Formation of volume discharges in dense gases at pulse repetition rates up to 10 kHz

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Abstract. It is shown that for the formation of stable volume discharges at pulse repetition frequencies up to 10 kHz and more, it is recommended to use sectioning of the discharge gap with subsequent excitation of discharges in each section from an autonomous pulse generator. The role of an autonomous pulse generator can also be performed by an auxiliary circuit that directs the necessary part of the energy stored in the main energy storage of a pulse generator with only a single switch to an individual discharge gaps. The description and results of the study of one of these variants of a partitioned discharge gap and a pulse generator are given. Pumping energy densities of 100–150 mJ cm\(^{-3}\) at pulse repetition frequencies up to 8 kHz in CO\(_2\) laser mixtures and 80–100 mJ cm\(^{-3}\) in N\(_2\)–Ne and Xe–Ne mixtures at pulse repetition frequencies up to 10 kHz were achieved.

1. Introduction

The ignition of self–sustained volume discharges at pulse repetition frequencies above 1 kHz (up to 20–25 kHz) is the primary basis for creating pulse–periodical TEA lasers for high–performance laser equipment that will be effectively used in laser chemistry, the production of pure and nanostructured materials, for processing metal, ceramic and polymer materials, as well as for marking and engraving plastic products [1–3].

TEA lasers operating at such high pulse repetition frequencies with radiation pulse durations from units to 20 nanoseconds with an average radiation power of tens of watts are a fundamentally new technological tool.

Carbon dioxide (\(\lambda = 9.2–10.8\) \(\mu\)m), molecular nitrogen (\(\lambda = 337\) nm), mixtures of inert gases (\(\lambda = 1.7–4.4\) \(\mu\)m) can used as active media. In order to generate the necessary level of average laser radiation power on these gas media, it is necessary to know the basic laws of the formation of pulse–periodical volume discharges resistant to localization with an acceptable level of energy density introduced into the plasma.

The main problem in the development of TEA–CO\(_2\) lasers operating at high pulse repetition rates is the ignition of a stable volume discharge. To obtain self–sustained volume pumping discharges, a number of conditions must be fulfilled:

1 – to carry out the initial ionization with the required level of free charge carriers in a time shorter than the time of voltage rise across the interelectrode gap [4];
2 – ensure the formation of volume discharges with a duration current pulses shorter than the development times of plasma instabilities [4–6];
3 – to minimize the magnitude of the “mismatch” voltages arising in the discharge gap as a result of incomplete transfer of energy from the pulse generator to the volume discharge plasma [7];
4 – to carry out convective renewal of the gas mixture in the interelectrode gap in the pause between pulses [2, 4, 8].

In addition, to achieve high values of the volume discharge ignition frequency it is advisable to use sectioning of the gas–discharge gap and to excite a volume discharge in each section from an autonomous pulse generator [9].

Dividing the main discharge gap into 3–5 sections requires the use of 3–5 high-voltage pulsed generators [9, 10], which greatly complicates the structure of a repetitively pulsed TEA laser. The limiting and alternative case of “sectioning” is the manufacture of the cathode in the form of a set of pins with simultaneous excitation of discharges in all sections from only one pulse generator. In this case, the distribution of currents and energies over the gaps can be carried out using capacitive or resistive limiters.

This work is devoted to determining the formation conditions and electrophysical parameters of volume discharges in the interelectrode gaps of the “set of pins – plane” type at pulse repetition rates of 1–10 kHz in the working mixtures of TEA–CO$_2$, TEA–N$_2$ and TEA–Xe lasers.

2. Experimental equipment

2.1. Electrode structure and gas discharge chamber

Figure 1 shows the structure of electrodes for the formation of a volume discharge in a plurality of the gas–discharge gaps. Here (A) is a common monolithic anode. The cathodes (C$_1$–C$_8$) are a set of 8 molybdenum pins. Each of them is connected to a limiting element – a set of ceramic capacitors C$_{1c}$–C$_{8c}$ (ceramic capacitors KVI–3 type). The common electrical contact (CC) is connected to the high-voltage pulse generator. The (VD) and (OA) – symbols denotes individual conical volume discharges and optical axis.

![Figure 1. Electrode structure for ignition of many volume discharges with identical parameters.](image-url)
at a length of 40 cm. Each of the pin electrodes was connected to a set of ceramic capacitors (6) of the KVI–3 brand with a total nominal values from 120 to 500 pF. The common output (10) from these capacitors was connected to a high–voltage pulse generator. The high–voltage output of the auxiliary electrode (8) is organized through the top cover (4) (not shown in figure 2).

Figure 2. Schematic image of a chamber for investigating the parameters of a volume discharge in the "pins–grid" electrode system in the pulse–periodical regime. The arrows reflect the direction of the high–speed gas flow.

A molybdenum mesh (7) made by laser drilling of holes was used as the for common anode. The diameter of the holes was 1 mm, the interval between centers was 1.5 mm. The grid was welded by spot welding on a stainless steel frame (7). In order to increase the current density and energy introduced into the plasma of a volume discharge in a pulse–periodical regime, preliminary ionization of working gases was applied in the "main" discharge gap formed by a set of individual gaps of the "pin–plane" type.

For this purpose, an auxiliary electrode (8) was located inside the frame with an anode grid in the form of a copper wire with a diameter of 0.6 mm wound helically on a metal rod with a step of 1 cm. The high–current corona discharge, which was ignited between the turns of the auxiliary electrode and the grid electrode, is an effective and reliable source of initial ionization in the main discharge gap in the pulse–periodic mode (1 kHz ≤ F ≤ 10 kHz).

The use of such an electrode structure makes it possible to position the source of ionizing VUV radiation as close as possible to the irradiated main discharge gap, in which a volume discharge is ignited.

To organize a "fast" energy input into the plasma of a volume discharge (VD), a common anode (7) was connected to the envelope of the discharge chamber by means of 100 copper plates (9). The symbols VD and CD in figure 2 indicate the zones of volume and auxiliary corona discharges.

The size of the main interelectrode gap ("pins–grid") varied from 1.6 to 2 cm. The velocity of the gas flow in the main interelectrode gap reached 40 m/s.

2.2. High–voltage pulse generators

The excitation of the auxiliary and main discharges was carried out from two autonomous pulse generators. Each of them was a two–stage Marx generator with switches based on pulsed hydrogen thyratrons TGI–1000/25 [11]. The moments of their start were set using a synchronizer. The scheme of one of these generators is shown in figure 3. The created generators provided stable formation of voltage pulses with an amplitude of up to 40–45 kV with a discharge current duration of 30–50 nanoseconds at pulse repetition frequencies up to 12–15 kHz.

The thyratron T1 of the first stage of the Marx generator is started from the master generator. The second thyratron (T2) is started automatically by a voltage pulse, which is formed using the divider R1–R2 immediately after the first thyratron is turned on. The anode and cathode of the thyratron T2 at that moment are under a double potential and the time of development of the discharge in it is reduced and reaches 10 nanoseconds.
The use of Marx generators for the excitation of auxiliary and volume discharges was due to the fact that this type of generators provides minimum values of the durations of the first front of voltage pulses and the implementation of a breakdown with some overvoltage. The volume discharge under these conditions is formed more stable. This is especially noticeable at increased pulse repetition rates.

The capacitances of the capacitors \( C_1 \) and \( C_2 \) of the Marx generator for the excitation of a volume discharge varied during the studies in the range from 3 to 7 nF.

One of the main disadvantages of Marx generators, in which hydrogen thyratrons are used as switches, is the need to provide heating of the cathode and the hydrogen generator in the second stage at a potential of up to 25 kV.

![Figure 3. Electrical scheme of the Marx generator for the formation of volume discharges in the pulse–periodical regime.](image)

\( T_1 \) and \( T_2 \) are pulsed hydrogen thyratrons TGI–1000/25; \( C_1 \) and \( C_2 \) are storage capacitors, KVI–3; \( L_1–L_4 \) are charge–discharge inductances; \( R_1, R_2 \) are a resistive divider for starting the \( T_2 \) thyratron in the second stage of the generator; \( T_r \) and \( PTr \) are ordinary and "potential" incandescent transformers.

3. Experimental results

Simultaneous ignition of a numerous of individual volume discharges (up to 40 units) in a gas–discharge chamber in a pulse–periodical regime showed that individual discharges have the shape of cones with an visible base area of 0.16–0.5 cm\(^2\). At the height of the interelectrode gap \( d = 1.6–2 \) cm, the individual volumes occupied by the volume discharge plasma are \( V_i = 0.25–0.52 \) cm\(^3\). For 40 individual gas–discharge gaps, the total plasma volume is in the range from \( V_\Sigma \approx 15 \) to \( V_\Sigma \approx 20 \) cm\(^3\).

The maximum energy density introduced into the plasma of a volume discharge was estimated by the amount of energy stored in the storage elements of a pulse generator. The capacitances of the storage capacitors of the main Marx generator varied in the range from 3 to 7 nF. At charge voltages up to 20 kV, energy is stored in storage capacitors at the level of \( W = 1.2–2.4 \) J.

The ignition of the volume discharge was carried out in the following working mixtures:

- \( \text{CO}_2:\text{N}_2:\text{He} = 1:1.8–1:1.4 \) (\( P_\Sigma = 1 \) Atm);
- \( \text{N}_2:\text{He} = 0.2:10–0.5:10 \) (\( P_\Sigma = 1 \) Atm);
- \( \text{Xe}:\text{He} = 0.1:10–0.1:20 \) (\( P_\Sigma = 1 \) Atm).

The investigate of the conditions for the formation of volume discharges in these mixtures at pulse repetition frequencies up to 10 kHz or more is aimed at achieving high levels of average laser radiation power at relatively small values of the radiation energy in the pulse in the infrared and ultraviolet ranges.

The research included the study of the influence of such factors as the input energy into the discharge, the chemical composition of working mixtures and the conditions of preliminary ionization of gases using ultraviolet radiation on the ignition frequency of a volume discharge in an electrode structure with a set of cathode pins.

Figure 4 shows the dependences of the average electrical power injected into the plasma of a volume discharge on the pulse repetition frequency in \( \text{CO}_2 \)–laser mixtures with different component
compositions at full pressure in one atmosphere. These dependences are obtained when volume discharges are ignited using pre-ionization. Despite the fact that a volume discharge in an electrode structure with a set of pin cathodes is formed without preliminary ionization, its properties are inferior to a discharge with preliminary ionization. These differences are reflected in a 20–30% decrease in energy and average electrical power introduced into the discharge, as well as in noticeably less spatial uniformity.

With an increase in the pulse repetition rate, the obtained dependences have an increasing character in the range from hundreds of watts up to 9 kW. They break off at pulse repetition rates at which volume discharges are transformed into local spark channels.

The dependences shown in figure 4 indicate the decisive role of helium in the composition of CO₂–laser mixtures in the formation of volume discharges in the pulse–periodic regime. Its role is to increase the maximum pulse repetition frequency at which the formation of volume discharges is possible, and to achieve the maximum value of the average electrical power introduced into the plasma of a volume discharge. For the mixture CO₂:N₂:He = 1:1:8, the maximum ignition frequency of the volume discharge \( F = 8 \text{ kHz} \) and the maximum level of average electrical power of 9.5 kW are characteristic. With a decrease in the concentration of helium in working mixtures (mixtures CO₂:N₂:He = 1:1:7 and 1:1:6) the maximum achievable ignition frequency of the volume discharge is reduced to the values \( F = 5.5 \text{ kHz} \) and \( F = 3.6 \text{ kHz} \). The achieved maximum values of the average electrical power injected into the plasma are 9–9.2 kW.

Similar measurements were carried out for mixtures of N₂:He and Xe:He. Were achieved pulse repetition rates up to 10 kHz at pump densities of 60–80 mJ/cm³. In mixtures with a high helium content, the maximum pulse repetition rates reached 11.5–12 kHz. At the same time, the levels of the average electrical power introduced into the discharge were 2–2.5 times less than those achieved in mixtures CO₂:N₂:He.

The maximum values of the ignition frequency of volume discharges in dense gases are primarily determined by the rate of renewal of the gas mixture in the interelectrode gap in the pause between pulses [2, 4, 8]. Analytically, the maximum value of the ignition frequency of a volume discharge is defined as [2, 4, 8]:

\[
F_{\text{MAX}} = \frac{V}{A \cdot \Delta}
\]

where \( V \) is the velocity of the gas flow in the interelectrode gap, \( \Delta \) is the length of the electrodes along the flow, \( A \) is a factor that takes into account the deceleration of the velocity in the near–electrode regions and its value ranges from 2 to 10.

The measured value of the velocity in the studied gas–discharge gap is 40 m/s. The diameter of the contact zone of the volume discharge plasma with the anode surface is 0.5–0.7 cm. In accordance with the expression (1), the frequency of gas change in the anode region has the values \( F_A = 2800–570 \text{ Hz} \). These values are several times less than the actually recorded ignition frequencies of the volume discharge. In the cathode region with the geometrical dimensions of the gas mixture refresh zone with
a cathode diameter of 1 mm, the refresh rate can reach \( F_C = 8 \times 10^3 \) Hz. The conducted estimates indicate that the localization of the volume discharge and the limitation of the frequency of its ignition are initiated primarily by processes occurring in the cathode part of the volume discharge with an increased value of the electrical field strength. The anode region with its sufficiently low electrical field strength in this case, despite the possible "accumulation" of various kinds of inhomogeneities, does not lead to the development of plasma instabilities, because the rates of development of these inhomogeneities exponentially depend on the strength of the electrical field \([12, 13]\).

4. Conclusion.
The conducted investigations have shown the following:

1. The validity of the idea of partitioning the discharge gap to increase the ignition frequency of a volume discharge is confirmed.

2. The spatial homogeneity of the self-sustained volume discharge in the "set of pins – grid" electrode system and the stability of the volume discharge to localization increase with the use of preliminary ionization of the gas mixture in the discharge gap.

3. In a laser mixture of \( \text{CO}_2: \text{N}_2: \text{He} = 1:1:8 \) at atmospheric pressure, the maximum value of the average electrical power introduced into the volume discharge plasma reaches 9.5 kW at a pulse repetition rate of up to 8 kHz. When using mixtures \( \text{CO}_2: \text{N}_2: \text{He} = 1:1:7 \) and \( 1:1:6 \) the maximum values of the average levels of electrical power and pulse repetition rates were 9 and 9.2 kW and 3.6 and 5.5 kHz.

4. In \( \text{N}_2: \text{He}– \) and \( \text{Xe}: \text{He}– \) mixtures, at maximum pumping energy densities of 60–80 mJ/cm\(^3\), pulse repetition frequencies of 10 kHz and average electrical power levels of 4–4.5 kW were achieved.

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