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*LASER APPLICATIONS AND OTHER TOPICS IN QUANTUM ELECTRONICS*

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# Stationary force produced by an optical pulsating discharge in a laser engine model

G.N. Grachev, V.N. Tishchenko, V.V. Apollonov,
A.I. Gulidov, A.L. Smirnov, A.V. Sobolev, M.I. Zimin

*Abstract*. **An optical pulsating discharge produced by repetitively pulses laser radiation (with a pulse repetition rate of up to 100 kHz) is studied in a cylindrical tube simulating the reflector of a laser engine. The pressure of shock waves and the propulsion produced by them are measured. The discharge produced the stationary propulsion $\sim 1$ N kW$^{-1}$.**

***Keywords***: *optical pulsating discharge, laser engine, shock waves, propulsion.*

## 1. Introduction

Since the 1970s, the possibility of using a laser engine to launch light satellites into orbit has been attracting the attention of researchers [1 – 9]. The solution of problems considered in [3] is still of current interest. This is an increase in the efficiency – the coupling coefficient $J_{\rm r}$ of using laser radiation (the ratio of the propulsion to the radiation power) by several times and the prevention of the shock damage of the apparatus, which appears when high-power repetitively pulsed laser radiation with low repetition rates $f$ is used. For example, for $J_{\rm r} \sim 0.3$ kN MW$^{-1}$ (this value is typical for an air-jet laser engine), the mass of 200 kg, and the acceleration of 10g, the required laser power should be $\sim 60$ MW (the energy $Q \sim 100$ g in the trotyl equivalent, $f \sim 100$ Hz), and the power of a power supply should be 0.5 – 1 GW. However, it seems unlikely that such a laser will be created in the near future. In our experiments, $J_{\rm r} \sim 1$ kN MW$^{-1}$ (obtained experimentally) and 3 – 5 kN MW$^{-1}$ (estimate, special conditions), which allows us to reduce the laser power by a factor of 3 – 10. A power of 10 – 15 MW can be obtained already at present with the help of gas-dynamic lasers by using the properties of repetitively pulsed lasing with high repetition rates and methods for power scaling of lasing [10, 11].

To solve these problems, it was proposed to use repetitively pulsed radiation with $f \sim 100$ kHz, the optical pulsating discharge (OPD), and the effect of merging of shock waves produced by the OPD [12 – 14]. The merging criteria were confirmed in experiments [15]. The OPD is laser sparks in the focus of repetitively pulsed radiation, which can be at rest or can move at high velocities [16 – 20]. The high-frequency repetitively pulsed regime is optimal for continuously-pumped $Q$-switched high-power lasers. In this case, the pulse energy is comparatively small and the stationary propulsion is possible.

The aim of our paper is to verify experimentally the possibility of using laser radiation with a high pulse repetition rate to produce the stationary propulsion in a laser engine.

## 2. Experimental

In the model considered in [12 – 14], the pulsed and stationary regimes are possible. Figure 1 explains the specific features of these regimes. An OPD is produced at the focus of a lens on the axis of a gas jet flowing from a high-pressure chamber or an air intake to a cylindrical reflector. The shock waves generated by the OPD merge to form a quasi-stationary wave – the high-pressure region

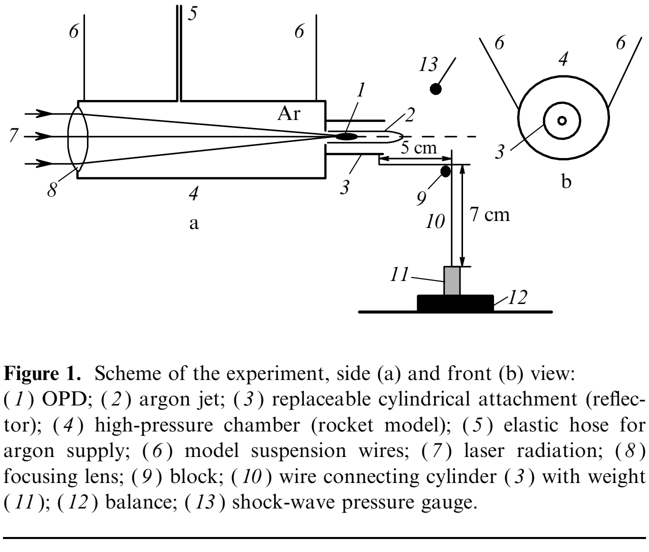

**Figure 1.** Scheme of the experiment, side (a) and front (b) view: (*1*) OPD; (*2*) argon jet; (*3*) replaceable cylindrical attachment (reflector); (*4*) high-pressure chamber (rocket model); (*5*) elastic hose for argon supply; (*6*) model suspension wires; (*7*) laser radiation; (*8*) focusing lens; (*9*) block; (*10*) wire connecting cylinder (*3*) with weight (*11*); (*12*) balance; (*13*) shock-wave pressure gauge.

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**G.N. Grachev, V.N. Tishchenko, A.L. Smirnov, M.I. Zimin** Institute of Laser Physics, Siberian Branch, Russian Academy of Sciences, prosp. Akad. Lavent'eva 13/3, 630090 Novosibirsk, Russia; e-mail: grachev@laser.nsc.ru;
**V.V. Apollonov** A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia; e-mail: vapollo@kapella.gpi.ru;
**A.I. Gulidov, A.V. Sobolev** S.A. Khristianovich Institute of Theoretical and Applied Mechanics, Siberian Branch, Russian Academy of Sciences, ul. Institutskaya 4/1, 630090 Novosibirsk, Russia; e-mail: gai@itam.nsc.ru

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between the OPD and reflector. As a result, the propulsion $F_r$ appears. In a cylindrical reflector, the coupling coefficient is maximal, $J_r = 1.1$ N kW$^{-1}$ [13], as for a plane explosion [21]. In the pulsed regime, the OPD is produced by trains of laser pulses. A narrow jet of diameter $D_j \sim 0.3R_d$ [13], which is smaller than the reflector diameter $D_r$, carries a plasma out from the OPD region, which is necessary for the efficient formation of shock waves. Here, $R_d = 2.15(q/P_0)^{1/3}$ is the dynamic radius of a spark, $q$ (in J) is the laser pulse energy absorbed in a spark, and $P_0$ (in atm) is the gas pressure. The propulsion acts during a pulse train, whose duration is limited by the air heating time. The hot atmospheric air is replaced by the cold air during the interval between pulses. In the stationary regime, gas continuously arrives to the reflector from the bottom, by forming a jet over the entire section. In experiments in this regime, we have $D_j \sim 2R_d \sim 3$ mm, which is comparable with the reflector diameter $D_r \sim 5$ mm.

The scheme of the experiment is shown in Fig. 1. The OPD was produced by radiation from a pulsed $CO_2$ laser. The pulse duration was $\sim 1$ μs, the duration of the front peak was 0.2 μs. The pulse repetition rate was varied from 7 to 100 kHz, the pulse energy was 0.1 – 0.025 J. The peak power was 300 – 100 kW, the average power of repetitively pulsed radiation was $W = 600 - 1700$ W, and the absorbed power was $W_a = \eta W$ ($\eta \approx 0.7$). Figure 2 shows the shapes of the incident pulse and the pulse transmitted through the OPD region. Note that for a short pulse duration and high power, $\eta \sim 0.95$. Because the radiation intensity at the focus is lower than the optical breakdown threshold in air, the argon jet was used. The length $l$ of sparks along the flow was $\sim 0.5$ cm.

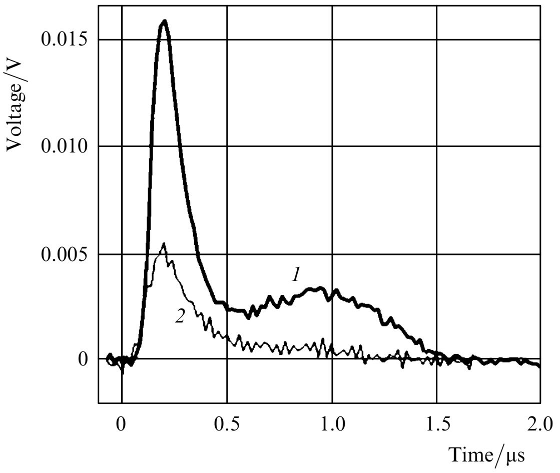

**Figure 2.** Oscillograms of the laser pulse (*1*) and radiation pulse transmitted through the OPD (*2*) for $f = 50$ kHz.

The model of a rocket with a laser engine was a duralumin cylinder of diameter $\sim 8$ cm, length $\sim 26$ cm, and weight 1.1 kg, which was suspended on four thin wires of length 1.1 m and capable of moving only in the axial direction. A reflector (replaceable cylindrical attachment) was mounted on the chamber end. Laser radiation was directed to the chamber through a lens with a focal distance of 17 cm. The argon jet was formed during flowing from a high-pressure chamber through a hole of diameter $\sim 3 - 4$ mm. The jet velocity $V$ was controlled by the pressure of argon, which was delivered to the chamber through a flexible hose. The force produced by the jet and shock waves was imparted with the help of a thin (of diameter $\sim 0.2$ mm) molybdenum wire to a weight standing on a strain-gauge balance (accurate to 0.1 g). The wire length was 12 cm and the block diameter was 1 cm.

The sequence of operations in each experiment was as follows. A weight fixed on a wire was placed on a balance. The model was slightly deviated from the equilibrium position (in the block direction), which is necessary for producing the initial tension of the wire ($\sim 1$ g). The reading $F_m$ of the balance was fixed, then the jet was switched, and the reading of the balance decreased to $F_1$. This is explained by the fact that the rapid jet produces a reduced pressure (ejection effect) in the reflector. After the OPD switching, the reading of the balance became $F_2$. The propulsion $F_r$ produced by the OPD is equal to $F_1 - F_2$. The pressure of shock waves was measured with a pressure gauge whose output signal was stored in a PC with a step of $\sim 1$ μs. The linearity band of the pressure gauge was $\sim 100$ kHz. The gauge was located at a distance of $\sim 5$ cm from the jet axis (see Fig. 1) and was switched on after the OPD ignition ($t = 0$). The pressure was detected for 100 ms.

Let us estimate the possibility of shock-wave merging in the experiment and the expected values of $F_r$ and $J_r$. The merging efficiency depends on the parameters $\omega = fR_d/C_0$ and $M_0 = V/C_0$ ($M_0 < 1$), where $C_0$ is the sound speed in gas. If the distance from the OPD region to the walls is much larger than $R_d$ and sparks are spherical or their length $l$ is smaller than $R_d$, then the frequencies characterising the interaction of the OPD with gas are

$$\omega_0 \approx 2.5M_0, \tag{1}$$

$$\omega_1 \approx 0.8(1 - M_0), \tag{2}$$

$$\omega_2 \approx 5.9(1 - M_0)^{1.5}. \tag{3}$$

For $\omega < \omega_1$, the shock waves do not interact with each other. In the range $\omega_1 < \omega < \omega_2$, the compression phases of the adjacent waves begin to merge, this effect being enhanced as the value of $\omega$ approaches $\omega_2$ In the region $\omega > \omega_2$, the shock waves form a quasi-stationary wave with the length greatly exceeding the length of the compression phase of the shock waves. For $\omega < \omega_0$, the OPD efficiently (up to $\sim 30$ %) transforms repetitively pulsed radiation to shock waves.

In the pulsed regime the value of $M_0$ in (1) corresponds to the jet velocity. Because shock waves merge in an immobile gas, $M_0 \approx 0$ in (2) and (3). The frequencies $f = 7 - 100$ kHz correspond to $R_d = 0.88 - 0.55$ cm and $\omega = 0.2 - 1.7$. Therefore, shock waves do not merge in this case. In trains, where the energy of the first pulses is greater by a factor of 1.5 – 2 than that of the next pulses ($\omega \approx 2$), the first shock waves can merge. The propulsion produced by pulse trains is $F_r = J_r\eta W = 0.3$ N ($\sim 30$ g), where- $J_r = 1.1$ N kW$^{-1}$, $\eta = 0.6$, and $W \sim 0.5$ kW.

In the stationary regime for $M_0 \sim 0.7$, the shock wave merge because $\omega > \omega_2$ ($\omega = 1.8$, $\omega_2 \approx 1.3$). A quasi-stationary wave is formed between the OPD and the cylinder bottom. The excess pressure on the bottom is $\delta P = P - P_0 = 0.54P_0(R_d/r)^{1.64} \approx 0.25 - 0.5$ atm, and the propulsion is $F_r \approx \pi(D_r^2 - D_j^2)\delta P/4 = 0.03 - 0.06$ kg.

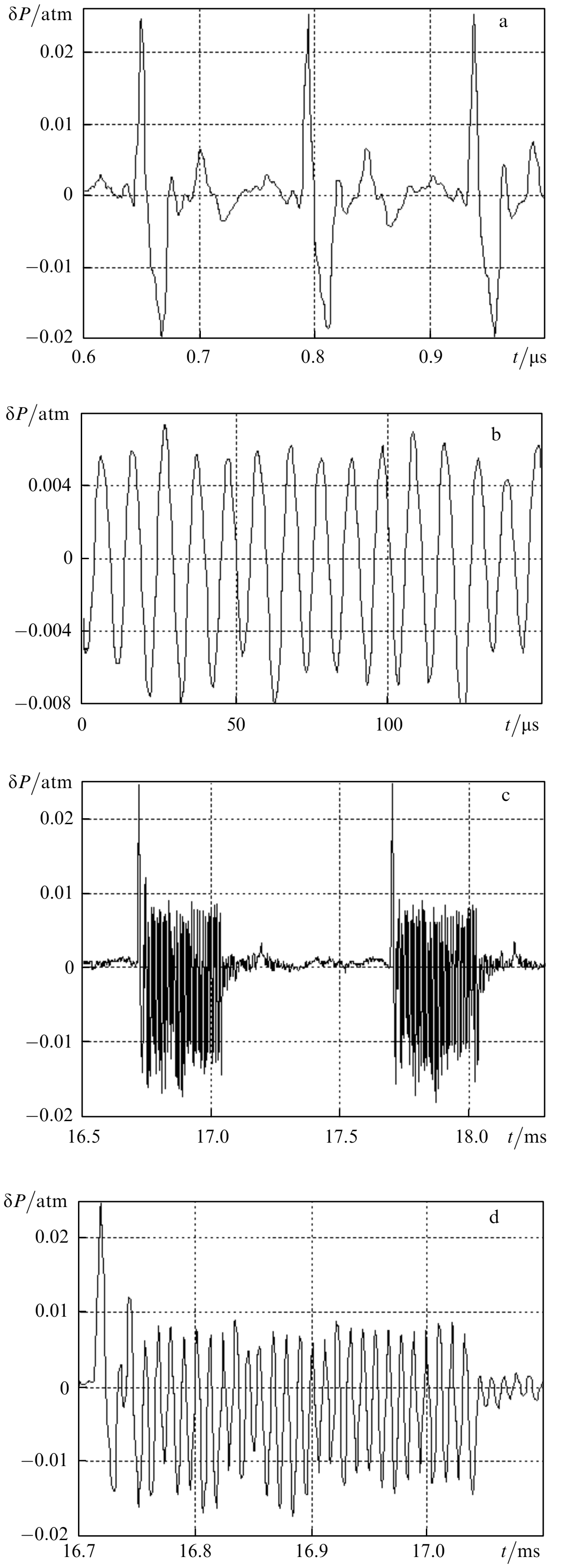

**Figure 3.** Pressure pulsations produced by the OPD for $V = 300$ m s $^{-1}$ (without reflector), $f = 7$ kHz, $W = 690$ W (a); $f = 100$ kHz, $W = 1700$ W (b), and $f = 100$ kHz, the train repetition rate $\varphi = 1$ kHz, $W = 1000$ W, the number of pulses in the train $N = 30$ (c); the train of shock waves at a large scale, parameters are as in Fig. 3c (d).

## 3. Results of measurements

### 3.1 Control measurements

The jet propulsions $F_{\rm j}$ and $F_{\rm r}$ and the excess pulsation pressure $\delta P = P - P_0$ were measured for the model without the reflector. We considered the cases of the jet without and with the OPD. The jet velocity $V$ and radiation parameters were varied. For $V = 50$, 100, and 300 m s$^{-1}$, the propulsion produced by the jet was $F_j = 6$, 28, and 200 g, respectively, and the amplitude of pulsations was $\delta P = 5 \times 10^{-6}$, $2 \times 10^{-5}$ and $3 \times 10^{-4}$ atm. The OPD burning in the jet did not change the reading of the balance. This is explained by the fact that the OPD is located at a distance of $r$ from the bottom of a high-pressure chamber, which satisfies the inequality $r/R_{\rm d} > 2$, when the momentum produced by shock waves is small [3, 22]. As follows from Fig. 3, pulsations $\delta P(t)$ produced by the OPD greatly exceed pressure fluctuations in the jet.

### 3.2 Stationary regime

The OPD was burning in a flow which was formed during the gas outflow from the chamber through a hole ($D_{\rm j} = 0.3$ cm) to the reflector ($D_{\rm r} = 0.5$ cm) (Fig. 4). Because the excess pressure on the reflector bottom was $\sim 0.5$ atm (see above), to avoid the jet closing, the pressure used in the chamber was set equal to $\sim 2$ atm. The jet velocity without the ODP was $V = 300$ and 400 m s$^{-1}$, $F_{\rm j} = 80$ and 140 g. The OPD was produced by repetitively pulsed radiation with $f = 50$ and 100 kHz and the average power $W \approx 1200$ W (the absorbed power was $W_{\rm a} \approx 650$ W). Within several seconds after the OPD switching, the reflector was heated up to the temperature more than 100 °C.

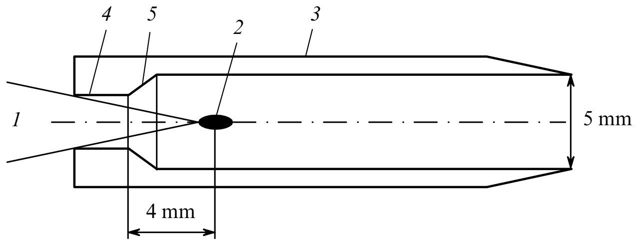

**Figure 4.** Reflector of a stationary laser engine: (*1*) repetitively pulsed laser radiation with $f = 50$ and 100 kHz, $W = 1200$ W; (*2*) OPD; (*3*) reflector; (*4*) hole of diameter $\sim 3$ mm through which argon outflows from a high-pressure chamber ($\sim 2$ atm) to the reflector; (*5*) reflector bottom, the angle of inclination to the axis is $\sim 30°$.

For $f = 50$ kHz and $V = 300$ m s $^{-1}$, the propulsion is $F_{\rm r} = 40$ g, and for $V = 400$ m s $^{-1}$, the propulsion is 69 g; the coupling coefficient is $J_{\rm r} \approx 1.06$ N kW$^{-1}$. The propulsion $F_{\rm r}$ is stationary because the criteria for shock-wave merging in front of the OPD region are fulfilled. Downstream, the shock waves do not merge. One can see this from Fig. 5 demonstrating pressure pulsations $\delta P(t)$ measured outside the reflector. They characterise the absorption of repetitively pulsed radiation in the OPD and, therefore, the propulsion. For $f = 50$ kHz, the instability is weak ($\pm 5$ %) and for $f = 100$ kHz, the modulation $\delta P(t)$ is close to 100 %. The characteristic frequency of the amplitude modulation $f_{\rm a} \approx 4$ kHz is close to $C_0/(2H)$, where $H$ is the reflector

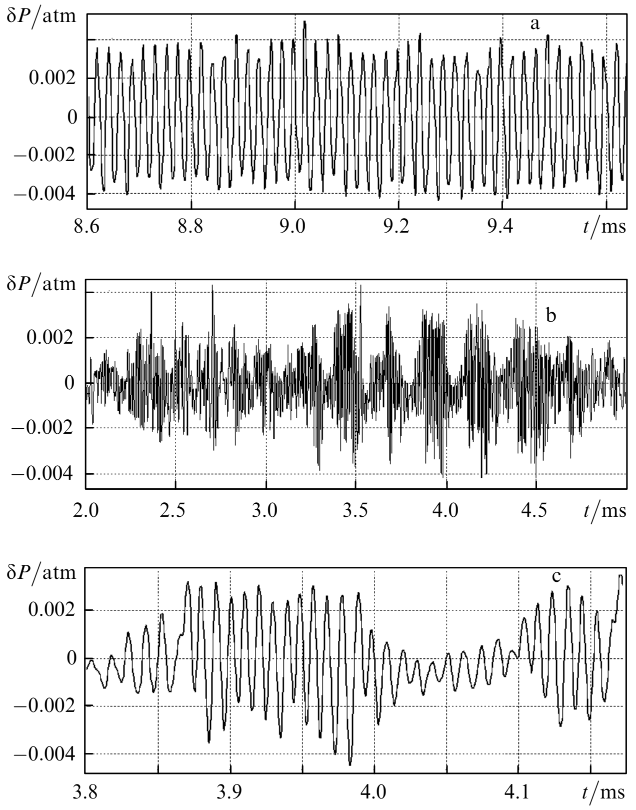

**Figure 5.** Pressure pulsations $\delta P$ produced upon OPD burning in the reflector with $D_r = 0.5$ cm, $H = 4.6$ cm, $V = 400$ m s$^{-1}$, $D_j = 0.3$ cm for $f = 50$ kHz, $W = 1300$ W (a) and $f = 100$ kHz, $W = 1200$ W (b, c).

length. The possible explanation is that at the high frequency $f$ the plasma has no time to be removed from the OPD burning region, which reduces the generation efficiency of shock waves. The jet closing can also lead to the same result if the pressure in the quasi-stationary wave is comparable with that in the chamber. Thus, repetitively pulsed radiation can be used to produce the stationary propulsion in a laser engine.

### 3.3 Pulsed regime

To find the optimal parameters of the laser engine, we performed approximately 100 OPD starts. Some data are presented in Table 1. We varied the diameter and length of the reflector, radiation parameters, and the jet velocity (from 50 to 300 m s$^{-1}$). For $V = 50$ m s$^{-1}$, the ejection effect is small, for $V = 300$ m s$^{-1} \approx C_0$, this effect is strong, while for $V \approx 100$ m s$^{-1}$, the transition regime takes place. In some cases, the cylinder was perforated along its circumference to reduce ejection. The OPD was produced by radiation pulse trains, and in some cases – by repetitively pulsed radiation. The structure and repetition rate of pulse trains was selected to provide the replacement of the heated OPD gas by the atmospheric air. The train duration was ~ 1/3 of its period, the number of pulses was $N = 15$ or 30, depending on the frequency $f$. The heating mechanism was the action of the thermal radiation of a plasma [23], the turbulent thermal diffusivity with the characteristic time ~ 300 μs [24] and shock waves.

The propulsion $F_r$ was observed with decreasing the reflector diameter and increasing its length. The OPD burned at a distance of ~ 1 cm from the reflector bottom. One can see from Fig. 6 that the shock waves produced by the first high-power pulses in trains merge. For $f = 100$ kHz, the pulse energy is low, which is manifested in the instability of pressure pulsations in trains. As the pulse energy was approximately doubled at the frequency $f = 50$ kHz, pulsations $\delta P(t)$ were stabilised. The OPD burning in the reflector of a large diameter ($D_r/R_d \approx 4$) at a distance from its bottom satisfying the relation $r/R_d \approx 3$ did not produce the propulsion.

Table 1 presents some results of the measurements. One can see that the coupling coefficient $J_r$ strongly depends on many parameters, achieving 1 N kW$^{-1}$ in the stationary

**Table 1.** Experimental conditions and results.

| $f$/kHz | $\varphi$/kHz | $D_r$/mm, [$H$/mm] | $N$ | $V$/m s$^{-1}$ | $W$/W | $F_j$/g | $F_r$/g | $J_r$/N kW$^{-1}$ | Reflector material |
|---|---|---|---|---|---|---|---|---|---|
| 45 | RP | 5, [46] | – | 300 | 1300 | 80 | 40 | 0.61 | duralumin |
| 45 | RP | 5, [46] | – | 400 | 1300 | 141 | 69 | 1.06 | –"– |
| 100 | RP | 5, [46] | – | 400 | 1200 | 155 | 54 | 1.08 | –"– |
| 100 | 1 | 15, [50] | 30 | 300 | 720 | 49 | 4 | 0.085 | –"– |
| 45 | 1 | 15, [50] | 15 | 50 | 720 | 0.9 | 2.1 | 0.042 | –"– |
| 45 | 1 | 15, [50] | 15 | 300 | 720 | 49.1 | 4.5 | 0.09 | –"– |
| 45 | 1 | 15, [50] | 15 | 50 | 720 | 1.2 | 1.4 | 0.028 | duralumin* |
| 45 | 1 | 15, [50] | 15 | 100 | 720 | 6.3 | 5.6 | 0.11 | –"– |
| 45 | 1 | 15, [50] | 15 | 300 | 720 | 62.7 | 4 | 0.08 | –"– |
| 45 | 1 | 15, [50] | 5 | 170 | 500 | 17.7 | 3.5 | 0.1 | –"– |
| 45 | 2 | 15, [50] | 5 | 100 | 600 | 6.3 | 4.8 | 0.11 | –"– |
| 45 | 2 | 15, [50] | 5 | 164 | 600 | 18.5 | 7.5 | 0.18 | –"– |
| 45 | 2 | 15, [50] | 5 | 300 | 600 | 70 | −4 | 0.095 | –"– |
| 12.5 | RP | 25, [35] | – | 60 | 430 | 2.4 | 4 | 0.13 | quartz |
| 12.5 | RP | 25, [35] | – | 100 | 430 | 5 | 7 | 0.23 | –"– |
| 12.5 | RP | 25, [35] | – | 150 | 430 | 11 | 11 | 0.37 | –"– |
| 12.5 | RP | 25, [35] | – | 300 | 430 | 51 | 16 | 0.53 | –"– |
| 12.5 | RP | 25, [35] | – | 50 | 430 | 6 | 1 | 0.033 | duralumin** |
| 12.5 | RP | 25, [35] | – | 100 | 430 | 12 | 7 | 0.23 | –"– |
| 12.5 | RP | 25, [35] | – | 300 | 430 | 195 | −97 | −3.2 | –"– |

Note. Laser radiation was focused at a distance of 1 cm from the reflector bottom; * six holes of diameter 5 mm over the reflector perimeter at a distance of 7 mm from its exhaust; ** six holes of diameter 5 mm over the reflector perimeter at a distance of 15 mm from its exhaust.

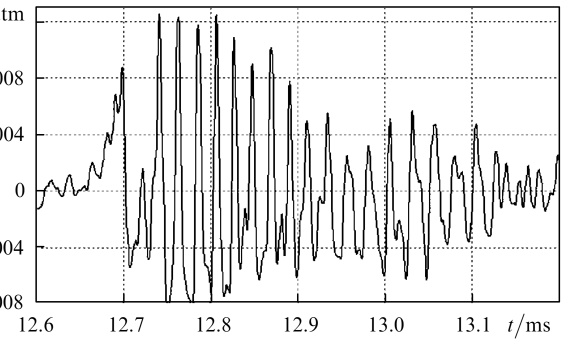

**Figure 6.** Pressure pulsations $\delta P$ in the OPD produced by pulse trains with $\varphi = 1.1$ kHz, $f = 50$ kHz, $W = 720$ W, $N = 15$, $V = 300$ m s$^{-1}$, $D_{\rm r} = 1.5$ cm, $H = 5$ cm, $D_{\rm j} = 4$ mm, and $F = 4.5$ g.

regime and 0.53 N kW$^{-1}$ in the pulsed regime. At present, the methods of power scaling of laser systems and laser engines, which are also used in laboratories, are being extensively developed [10, 25]. Let us demonstrate their application by examples. We observed the effect when the OPD produced the 'negative' propulsion $F_{\rm r} = -97$ g (see Table 1), which correspond to the deceleration of a rocket. The value of $J_{\rm r}$ can be increased by approximately a factor of 1.5 by increasing the pulse energy and decreasing their duration down to $\sim 0.2$ μs. An important factor characterising the operation of a laser engine at the high-altitude flying is the efficiency $I_{\rm m}$ of the used working gas. The value $I_{\rm m} = 0.005$ kg N$^{-1}$s$^{-1}$ can be considerably reduced in experiments by using a higher-power radiation. The power of repetitively pulsed radiation should be no less than 10 kW. In this case, $F_{\rm r}$ will considerably exceed all the other forces. The gas-dynamic effects that influence the value of $F_{\rm r}$, for example, the bottom resistance at the flight velocity $\sim 1$ km s$^{-1}$ should be taken into account.

Thus, our experiments have confirmed that repetitively pulsed laser radiation produces the stationary propulsion with the high coupling coefficient. The development of the scaling methods for laser systems, the increase in the output radiation power and optimisation of the interaction of shock waves will result in a considerable increase in the laser-engine efficiency.

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