ISSN 1063-780X, Plasma Physics Reports, 2015, Vol. 41, No. 10, pp. 858–861. © Pleiades Publishing, Ltd., 2015.
Original Russian Text © I.G. Rudoy, N.G. Solovyov, A.M. Soroka, A.O. Shilov, M.Yu. Yakimov, 2015, published in Fizika Plazmy, 2015, Vol. 41, No. 10, pp. 929–932.

LOW-TEMPERATURE PLASMA

Xenon Plasma Sustained by Pulse-Periodic Laser Radiation

I. G. Rudoy, N. G. Solovyov, A. M. Soroka, A. O. Shilov, and M. Yu. Yakimov
A. Ishlinsky Institute for Problems in Mechanics, Russian Academy of Sciences,
pr. Vernadskogo 101-1, Moscow, 119526 Russia
e-mail: yakimov@lantanlaser.ru

Received March 16, 2015

Abstract—The possibility of sustaining a quasi-stationary pulse-periodic optical discharge (POD) in xenon at a pressure of $p = 10–20$ bar in a focused 1.07-μm Yb^{3+} laser beam with a pulse repetition rate of $f_{rep} \geqslant 2$ kHz, pulse duration of $\tau \geqslant 200$ μs, and power of $P = 200–300$ W has been demonstrated. In the plasma development phase, the POD pulse brightness is generally several times higher than the stationary brightness of a continuous optical discharge at the same laser power, which indicates a higher plasma temperature in the POD regime. Upon termination of the laser pulse, plasma recombines and is then reinitiated in the next pulse. The initial absorption of laser radiation in successive POD pulses is provided by $5p^5 6s$ excited states of xenon atoms. This kind of discharge can be applied in plasma-based high-brightness broadband light sources.

DOI: 10.1134/S1063780X15100086

1. INTRODUCTION

The development of the physics of a continuous optical discharge (COD) [1], as well as progress in technology of powerful lasers used for their sustaining, has made it possible to create efficient light sources with a spectral brightness substantially exceeding that of traditional plasma-based sources. An important achievement of the recent years was application of near-IR solid-state lasers to sustain COD [2–4], because the radiation of near-IR lasers may be efficiently absorbed by high-pressure noble-gas plasmas due to the broadening of spectral transitions between excited atomic levels [5]. Several light sources on this basis were developed and patented [2, 3, 6].

COD provides a high plasma spectral brightness, reaching several units of W cm^{-2} nm^{-1} sr^{-1} in the visible region for high-pressure xenon, which is several times greater than the maximum brightness of arc-discharge plasma under similar conditions. In this case, due to high temperature, the COD brightness in the UV region is one order of magnitude higher than that of arc-discharge plasma [4, 7].

The laser energy deposited in COD plasma is limited by refraction on the density gradients of the neutral gas and free electrons [5]. Refraction manifests itself in defocusing of the laser beam as it propagates through regions with heated ionized gas and, along with absorption of laser radiation in plasma, deteriorates conditions for COD sustaining. Similar to absorption, the influence of refraction increases with increasing pressure of the plasma-forming gas. To a certain extent, refractive defocusing can be compensated for by a tighter focusing of the laser beam. Nevertheless, as the pressure is increased further (e.g., to raise the brightness of the plasma-based source), refraction leads to a decrease in the plasma temperature and saturation of the growth of the electron density with increasing pressure.

When the refraction effects are dominating (i.e., at weak focusing and/or high pressure), the electron temperature and density in an optical discharge can be substantially increased by applying pulse-periodic excitation. Such a mode of an optical discharge is called the pulse-periodic optical discharge (POD). This possibility was demonstrated in experiments on sustaining COD and POD in high-pressure hydrogen by means of continuous and pulse-periodic CO_2 lasers, respectively [8].

So far, PODs with repetition rates of a few kHz to several hundred kHz and higher were implemented using CO_2 lasers [8–10]. It is important that, in those experiments, the laser intensity in the focal spot corresponded to the threshold for optical breakdown (with allowance for the high repetition rate) and the plasma in its characteristics was closer to the plasma of optical breakdown than to COD plasma.

In this work, the conditions are determined for the first time for sustaining a pulse-periodic plasma that is closer to COD plasma in the threshold sustaining power, stability, and reproducibility as compared to the optical breakdown plasma, but surpasses COD plasma in the temperature and brightness due to specific features of pulse-periodic excitation.

2. EXPERIMENT ON SUSTAINING POD

The experiments on sustaining COD and POD were performed in quartz bulbs filled with xenon at a pressure of $p_0 = 8–14$ bar. Optical discharges in a focused laser beam were initiated by a short-time arc discharge excited between auxiliary electrodes. In this case, the pressure increased to $p = 13–21$ bar due to gas heating.

A YLR-150/1500-QCW fiber ytterbium laser manufactured by IPG Photonics was used as a source of pulse-periodic radiation with a wavelength of 1.07 μm and a bandwidth of 3–5 nm (depending on the power). The peak pulse power was up to $P = 1.5$ kW, the average power was up to $P_a = 160$ W, the pulse duration was $\tau = 0.2–10$ ms, the pulse repetition rate was $f_{\rm rep} \leqslant 2.7$ kHz, and the beam diameter at the collimator exit was $d_0 = 9$ mm. The laser bean radiation pattern is described by the so-called beam parameter product (the product of the beam radius at the collimator exit and the half-angle of the beam divergence in the far field), $BPP = 1.2$ mm mrad, or by the laser beam propagation factor, $K = 1/M^2 = 1/3.5$.

The laser beam with a diameter of $d \geqslant d_0$ was focused by a quartz lens with a focal length f and focusing parameter of $F = f/d = 3.3–8$, which for $P = 260–300$ W provided a focal intensity at a level of $I_f \approx 10^7–10^8$ W cm^{-2}. To compare POD with COD, the same laser operating in a continuous mode with a maximum radiation power of up to 260 W was employed to sustain COD.

It was found that, after initiation by the arc discharge and termination of it, POD in xenon could be steadily sustained similarly to COD plasma by a focused laser beam at a pulse repetition rate of $f_{\rm rep} \geqslant 2$ kHz, pulse duration $\tau \geqslant 200$ μs, and minimum peak pulse power of $P = 200–300$ W (depending on the pressure, which was varied in the range of $p = 10–21$ bar).

Figure 1 shows typical waveforms of the pulse-periodic laser power incident onto the plasma and passed through it and the integral plasma radiation intensity, which characterizes the plasma formation time after discharge initiation in each pulse, as well as the plasma decay time upon termination of the laser pulse. The processes of plasma formation and plasma decay were almost completed in a time $\tau_d \leqslant 100$ μs.

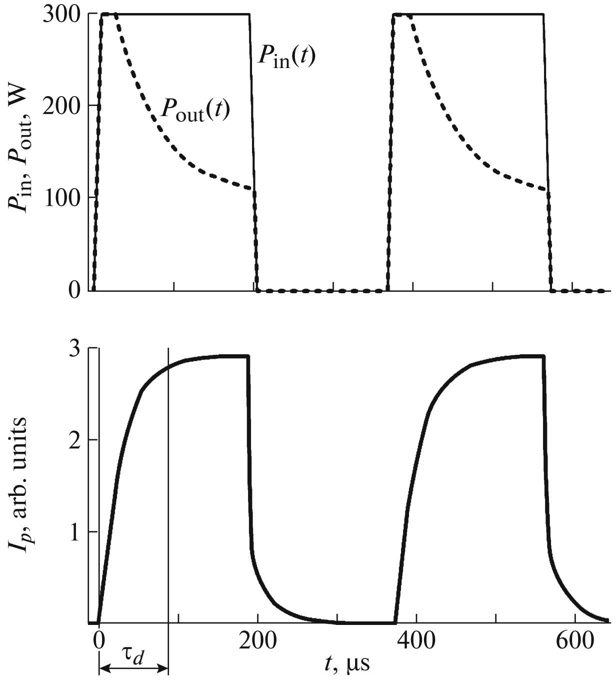

Fig. 1. Typical waveforms of the incident laser power $P_{\rm in}$ and the power $P_{\rm out}$ transmitted through the plasma, as well as of the intensity of thermal radiation I_p of POD plasma.

Although plasma almost fully recombines upon termination of the laser pulse over a time of about 50 μs, the number of excited atoms remaining in the gas by the beginning of the next pulse is sufficient to initiate plasma formation at a radiation intensity of $I_f \sim 10^7$ W cm^{-2}, which is two orders of magnitude lower than the breakdown intensity. Strong nonlinear absorption required for plasma formation in the next pulse is probably ensured by fast gas heating due to radiation absorption by excited xenon atoms in $5p^56s$ and $5p^56s'$ metastable states, as well as in the resonant states the relaxation of which at a high pressure and a temperature of a few thousands of kelvins is hampered due to the small free path length (capture) of resonant radiation. Fast gas heating is also assisted by the high rate of collisional relaxation of excited Xe atoms produced due to the absorption of laser photons in the $6s–6p$ transitions.

Figure 2 shows time-averaged images of COD and POD plasmas (obtained using a mirror optical system) depicted by contour lines of the brightness with a step of 10% of its maximum value. The images were obtained under similar conditions. The laser peak pulse power in the case of POD was nearly equal to the continuous laser power in the case of COD. It can be seen that both images are similar in appearance; the difference is that the COD image represents a stationary process, while the POD image is a result of the time averaging of the plasma propagation process in the beam channel, which is repeated in each pulse. The straight lines show a conditional boundary of the laser beam in the focal region in the absence of plasma.

To measure the pulsed spectral brightness of plasma, the point of the maximum brightness was determined on a 40-fold magnified POD image and the 0.45-mm-diameter entrance aperture of the fiber guide was placed there. The point of the instantaneous maximum brightness nearly coincided with the point

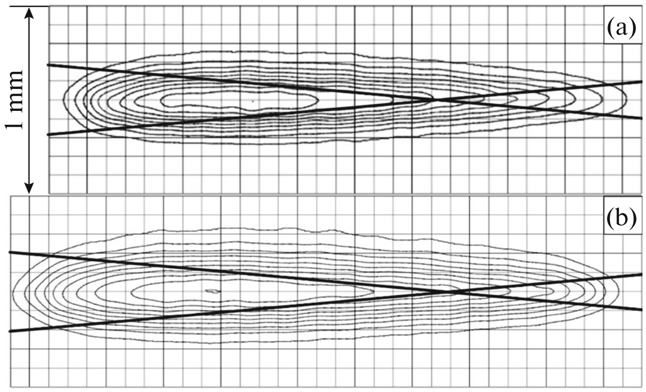

Fig. 2. Time-averaged distributions of the brightness of (a) POD and (b) COD plasmas (the contour lines of the brightness are drawn with a step of 10% of its maximum value). The working gas is xenon at a pressure of $p = 11 \pm 1$ bar. The focusing parameter is $F = 5.6$. The POD parameters are as follows: $f_{\text{rep}} = 2.7$ kHz, the incident peak pulse laser power is $P_{\text{in}} = 268$ W; the time-averaged incident and output laser powers are $\langle P_{\text{in}} \rangle = 140$ W and $\langle P_{\text{out}} \rangle = 53$ W, respectively; the plasma length is $L_p = 2.3$ mm; and the plasma diameter is $D_p = 0.33$ mm. The COD parameters are as follows: the incident laser power is $P_{\text{in}} = 230$ W, the output laser power is $P_{\text{out}} = 65$ W, $L_p = 2.8$ mm, and $D_p = 0.38$ mm.

of the maximum brightness in the time-averaged plasma image shown in Fig. 2.

When measuring the waveform of the POD total brightness, the output of the fiber guide was connected to a photomultiplier with a broadband photocathode, whereas when recording the time-integrated spectrum, it was connected to a survey CCD spectrometer with an operating spectral range of 200–1100 nm and an average wavelength resolution of 0.25 nm. The spectrometer was precalibrated in the absolute brightness of the light source by using a UV deuterium lamp and a ribbon tungsten lamp emitting in the visible and IR regions. To obtain the pulsed spectral brightness of POD, the time-integrated spectrum was multiplied by the average duty factor determined from the waveform of the total brightness. In so doing, the dependence of the duty factor on the wavelength was ignored. Actually, the duty factor of plasma radiation pulses varies in the range of 10–15%, growing with decreasing radiation wavelength.

3. COMPARISON OF COD VERSUS POD

Figures 3a and 4a compare the waveforms of the integral plasma radiation intensity $I_p(t)$ at the point of the maximum brightness for COD and POD, while Figs. 3b and 4b show the spectral brightnesses $IS_p(\lambda)$—the continuous one for COD and the peak pulse one for POD, respectively. The results were obtained for the same focusing parameter of $F = 8$ and different xenon pressure: $p_3 = 11 \pm 1$ bar for Fig. 3 and $p_4 = 19 \pm 1$ bar for Fig. 4. The pressure value influences the role of refraction and the observable distinctions in the waveforms and spectra of COD and POD plasma radiation.

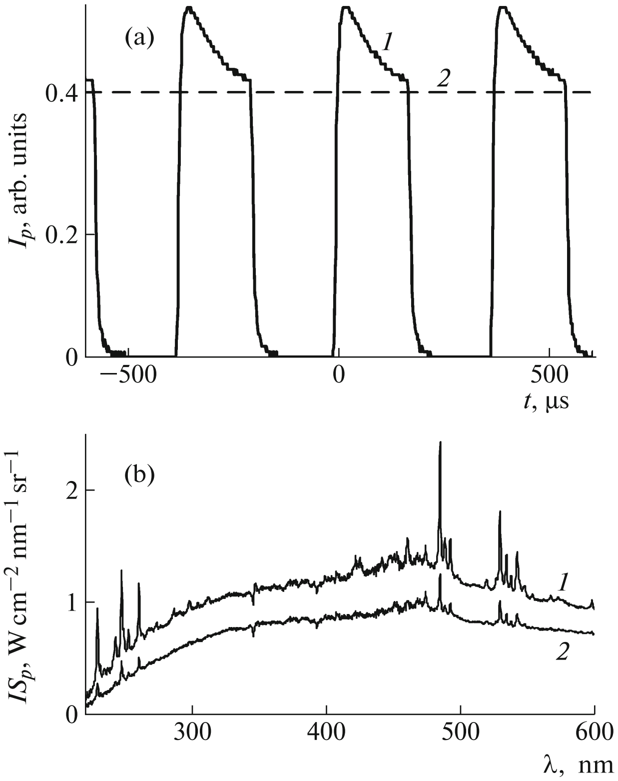

Fig. 3. Waveforms of the (a) plasma radiation intensity $I_p(t)$ and (b) spectral brightness $IS_p(\lambda)$ for (*1*) POD and (*2*) COD in xenon at a pressure of $p_3 = 11 \pm 1$ bar and focusing parameter of $F = 8$. The POD parameters are as follows: $P_{\text{in}} = 232$ W and $f_{\text{rep}} = 2.7$ kHz, where P_{in} is the incident peak pulse laser power. The incident laser power for COD is $P_{\text{in}} = 230$ W.

At the pressure $p_4 = 19 \pm 1$ bar, the POD plasma dynamics is significantly affected by the refraction of laser radiation, which is reflected in the shape of the light pulse in the course of plasma formation. In Fig. 4a, one can see pronounced peaks corresponding to the passages of two plasma fronts during one laser pulse. At the pressure p_4, the pulsed brightness of POD plasma at the first front is nearly one order of magnitude higher than the brightness of COD plasma, whereas at the pressure $p_3 = 11 \pm 1$ bar, the brightness of POD plasma only slightly exceeds that of COD plasma. The reason for this difference is that, at the increased pressure p_4, the brightness of COD plasma is reduced due to refraction. In the initial stage of its formation, POD plasma is in the region with a high intensity of the laser beam and the beam refraction is weak due to the small thickness of the plasma front.

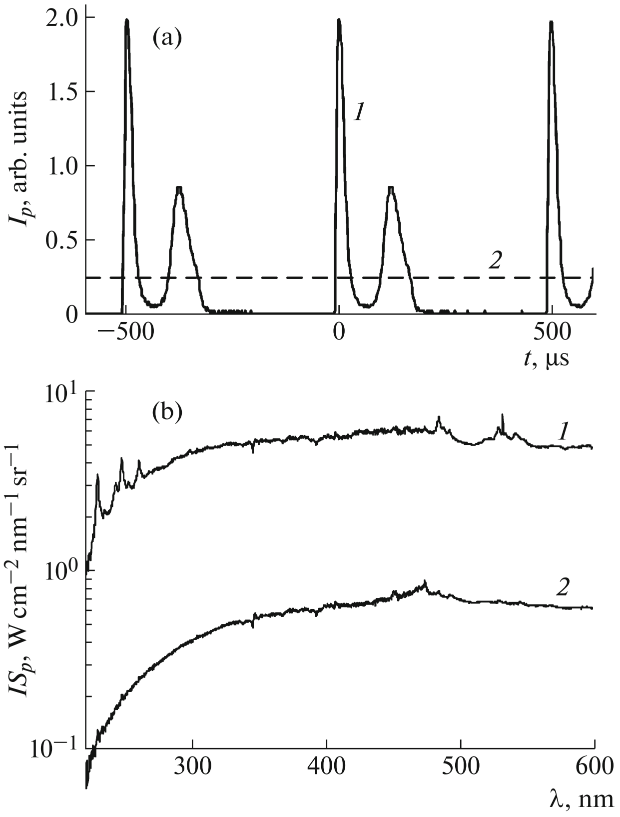

Fig. 4. Waveforms of the (a) plasma radiation intensity $I_p(t)$ and (b) spectral brightness $IS_p(\lambda)$ for the (*1*) POD and (*2*) COD in xenon at a pressure of $p_4 = 19 \pm 1$ bar and focusing parameter of $F = 8$. The POD parameters are as follows: $P_{in} = 270$ W and $f_{rep} = 2$ kHz, where P_{in} is the incident peak pulse laser power. The incident laser power for COD is $P_{in} = 230$ W.

The high temperature of the propagating POD plasma is indicated by the sharp enhancement of spectral lines of xenon ions as compared to those in COD (cf. Figs. 3b and 4b).

At the increased pressure p_4, the difference in the spectral brightnesses between COD and POD is reduced as F decreases, i.e., as the optical compensation for the refraction effects is introduced. This occurs mainly due to an increase in the COD brightness with decreasing F. As far as the refraction is compensated for by a decrease in F, the POD brightness increases only slightly, because, in the pulsed mode, refraction insignificantly affects the brightness of the first plasma front.

In our experiments, the maximum spectral brightness of POD plasma of about 8 W cm^{-2} nm^{-1} sr^{-1} within the wavelength range 450–500 nm was achieved for the focusing parameter $F = 3.3$ and xenon pressure $p = 19 \pm 1$ bar. Such a spectral brightness is twice as large as the maximum brightness of COD plasma under similar conditions.

4. CONCLUSIONS

For the first time, the conditions have been determined for sustaining POD xenon plasma that is close to COD plasma in the threshold power, stability, and reproducibility, but surpasses COD plasma in the temperature and brightness due to specific features of pulse-periodic excitation. The existence of such a regime is explained by the preservation of the nonequilibrium density of $5p^56s$ excited xenon states between laser pulses, due to which the gas is able to absorb laser radiation for more than 100 μs after termination of the laser pulse.

This kind of discharge may be used to generate plasma with an enhanced density (close to nonideal), as well as to develop broadband light sources with a very high brightness and a small size of the emitting region. POD with a pulse duration on the order of 10 μs and a sufficiently high repetition rate may be used for the same purposes as a COD, but with a higher efficiency.

ACKNOWLEDGMENTS

The authors are grateful to NTO IRE-Polyus (IPG Photonics branch) for providing them with continuous and pulse-periodic fiber ytterbium lasers.

REFERENCES

1. Yu. P. Raizer, Sov. Phys. Usp. **23**, 789 (1980).
2. D. K. Smith, Patent US No. 7435982 (2008).
3. D. K. Smith, W. M. Holber, and J. A. Casey, Patent US No. 8309943 (2012).
4. S. Horne, D. Smith, M. Besen, M. Partlow, D. Stolyarov, H. Zhu, and W. Holber, Proc. SPIE **7680**, 76800 (2010).
5. V. P. Zimakov, V. A. Kuznetsov, N. G. Solovyov, A. N. Shemyakin, A. O. Shilov, and M. Yu. Yakimov, Proc. SPIE **8600**, 860002 (2013).
6. P. S. Antsiferov, K. N. Koshelev, V. M. Krivtsun, and A. A. Lash, Patent Application No. RU2013116408/07 (2013), Patent RF No. 2534223 (2013).
7. U. Arp, R. Vest, J. Houston, and T. Lucatorto, Appl. Opt. **53**, 1089 (2014).
8. J. Uhlenbusch and W. Viol, J.Quant. Spectros. Radiat. Transfer **44**, 47 (1990).
9. P. K. Tret'yakov, G. N. Grachev, A. I. Ivanchenko, V. L. Krainev, A. G. Ponomarenko, and V. N. Tishchenko, Doklady Phys. **39**, 415 (1994).
10. G. N. Grachev, A. G. Ponomarenko, A. L. Smirnov, V. N. Tischenko, and P. K. Tret'jacov, Laser Phys. **6**, 376 (1996).

Translated by M. Samokhina