High-pressure gas lasers excited by an avalanche self-sustained discharge

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The paper presents some results of experimental investigations on pumping gas lasers by an avalanche discharge sustained by UV or X-ray preionization, or by a nonavalanche discharge. Basic methods are proposed for obtaining volume avalanche self-sustained discharges of long-duration to pump XeCl, KrCl, KrF, and CO_2 lasers. The conditions are determined for generating long-duration pulses connected with selecting components of buffer gas, modes of operation of UV preionization, and modes of pumping energy into the active media.

It is an urgent problem for high-pressure gas-discharge lasers to produce the long pulses with high specific radiation parameters for applied problems. The excitation of laser active media is mainly realized using a fast high-pressure discharge. This is true for their contraction because of the volume and electrode instability. Accordingly short radiation pulses are realized.

In this paper we consider the peculiarities of generating avalanche self-sustained discharges for excitation of high-pressure gas lasers. As a result of the investigations of XeCl-laser we have proposed and realized a quasistationary excitation regime for excimer lasers maintaining their high efficiency and long generation pulses.

In the early 1970s Reilly[1] and Hill[2] have shown a possibility of using for pulsed gas lasers of an electric pump circuit with two power sources. It was used for a low-pressure CO_2-laser. A peaking high-voltage power source provided a breakdown of gas medium and generation of the initial electron concentration necessary for the maintenance of a volume discharge. A low-voltage storage power source maintained the corresponding magnitude of E/P at the electrodes, which ensures the CO_2 molecular vibrational excitation to the upper lasing level. In this case the ionization of an active medium was minimum. This method of pumping was not widely used for high-pressure CO_2-lasers because of nonoptimal excitation conditions.

In 1977 the researches[3,4] of XeCl and XeF lasers and XeF and KrF lasers[5] have made it possible to obtain the generation pulses of the duration longer than 100 ns using an additional spark source of UV preionization. We have first developed an idea of employing two power sources for pumping excimer lasers.[3,4,6] Figure 1 shows a two-contour electric pump circuit with an automated spark UV preionization for a XeCl laser.[3,4] The role of the peaking power source was played by the capacity of distributed capacitors (C_p), and the distributed capacity ($C_s \geq 2C_p$) was the storage power source.

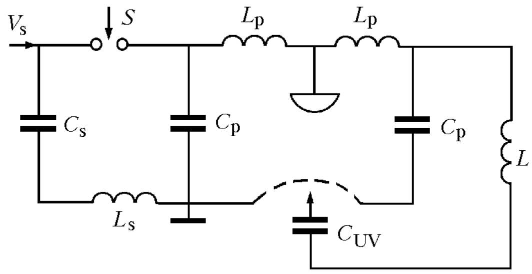

Fig. 1. An electric double-contour power supply circuit with an automated spark UV preionization where C_p is the peaking capacitor of the power source, C_s is the storage capacitor of a power source; S is the spark commutator.

Spark preionization was realized by means of decoupling capacitors (C_{UV}). The time lag of the main self-maintained discharge relative to a preionization pulse did not exceed 100 ns. We have first obtained the volume excitation discharges with Ar and He as buffer gases of the duration up to 200 and 400 ns, respectively.[4] It was shown that the main power was contributed to an active medium at the quasistationary stage of the discharge (Fig. 2).

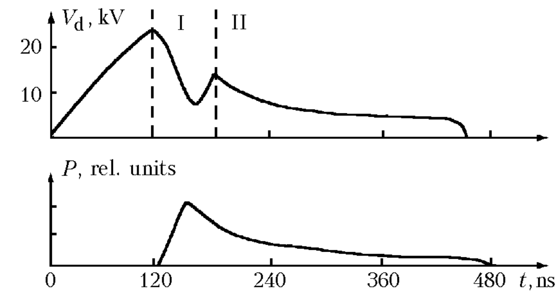

Fig. 2. The voltage pulse oscillograms at the gap and intensities of spontaneous radiation in the mixture He:Xe:CCl_4 at 1 atm pressure and V_s = 30 kV.

The obtained results have shown a possibility of producing a new efficient mode of XeCl-laser excitation taking into account the quasistationary stage of a discharge. A peaking power circuit provided a high-voltage excitation prepulse.

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Figure 3 shows the equivalent power supply circuit diagram with a constant UV preionization for a new excitation mode of excimer lasers. As UV preionization we used a spark,[3] corona,[6] and plasma[7] discharges. Structural version of plasma electrodes is given in the literature.[8–12]

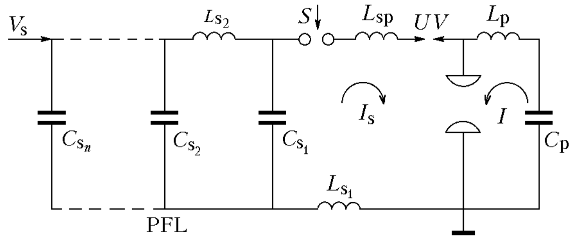

Fig. 3. An equivalent electric power supply circuit with the automated spark or plasma UV-preionization for quasistationary excitation mode of excimer lasers under condition $I_d = I_p + I_s$ where the pulse forming line (PFL) equals the capacitance C_s.

A peculiarity of the operation of the power supply circuit is that the first short excitation pulse creates the radiation generation and then it is changed for the main excitation pulse at the expense of energy remained in the storage power supply source. It was shown that for the realization of this excitation mode the relation of the power supply source capacities should satisfy the following condition: $C_s/C_p \geq 5$ (Ref. 6). In this case the storage source must be produced in the form of a distributed capacitor or an electric line from LC-elements.[9–12] The overall discharge current summed the current of peaking and storage power sources ($I_d = I_p + I_s$). Laser active medium was excited both during the fast and quasistationary stages of the discharge controlled by UV preionization.[9–16] It was shown that the pulse shape was determined by the parameters of the power source and the cavity Q factor.[14–16]

Characteristic properties of the discharge and optical radiation parameters for XeCl laser excited by an avalanche self-sustained discharge (ASSD) are given in Fig. 4.

The ASSD voltage has two characteristic features. Those are the breakdown voltage (V_{br}) of a self-maintained discharge and the self-sustaining voltage (V_{ss}) at the quasistationary stage of the discharge. The current of SSD provided by the method of excitation used is its specific feature as the power source is operated in aperiodic (*1*) and quasistationary (*2*) mode. The most stable and extended mode of existence of SSD is realized at aperiodic development of the discharge current that occurs due to the peculiarities of active media of excimer molecules. In contrast to this, for CO_2 laser the quasistationary mode of the development of discharge current is typical. We call this excitation mode "quasistationary" because the major amount of energy is contributed at the quasistationary discharge stage. This method of excitation, as compared with the method known from the literature,[1,2] differs from the above one in that we used an additional UV preionization source. The quasistationary voltage of the main power source was chosen from optimal conditions of excitation by a self-sustained discharge. The voltage amplitude of the maintenance of a quasistationary discharge was ensured at a level sufficient for ionization of the active medium, balancing the processes of adhesion and recombination of electrons. These processes were controlled by the UV preionization. The conditions were found for fast discharge transfer to a self-sustained discharge, i.e., to the SSD excitation.

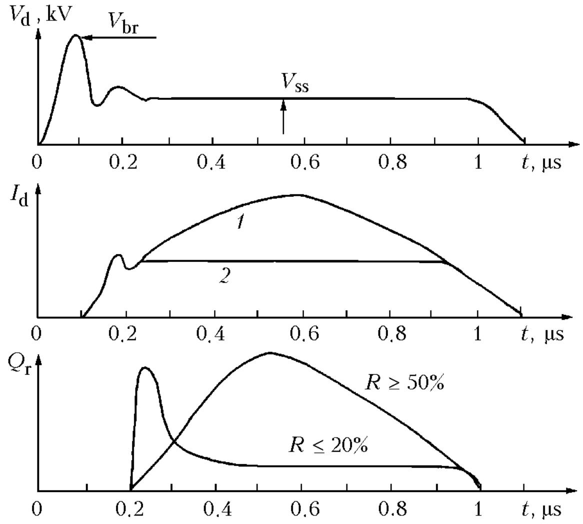

Fig. 4. Standard characteristics of voltage at the gap, of discharge current, and radiation for SSD of the quasistationary excitation mode of XeCl laser; R is the coefficient of reflection of the output mirror of the resonator.

Traditionally, for high-pressure CO_2 lasers, helium is used as a buffer gas. Preionization provides the necessary initial electron concentration in the discharge gap for maintaining the volume excitation discharge. Buffer gas decreases the temperature of active medium at high energy contributions and at high repetition frequency modes of laser operation. Partially the same situation occurs for excimer lasers excited by a fast discharge.

The role of the buffer gas and the UV-preionization source changes greatly in realizing the quasistationary excitation regime.[3,15–19] In excimer lasers buffer gases He, Ne, Ar or admixtures of Ar to He or Ne buffer gases affect both the generation of the initial electron concentration in a discharge and the power distribution of the electrons. Channels of generation of operating molecules and optimal conditions for their excitation vary accordingly.[15,18,20,21] It was shown that for XeCl laser with Ar and Ne buffer gases the specific parameters of radiation depend on the energy deposit into the UV-preionization. In this case the pulse duration was determined by the time of UV preionization of the active medium.[16,18,19] Therefore, the quasistationary excitation mode is one of the effective methods of obtaining SSD of long duration. Because the volume discharge was sustained by UV preionization created by plasma electrodes or spark gaps, they may be qualified as self-maintained discharges controlled by UV preionization.[10,14–16,18,19] We were first to obtain, for XeCl laser, the radiation pulses of 250 ns duration and 0.5 J energy at the efficiency of 1.4% (Ref. 11) and SSD excitation of 1 μs duration.[12] The results of our investigations were confirmed by other authors[13]; in that paper the radiation pulses of 1 μs duration were obtained for the same laser with plasma electrodes.

Actually, this excitation mode was realized in Ref. 22. For the preionization an X-ray radiation source was used. The duration of X-radiation effect on the active medium of XeCl laser exceeded the time of a self-sustained discharge glow. The quasistationary excitation mode was studied in Ref. 23, where a possibility of increasing the laser efficiency up to 4.2% was demonstrated. The authors used two self-sustained power sources on water-capacitor lines switched on at laser interval by way of low inductance switches (Fig. 5).

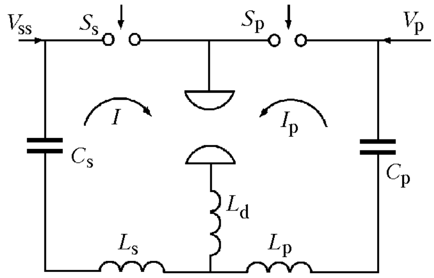

Fig. 5. The electric excitation circuit with two independent power supply sources, where C_p is the capacitance of the source of a preliminary excitation pulse, C_s is the capacitance of the storage excitation source, S_p and S_s are the spark switches.

The X-radiation source was used as a preionizer. The power supply system we called the electric discharge pump method with an excitation prepulse. In this case a high-voltage prepulse was equivalent to a peaking pulse we used for the quasistationary excitation mode. This method of quasistationary excitation mode can be characterized as a self-maintained discharge supported by a semi-self-maintained excitation discharge.

A possibility of laser operation in a pulse-repetitive mode was limited by the low-inductance switches. In Ref. 24 the authors used a magnetic switch for forming the excitation prepulse. The storage power source was connected directly to laser electrodes what is a serious disadvantage of this excitation method. A KrF laser was used as a preionizer. Later the authors described a way to increase duration of the XeCl laser radiation pulses up to 2 μs.[25]

The use of quasistationary excitation mode was demonstrated most successfully in the literature[26] for the pulse-repetitive mode of laser operation. An additional power source (storage), Fig. 6, in the form of the distributed shaping line,[12] was connected through a magnetic switch with the power source providing the quasistationary excitation mode. In this case the problem was removed of electrodes being under constant voltage and the duration of energy pump to the main discharge was increased. The authors described a possibility of obtaining the energy of 1 J with the pulse duration of 275 ns at a pulse repetition frequency of 220 Hz. The use of the similar pumping system with the corona preionization, which could control both power sources, has enabled Sato et al.[27] to obtain the mean power of 505 W at the pulse duration of 340 ns and pulse repetition frequency of 505 Hz.

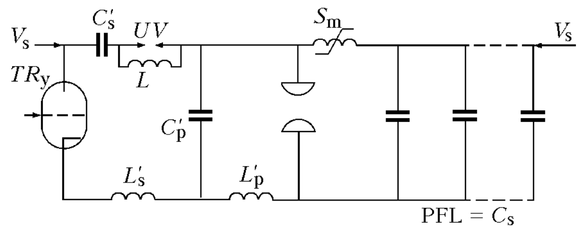

Fig. 6. The electric excitation circuit with thyratron (TR_y) and magnetic (S_m) switches, supplementary storage power sources (PFL), and the automated spark UV-preionization.[26]

Reference 28 describes the use of an X-radiation preionizer for realizing maximum efficiency in a XeCl laser, being equal to 5%, at the pulse power of 0.28 J and the pulse duration of 400 ns. In Refs. 29 and 30 it was proposed to use the second magnetic switch in the circuit of an excitation prepulse. They investigated in detail different types of switches used for a given excitation mode of excimer lasers. Main results of realization of the methods of the quasistationary excitation mode and the generation of long optical pulses are based on the use of XeCl laser. This is due to its high amplification factor at relatively low specific pump power needed from a self-maintained discharge.[31]

We have formulated general requirements to the realization of a given excitation mode for excimer lasers: (1) formation of 2–3 fold overvoltage in the interval ≤ 100 ns; (2) formation of a fast discharge stage within time intervals ≤ 100 ns at the pump power ≥ 1 MW/cm^3; (3) maintenance of power pumped into the discharge at a level of ≤ 0.2 MW/cm^3 during more than 100 ns; (4) the density of discharge current is limited to be ≤ 200 A/cm^2 depending on the choice of a buffer gas. These requirements can be extended to other types of high pressure gas lasers.[16,19]

We first described a possibility of efficient using the given mode of excitation for CO_2 laser.[32] We obtained the generation pulses of duration up to 2.5 μs with the power of 2.5 J and the efficiency equal to 8%. Our results were confirmed in the literature.[33] The authors of Ref. 33 obtained the radiation pulses of 5 μs duration and energy of 4.5 J, the efficiency being equal to 10%. Maximum efficiency for CO_2 laser at present equals 22% with the energy of 5 J per pulse.[34] As a high-voltage excitation prepulse an inductive charge integrator can be used.[35] The authors of Ref. 35 obtained the lasing efficiency of 17% with the energy of 3 J per pulse. Investigations of the CO_2 laser have shown that this excitation mode can be used effectively for high-pressure lasers to increase the efficiency and duration of radiation pulses.

More strict requirements are imposed on the excitation modes for excimer fluorine molecules, for example, KrF, ArF, etc. This is connected both with the difficulties in obtaining a self-maintained long volume excitation discharge and with a strong dependence, for the case of these molecules, of the amplification factor on specific pump power.[31] Earlier an advantage was demonstrated in the literature[36] of high-speed excitation mode for KrF, XeCl, KrCl molecules. The radiation energy of 0.25, 0.1, and 0.1 J per pulse was obtained at the pulse duration of 30, 60, and 60 ns, respectively. The advantage of the quasistationary excitation mode for KrF laser was shown in Ref. 37 using a double-contour power supply circuit with an automated corona preionization. Dr. R. Sze[37] obtained the generation pulses of 80 ns duration with the energy of 3.7 mJ with the controlled radiation aperture. In Ref. 26 the authors obtained the radiation pulses of up to 200 ns duration with the energy of 0.2 J at the pulse repetition frequency of 220 Hz using the automated spark preionization and an additional storage supply power source. The maximum efficiency of KrF laser of 1% was obtained in Ref. 38 at a pulse duration of 170 ns at half-maximum and energy of 0.08 J per pulse.

The quasistationary excitation mode was also successfully used for pumping KrCl laser.[39] The authors obtained the pulses of 185 ns duration with the energy of 0.12 J and the efficiency of 0.75%. The maximum energy of 0.65 J per pulse at the pulse duration of 90 ns and the efficiency of 0.65% was obtained in the Ref. 40.

At present for the excimer molecules emitting in the short-wave range ArCl (λ = 175 nm) and ArF (λ = 193 nm) the optical pulses of no longer than 15–30 ns duration were obtained. Their duration can be greatly increased as required in some problems by use of the quasistationary excitation mode.

Based on the investigations performed and the analysis of papers devoted to a given excitation method, we can draw a conclusion that this method can be effectively used for high-pressure gas lasers.

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