Quantum Electronics **32** (2) 115 – 120 (2002)

CONTROL OF LASER RADIATION PARAMETERS

PACS numbers: 52.80.Mg; 52.50.Jm; 42.55.Lt
DOI: 10.1070/QE2002v032n02ABEH002140

Electric-discharge guiding by a continuous spark by focusing CO_2-laser radiation with a conic mirror

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***Abstract*. The feasibility of producing continuous laser sparks (CLSs) with a resistance per unit length of 100 – 400 Ω cm^{-1} by focusing radiation from CO_2 laser with a conic mirror is demonstrated. The laser energy input per unit length required for this is experimentally found to be equal to $\sim$200 J m^{-1}. The possibility to efficiently control the trajectory of an electric discharge by means of a CLS is demonstrated. A CLS is found to be an analogue of a high-conductivity metal rod during the electric breakdown and electric potential transfer. The effect of polarity in the electric breakdown of air gaps between the CLS plasma channel and a metal rod is discovered and interpreted. The transverse structure of the CLS conductivity is investigated. Most likely the CLS conductivity at the initial stage is due to the photoionisation of air by the radiation of primary nuclei of the optical breakdown.**

Keywords: *optical breakdown, long laser spark, CO_2 laser, laser-spark guided electric discharge.*

1. Introduction

The solution of some scientific and applied problems requires the production of long plasma channels in the atmospheric air with controllable location and shape. Such channels can find application for energy transfer [1 – 3], the transportation of charged particle beams [4, 5], the production of plasma antennas [6], and for lightning protection [7 – 10]. In the investigation of these problems, considerable attention was given to the control of the trajectory of an electric discharge or, in other words, to the production of guided electric discharges [1 – 3, 11, 12].

One of the most promising methods for producing a plasma channel or controlling the trajectory of an electric discharge is the exposure of gas to laser radiation. Of all kinds of laser action, an optical breakdown leads to the longest and most intense gas perturbation. The length of optical breakdown channel, called a long laser spark (LLS), under real atmospheric conditions can amount to tens of metres and over [13, 14], which makes it possible to produce guided electric discharges several metres long [1, 8].

In Ref. [9], the length of a guided discharge was equal to 16 m for a 3-MV voltage across the discharge gap and a 460-J output energy of a pulsed CO_2 laser used to obtain the LLS. However, an LLS produced by spherical optics consists of separate breakdown nuclei located at random in the caustic of the focusing element, i.e., it is immanently discontinuous. For this reason it has not been possible to attain good reproducibility in attempts to control the trajectory of very long discharges with the use of an LLS. This is also evidenced by the results of the tests of a laser lightning-protection system under real thunderous conditions in Japan, which failed because two events of time coincidence of a thunderbolt to the lightning rod with the triggering of a laser were observed, but the trajectories of the lightning channel and the LLS did not coincide [10].

A continuous optical breakdown channel devoid of gaps, or a continuous laser-induced spark (CLS), can be obtained by focusing laser radiation with a conic lens (an axicon) [15]. A $\sim$1-m long CLS was experimentally obtained [16] by focusing Nd-laser radiation ($\lambda = 1.06$ μm) with an axicon. The electrical characteristics of a 9 – 12 cm long CLS produced by a Nd laser emitting 40-ns pulses were investigated in Ref. [3]. For an output laser energy of 100 J, the resistance of the spark under investigation was 0.5 – 1 Ω. On applying a voltage of 1 – 25 V across the spark, the electric current reportedly started flowing immediately after the optical breakdown. The results of Ref. [3] demonstrate that the efficient control of the trajectory of electric discharges is possible using CLSs produced by focusing laser radiation with conic optics. However, considerably longer CLSs may be needed for practical applications. For instance, estimates made in Ref. [17] show that the plasma channel length in real lightning protection systems should be equal to $\sim$20 m.

Increasing the wavelength of laser radiation results in a lowering of the optical breakdown threshold, which should permit increasing the CLS length – a parameter critical for practical applications [18]. In this paper, we investigate the feasibility of producing a CLS with the use of a CO_2 laser ($\lambda = 10.6$ μm), and also the feasibility of its application for guiding electric discharges and transferring the electric potential.

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Received 22 October 2001
Kvantovaya Elektronika **32** (2) 115 – 120 (2002)
Translated by E.N.Ragozin

2. Experimental setup

The schematic diagram of the setup for studying CLSs is shown in Fig. 1. The radiation of an electric-discharge TS-300 CO_2 laser [19] with a maximum output energy of 300 J and the radiation divergence at half-maximum of $\sim 3.5 \times 10^{-4}$ rad was focused with conic aluminium mirrors (*1*) with a cone angle $\gamma = 177.8$ or $179.16°$. The angle of incidence of the laser beam (*2*) on the focusing mirror did not exceed 5°. The radiation of a laser spark in the visible range was recorded with a fast photodiode (*3*) and was also photographed with an Olympus C-3030 digital camera (*4*).

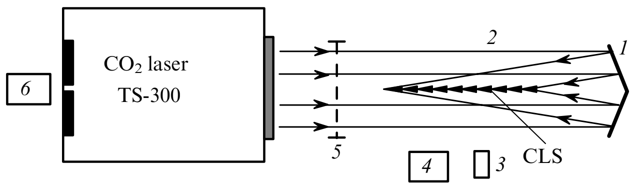


Figure 1. Schematic of the setup for CLS production: (*1*) conic mirror; (*2*) laser beam; (*3*) photodiode; (*4*) digital photographic camera; (*5*) transmission bolometer; (*6*) photodetector.

The laser beam with a cross section in the form of a frame with external and internal dimensions of 10 × 10 cm and 3.3 × 3.3 cm, respectively, was formed by an unstable telescopic resonator with a magnification $M = 3$. The output laser energy was recorded with a transmission bolometer (*5*) in every shot; the shot-to-shot energy spread was within 5 %. The output laser energy was varied during expreiments by varying the pressure of the working laser medium and the voltage of the pump source, because introducing plastic film or metal mesh filters into the laser beam resulted in beam wafefront distortions and deterioration of CLS quality.

The shape of output laser pulses was monitored with an FP-3 photon drag detector (*6*) through the alignment opening in the rear resonator mirror. Typical oscilloscope traces of an output laser pulse are given in Fig. 2. One can see from Fig. 2a that the shape of the output pulse is typical for electric-discharge CO_2 lasers – a short (~ 40 ns) primary peak and a long (~ 3 μs) tail. Due to spontaneous mode-locking, the pulse was modulated with short (~ 3 ns) peaks spaced at ~ 10-ns intervals (see Fig. 2b).

The electrical CLS characteristics were investigated employing the circuit shown in Fig. 3a. The ends of two metal rods 2 mm in diameter were introduced into the CLS plasma. The rods were connected to oppositely (relative to the common ground) charged capacitors *C* with capacitances of 0.25 μF each and were variously spaced in different experiments. The highest capacitor charging voltage was 50 kV, so that the potential difference across the rods could be as high as 100 kV. When studying the electric breakdown of the air between the metal rod and the CLS plasma column, one or both rods were shifted perpendicular to the CLS axis through a distance required in the experiment. The polarity of the rod moved aside could be altered.

The circuit for studying the electric field distortion and potential transfer with the aid of an LLS is shown in Fig. 3b. In these experiments, one of the rods dipped into the plasma was connected to a resistive voltage divider ($R_1 = 5$ kΩ, $R_2 = 60$ Ω). The other rod remained connected to the capacitor, whose charging voltage did not exceed

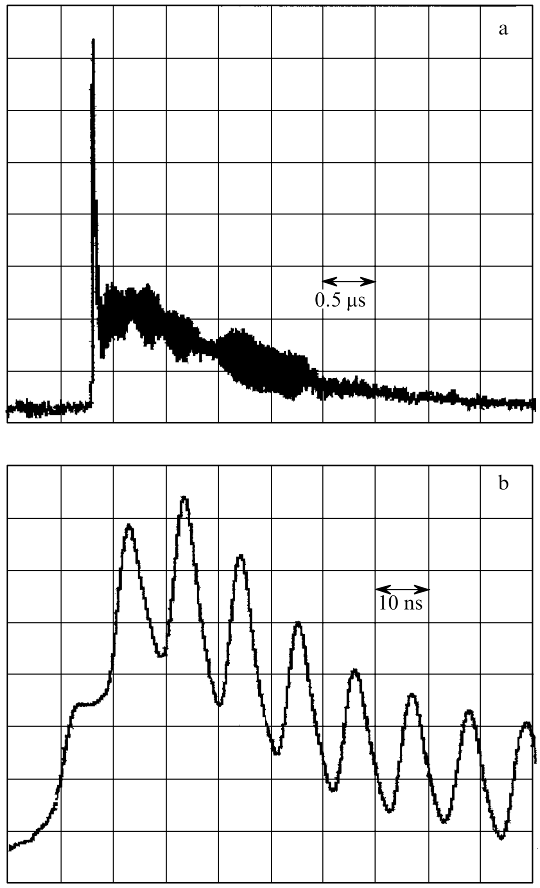


Figure 2. Oscilloscope traces of the pulse of CO_2-laser radiation.

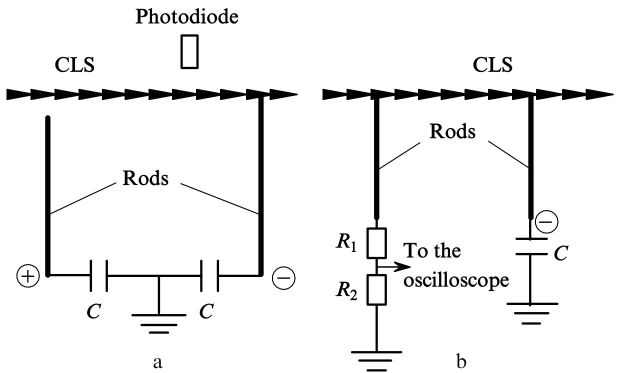


Figure 3. Circuits for studying the electrical characteristics of a CLS.

600 V, allowing us to avoid the development of ionisation in the electric field.

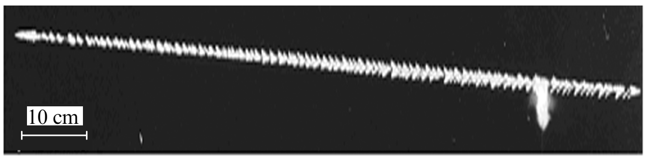
The electric field perturbation and the potential transfer during the production of a CLS were also investigated employing a capacitive voltage divider. The high-voltage arm of the divider was the capacitance between the CLS plasma channel, or the electric-discharge channel, and the metal plate mounted on the divider. This capacitance could be varied by varying the plate area and the distance between the plate and the plasma channel. A ceramic capacitor, whose second plate was connected to the grounded body of the divider, served as the low-voltage arm.

The voltage dividers were calibrated directly at the measurement site by applying voltage drops of different amplitude across them from a capacitor C (see Fig. 3b). When calibrating the capacitive divider, the CLS was simulated by metal rods of different diameters. As in the setup of Fig. 1, the instants of spark initiation and the electric-discharge development in it during the study of electrical CLS characteristics were recorded with a fast photodiode. The signals from the photodetectors and voltage dividers were recorded employing a Tektronix TDS 220 oscilloscope with a pass band of 100 MHz.

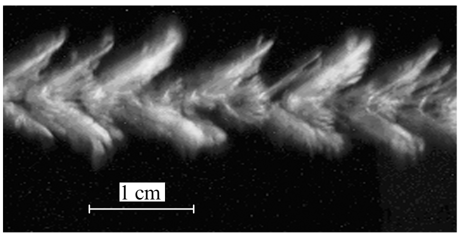
3. Experimental results and discussion

The photograph of a CLS produced by focusing the CO_2-laser radiation with a conic mirror with a cone angle $\gamma = 177.8^\circ$ is shown in Fig. 4a. One can see that the laser spark looks like a continuous column consisting of bright cone-shaped elements. The breaks characteristic of the sparks produced by beam focusing with spherical optics are absent in this case. This pattern is observed for an output laser energy of 180 – 300 J. The CLS length, determined by the cone angle and the beam dimensions in the cross section of the cone, was equal to ~ 90 cm. The CLS onset is displaced from the mirror surface because the radiation is absent in the beam centre. When the output laser energy was less than 150 J, at the ends of the spark, where the input of laser energy is lower than in the central region, visible breaks appeared in accordance with the energy distribution over the beam section.

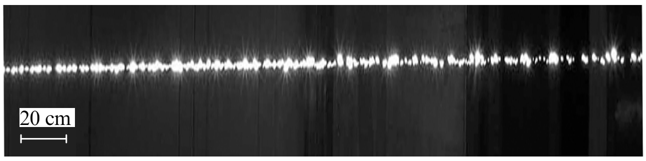
The photograph of a CLS fragment is shown in Fig. 4b, in which the longitudinal spark structure in the form of bright cone-shaped elements is clearly visible. The same structure was observed when the CLS was produced by Nd-laser radiation [3, 16], but the structure period and the transverse dimension of the CLS were significantly smaller than in the case under study due to the different emission wavelengths of Nd and CO_2 lasers.



a



b



c

Figure 4. Photographs of an LLS produced by CO_2-laser radiation focusing with a conic mirror with a cone angle $\gamma = 177.8$ (a, b) and 179.16° (c).

For comparison, Fig. 4c shows the photograph of an LLS obtained by using the mirror with a cone angle $\gamma = 179.16^\circ$ for an output CO_2-laser energy of 300 J. One can see that the increase in cone angle, as expected, led to the increase in the spark length up to ~ 3 m. However, the spark was no longer continuous, because the laser energy inputted per unit length of the spark was not high enough. The transverse dimension of the plasma nuclei in the spark also increased appreciably (by a factor of ~ 1.5). However, even for an output laser energy insufficiently high to produce a continuous channel, the radiation focusing with a conic mirror makes it possible to attain a higher density of plasma nuclei per unit length of the spark compared to that obtained by focusing with spherical optics (the spark lengths being equal) because of the more uniform distribution of laser radiation energy over the spark length.

Estimates made on the basis of photographs show that to produce an almost continuous spark structure by focusing the CO_2-laser beam with a conic mirror, a linear laser energy input of ~ 200 J m^{-1} is required. Note that these estimates are valid only for the shape of output laser pulses shown in Fig. 2. The use of techniques for raising the peak output power, for instance, by injecting a nanosecond pulse into the resonator [20], will reduce the output laser energy required for the CLS production.

The electrical properties of the laser spark were investigated by focusing radiation with a mirror with a cone angle $\gamma = 177.8^\circ$ (the total spark length was ~ 90 cm). These studies confirmed that these sparks can be efficiently applied for electric-discharge guidance. Even for an output laser energy of 140 J, when noticeable discontinuities were observed at the spark ends and the length of the continuous part did not exceed 50 cm, an electric breakdown was observed in the spark between the rods immersed into the spark plasma and spaced at $d = 80$ cm for a minimal average electric intensity $E_{min} \approx 77$ V cm^{-1}.

Fig. 5 shows the average propagation velocity V_{ch} of the conducting channel of laser-guided discharge along the spark as a function of the average electric intensity in the gap E for $d = 80$ cm and an output laser energy of 140 J. The velocity V_{ch} was estimated from the time interval between the signals from the photodiode corresponding to the instants of laser spark initiation and the appearance of the guided discharge. One can see from Fig. 5 that for $E = 385$ V cm^{-1}, the channel velocity $V_{ch} = 4 \times 10^7$ cm s^{-1}.

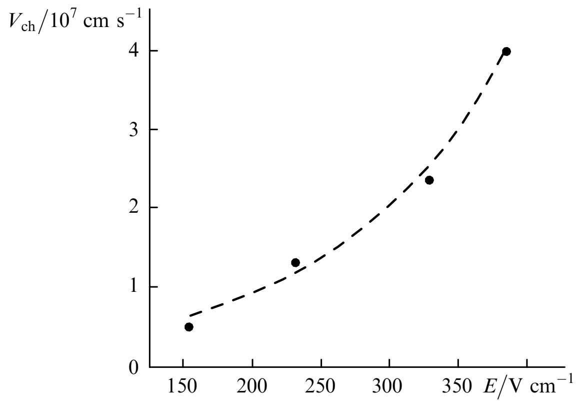


Figure 5. Velocity of propagation of the conducting channel V_{ch} as a function of the electric field intensity E.

The experiments on the electric breakdown of the air gaps between the CLS column and the metal rod were performed using the circuit shown in Fig. 3a for a 100-kV voltage across the rods, an output laser energy of 270 J, and a horizontal rod separation $d = 45$ cm. For a positive polarity of the rod displaced relative to the CLS, the longest vertical distance H between the rod upper end and the CLS plasma column at which the electric breakdown occurred amounted to 13 cm. The photograph of a laser-guided discharge in this case is shown in Fig. 6.

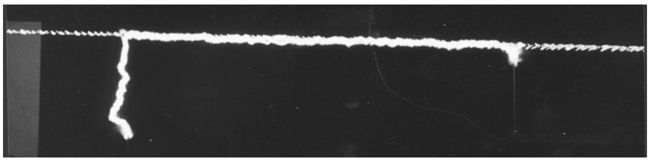


Figure 6. Photograph of a CLS-guided electric discharge.

Fig. 7 shows the oscilloscope trace of signals from the photodiode recorded under the same conditions. The first peak in the oscilloscope trace reflects the CLS production, while the other, with a ~ 100-μs delay, corresponds to the current of the guided discharge. Under the same experimental conditions and a negative polarity of the rod, the longest distance H at which the electric breakdown of the air gap occurred was only 6 cm. Therefore, upon the breakdown of the air gap between the CLS plasma column and the rod, we observed a distinct polarity effect indicating that the real transverse dimension of the CLS is significantly larger than that demonstrated by the photographs (~ 1 cm). Indeed, when the CLS was replaced by metal rods of different diameters, the polarity effect in the air gap breakdown comparable to the polarity effect observed in the CLS-guided discharge experiment manifested itself only for a rod diameter of over 4 cm.

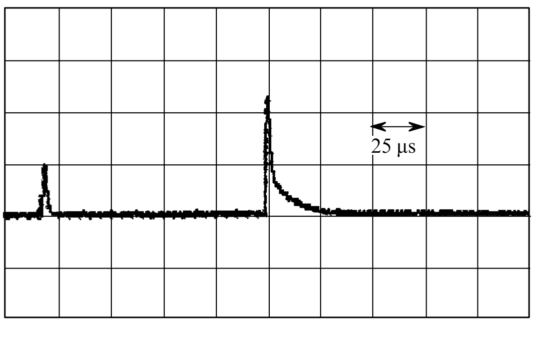


Figure 7. Oscilloscope trace of the signal from the photodiode: the CLS radiation (the first peak) and the radiation of CLS-guided electric discharge (the second peak).

Therefore, our experiments showed that the CLS produced by focusing the CO_2-laser radiation with a conic mirror behaves similarly to a conducting rod, its conductivity, as follows from the oscilloscope trace in Fig. 7, persisting for a rather long period of time.

The CLS conductivity and the feasibility of transferring the electric potential via the CLS were investigated using the circuit shown in Fig. 3b for an output CO_2-laser energy of 150 J. Under these conditions, only the central ~ 65-cm long part of the spark was continuous. The distance d between the rods immersed into the CLS plasma was varied between 10 and 60 cm. The position of the rod under potential remained invariable in the experiment, and only the rod connected to the resistive voltage divider was moved. The polarity of the rod under potential was negative. Fig. 8 shows the oscilloscope traces of the signals from the voltage divider and the photodiode (recording the CLS plasma emission) obtained for $d = 10$ cm. One can see that these signals commence simultaneously, i.e., the CLS is conducting since the instant of its initiation. The leading edge of the voltage pulse at the divider has a characteristic step shape, the regions of rapid voltage build-up being replaced with the regions of slow voltage growth. The voltage rise time τ_f and, accordingly, the CLS plasma conductivity rise time are independent of the rod separation d and are equal to ~ 28 μs. The large duration τ_f points to an important role of gas dynamic processes in the production of CLS conductivity.

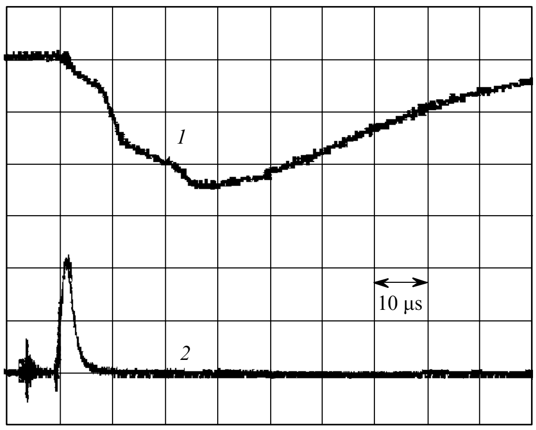


Figure 8. Oscilloscope traces of the signals from the voltage divider at the spark axis (*1*) and from the photodiode (*2*).

Fig. 9 shows the ratio U/U_0 (where U is the voltage amplitude recorded by the resistive divider and U_0 is the charging voltage of the rod under potential) as a function of the distance d between the metal rods immersed into the CLS plasma. This dependence reflects the CLS-assisted potential transfer. The scatter of points may be due to an inaccurate mounting of the movable rod in the plasma channel. This dependence allows us to estimate, taking into account that the resistance of the resistive divider is $R_d = 5.06$ kΩ, the resistance R_s of the CLS produced with a conic mirror: $R_s = 988\ \Omega$ for $d = 10$ cm and $R_s = 23.9$ kΩ for $d = 60$ cm (the resistance per unit length is $100-400\ \Omega\ \text{cm}^{-1}$). This result confirms that the CLS conductivity is high. Note that a CLS produced by focusing a laser beam with a spherical mirror is not conducting at all due to the immanent structural discontinuities between the plasma nuclei.

In the experiment being outlined, for $d > 70$ cm no signal from the resistive divider was detected as well. This indicates that the spark is nonconducting due to the appearance of breaks in its structure (recall that the experiment was performed for an output laser energy of 150 J).

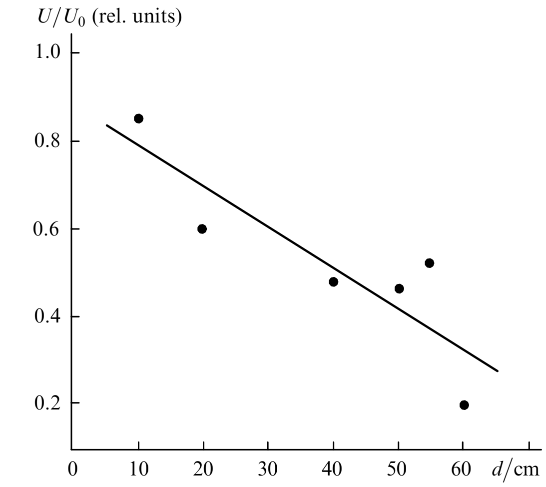


Figure 9. Dependence of U/U_0 on the distance d between the rods dipped into the CLS plasma.

However, the capacitive divider produced signals as d was increased up to 90 cm, which confirms the existance of significant electric-field distortions in the gap induced by the spark under study, despite the discontinuities in the spark structure. This is consistent with the results of measurements of the breakdown fields along the spark considered above.

Of immediate interest was the investigation of electrical conduction of the CLS in its cross section in connection with the discovery of polarity effect in the electric breakdown of CLS – rod air gaps. For this purpose, the rod connected to the resistive voltage divider was displaced perpendicular to the CLS axis. This experiment was conducted for a separation $d = 10$ cm and an output CO_2-laser energy of 270 J.

Fig. 10 shows the voltage amplitude U recorded by the voltage divider as a function of the distance r between the upper end of the measuring rod and the CLS axis. One can see that the maximum distance r at which the signal from the divider is still recorded is equal to ~ 2 cm. This is consistent with the results of the experiment on the modelling of polarity effect when the CLS was simulated by metal rods of different diameters. Fig. 11 shows the oscilloscope traces of

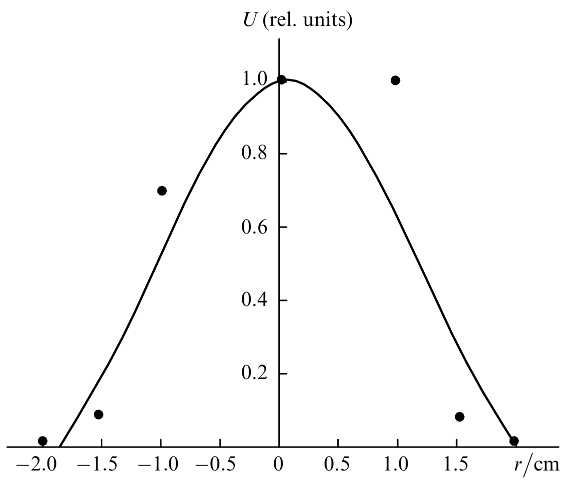


Figure 10. Voltage U across the divider as a function of the distance r between the CLS axis and the tip of the rod.

the signals from the resistive divider and the photodiode recorded for $r = 1.5$ cm. Note that the voltage rise time $\tau_f \approx 3$ μs in Fig. 11 is substantially (about an order of magnitude) shorter than the corresponding time in the oscilloscope trace of the voltage signal shown in Fig. 8, and the voltage drop from the peak value in Fig. 11 occurs considerably faster than in Fig. 8.

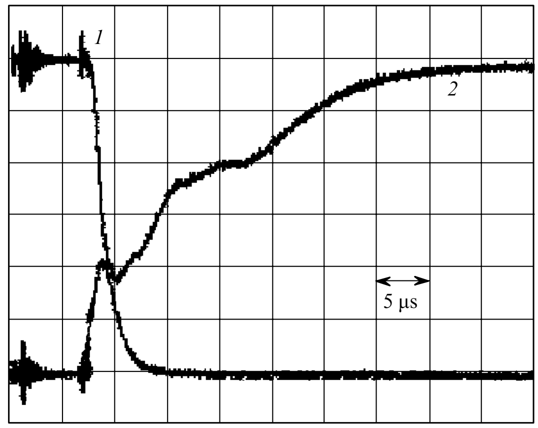


Figure 11. Oscilloscope traces of the signals from the voltage divider (*1*) and the photodiode (*2*) for $r = 1.5$ cm.

Note that the duration τ_f in Fig. 11 is approximately equal to the duration of the initial period of rapid voltage build-up in Fig. 8. Therefore, we can assume that the initial CLS conductivity, both on the axis and in the peripheral regions of the CLS (in the cross section), is due to the photoionisation of air by the radiation of initial nuclei of optical breakdown. The ionisation corona around a spark produced by focusing a laser beam with a short-focus lens was earlier observed in Ref. [21]. However, we believe that this interesting effect invites further investigation.

In conclusion, we estimate the CO_2-laser energy required for producing CLSs in a real lightning protection system. Taking into account the estimates [17] of the plasma-channel length required to initiate a lightning and a linear energy input of 200 J m^{-1} required for the CLS production, which was experimentally obtained in our work, the output laser energy should be ~ 4 kJ. At present there already exist CO_2 lasers with an output energy of 5 kJ, and further improvement of their output characteristics is also possible [22]. Note, however, that we give here an understated estimate that does not take into account the increase in the transverse dimension of the laser-induced spark with increasing cone angle, which was observed in our work.

Acknowledgements. This work was supported by the International Science and Technology Centre (Project No. 880-99).

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