Localization of an electric arc discharge in a laser-induced plasma channel

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Abstract. In this work an experiment on the interaction of femtosecond laser radiation with an electric arc is described. An experiment was conducted to determine the behavior of an electric arc in a laser-induced plasma channel. As a result, it was found that the electric arc follows directly strictly through the laser-induced plasma channel. The formation of the electric arc through the plasma area mainly depended on the frequency of the laser pulses. As a result of these experiments, it was confirmed that the follow of the electric arc can be carried out strictly through the induced plasma channel.

1. Introduction
The possibility of forming plasma channels through which electrical energy can be transmitted is of great interest. Currently, actively solved the problem of wireless power transmission over distances, lightning protection. However, there are other directions where you do not need to create channels over long distances. One of these areas is the processing of the material. In the works [1, 2] conducting laser plasma channels were used as electrodes tools for electrical discharge processing of materials.

To achieve the task it is necessary to create an area in which an electric discharge would flow. One of the most effective tools for creating a narrowly focused, space-limited plasma channel is laser radiation. Currently, lasers with femtosecond pulse duration are popular. With the help of such pulses can be created in a variety of area along the direction of propagation of the laser beam extended plasma channels in the filament. When using femtosecond pulses, it is possible to create a channel to control the electric discharge at a length of up to 3 m at a voltage at a discharge interval of 2 MV [3]. If the purpose is not to create longer channels, these parameters can be used for various studies on the combined processing of the material. However, it is necessary not only to create a laser-induced plasma channel, but also to create such conditions that this channel has the necessary amount of free charge carriers to transmit electrical energy through it. For atmospheric air, a breakdown is formed when about $10^{13}$ electrons are born in the field during the exposure to the laser pulse [4]. This value in particular depends on such conditions as the medium in which the laser plasma channel is created, the power density of the laser radiation, the wavelength of the laser radiation, the focusing system and the frequency of laser pulse generation.

Thus, choosing the optimal conditions, it is possible to create a stable laser-induced plasma channel for the transmission of electrical energy through it.

2. Review of literature
The choice of an optical system for the realization of a laser-induced plasma channel is a very important. From the focal length of the lens depends on the power density in the caustic area, the
intensity of plasma formation, the length of the plasma channel, shape of plasma channel. Unlike lightning protection purpose, atmospheric sounding, for application in the area of materials processing, a small length of laser – induced plasma channel in the medium is enough - from several units to tens of millimeters. Figure 1 shows the results of [5] work on the creation of laser-induced plasma channels with using different optics.

**Figure 1.** Conducting laser channels with using different lenses: a, d – axicon, b, c – spherical lens with a focal length of 30 mm, c, f - spherical lens with a focal length of 80 mm, medium: water (a, b, c), oil (d, e, f) [5].

In Figure 1a and 1g focusing of the laser beam was carried out with using an axicon - which transforms the laser beam into a ring shape. The plasma channel is “locked” in the ring, which contributes to plasma amplification, since it does not extend beyond the limits of the final form. The use of an axicon as a lens makes it possible to obtain a plasma channel with a large ratio of length to diameter. However, if the laser power is not enough, the channel has gaps. The energy in the channel spread over a large area, which led to a violation of its electrical conductivity. The spherical optics is more useful if laser energy is smaller - the breakdown occurs in a limited area and then spread in the direction of spread of the laser radiation, has a more uniform structure.

The intensity distribution in a laser-induced plasma channel affects the spread of an electric arc. Figure 2 shows the results of an experiment on the flow of an electric discharge in a laser plasma channel with using different optics [6]. The laser is represented in green, the plasma channel is in blue, and the discharge is depicted in white.

**Figure 2.** The flow of an electric discharge in a laser plasma channel using different optics, and the corresponding intensity distribution: a - Gaussian beam focused by a lens, b - a Bessel beam formed after an axicon, c - an Airy beam produced by a binary phase mask [6].

In order for the electric discharge to pass strictly through the laser-induced plasma channel, it is necessary that this channel has a sufficient number of free electrons. The more free electrons in the optical breakdown area, the more stable the electric discharge will pass through the laser-induced plasma channel. To increase the concentration of energy in a unit of area leads to a decrease in the focal length of the lens. According to [7], when using femtosecond laser radiation, a decrease in the beam diameter with a simultaneous increase in the pulse duration leads to a fivefold increase in the concentration of free electrons in the filament – Figure 3.
To form a stable continuous electric arc in the area of laser plasma channel, it is necessary to choose the most effective conditions of discharge generation. One of these parameters is the frequency of electrical and laser pulses. Figure 4a shows the formation of electrical discharges between the plasma channel and the solid-state electrode. Figure 4b - the phenomenon of destruction of the plasma channel [1].

The destruction of the channel occurs if the frequency of electrical discharges exceeds the frequency of formation of the plasma channel. The formation of a laser plasma channel is also influenced by such characteristics as the value of laser energy absorption, the presence of free charge carriers, and the degree of ionization. All these parameters depend on the medium in which the laser-induced plasma channel is formed. For example, gases with a low ionization threshold, such as argon and helium, require less laser energy. It is estimated that the breakdown of atmospheric air, nitrogen and argon using femtosecond radiation with an energy of 1 MJ and a laser pulse duration of 100 ps requires a density of the order of power at atmospheric pressure of $10^{13}$-$10^{14}$ W/cm$^2$ [8, 9]. When using liquid media, such as water, high density prevents the expansion of plasma channels, so the plasma channels formed in the water environment have a longer length, continuous structure and a smaller diameter, compared with the channels obtained in the air [1].

Based on the literature data, it can be concluded that using femtosecond laser radiation in the atmosphere of the air, it is possible to form a stable plasma channel with subsequent transmission of electric energy strictly along it.

3. Conducting an experiment and discussing the results
To form laser-induced plasma channels the ytterbium femtosecond laser TETA-10 was used as a source of laser radiation, which has the following parameters: wavelength $\lambda = 1029$ nm, pulse duration $\tau = 280$ fs, repetition frequency $F_{\text{max}} = 10$ kHz, pulse energy $E_{\text{max}} = 150$ µJ. Polarization of laser radiation is linear. In the experiments, the laser repetition frequency varied from 1 to 10 kHz. A spherical lens with a focal length of 100 mm was used to focus the laser radiation. The experiment was carried out under normal conditions without the use of any gases in the atmosphere air. The electric arc was created by a constant voltage source of 25 000 V, with a frequency of generation less than the
frequency of laser pulses, 0.1 kHz. The arc passed through the air gap between the tungsten electrodes area at a distance of 10 mm. The caustic area was located at a distance of 0.8 - 0.9 mm above the right electrode. Figure 5 shows the scheme of the experiment.

Figure 5. The scheme of the experiment: 1 – high voltage DC source, 2 – electric arc discharge, 3 – optical breakdown area, 4 – tungsten electrode, 5 – laser beam, 6 – focusing lens, 7 – laser system, 8 – CCD camera

When an optical breakdown is formed, conditions are created for the spread of an electric arc discharge because in the area formed the enough number of electrons ($10^{13}$ electrons). Thus, the electric arc spread strictly in the area of laser-induced plasma channel formation (Figure 6a). When the pulsed power of laser radiation is reduced to 100 µJ per pulse at the same laser repetition frequency, the luminescence intensity of the laser-induced plasma channel is reduced too (Figure 6b). However, the shape of the arc discharge and the area of its spread are not disturbed. Figure 6c shows the spread of the electric arc discharge under the following parameters of femtosecond laser radiation: the energy in the pulse 100 µJ, the laser repetition frequency 1 kHz. The intensity of the luminescence of the optical breakdown area under such conditions of interaction is practically not recorded by the camera. However, when starting the generation of the arc discharge, distribution of arc discharge is also carried out over a given area – Figure 6c. With a decrease in the frequency of laser pulses, a change in the tail part of the arc discharge is noticeable – figure 6c (indicated by a dotted ring), in contrast to the shape of the tail of the arc discharge on the electrodes in Figure 6a and 6b. This effect is caused by a decrease in the concentration of free electrons.

Figure 6. The flow of an electric arc through the plasma channel: a – laser pulse energy 140 µJ, laser repetition frequency 10 kHz, b - laser pulse energy 100 µJ, laser repetition frequency 10 kHz, c - laser pulse energy 100 µJ, laser repetition frequency 1 kHz.

4. Conclusion
During the experiments it was confirmed that the distribution of the electric arc can be carried out strictly by laser-induced plasma channel. It is also found that the shape of the discharge gap is affected by the frequency of laser pulses. This scheme can be successfully used for processing conductive materials. The meaning of this approach is to localize the electric arc discharge due to the formation of a conductive part of the area under the action of laser radiation. Thus, it is possible to significantly increase the energy applied to the site of exposure due to the combined effect of an electric arc discharge and laser radiation creating a directly conducting area in the processing area. Increasing the efficiency of processing conductive materials is achieved by increasing the energy of the system with the help of an electric energy source, and not with the help of laser radiation.

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