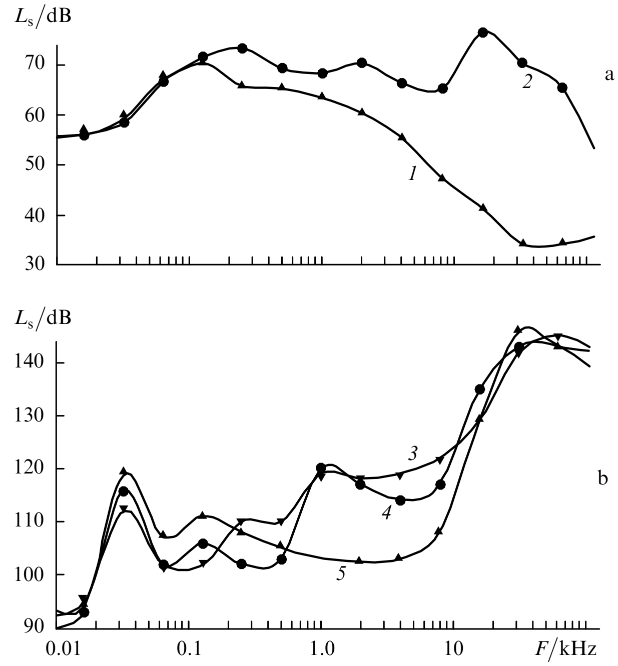

Figure 5. Spectra of the background (a) and of the OPD and the background (b) in the $F_i \pm F_i/2$ frequency bands: (*1*) the background was produced by the laser, the measurements were performed employing a microphone placed at a distance $R = 140$ cm from the OPD, the intensity integrated over the spectrum was $B = 73$ dB; (*2*) the background was produced by the laser, the jet ($V = 110$ m s^{-1}), and the modulator of laser radiation for $B = 81$ dB, the data were obtained using the piezoelectric sensor ($R = 5$ cm); (*3*) the pulse repetition rate $f = 52$ kHz, the train and packet-of-trains repetition rates $F_0 = 1.2$ and $F_1 = 0.036$ kHz, $W = 440$ W; (*4*) $f = 25$ kHz, $F_0 = 1.2$, $F_1 = 0.036$ kHz, $W = 285$ W, and $B = 147$ dB; (*5*) $f = 25$ kHz, $F_0 = 1.2$ kHz, $F_1 = 0.036$ kHz, $W = 675$ W, and $B = 149$ dB.

with a repetition rate $f \approx 52$ kHz (curve *3*) or 25 kHz (curve *4*). With reference to Fig. 5b, the spectrum shows intensity peaks whose position in the ultrasonic domain corresponds to the laser pulse repetition rate in a train and in the low-frequency domain to the train repetition rate $F_0 = 1.2$ kHz and the packet-of-trains repetition rate $F_1 = 0.036$ kHz. Here, the main part of power of the waves is radiated at the laser pulse repetition rate.

The results of measurements, including those not presented in the paper, suggest that under our experimental conditions there occurred neither the generation of SWs or low-frequency sound (extracted from the background) unrelated to the action of the OPD nor the generation of low-frequency sound as a result of either the interference of the waves reflected from the walls or the vibration of the elements of the setup. This is confirmed by the following data: the SW repetition rate coincided with the laser pulse repetition rate; the intensity of SWs lowered with receding from the OPD; lowering the output laser power reduced the intensity of low-frequency sound and the average power of waves; the pressure in wave trains was much higher than in the pause between the trains; when the train repetition rate was smoothly increased ($F_0 \approx 0.3 - 15$ kHz), the tonality of the low-frequency sound rose, the sound causing weak acoustic sensations for $F_0 > 10$ kHz. The frequency F_0 was subsequently varied in the reverse order: it was lowered from 15 to 0.3 kHz. In this case, there appeared intense sound, and its frequency lowered as F_0 was decreased. A similar experiment was performed involving the variation of F_0 from ~ 30 to 150 Hz. The experimental facility did not contain elements whose vibrational excitation might produce the low-frequency sound tuneable over such a broad frequency range with an intensity well above the background one.

Therefore, the OPD converts laser radiation to spherical SWs – periodic waves or waves combined in trains. The spectrum of periodic waves contains several intense lines in the ultrasonic frequency region ('noiseless' SWs). The spectrum of SW trains exhibits lines located at the laser pulse repetition rate and the low frequency of train recurrence, and also their harmonics. A strong low-frequency sound is produced in this case. In both cases, the main part of power of the waves is concentrated near the laser pulse repetition rate. During the discharge, the spectrum of waves can be promptly controlled over a broad frequency range by varying the modulation frequencies of laser radiation and (or) by varying its power. The conversion efficiency of laser radiation to SWs amounted to $\sim 25\,\%$ and maximum average power of waves was ~ 160 W.

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