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Formation of an optical pulsed discharge in a supersonic air flow by radiation of a repetitively pulsed CO_2 laser

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Abstract. **Results of optimisation of repetitively pulsed CO_2-laser generation are presented for finding physical conditions of forming stable burning of an optical pulsed discharge (OPD) in a supersonic air flow and for studying the influence of pulse parameters on the energy absorption efficiency of laser radiation in plasma. The optical discharge in a supersonic air flow was formed by radiation of a repetitively pulsed CO_2 laser with mechanical *Q*-switching excited by a discharge with a convective cooling of the working gas. For the first time the influence of radiation pulse parameters on the ignition conditions and stable burning of the OPD in a supersonic air flow was investigated and the efficiency of laser radiation absorption in plasma was studied. The influence of the air flow velocity on stability of plasma production was investigated. It was shown that stable burning of the OPD in a supersonic flow is realised at a high pulse repetition rate where the interval between radiation pulses is shorter than the time of plasma blowing-off. Study of the instantaneous value of the absorption coefficient shows that after a breakdown in a time lapse of 100–150 ns, a quasi-stationary 'absorption phase' is formed with the duration of $\sim$1.5 μs, which exists independently of air flow and radiation pulse repetition rate. This phase of strong absorption is, seemingly, related to evolution of the ionisation wave.**

Keywords: *high-power repetitively pulsed CO_2 laser, mechanical Q-switching, supersonic air flow, optical pulsed discharge, air optical breakdown, absorption coefficient of plasma.*

13. Introduction

Study of laser radiation employment in controlling parameters of supersonic air flow [1, 2], in plasma chemistry [3] etc. is a promising direction. Laser radiation energy can be injected into a gas flow by means of a continuous optical discharge (COD) [4]. However, such a discharge cannot be formed at flow velocities exceeding several dozens of meters per second [5]. In [6–8], an optical pulsed discharge (OPD) was obtained which burned in a focused radiation beam of a repetitively pulsed CO_2 laser in a supersonic argon flow and affected the beam similarly to the COD. Nevertheless, as early as in [8, 9] it was shown that an optical breakdown in air requires the radiation power by an order of magnitude greater than that used in experiments with argon. Hence, experiments in real supersonic wind tunnels require creation of specific radiation sources possessing high energy characteristics [10, 11].

In [12, 13], we have described a repetitively pulsed CO_2 laser with the pulse repetition rate f of up to 80 kHz and power of 4.5 kW. Characteristics of the laser made it possible for the first time to burn the OPD in a supersonic air flow and determine the requirements to gas density, fulfilment of which allows obtaining high (up to 60%) absorption of power in the flow. However, even these first experiments showed that obtaining stable burning of the OPD in each radiation pulse and realisation of high absorption coefficients place sufficiently strong requirements on the shape and frequency of the pulses. In [9], specific features of radiation absorption in COD plasma were thoroughly considered. In contrast to the COD, a pulsed discharge is essentially nonstationary and the dynamics of OPD evolution in air has not been studied experimentally. A most important characteristic determining the character of laser pulse energy absorption is a relation between the radiation pulse duration and time of plasma expansion (the formation time for a cavern, i.e., the domain with lower gas density). One should remember that parameters of laser generation in a repetitively pulsed regime cannot be chosen arbitrarily. The shape and duration of a single pulse depend on the repetition rate.

Thus, the present work was aimed at optimising the regime of generation for finding physical conditions for stable OPD burning in a supersonic air flow and studying an influence of pulse parameters on the efficiency of absorption of laser radiation in plasma.

14. Experimental results

A model supersonic flow was produced on a special bench including an antechamber and conic nozzle. The pressure in the antechamber was 1.8 MPa. The conic nozzle with the aperture angle of 13° at the cut diameter of 10 mm and critical section diameter of 8 mm corresponded to the geometric Mach number of 1.9 (the gas velocity was 500–600 m s^{-1}), the gas consumption was 2–4 kg s^{-1}.

The average powers of the laser output passing to the flow (incident radiation) and leaving the flow (passed radiation) were measured by a NOVA-2 calorimetric gauge (with the utmost power of up to 5 kW). Plasma was formed by a lens made of ZnSe with antireflection coatings on both sides (the focal length was 63 mm). A FSG 22-3A1 photodiode was used for controlling the time shape of laser radiation both incident and passed through plasma. A FEK-22 vacuum photocell measured glow intensities of plasma optical breakdown. For calculating the pulsed power of laser radiation, the energy of

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a single pulse (E_p) was determined as the ratio of the average power to pulse repetition rate. Following calculations were performed by numerical integration of oscillograms.

The optical discharge in a supersonic flow was formed by a radiation of the repetitively pulsed CO_2 laser with mechanical Q-switching pumped by a volume discharge with convective cooling of the working gas [12].

Formation of a generation pulse starts at the instant of switching on the cavity Q-factor. In a time lapse between the generation pulses when the modulator disk shutters the cavity axis and the pump current flows through the active medium, the upper laser level is excited and lower level relaxes. The gas flow moved normally to the discharge at the speed of ~50 m s^{-1}. The optical axis and generation beam were perpendicular to both the flow and discharge. In our experiments with the pulse repetition rate varied within the limits 7–70 kHz, in a time lapse between the pulses, gas covered a distance of 7–0.7 mm. Since the characteristic dimension of the discharge zone in the flow direction was ~100 mm and a multipass cavity was used, no gas exchange occurred between pulses, so that the radiation pulses were formed in a medium with various states of excitation (see Fig. 1).

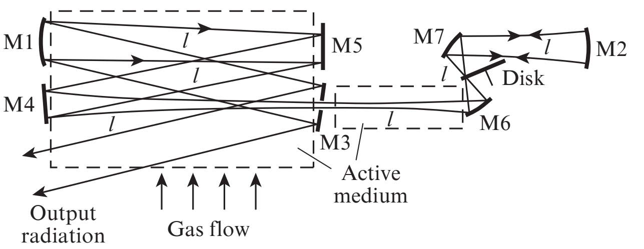

Figure 1. Schematic of the self-filtering resonator with the intracavity cylindrical telescope and the modulator disk:
(M1–M5) mirrors of a multipass resonator; (M6, M7) mirrors of the cylindrical telescope.

The Q-switching system provides a wide variation in the pulse repetition rate, the duty factor, and shape due to a change in the disk rotation rate, slit width, number of slits, and composition of a working gas mixture. We used disks with the number of slits n = 40, 120, 300, and 400, which provided the maximal pulse repetition rate of up to 80 kHz at a maximal disk rotation frequency of 180 Hz. The slit width was 1 mm for the disk with n = 40 and 0.5 mm for disk with n = 400. At the working rotation frequency of 176 Hz and disk diameter of 220 mm the linear velocity of slit motion was 1.2×10^5 mm s^{-1} and the time of slits with the widths of 1 and 0.5 mm passing through the cavity axis was 8.3 and 4.15 μs, respectively.

In Figs 2, 3, typical oscillograms (*1*) are shown of laser radiation pulses with Q-switching by disks with n = 400 and 40; the slit widths were 1 and 0.5 mm, respectively. The generation pulse oscillograms have a specific front peak and the plateau of quasi-stationary generation. It is important that in the case of modulator with n = 40 the front peak has a sharp leading edge and the FWHM of ~300 ns. The total pulse duration was ~7.5 μs and was close to the Q-switching setup time (8.3 μs).

Employment of a disk with n = 400 at the same rotational velocity principally changed the pulse shape. Its FWHM was ~1 μs and the total duration was ~2 μs, which is shorter than the Q-switching setup time (~4.15 μs). In this case the time lapse between pulses was too short to acquire energy at the

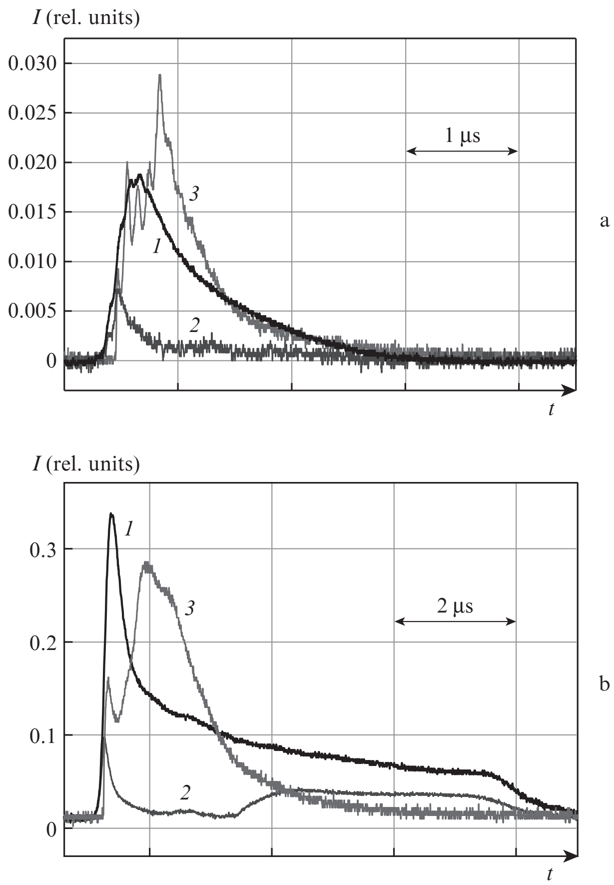

Figure 2. Oscillograms of the pulses of incident (*1*) and passed (*2*) laser radiation and intensity of plasma glow in a supersonic air flow (*3*); n = 400, f = 70.4 kHz (a); n = 40, f = 7.04 kHz (b).

upper laser level and to empty the lower one. This circumstance is responsible for a reduction of the peak power with frequency (see Fig. 4). From Fig. 4 one can see that the pulse power at f = 7 kHz reaches ~220 kW at the peak duration no longer than 500 ns (Figs 3, 5) and reduces to 70 kW at f = 70 kHz. The disk rotation frequency remained constant and equal to 176 Hz.

Investigation results for plasma produced at f = 70 and 7 kHz for disks with n = 400 and 40 are shown in Figs 2, 3. Two cases are presented of plasma production – in a supersonic air flow (Fig. 2) and in a steady gas (Fig. 3).

From Figs 2b and 3b it follows that at f = 7 kHz regardless of the presence of a supersonic air flow there is a characteristic time (1.5–2 μs at the total pulse duration of 7.5 μs) during which an intensive plasma glow is observed and a maximal absorption of laser radiation by plasma, so that the intensity of light passed through plasma is minimal. Then the character of interaction between laser radiation and plasma changes – the intensity of passed laser radiation sharply increases severalfold and oscillations are observed during the plateau stage of quasi-stationary generation. The intensity of plasma glow is maximal at strong absorption and then it monotonically falls. In steady air (the flow is switched off) the interaction process actually does not change.

Air flow had no significant effect on the character of single pulse interaction with plasma; however, it broke stability of OPD ignition: variations of intensity and misfires were observed, i.e., not all pulses were accompanied with gas breakdown. Naturally, the average absorption of laser radiation in pro-

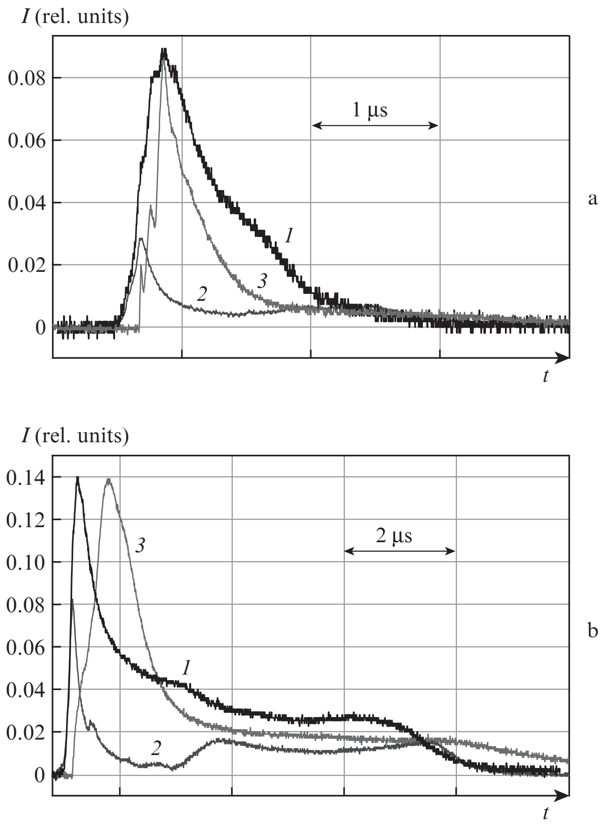

Figure 3. Oscillograms of the pulses of incident (*1*) and passed (*2*) laser radiation and intensity of plasma glow without air flow (*3*); $n = 400$, $f = 70.4$ kHz (a); $n = 40$, $f = 7.04$ kHz (b).

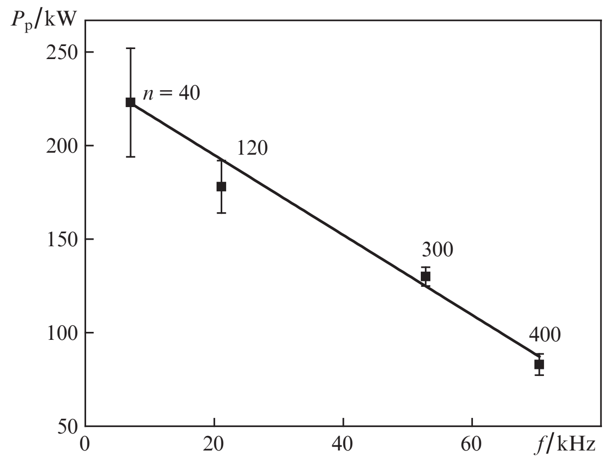

Figure 4. Dependence of pulsed laser radiation power versus the number of slits on the modulator disk at the maximal rotation rate.

ducing plasma at $f = 7$ kHz in a gas flow was relatively lower (30%–40%). For comparison: in a steady gas in the same generation regime of operation the absorption reaches 59%.

In employing short (~2 μs) laser pulses (Figs 2a and 3a), intensive absorption is observed during 1.5–2 μs, i.e., actually till the pulse end, and discharge formation in each laser pulse is stable. A similar situation is observed for such pulses without gas flow. Nevertheless, whereas the characteristic lifetime of absorption is weakly affected by the air flow, gas motion leads to noticeable changes in the intensity of the plasma glow and integral absorption coefficient. With a supersonic air flow, the characteristic FWHM duration of the OPD glow at $f = 70$ kHz and average absorption coefficient of 69% was ~0.6 μs. Switching off the flow resulted in a reduction of the discharge glow time to 0.2–0.3 μs and reduced the average absorption coefficient to 40% which is, seemingly, explained by a change in the density (or by gas burning out in the zone of interaction with laser radiation) [8], which has no time enough for recovering at $f = 70$ kHz.

15. Discussion of results

The process of discharge ignition comprises several stages, each of them affecting the final result – the efficiency of energy absorption in plasma.

15.1. Gas breakdown

Problems of gas breakdown by long-wavelength radiation of a CO_2 laser are thoroughly considered, for example, in monograph [14]. It was shown that in pure air a breakdown requires the intensity on the order of 10^{10} W cm^{-2}, whereas in impure air the threshold intensity reduces to 2×10^9 W cm^{-2}; an important role of initial seed electrons is mentioned. Due to attachment processes in atmospheric air the number of free electrons is not sufficient for discharge ignition. Here, important become impurities, aerosol particles and so on. In our experiments, the intensity of laser radiation at the lens focus was $\sim2\times10^9$ W cm^{-2}, i.e., it was close to the threshold value in the case $n = 40$ and $f = 7$ kHz and reduced to 7×10^8 cm^2 at $f = 70$ kHz.

Thus, a paradoxical situation arises: in an air flow moving at the velocity $V \sim 500$ m s^{-1}, the OPD reliably burned at $f = 70$ kHz, that is, at the intensity below the threshold. Nevertheless, lowering the frequency to 7 kHz and increasing the intensity to a value above the threshold results in misfiring. One may assume that this effect is related to specificity of plasma dynamics in the flow. The characteristic time of plasma blowing-off at the cloud dimension $D \sim 10$ mm is $D/V = 20$ μs. Hence, at a higher pulse repetition rate (up to 70 kHz), at the instant of next pulse passing there is a residual concentration of free electrons, which facilitates the breakdown. Note one possible important role of photoionisation of ambient gas. At a low pulse repetition rate, in a time lapse between pulses of ~150 μs plasma is blown off by the flow and a breakdown occurs irregularly in a fresh gas portion.

The conclusion on the important role of residual ionisation well agrees with results of experiments with a steady gas. In this case, the breakdown is regular over the whole frequency range, that is, residual plasma has more beneficial effect than complicated processes of cavern dynamics, including gas density reduction during the cloud expansion and recovery, in particular, due to gas 'self-circulation' in the OPD [8].

Note that at a low pulse repetition rate, the power in the front peak of radiation pulse reaches 220 kW; however, it is not sufficient for stable discharge formation. At a high pulse repetition rate (70 kHz), the maximal peak power falls; however, stable formation of OPD in a supersonic air flow was observed under its reduction to 50 kW (5×10^8 W cm^{-2}).

15.2. Discharge development

After gas breakdown, an ionisation front is formed which propagates along the caustic towards the laser beam. There are several mechanisms for plasma transfer. At laser radiation intensities obtained in our experiments (5×10^8–2×10^9 W cm^{-2}), both laser-supported detonation wave (LSDW) [9] and fast ionisation wave (FIW) caused by gas photoionisation and electron multiplication in laser radiation field [15] may be realised. In this case, the rate of FIW process had the characteristic value of 2×10^6 mm s^{-1}. The length of plasma bunch along the beam was several millimetres. Thus, the characteristic time of discharge development was 1 – 2 μs.

The absorption index μ and refraction angle θ for radiation in plasma, according to [14, 16], can be estimated from the expressions

$$\mu = 1.8\times10^{-35} n_e^2 T_e^{-3/2}, \quad \theta = 5\times10^{-20}\int(\partial n_e/\partial r)\,ds. \qquad (1)$$

Here, n_e is the electron concentration (cm^{-3}); T_e is the plasma electron temperature (eV). Integration is performed along the laser beam trace.

In Fig. 5, dependences of absorption coefficient A of radiation in plasma are presented versus time during the pulse action for f = 70.4 and 7.04 kHz with air flow and without it.

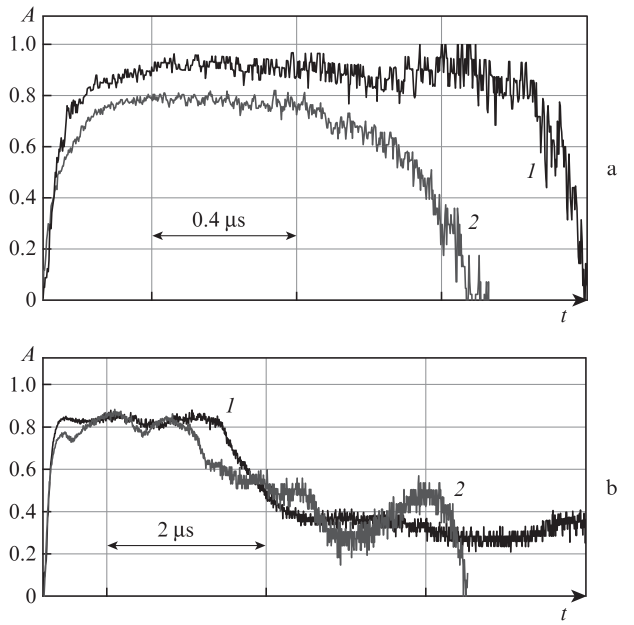

Figure 5. Time dependence of absorption coefficient in OPD plasma in a supersonic air flow (*1*) and in steady air (*2*); disk with n = 400 with the slit width of 0.5 mm, f = 70.4 kHz (a); disk with n = 40 with the slit width of 0.5 mm, f = 7.04 kHz (b).

From Fig. 5a one can see that the intensity of plasma glow as well as absorption increase for a time of ~100 ns. At a high pulse repetition rate (70.4 kHz), the absorption coefficient remains constant for 1.5 μs, i.e., actually during the whole pulse duration. According to data [9, 10], the temperature of plasma in air breakdown by CO_2-laser radiation may reach $(15-20)\times10^3$ K, and plasma concentration may become critical (10^{19} cm^{-3}). Under these conditions, from (1) follows that $\mu = 10^2 - 10^3$ cm^{-1}. At so high absorption index values, plasma at the front of LSDW becomes opaque. Note that at the stage of LSDW propagation under very strong absorption the influence of refraction and scattering is negligible [14, 16], whereas at the stage of interaction of laser radiation with already formed cloud the refraction may play an important role. Elucidation of the roles of these processes in the observed reduction of the beam intensity necessitates additional investigations.

One may assume that quasi-stationary absorption for 1.5 μs is explained by interaction with an LSDW front. Principal laws of LSDW formation and propagation are determined by caustic geometry and radiation intensity, that is, LSDW damps while leaving the focus zone where the radiation intensity falls. Hence, the characteristic lifetime for strong absorption proved to be independent of the pulse repetition rate and presence or absence of air flow. Beyond the LSDW front, plasma freely expands at a thermal velocity $V_T \approx (1-2)\times10^6$ mm s^{-1}.

At the pulse repetition rate of 70.4 Hz and modulator slit width of 0.5 mm, the total pulse duration just amounts to 1.5 – 2 μs. In this case, the regime was realised of matching the pulse duration with the time of LSDW development, where strong quasi-stationary absorption of radiation by plasma is observed (see Fig. 5a). The most of passed radiation power, seemingly, originates from peripheral laser beam parts.

At a low pulse repetition rate (7.04 kHz) we also observe strong absorption for ~1.5 μs which then abruptly falls, however, extending to the radiation pulse end (see Fig. 5b).

16. Conclusions

In the present work we for the first time investigated an important influence of radiation pulse parameters on the conditions of ignition and stable burning of the OPD in a supersonic air flow and studied the efficiency of laser radiation absorption in plasma. The following results was obtained.

(i) The possibility is shown to absorb 60%–70% of laser radiation energy under the condition of matching the pulse duration with the time of development of the ionisation wave on the front of which strong absorption occurs.

(ii) An influence of the air flow velocity on stability of plasma production is investigated. It is shown that stable OPD burning in a supersonic flow is realised at a high pulse repetition rate, where the time lapse between pulses is shorter than the time of plasma blowing-off.

(iii) It is shown that after a breakdown in a time lapse of 100 – 150 ns, a quasi-stationary phase of absorption is formed with the duration of ~1.5 μs, existence of which is independent of the air flow and the radiation pulse repetition rate. This phase of strong absorption, seemingly, is related to a developing ionisation wave.

(iv) After the ionisation wave vanishes, the absorption of laser radiation by decaying plasma sharply reduces.

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