Quantum Electronics **44** (1) 89 – 93 (2014)

PACS numbers: 42.55.Lt; 52.80.–s
DOI: 10.1070/QE2014v044n01ABEH015267

Discharge formation systems for generating atomic iodine in a pulse-periodic oxygen – iodine laser

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***Abstract*. Generation characteristics of a pulse-periodic oxygen – iodine laser with the electro-discharge production of atomic iodine were compared with inductively stabilised edged or anisotropic-resistive cathodes used for ignition of the volume discharge. The discharge was initiated by the radiation of a barrier discharge from the side of a grid anode. It was found that at equal specific electrical energy depositions to the gas-discharge plasma, the system with the anisotropic-resistive cathode provides a more stable and uniform volume discharge with the possibility of varying the composition and pressure of working mixtures over a wide range and a greater specific extraction of laser energy is observed (up to 2.4 J L^{-1}). At a high pulse repetition rate of laser pulses (50 – 100 Hz) and long duration of the pulse trains (longer than a minute) the surface of anisotropic-resistive cathode became eroded.**

Keywords: *pulse-periodic oxygen – iodine laser, atomic iodine, uniform diffuse discharge, anisotropic-resistive cathode, energy deposition.*

1. Introduction

Atomic iodine in pulsed oxygen – iodine lasers (OILs) is produced by using the photo-dissociation and electro-discharge methods [1 – 3]. In the electro-discharge method of atomic iodine generation, the pulsed longitudinal [4 – 6] and transversal [2, 4, 7] uniform diffuse discharges (UDDs) are used, which are formed directly in the working medium of a laser comprising a mixture of singlet oxygen with one of iodides and a buffer gas (nitrogen, helium, argon).

In a pulse-periodic regime the atomic iodine is usually produced under the conditions of a transversal UDD due to the dissociation of iodine by an electron impact. The stability of the UDD and degree of filling the working volume by a gas-discharge plasma are the main factors determining the efficiency of atomic iodine generation and, ultimately, the efficiency of pulse-periodic OILs (PP OILs). There are various methods for stabilising UDDs. For example, a resistive stabilisation of the current was realised in [2] through separate sections of the cathode presented by metal rods loaded to ballast resistors. In [7], edge electrodes with a special profile were employed and the current was supplied to the edges through identical ballast inductance coils [8]. The UDD in a large gas volume [9, 10] was realised by employing the anisotropic-resistive cathode based on thin carbon threads first suggested in [11].

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Received 28 June 2013; revision received 1 August 2013
Kvantovaya Elektronika **44** (1) 89 – 93 (2014)
Translated by N.A. Raspopov

Obviously, the degree of filling the working volume by the discharge plasma depends on the degree of cathode discreteness (the ratio of the area of the electrode surface covered by the discharge to the total area) even in the regime of stable UDD burning. Hence, the generation efficiency of PP OILs will also depend on the degree of discreteness. For example, in the edge electrode system thoroughly described in [7] the distance between separate edges of the cathode was ~3 mm, whereas the surface of the anisotropic-resistive cathode was actually totally covered by the discharge [9, 10]. It is interesting to directly compare the generation characteristics of the PP OILs with electro-discharge production of atomic iodine based on these two electrode systems. Such a comparison was the main goal of the present work.

2. Experimental setup

The working medium of the laser was formed by introducing gaseous iodide CH_3I into the flowing mixture of singlet oxygen with a buffer gas (nitrogen). Usually, the partial pressure ratio of the working mixture was $CH_3I : O_2 : N_2 \approx 6 : 120 : 320$ at the total pressure of 12 – 15 Torr. Approximately 50 % – 60 % of oxygen was in the singlet state.

The mixture flowed horizontally between the electrodes placed above and below the flow, as shown in Fig. 1. The mirrors of the 1670-mm-long cavity were mounted to the right and left with respect to the flow direction. The radius of curvature for the highly reflecting mirror was 10 m. The radiation was extracted through a plane outcoupling mirror. The discharge was photographed through special diagnostic windows at a small angle to the optical axis of the laser.

The capacity C = 100 – 300 nF was charged to a voltage U_{HV} = 6 – 12 kV and then discharged to the gap with the separation between electrodes d = 5 cm. The UDD current and voltage were measured by a low-inductance shunt and resistive voltage divider, respectively. The repetition rate of discharge pulses varied from 10 to 100 Hz. The parameters of the PP OIL were controlled in each pulse. The radiation energy was measured by an Ophir calorimeter with a piroelectric head, and the pulse shape was detected by a FD-10G photodiode.

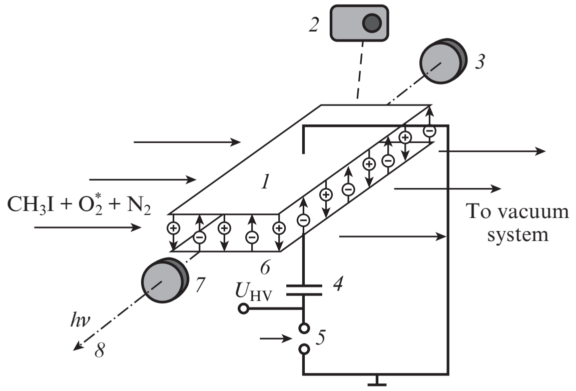

Figure 1. Scheme of a PP OIL: (*1*) anode; (*2*) photographic camera; (*3*) spherical highly reflecting mirror; (*4*) capacitor; (*5*) spark gap; (*6*) cathode; (*7*) plane semi-transparent mirror; (*8*) output laser mirror; (U_{HV}) high voltage.

The edge cathode thoroughly described in [7] had the size (length×width) of 50×15 cm, and the size of the anisotropic-resistive cathode was 45×12 cm. The specific resistance of the anisotropic-resistive layer of thickness 10 mm in the direction of the electric field was 26 Ω cm, the layer was glued to a brass plate by a conductive glue.

As we mentioned earlier [9, 10] the main problem in obtaining a UDD in the working mixtures of OILs with pulsed discharge production of atomic iodine is, irrespective of the type of stabilisation, a uniform distribution of the current density over the cathode surface under the conditions of limiting compact electrodes. Under the limiting compact electrode system we mean the system geometry in which the discharge almost totally covers the surface of the cathode (for example, of the plane cathode with sharp edges). In this geometry, the electric field at periphery of the discharge gap is noticeably higher than in a central zone, which would shift the current to the periphery and lead to a nonuniform distribution of characteristics of the active medium unless special measures are taken. Thus, in the conditions of the limiting compact electrode system, the main problem is realisation of a UDD with an almost uniform distribution of energy deposition over the discharge gap in the working mixtures typical of PP OILs with low pressure and low contents of an electronegative component.

In such conditions, initiation of the volume discharge is only possible due to photoeffect on the cathode, because the conventional methods for forming a volume self-sustained discharge (gas pre-ionisation in the gap, filling the gap by electrons due to their drift in an electric field, making conditions for obtaining self-initiated volume discharge) [12–15], cannot be employed. The distribution of the energy, deposited into gas, over the discharge gap in PP OILs depends both on the degree of uniformity of the electric field and on the distribution of illumination from the source of UDD initiation (for example, by a barrier discharge) over the cathode surface. For example, under a uniform illumination of the surface of the plane cathode with sharp edges, the UDD will be shifted to the gap periphery due to the electric field enhancement, whereas in the case of illuminating only a part of the cathode surface the discharge will only burn in the illuminated zone. Hence, in the conditions of the limiting compact electrode system the peripheral enhancement of the electric field in the discharge gap should be compensated for either by a specific (with difficult calculations) anode profile (with the electric-field separation of a central zone of the discharge gap) as was done in [9, 10], or by illuminating the cathode surface by UV radiation from the side of the anode so that the maximal illumination, hence, maximal photo-electron concentration (photoeffect on the cathode) would be achieved at a central zone of the cathode surface. In the present work, the second approach to UDD initiation was realised.

The electrical schematic of the installation utilising the second variant of illumination (cathode illumination) from the side of the anode is shown in Fig. 2 for the case of an anisotropic-resistive electrode used as the cathode. The grid anode is made of stainless steel and has the transparency of ~60%. The grid is stretched onto a special form and connected to the duralumin plate of size 45×10 cm. The wire of diameter 3 mm in polyethylene isolation is wound onto the plate with the coil pitch of 1.5 cm in the longitudinal direction and connected to the cathode. The separation between the grid and plate is 1 cm. The wire serves as an initiating electrode. A barrier discharge arises between the surfaces of wire and duralumin plate if a high voltage pulse is applied across the discharge gap, which initiates electrons from the cathode surface due to photoeffect. One can easily show that in such illumination geometry the maximum intensity is obtained at a central zone of the cathode surface, which gives the possibility to compensate for the enhanced peripheral electric field in the discharge gap. The total dimension of the grid anode was 50×18 cm. The anode was used with anisotropic-resistive or edge cathodes.

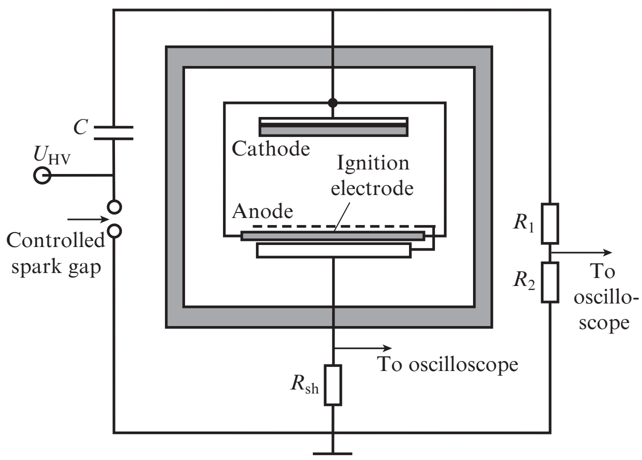

Figure 2. Electrical scheme of the installation with a grid anode and an anisotropic-resistive cathode: (C) capacitor; (R_{sh}) current shunt; (R_1) and (R_2) resistors of a high-voltage divider.

Photographs of the UDD were taken in model experiments in a mixture of iodide with air in the electrode system with an anisotropic-resistive cathode and the grid anode described above. From this data, a spatial distribution of gas-discharge plasma luminescence intensity I in the discharge gap was found. An example of such a distribution in the x axis (parallel to the surfaces of electrodes and crossing the optical axis of the system) is shown in Fig. 3. One can see that in the case of two plane electrodes the width of the intensity distribution of UDD plasma luminescence at the 0.5 level is much greater than for the electrode system with the anode having the Chang profile [10] and the discharge totally covers the

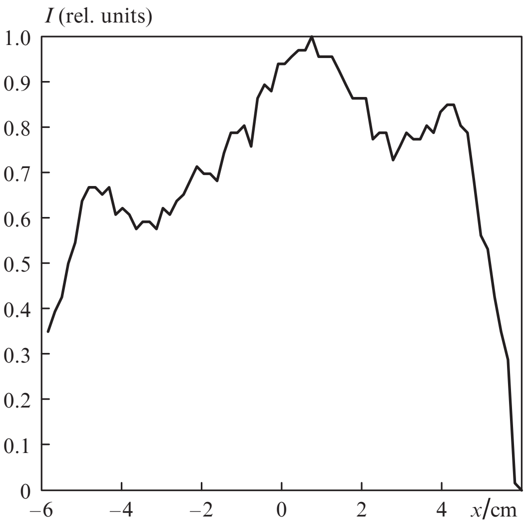

Figure 3. Intensity distribution of discharge plasma luminescence I over the x coordinate in the plane parallel to the surfaces of electrodes (the system with the anisotropic-resistive cathode). The distance is counted from the optical axis position.

cathode surface. Qualitatively, this distribution reproduces the distribution of energy deposition in the gap.

3. Experimental results and discussion

3.1. Comparison of the characteristics of PP OILs with anisotropic-resistive and inductively stabilised edge cathodes

In this series of PP OIL shots, the capacity was C = 300 nF and the charge voltage was U_{HV} = 7 kV. Table 1 lists the average laser pulse parameters of the series for the pulse repetition rate of 10 Hz. The deviation of the pulse radiation energy from the average value was within 11%. Due to the high velocity of the gas flow in the discharge chamber, *a fortiori* providing gas replacement in the gap in a time interval between discharge pulses, the average radiation energy in a series was actually independent of the repetition rate, which varied from 10 to 100 Hz. In the case of a single pulse shot, the radiation energy also slightly differed from the average energy of the pulse-periodic regime.

From Table 1 one can see that the specific energy extraction in the case of the anisotropic-resistive cathode is by 25% greater than in the case of the edge cathode system. The total radiation energy of the laser is limited by the volume of the active medium contained in the resonator caustic (1.15 and 1.22 L for the systems with anisotropic-resistive and edge cathodes, respectively). The total discharge volume (2.7 and 3.75 L for the systems with anisotropic-resistive and edge cathodes, respectively) noticeably exceeds that of the resonator caustic. Hence, with an appropriate resonator one may expect to observe more than a double increase in the radiation energy. Photographs of the UDD in operating a PP OIL with anisotropic-resistive and edge cathodes are shown in Figs 4 and 5, respectively. One can see that the anisotropic-resistive stabilisation yields a noticeably more uniform discharge. In the case of the edge cathode, the discharge is also diffuse, but comprises a series of diffuse jets, which alter their positions from pulse to pulse, that is, the gas-discharge plasma incompletely occupies the working volume. Finally, this results in that the energy extraction is greater in the case of the resistive electrode.

Table 1. Average parameters of laser pulses.

Cathode dimension	Radiation energy/J	Specific energy extraction/J L^{-1}	Half-height duration of generation pulse/μs
Resistive/12×15 cm	2.75	2.4	50
Edge/15×50 cm	2.32	1.9	60

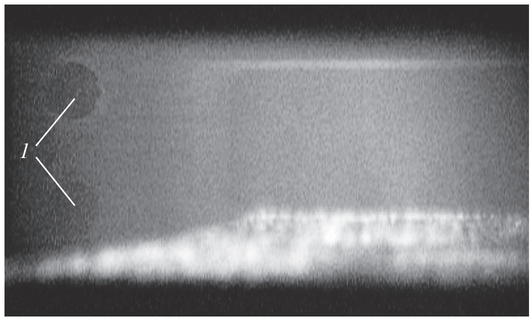

Figure 4. Photograph of the UDD in a working mixture of the PP OIL, obtained in the system of electrodes with the anisotropic-resistive cathode (bottom electrode) and the grid anode: (*1*) diagnostic windows of the chamber.

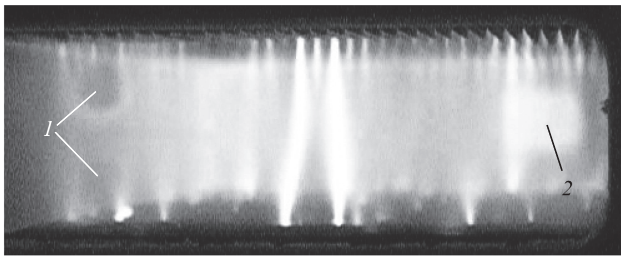

Figure 5. Photograph of the UDD in a working mixture of the PP OIL, obtained in the system with the inductively stabilised edge cathode: (*1*) diagnostic windows of the chamber; (*2*) output radiation window.

The UDD with the anisotropic-resistive cathode is more stable when some parameters are tuned: the discharge voltage, composition of medium, pressure, etc. The edge electrodes necessitate a more accurate choice of the parameters of a gas mixture and their maintaining in the process of laser operation. Normalised radiation pulses detected in the laser with edge and anisotropic-resistive cathodes are presented in Fig. 6. As follows from Table 1 and Fig. 6 the durations of the radiation pulses in these two cases are almost equal. Thus, one may assume that despite a noticeable difference in the uniformity of the discharges, the concentrations of atomic iodine in both systems are close.

3.2. Electrode system with the anisotropic-resistive cathode at high pulse repetition rates of discharge pulses

From the results of above considerations it follows that the electrode system with anisotropic-resistive stabilisation of the discharge has some advantages in production of atomic iodine in PP OILs with electro-discharge generation over the system with inductively stabilised edge electrodes. The main

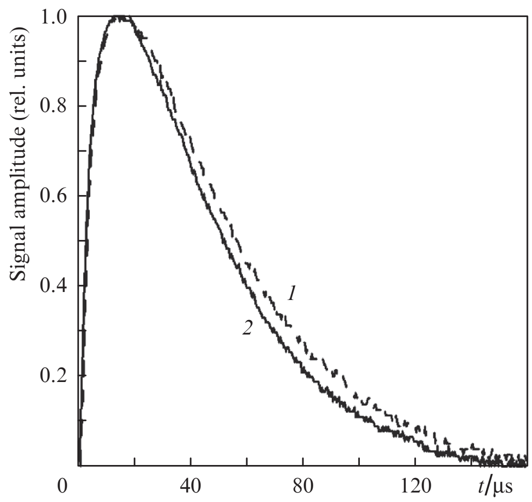

Figure 6. Normalised radiation pulses of the PP OIL with the electrode systems comprising inductively stabilised edge (*1*) and anisotropic-resistive (*2*) cathodes.

advantages of the anisotropic-resistive system are high UDD stability at long durations of the discharge current, good reproducibility of generation energy of pulses of the PP OIL in a series, efficient production of atomic iodine.

The results given above have been obtained at the pulse repetition rates of up to 10 Hz and the series duration from 5 to 10 s. With increasing pulse repetition rate to 50–100 Hz, a disappointing problem arose. At the beginning of a series, the UDD in some pulses contracted; then, in the following series actually each pulse resulted in a spark discharge. It is specific that the spark was not related to a particular place on the cathode surface, as it moved over the discharge surface from pulse to pulse. The velocity of the gas flow in this case was definitely above the value needed for stable operation of the system at such repetition rates, that is, the contraction could not be explained by an incomplete removal of the waste gas from the gap. In returning, after having passed a series of pulses at the rate close to 100 Hz, to the single pulse regime the UDD contraction was observed as well. Visual examination of the cathode revealed numerous burns through an anisotropic-resistive material, which were distributed over the cathode surface and penetrated into the material to a depth of several millimeters.

Hence, the experiments carried out show inappropriateness of the anisotropic-resistive cathode based on carbon threads for prolonged operation of a PP OIL at high pulse repetition rates. The obtained negative result is unexpected because cathodes made of precisely the same material are successively used in nonchain electro-discharge HF lasers at the specific electrical energy depositions of above 100 J L^{-1}, currents of up to 100 kA, and pulse repetition rates of 50–100 Hz [14–17]. However, in our case the deposition of the electrical energy to plasma was no greater than 6 J at the specific energy depositions of at most 2 J L^{-1}.

Reasons for destruction of the anisotropic-resistive electrode based on carbon in PP OILs are presently far from understanding and require further investigation. From general considerations one may assume that they are related to the working mixture composition of the PP OIL, in particular, to the interaction of carbon plasma in a cathode spot with iodine and, possibly, oxygen atoms. Note that investigation of the mechanisms of carbon cathode breakdown in gas-discharge plasma of PP OILs at comparatively small energy depositions is interesting for gas-discharge physics and possible applications of the effect observed.

4. Conclusions

It was established that in the working mixture of PP OILs at comparable energy depositions into discharge plasma, the system with an anisotropic-resistive cathode provides a more stable and uniform electrical discharge as compared to an inductively stabilised edge cathode, which increases the specific laser energy extraction. A consequence of this fact is good reproducibility of the pulse generation energy in a series of pulses. At the PP OIL pulse repetition rates of 50–100 Hz, the material of the anisotropic-resistive cathode was destroyed, numerous burns through the electrode surface were observed, through which the discharge was shorted to a metal substrate of the electrode. It was suggested that a reason for the breakdown is the interaction of carbon plasma in a cathode spot with iodine and oxygen atoms. The physics and chemistry of such process are still obscure.

Acknowledgements. This work was supported by the Russian Foundation for Basic Research (Grant No. 12-08-00321).

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