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Electric-discharge gas laser based on a multisectional discharge gap

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Abstract. An electric discharge laser with an electrode unit of novel design was developed. An electric discharge system was based on multisectional plate-like electrodes and an automatic UV preionisation that makes it possible to form a highly stable volume discharge. High-efficiency lasing in N_2 and XeF lasers was achieved. A pulse repetition rate up to 200 Hz was realised in the N_2 laser without recourse to gas circulation.

One of the trends in the development of pulse-periodic electric discharge gas lasers is towards higher pulse repetition rates. For instance, an implementation of an excimer XeCl laser with a pulse repetition rate of 5 kHz and an average output power of 560 W was reported in Ref. [1]. The gas flow velocity in the working gap reached 137 m s^{-1} and the laser chamber dimensions were 1.5 m × 2.5 m × 2 m. Of practical interest is the development of compact excimer lasers ranging in pulse energy from several to tens of millijoules, and of nitrogen lasers with pulse repetition rates of several kilohertz and moderate gas velocities. These lasers may be used in materials processing, photolithography, laser-assisted surface cleaning, isotope separation, etc.

Let us consider the main prerequisites to the implementation of lasers with a high repetition rate. As the pulse repetition rate in electric discharge lasers is increased, the discharge stability in the presence of near-electrode perturbations and to gas density perturbations in the working volume becomes most important. These processes are responsible for deterioration of the discharge homogeneity, its contraction, and (as a result) the quenching of lasing [2]. We shall regard a discharge as highly stable if it does not go over to the spark phase even in the case of strong gas density perturbations ($\Delta\rho/\rho > 0.02$). The feasibility of attaining high pulse repetition rates in a laser is determined by many factors, including the discharge gap geometry, electrode design, preionisation system, flow velocity of the working gas, and also by the presence of additional devices to reduce acoustic perturbations in the interelectrode gap.

The high-repetition-rate operating mode of an electric discharge laser is realised most easily for a small width of the cross section of the pump discharge. In this case, lower gas transport velocities are required, the energy deposition per unit length of discharge is reduced, and, accordingly, the intensity of shock waves in the working volume and the pump pulse length are reduced. As a consequence, the discharge stability improves.

In excimer active media, the discharge stability depends to a large degree also on the initial electron density produced by the preionisation source. In lasers with UV preionisation, which enjoys the widest acceptance, the initial electron density depends both on the energy deposition in the spark gaps per unit length of the pump discharge and on the distance from the gaps to the active volume. In the design of lasers with a low output energy, reduction of the energy stored in the pump source capacitor should be accompanied by reduction of the energy deposited in the spark gaps. This makes it necessary to bring the spark gaps closer to the active volume in order to maintain the required initial electron density. In the high-repetition-rate mode, bringing the spark preionisation system closer to the discharge region can often provoke arcing in the discharge gap.

The duration of the diffuse phase of the discharge in dense gases decreases with reduction of the interelectrode gap. For instance, a typical lifetime of the diffuse phase of the discharge for an interelectrode gap of 4 mm is (according to Sze and Seegmiller [3]) ~ 10 ns. More recently it was possible to increase significantly the duration of a stable discharge in KrF and XeCl excimer lasers employing inductive discharge stabilisation [4]. In this case, a sectioned cathode consisted of isolated segments each connected to the common busbar by inductors. UV preionisation was effected through a grid anode located at 2.5 mm from the cathode. The stable discharge duration was several tens of nanoseconds.

One of the primary results of Ref. [4] was the realisation of a pulse-periodic laser operating mode with a pulse repetition rate of several tens of hertz without recourse to circulation of the gas mixture. The pulse repetition rate typical of lasers without inductive stabilisation is much lower [3].

It is pertinent to note that the heat-release-related density perturbations of the working gas in the active volume of a laser without gas circulation operating at a repetition rate above ten hertz are far greater than in a gas-flow laser. The reason is that the heated gas escapes from the working gap of a gas-flow laser in the interpulse period. In absence of gas circulation, the realisation of a diffuse discharge in a laser device at a pulse repetition rate of several tens of hertz is indicative of the attainment of a high discharge stability. With gas circulation in a similar laser device, it is possible to attain high pulse repetition rates for small clearance ratios without recourse to complex devices to reduce acoustic perturbations. The development and investigation of these laser

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devices is thus critical to the attainment of significantly higher pulse repetition rates, up to 5 – 10 kHz.

A new version of an electrode unit [5] of plate-like design involving UV preionisation, developed for compact high-repetition-rate lasers, was investigated by us. Fig. 1 is a schematic diagram of an electric discharge laser with plate-like electrodes. Experiments were staged by using a discharge chamber, made of an aluminium alloy, with an external diameter of 24 cm and of 38 cm length. Inside it, three feed-through insulators supported the electrode unit of two identical plate-like electrodes. Each electrode consisted of 49 (of 37 in some experiments) 1-mm-thick brass plates with a working edge 60 mm in radius, which were insulated from one another and equally spaced at 5 mm. The electrodes were mounted in such a way that every cathode plate was located in the plane of the corresponding anode plate and the distance between the working edges of the anode and cathode plates was adjustable from 8 mm to 15 mm.

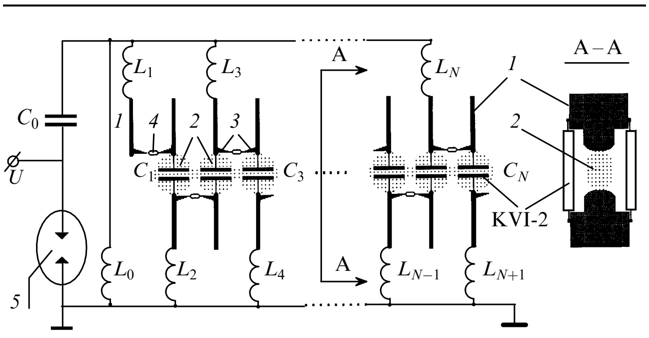

Figure 1. Schematic diagram of the experimental setup: C_0 is a storage capacitor; $C_1, \ldots, C_n$ are peaking capacitors; $L_1, \ldots, L_{N+1}$ are decoupling inductors; L_0 is a charging inductor; (*1*) electrode plates; (*2*) volume discharge region; (*3*) preioniser points; (*4*) spark gaps; (*5*) spark gap.

Each pair of plates lying in one plane was connected to one or two capacitors with a total capacitance C_i located inside the chamber near the electrode plates, as shown in Fig. 1, and formed an electrode section. This made it possible to attain a minimum inductance of the discharge circuit. A typical oscillation period of the discharge current in the electrode sections was $2\pi(LC)^{1/2} \leqslant 20$ ns. Each of the electrode sections was connected to the pump source through a stabilising inductor L_i (200 – 400 nH) and a spark gap, which ensured the UV preionisation.

The discharge in the interelectrode gap was excited by a high-voltage two-circuit (*C–C*) generator with a RU-73 spark-gap-based switch. The storage capacitor of the pumping source C_0 was assembled from series-parallel KVI-3 capacitors (0.68 nF, 20 kV) placed outside the discharge chamber. In almost every experiment we conducted, the storage capacitance C_0 was selected such that it was equal to the total peaking capacitance: $C_0 \approx \sum_{i=1}^{N} C_i$, where $N = 49$ or 37. KVI-2 capacitors (20 pF, 30 kV; 33 pF, 20 kV; 47 pF, 20 kV) were used in experiments as the peaking capacitors. After operation of the spark gap *5*, a voltage appeared across the interelectrode gap. Its rise time was determined by the time for charge exchange between the storage capacitance C_0 and the total peaking capacitance. The mirrors of the plane-parallel laser cavity were placed on the flanges of the laser chamber. These mirrors served also as the end windows of the discharge chamber.

A laser with a nitrogen active medium was used in the majority of experiments as a model for studying the discharge stability in the presence of temperature perturbations of the gas density in the pulse repetition mode. A nitrogen laser operates in a broad range of pressures of nitrogen and admixtures of different buffer gases. The maximum repetition rate f_{lin} at which the average output radiation power is still a virtually linear function of the repetition rate was taken as a criterion characterising the discharge stability.

A homogeneous spark-free discharge was observed along the optical axis of the nitrogen laser in a wide range of pressures of the working mixture. When viewed from the side, the discharge appeared to consist of isolated barrel-shaped diffuse plasma objects lying in one plane between the anode and cathode plates and not overlapping in the central discharge region.

Fig. 2 shows the output power and the laser efficiency as functions of the charging voltage U of the storage capacitor C_0 for a pulse repetition rate of 10 Hz and discharge gap heights $h = 10$ mm and 15 mm. It is clear that the laser efficiency increases significantly (by more than a factor of 1.3) with an increase in height of the discharge gap. This is apparently due to better load matching with the pump source and to the increase in energy transferred to the peaking capacitor. The maximum efficiency of the nitrogen laser with a discharge gap height $h = 10$ mm was 0.055% and 0.075% for $h = 15$ mm. Typical efficiencies of nitrogen electric-discharge lasers are usually 0.05 – 0.1%. It is noteworthy that the laser efficiency for a pulse repetition rate of 10 Hz is virtually equal to the efficiency in the infrequently-repeating-pulse regime.

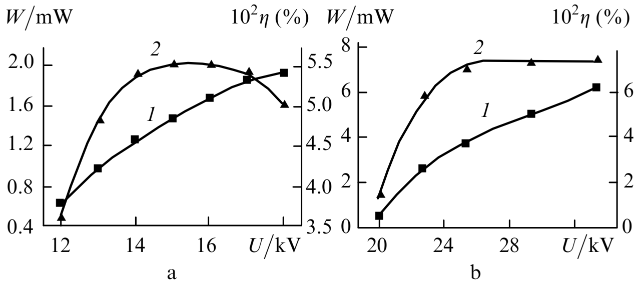

Figure 2. Output power W (*1*) and efficiency of the nitrogen laser η (*2*) as functions of the charging voltage U of the storage capacitor C_0 for a height of the discharge gap $h = 10$ (a) and 15 mm (b), $C_0 = 2.2$ (a) and 2 nF (b), $C_i = 66$ (a) and 40 pF (b), and the nitrogen pressures 91 (a) and 114 Torr (b).

The dependence of the average output power of a nitrogen laser without UV preionisation on the pulse repetition rate is given in Ref. [6]. The specific pump energy per unit length of the active volume (along the optical axis) was $\sim$0.1 J cm^{-1}. Pure nitrogen was used as the active medium. A linear rise of the laser radiation power was observed up to $f_{\text{lin}} \approx 10$ Hz. Lomaev et al. [7] obtained a higher pulse repetition rate $f_{\text{lin}} \sim 20 - 25$ Hz in a nitrogen laser with UV preionisation by using a nitrogen – helium mixture, with the laser design ensuring gas self-circulation. The specific pump energy was $\sim$0.15 J cm^{-1}. Similar results were obtained for an He – Xe – HCl mixture in an excimer laser [7].

In our investigation the emphasis was on the dependence of the average output power of the nitrogen laser on the pulse repetition rate. The specific pump energy was typically $\sim$0.02 – 0.05 J cm^{-1}. The experimental results are given in

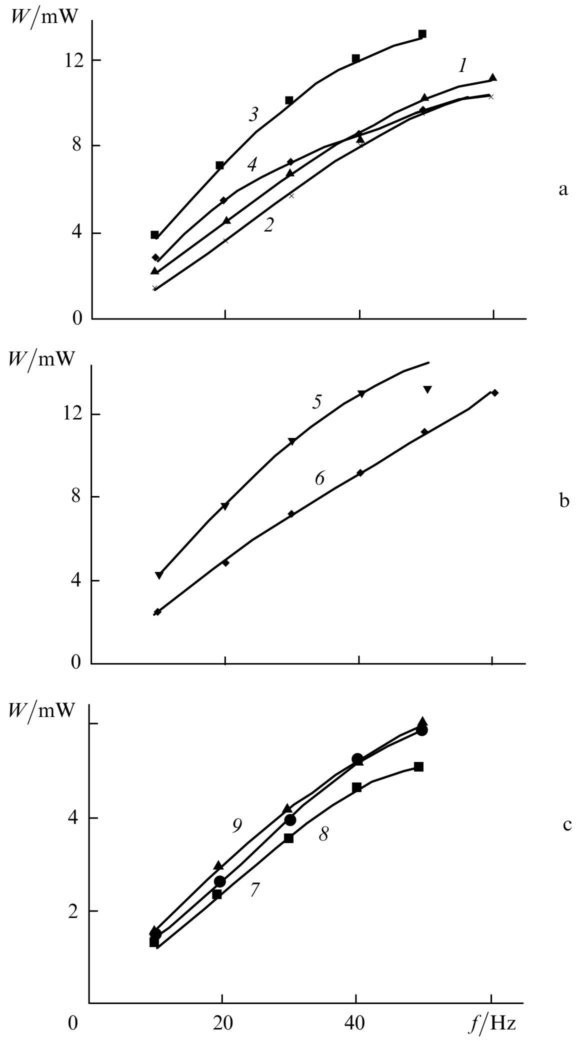

Figure 3. Average output power of the nitrogen laser W versus pulse repetition rate f: (a) $h = 10$ mm, $C_0 = 4.7$ nF, $C_i = 94$ pF, $U = 16$ (*1, 2*) and 22 kV (*3, 4*), nitrogen pressure of 91 (*1*), 114 (*2, 3*), and 152 Torr (*4*); (b) $h = 10$ mm, $C_0 = 4.7$ nF, $C_i = 94$ pF, $U = 22$ kV, a nitrogen pressure of 91 Torr (*5*) for the mixture composition $N_2:He = 46:1000$ Torr (*6*); (c) $h = 8.8$ mm, $C_0 = 2.35$ nF, $C_i = 47$ pF, $U = 22$ kV, nitrogen pressure of 91 (*7*) and 114 Torr (*8*) for the mixture composition $N_2:He = 46:760$ Torr (*9*).

Fig. 3. For a specific pump energy of ~ 0.05 J cm^{-1}, the average output power of pure nitrogen rose linearly up to $f_{\text{lin}} \sim 20 - 30$ Hz (curves *3–5* in Fig. 3). For a nonoptimal pressure of the working mixture, the output power grew more slowly with the pulse repetition rate (curve *4*). Reduction in the specific pump energy to ~ 0.026 J cm^{-1} by reducing either the storage capacitance or the charging voltage caused f_{lin} to increase to 40 – 50 Hz (curves *1, 7*, and *8*). Reduction in the specific pump energy to ~ 0.01 J cm^{-1} made it possible to realise experimentally a sparkfree diffuse discharge with a pulse repetition rate of 200 Hz and an output power of 6 mW. In this case, the laser efficiency was lower by a factor of ~ 1.5. A further increase in the pulse repetition rate was limited by the capabilities of the charging system.

The most significant increase in f_{lin} occurred on addition of the He buffer gas to nitrogen (curve *6*). In this case, $f_{\text{lin}} > 60$ Hz and an average output power of 13 mW were obtained for a specific pump energy of ~ 0.05 J cm^{-1}. Clearly this is related to the reduction in density perturbations in the active medium, which is due to a significant increase in the heat capacity of the working gas on addition of helium. For a specific pump energy of ~ 0.026 J cm^{-1}, the addition of He at 1 bar to nitrogen (curve *9*) did not increase f_{lin} ($f_{\text{lin}} \sim 40$ Hz). This is probably related to an insignificant excess above the lasing threshold on reduction in the pump energy and to an increase in the losses of the laser radiation on increase in the pulse repetition rate.

Noteworthy is the faster than linear rise of the average output power with increase in the pulse repetition rate from 10 Hz to 60 Hz at a nitrogen pressure of 114 Torr (curve *2* of Fig. 3). This rise occurs because the density of the working mixture in the working gap is reduced significantly by gas heating on increase in the pulse repetition rate. As a result, the gas density in the discharge region approaches the optimal value (when operating in the mode of infrequently repeated pulses, the optimal nitrogen pressure is ~ 90 Torr). Estimates suggest that there occur significant fluctuations in the gas density ($\Delta\rho/\rho \sim 0.1 - 0.2$) in the laser active medium.

A study was also made of the parameters of an XeF excimer laser, with NF_3 as the donor of fluorine and with Ne and He buffer gases at pressures up to 2 bar. In all cases a spark-free diffuse discharge was observed. Measurements were made of the output energy of single pulses and of the average output power at a pulse repetition rate of 10 Hz.

Fig. 4 shows typical dependences of the energy of single pulses, of the average output power, and the laser efficiency on the charging voltage of the storage capacitor for discharge gap heights of 10 mm and 15 mm. It is evident that the maximum efficiency of the laser employing the mixtures $NF_3:Xe:Ne = 6:15:760$ and $5:10:760$ at a total pressure of ~ 1 bar exceeds 0.34%. This efficiency is typical of an NF_3-based XeF laser pumped by short pulses (see, e.g. Ref. [8]). We emphasise that in our work the XeF laser was not optimised thoroughly.

The linear rise of the average output power of the XeF laser on increase in the pulse repetition rate took place up to $f_{\text{lin}} \sim 30$ Hz. A homogeneous diffuse discharge was observed in the entire range of pulse repetition rates (up to 60 Hz) and pressures of the active medium (up to 2 bar) investigated. In the experiments, the specific pump energy was ~ 0.02 J cm^{-1} – 0.04 J cm^{-1}. These conditions ensured the required initial electron density.

A laser with plate-like electrodes and inductive – capacitive stabilisation thus possesses a high discharge stability in the presence of density perturbations of the active-gas

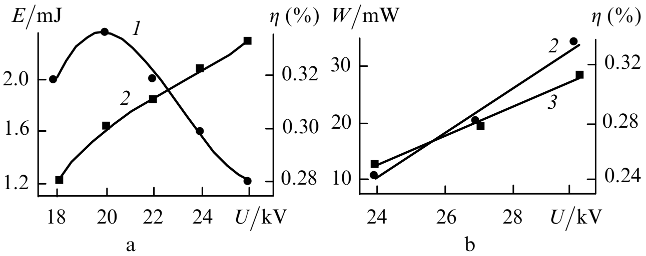

Figure 4. Energy E (*1*), lasing efficiency η (*2*), and output power W at a pulse repetition rate of 10 Hz (*3*) of a XeF excimer laser as functions of the charging voltage U of a storage capacitor C_0, with the working mixtures of composition $NF_3:Xe:Ne = 6:15:760$ Torr: (a) $h = 10$ mm, $C_0 = 2.2$ nF, $C_i = 66$ pF; (b) $NF_3:Xe:Ne = 5:10:760$ Torr for $h = 15$ mm, $C_0 = 2$ nF, $C_i = 40$ pF.

medium. Plate-like electrodes can be used in high-repetition-rate electric discharge lasers and exciplex lamps. An important advantage of plate-like electrodes is the ability to pump the active-gas medium through the electrodes. In our opinion, this makes it possible to reduce considerably the clearance ratio (below 1.5) in the pulse-repetition mode of laser operation.

For a small specific pump energy of ~ 0.01 J cm^{-1}, if a nearly diffraction-limited radiation divergence is not necessary, it is possible to construct electric discharge gas-circulation lasers with a clearance ratio far less than unity. This opens up the way for development of relatively simple, high-repetition-rate (5 – 10 kHz) exciplex lamps and electric discharge lasers with moderate gas flow velocities of $\sim 10-20$ m s^{-1}.

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