LETTERS

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A pulsating optical discharge moving in a gas

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***Abstract*. A pulsating optical discharge (POD) moving in a gas behind the laser beam focus at a high velocity is produced using repetitively pulsed CO_2 laser radiation. A technique is worked out for creating a focusing system to stabilise the parameters of such a discharge. The radiation energy spent per unit length for burning the plasma channel is 3 – 8 J m^{-1}. The maximum velocity of discharge ($\sim$100 m s^{-1}) is limited by the experimental conditions. The prospects of using a POD moving at a considerable distance from the emitter are assessed.**

Keywords: *moving pulsating optical discharge, repetitively pulsed laser radiation.*

A pulsating optical discharge (POD) in a supersonic gas flow, which is stable in the focal region at a high pulse repetition rate ($f \sim 20 - 100$ kHz), was realised in [1 – 3]. A POD in a gas flow is used for aerophysical simulation [4] and is also of interest for problems in aerospace [5 – 9] and plasma chemistry [10].

Here, we report on a moving pulsating optical discharge (MPOD) created in a stationary gas using repetitively pulsed CO_2 laser [11]. This discharge is initiated in the moving focus of a laser beam and forms during its propagation at a high velocity an extended trace of the ionised gas, whose length is determined by the laser power and the parameters of the optical system for moving the focus. High-power lasing at a high pulse repetition rate was obtained in a continuously pumped *Q*-switched lasers [11, 12].

According to theoretical studies [13, 14], a MPOD may produce a plasma jet, generate wave fields with the spectrum tunable in a broad range, and also burn a plasma channel in a gas with small energy expenditures, which is important for solving the lightning control problem [15].

In this study a MPOD was produced to study new effects appearing under the action of repetitively pulsed radiation on a gas due to the mechanism of shock-wave merging [16, 17]. In this connection, MPOD studies require the stability of laser spark energy and of the discharge velocity over a path segment no less than 25 cm. A technique is developed for calculations and for construction of a mirror – lens system in which these conditions are satisfied for a beam focusing of nearly diffraction quality. The parameters of prospective PODs moving at a high velocity ($\sim$1 km s^{-1}) over large distances (tens or hundreds of metres) are estimated.

Experiments were made on a setup (Fig. 1) in which the beam focus in the chamber containing argon at atmospheric pressure was displaced by a mirror – lens system consisting of a Cassegrain mirror telescope and a convex KCl lens ($F = 100$ cm, optical diameter 11 cm, distance from the large mirror equal to 85 cm). The laser beam introduced through an aperture in a stationary concave spherical mirror (radius of curvature 47 cm, diameter 24 cm) was scattered by a small aspherical mirror (of diameter 3.5 cm) and subsequently focused by a mirror – lens system in the chamber. The small aspherical mirror was displaced to the right by a pneumatic device while the focus of the system moved towards the optical system. The MPOD plasma was ignited by the radiation of a repetitively pulsed *Q*-switched CO_2 laser [11]. The front peak of the laser pulse (with a FWHM of $\sim$250 ns) contained about 70 % of the energy, the remaining energy was confined in the quasi-stationary tail part ($\sim$1 μs). The radiation loss in the focus displacement system attained values $\sim$40 % due to reflection at the lens surfaces, absorption by the mirrors, and a partial scattering of the beam by the movable mirror components and the movable mirror itself. Experiments were performed for $f = 6$, 12 and 25 kHz with average repetitively pulsed radiation powers of 300, 540 and 800 W respectively in the chamber. The corresponding pulse power was 150, 125 and 90 kW, respectively. The initial plasma in the POD channel

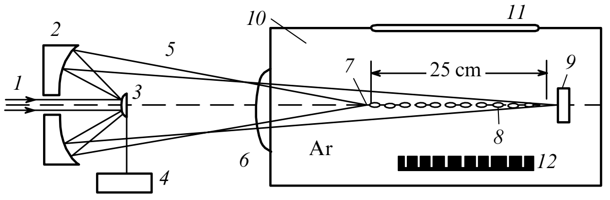

Figure 1. Scheme of the experiment: (*1*) repetitively pulsed radiation; (*2*, *3*) telescope mirrors; (*4*) mirror displacement device; (*5*) laser beams; (*6*) focusing lens; (*7*) moving focus; (*8*) laser sparks; (*9*) graphite target; (*10*) chamber; (*11*) viewing window; (*12*) photodiode array for measuring displacement of the plasma spark glow.

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was produced by irradiating a graphite target. The velocity of a MPOD was detected by signals from an array of FD-256 photodiodes separated by distances of 3 cm.

It is known [18] that, in the absence of initial electrons, the intensity of CO_2 laser radiation required for an optical breakdown of argon at atmospheric pressure is $\sim 10^9$ W cm^{-2}. At the same time, in our previous studies [2, 3], we observed the effect of significant lowering of the POD ignition threshold in high-velocity argon flows (to be more precise, we observed the lowering of the POD sustaining thresholds after the ignition of the first optical discharge) due to residual ionisation and appreciable number density of excited atoms. To formulate the requirements imposed on the focus moving system, we preliminarily determined the POD ignition thresholds in stationary argon using a KCl lens with a focusing angle close to the rated angle for focus moving systems ($\sim$0.1 rad). The threshold intensity averaged over the focal waist cross section of diameter 0.2 mm (at a level of 60 % of transmitted power) was 180 ± 15 and 140 ± 10 MW cm^{-2} for $f = 1.1$ and 30 kHz, respectively.

For obtaining a stable intensity (exceeding the threshold value), we developed the computational technique for the mirror – lens system with a small aspherical mirror (the computational algorithm for the aspherical surface is similar to the one used in [19]). The problem was solved in the diffraction approximation for the entire complex including the laser cavity and the focus moving system. The calculations ensured a laser power almost thrice as large as the threshold value over a segment $\sim$30 cm of focus displacement.

The copper aspherical mirror was prepared by using a programmable drive for turning with a diamond cutter, followed by polishing and surface quality control with an error not exceeding ± 0.5 μm.

Figure 2 shows the result of comparative calculations of radiation intensity on the optical axis of the mirror – lens system (with the above parameters) for the rated surface of the small mirror [curve (*1*)], the finished mirror surface [curve (*2*)], and a mirror system with a plane – parallel KCl window instead of the lens [curve (*3*)], where F_s is the distance between the focal spot and the large telescope mirror.

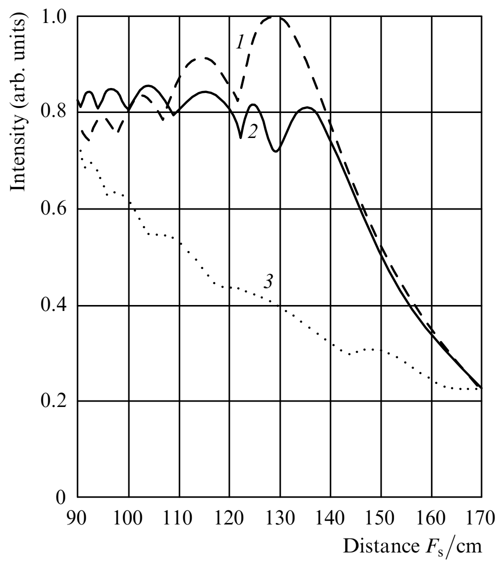

Figure 2. Dependence of the radiation intensity on the optical axis of the mirror – lens displacement system with theoretical [curve (*1*)] and prepared [curve (*2*)] surfaces of the small mirror, as well as for the mirror system with a plane – parallel window instead of the lens [curve (*3*)].

Experiments on the ignition of the MPOD plasma were carried out in the range of variation of F_s between 120 cm (position of the graphite target) and 95 cm. The pneumatic system of displacement of the aspherical mirror ensured its acceleration up to 1200 m s^{-2} and a velocity up to 10 m s^{-1}, which determined the maximum velocity $V_f \sim 100$ m s^{-1} of the focus. This value was maintained constant (to within 5 %) in the MPOD displacement range. Figure 3 shows typical photographs of the MPOD plasma channel. In most of the cases, the initial part (from the graphite target) of the MPOD plasma channel was intermittent. This is apparently due to deterioration of the beam quality caused by stray feedback emerging upon reflection of radiation from the spherical surface of the lens.

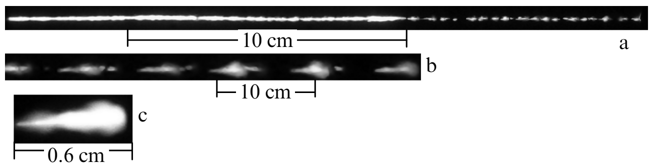

Figure 3. Photographs of the MPOD plasma channels for a focus displacement velocity $V_f = 100$ m s^{-1} and a laser pulse repetition rate $f = 25$ (a) and 12 kHz (b), as well as the plasma channel of a stationary POD ($f = 12$ kHz, exposure time 1 ms) (c).

The MOPD produced a continuous plasma channel (Fig. 3a) for a pulse repetition rate $f \geqslant V_f/l$ (l is the laser spark length). In the opposite case, the trace consisted of individual laser sparks (Fig. 3b). The photograph of a stationary POD (Fig. 3c) corresponds to integrated luminescence of the plasma formed by a large number ($\sim$12) of sparks.

The energy expenditures per unit length for the formation of ionised argon channels varied from 3 to 8 J m^{-1} for f in the range of 6 – 25 kHz, respectively, which is much lower than the energy expenditure for a laser spark produced by a single pulse (see, for example, [20 – 22]).

The application of the computational technique developed for a focus moving system with an aspherical mirror indicates the possibility of producing a MPOD at considerable distances in the atmosphere. In particular, the focus moving system for a large mirror of diameter 1 m ensures an almost diffraction-limited focusing of the Gaussian beam over a distance of 100 m with a waist diameter of 2 mm (at 0.8 power level) and a length of 0.8 m (at 0.5 intensity level). A radiation power of $\sim$30 MW is required for producing a MPOD in such a waist (the threshold intensity is estimated as $\sim 10^9$ W cm^{-2} [23, 24]).

The optical breakdown in a moving focus (during a pulse), as well as bead-shaped sparks produced by a sequence of laser pulses, was studied by solving the problem of ionised channel formation in a gas [20 – 22, 25 – 27]. The MPOD can be generated through on-line control of several parameters (the pulse power and repetition rate, the velocity and trajectory of MPOD, etc.). Depending on radiation parameters, MPOD can burn a through plasma channel, produce wave fields with a controllable spectrum at large distances from the laser, and simulate effects (shock wave, plasma jet) analogous to those observed during the flight of missiles.

Thus, high-power repetitively pulsed laser radiation can be used for producing an OPD (stationary or moving quasi-continuously in a gas at a high velocity). A continuous or discrete plasma trace is formed in this case. The distance between the MPOD and the laser, the maximum velocity and the length of the discharge channel are limited by the laser power and characteristics of the focusing system. Consequently, the development of powerful MPODs propagating at an ultrasonic velocity is very important for acoustic and aerospace applications; such MPODs can also be used for burning plasma channels and in developing new technologies in plasma chemistry.

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