Electroconductivity of the laser plasma

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The results of investigation of the conductivity of laser plasma excited near the surface of the 22XC ceramic by pulsed laser radiation with the wavelength of 1.06 μm and pulse duration of 10^{-7} s under the action of external electric fields normal to the direction of laser radiation incidence are presented. The conductivity of plasma can be characterized by the plasma current. Depending on the power density of laser radiation, some typical regions can be separated out in plasma, namely, the region of laser plasma having no conductivity, the region of conducting plasma whose current varies in direct proportion to the radiation power density and the square strength of the external electric field, and the region of conducting plasma whose current varies in direct proportion to the radiation power density and the strength of the external electric field, and the region of plasma whose current is independent of the radiation power density and varies in direct proportion to the strength of the electric field.

The papers devoted to the study of various characteristics of plasma excited by laser radiation near the surface of solid bodies are rather numerous now (see Refs. 1–7). It should be noted that most of the papers consider X-ray,[4] optical,[5,6] and thermal[7] properties of such plasma, whereas only few papers deal with the study of laser plasma properties in electric fields.[8,9]

Under the exposure of the surface of a solid body to laser radiation, plasma is formed of ions of the ambient medium and/or ions of the target matter emitted from the exposure zone. The plasma jet formed in such a way begins to decompose some time later because of the diffusion of plasma components into the ambient medium and/or their adsorption on the target surface. Applying of an external electric field to the region of the plasma jet leads to concentration of plasma components on the corresponding electrodes depending on the electric charge of these components and allows the processes of jet decomposition to be controlled.

The practical use of the above processes of plasma jet decomposition controlled by external electric fields will allow the efficiency and quality of processing of various targets to be improved, the probability of inverse deposition of the evaporated target matter to be decreased, and the products of evaporation to be collected in a local zone of the processed material on the electrodes. The use of changeable electrodes in the plasma jet zone makes possible the collection and subsequent processing of the evaporation products of the treated material. The above peculiarities motivate the urgency of studying the electric properties of the laser plasma excited near the surface of solid bodies.

Reference 9 presents some results of studying the electric conductivity of laser plasma excited near the ceramic surface by pulsed laser radiation (PLR) with the wavelength of 1.06 μm, pulse duration of 10^{-3} s, and power density W_P ranging from $3 \cdot 10^4$ to $1 \cdot 10^6$ W/cm^2.

Based on the study in Ref. 9, the characteristic regions of where laser plasma exists with the conductivity properties were revealed. The threshold PLR power density, at which the conducting plasma arises, is $7 \cdot 10^4$ W/cm^2. At W_P ranging from $7 \cdot 10^4$ to $1 \cdot 10^5$ W/cm^2, the plasma is excited with the current varying directly proportional to the power density to the squared strength of the electric field E^2. At $W_P > 1 \cdot 10^5$ W/cm^2, the current excited varies in direct proportion to W_P and E up to $W_P = 1 \cdot 10^6$ W/cm^2.

The aim of this paper is to study the electric conductivity of the laser plasma excited near the ceramic surface by PLR with time characteristics different from those in Ref. 9.

As an object of the study, we used the laser plasma excited near the surface of 22XC ceramic by PLR with the wavelength of 1.06 μm, pulse duration of 10^{-7}s, and power density ranging from $1 \cdot 10^6$ to $2 \cdot 10^9$ W/cm^2. The values of the PLR power density used practically did not lead to destruction of ceramic samples and metal electrodes. Consequently, we can assume that plasma formed under the exposure to PLR is mostly formed due to ionization of the components of the ambient atmosphere. The PLR power density depended on focusing of the laser beam and on the laser operation mode. The experiments have been conducted at the atmospheric pressure and at room temperature with the atmospheric air as an ambient medium.

Figure 1 shows schematically the setup used in this study. Sample *1* made of 22XC ceramic was set between the electrodes *2* and *3*, to which the voltage from the power supply *4* was applied. Changing the applied voltage and the dimensions of the sample *1*, we could

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change sufficiently widely the strength of the electric field applied to the plasma jet region. The PLR from the source *5* was incident on the surface of the sample under study normally to the direction of the electric field strength. The plasma current was measured with a storage oscilloscope *6* as voltage fall on a precision current resistance R_c. The PLR source and the storage oscilloscope were synchronized using a synchronization unit *7*. It should be noted that in all experiments the area of the laser beam significantly exceeded the area of the studied sample together with the metal electrodes.

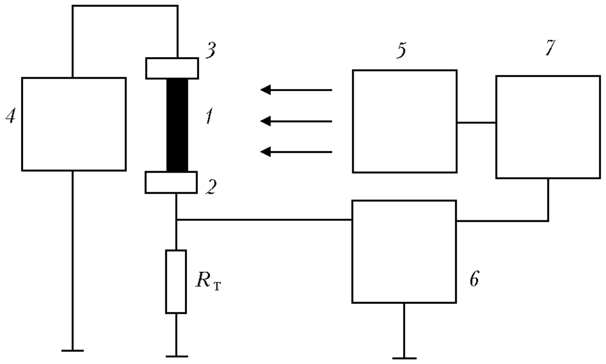

Fig. 1. Setup for studying the electric conductivity of laser plasma in the external electric field.

The electric conductivity of the laser plasma excited near the surface of the ceramic sample was characterized by the plasma current. The value of the plasma current was determined by the amplitude of the current through the plasma at a given electric field strength and the PLR power density. The time characteristics of relaxation of the plasma current are considered in this paper only partly and will be the subject of future publication.

Figure 2 shows the dependence of the amplitude of plasma current on the PLR power density for different strength of the electric field applied to the plasma. As is seen from the obtained dependence, three characteristic regions can be separated out in laser-induced plasma possessing conductivity. First of all, it is the region with $W_P < 8 \cdot 10^7$ W/cm^2, in which no conducting plasma arises. The second region is the region of $8 \cdot 10^7 < W_P < 5.1 \cdot 10^8$ W/cm^2, in which the plasma current depends on the electric field strength and the PLR power density, and the third region is the region where $W_P > 5.1 \cdot 10^8$ W/cm^2, in which the plasma current is dependent on the field strength, but independent of the power density.

Of certain interest is the study of the dependence of the plasma current on the electric field strength. Figure 3 shows this dependence for different values of the PLR power density. As is seen from the obtained results, the plasma current varies in direct proportion to the electric field strength in the entire studied range of the PLR power density. Thus, the laser plasma can be represented as an ohmic resistor connected between the metal electrodes in parallel to the ceramic sample.

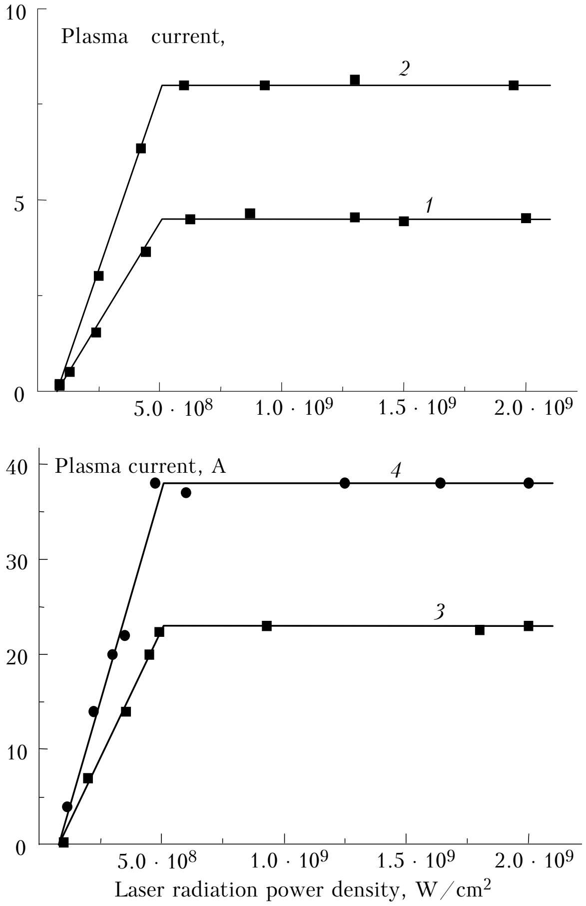

Fig. 2. Amplitude of plasma current vs. PLR power density for different values of the electric field strength: 26.3 (*1*), 52.6 (*2*), 158 (*3*), 263 V/cm (*4*).

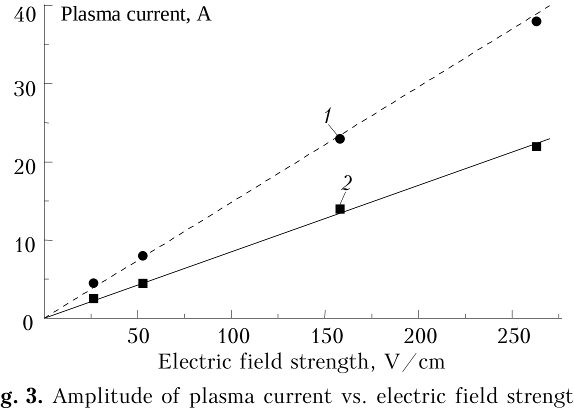

Fig. 3. Amplitude of plasma current vs. electric field strength: $W_P = 1.5 \cdot 10^9$ (*1*) and $3 \cdot 10^8$ W/cm^2 (*2*).

The experimental results presented in this paper and the results from Ref. 9 are summarized in the Table for convenience of the further analysis.

Now consider in a more detail the results of the study of the laser-induced plasma at different duration τ of laser pulses. At the pulse duration of 10^{-7} s, the region II was not found, most likely because it is near the threshold of formation of conducting plasma and occupies rather narrow region of the PLR power density (as for the case of pulse duration of 10^{-3} s).

Table. Peculiarities of laser plasma

Region	Characteristic of plasma current	PLR power density, W/cm^2	
		$\tau = 10^{-7}$ s	$\tau = 10^{-3}$ s (Ref. 9)
I	Plasma with conducting properties does not arise	$< 8 \cdot 10^7$	$< 7 \cdot 10^4$
II	Plasma current is directly proportional to W_P and E^2	Not found	$7 \cdot 10^4 < W_P < 1 \cdot 10^5$
III	Plasma current directly proportional to W_P and E	$8 \cdot 10^7 < W_P < 5.1 \cdot 10^8$	$> 1 \cdot 10^5$ character does not change up to $1 \cdot 10^6$
IV	Plasma current is independent of W_P and directly proportional to E	$> 5.1 \cdot 10^8$	Not found

This is confirmed to some extent by the following results. The analysis of the time characteristics of the plasma current near the threshold of its formation at different pulse durations has demonstrated their identity in the shape. Near the threshold of plasma formation, the current pulse has the following shape. First, we observe the delay in formation of the plasma current, whose value depends on the pulse duration and equals $(2–2.5) \cdot 10^{-6}$ s for the pulse duration of 10^{-7} s and $(0.5–1) \cdot 10^{-3}$ s for the pulse duration of 10^{-3} s. Then we observe the appearance of the plasma current, whose behavior can be characterized as follows: increase in the current of one polarity, achieving maximum, decrease down to zero, appearance of the current of the opposite polarity, achieving its maximum, and decrease down to zero. The presence of the plasma current of different polarity indicates that plasma particles having different charge may produce this current.

The transition to the region III (at the pulse duration of 10^{-3} s or at the increase of the power density somewhat higher above the threshold for the pulse duration of 10^{-7} s) leads to the appearance of the unipolar plasma current without the first component, which is observed near the threshold. The identical behavior of the plasma current in the region II at different pulse durations is indicative of the identical physical processes of formation of the conducting plasma.

The tabulated results also show that the region IV was not found for the pulse duration of 10^{-3} s. This is possibly connected with the fact that the power density used in Ref. 9 was insufficient for achieving this region. Another reason may be different electro-physical properties of the plasma at different pulse durations.

Thus, based on the above-said we can draw the following conclusions. Under the exposure to high-power laser radiation, the laser-induced conducting plasma is formed near the target surface. The threshold for formation of such plasma depends on the duration of the laser pulse. Applying the external electric field to the plasma zone leads to appearance of the plasma current, but with a delay relative to the laser pulse. This delay can be called the time for formation of the conducting plasma. The plasma can be considered as a resistor connected in parallel to the target.

Near the threshold of formation of the conducting plasma, its current varies in direct proportion to the squared strength of the electric field applied to the plasma zone and in direct proportion to the PLR power density (region II, see Table). This region is characterized by a narrow range of PLR power density values; therefore, it can be called a transition region. In this transition zone of existence of the conducting plasma, we observe the specific shape of plasma current pulses, which indicates that particles with the opposite charges produce the plasma current.

The increase of the PLR power density leads to formation of the plasma, whose current varies in direct proportion to the PLR power density and the electric field strength (region III). The shape of the current pulses observed in this region indicates that plasma particles with identical charge take part in the current. Possibly, disappearance of the earlier observed component of the plasma current is only imaginary. This may be a consequence of the fact that the duration of the plasma current of one polarity differs significantly from that of the current of another polarity with the increasing PLR power density and/or electric field strength.

The further increase of the PLR power density leads to saturation of the plasma current (region IV), what is likely indicative of the formation of the plasma jet with complete ionization of its components. We can assume that in this case the increase of the PLR power density results only in the increasing generation of the response of optical, X-ray, and/or thermal radiation,[4–7] as well as in absorption of laser radiation by the plasma jet.[10]

Thus, from the results of this study, we have revealed the characteristic regions of existence of the conducting laser-induced plasma excited near the ceramic surface by laser pulses of different duration. Each region is characterized by the specific dependence of the amplitude and time characteristics of the plasma current on the PLR power density and the strength of the electric field applied to the plasma zone.

In the future, the study of the time characteristics of plasma should be continued at different durations of the laser pulses, different strength of the electric field, and different optical characteristics of the laser radiation.

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