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Highly efficient chemical HF laser with inductive stabilisation of the discharge

B V Lazhintsev, V A Nor-Arevyan, V D Selemir

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Abstract. A chemical electric-discharge laser with a new design of the electrode unit was developed. Both electrodes consisted of a set of electrically insulated plates connected to a common bus of a pump source with separate stabilising inductances. It was found that a stable diffuse discharge occurred in such a device in a wide range of active-gas pressures 20 – 130 Torr for an electrode gap of 10 – 50 mm. A radiation energy of 1.2 J and a technical laser efficiency of 3.5% were achieved for an H_2-SF_6 mixture.

There is currently an upsurge of interest in chemical HF (DF) lasers with a large volume of the active medium [1]. An increase in the active volume of chemical lasers hinders its preionisation, requires an increased pump source voltage, and leads to an increase in its inductance, which lengthens the duration of the discharge and results in the loss of its stability. Development of a simple design of the electrode unit capable of forming a homogeneous stable discharge without the use of special preionisation devices is therefore a topical task. This task was performed successfully [1] for mixtures based on hydrocarbons (deuterocarbons), the use of which instead of $H_2(D_2)$ makes it possible to stabilise significantly the volume discharge.

The stabilisation of a self-sustained discharge in various active media by limiting the discharge current with the aid of resistive electrodes made of a semiconducting material [2, 3], ballast resistors [4, 5], and inductances [6, 7] is employed in various gas lasers based on HF [2, 3, 5], KrF (XeCl) [6], and CO_2 [7].

A resistive anode in an HF-laser cavity was made of ~2000 needles, the upper parts of which were covered by a solution of copper sulfate [5]. The maximum lasing energy of 11 J with a technical efficiency of 3.8% was achieved on the basis of the $H_2:SF_6 = 1:25$ mixture at a total pressure of 156 Torr and for a specific input energy 0.072 J cm^{-3}. A visually homogeneous discharge was observed at active-mixture pressures below 30 Torr.

In another study [3], the anode of an HF laser was made of polycrystalline Ge with a resistivity $\rho = 50\ \Omega$ cm, whereas the cathode consisted of a brass grid, through which UV preionisation radiation passed. Stable radiation pulses based on a $C_3H_8-SF_6$ mixture at a pressure of 55 Torr were generated with an efficiency of 2.5% in a laser with such an electrode module. The radiation energy fluctuations did not exceed 1% from pulse to pulse.

Since the resistive stabilising components are heated during the operation of a laser in the repetitively pulsed regime and this entails energy losses, the application of inductive stabilising components is preferred in such a regime.

Inductive stabilisation of a discharge in the active medium of an excimer KrF(XeCl) laser has been achieved [6]. A sectioned cathode, consisting of insulated segments connected to a common bus with the aid of 150 nH inductances, was employed. The UV preionisation radiation passed through a grid anode. The interelectrode distance was 2.5 mm and the gap between the segments was 0.79 mm. The maximum efficiency was 1.07% for the KrF laser and 0.6% for the XeCl laser (the total radiation pulse duration was ~100 ns). The laser operated at a pulse repetition frequency up to 70 Hz without circulation of the gas mixture. These results indicate a high discharge stability.

Inductive stabilisation of the discharge in a CO_2 laser has been attained [7]. In that case the laser anode was a solid aluminium plate with rounded edges. Metal sections 0.35 mm in diameter, distributed with a density of ~200 cm^{-2} and connected by ballast inductances to a common bus, were placed on the active surface of a sectioned cathode. This made it possible to expand the pressure range of the spark-free discharge by a factor of 2 – 3, to increase the laser output energy by a factor of 3 – 4, and to improve significantly the reproducibility of the results.

This communication reports a study of a new design of the electrode module of an electric-discharge HF laser based on an H_2-SF_6 mixture with inductive stabilisation of the discharge [8], but without the preionisation of the active volume. A stainless steel discharge chamber 24 cm in diameter and 50 cm long was used in the experiments. An electrode module, consisting of two identical plate electrodes approximately 280 mm long, was located in the chamber with the aid of feedthrough insulators. Each electrode consisted of 44 copper plates (insulated from one another), 1 mm thick and with a 200 mm radius of the working edge. They were distributed at 6.5 mm intervals. The electrodes were mounted in such a way that each cathode plate was in the plane corresponding to the anode plate and the distance between the working edges of the anode and cathode plates could be varied in the range 30 – 50 mm. Each plate was connected to one of the two common buses of the pump source with the aid of ~500 nH stabilising inductances. A laser cavity was formed by plane dielectric mirrors with the reflection coefficients of 98% and 65%. These mirrors served simultaneously as the end-face windows of the discharge chamber.

B V Lazhintsev, V A Nor-Arevyan, V D Selemir All-Russia Scientific Research Institute of Experimental Physics (Russian Federal Nuclear Centre), prospekt Mira 37, 607190 Sarov, Nizhny Novgorod province, Russia, tel.: +7(83130) 45584, e-mail: selemir@vniief.ru

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Fig. 1 illustrates the electric circuit of a chemical electric-discharge laser. A high-voltage pump generator was assembled from 32 K15-24 capacitors (4.4 nF, 30 kV), based on a circuit comprising two *LC* oscillators, and it was charged to a voltage of ±22 kV from a bipolar power supply. After switching-on the P_1-P_4 (RU-73) spark gaps, the voltage across the discharge gap increased at a rate determined by the recharging time of the C_0 capacitors.

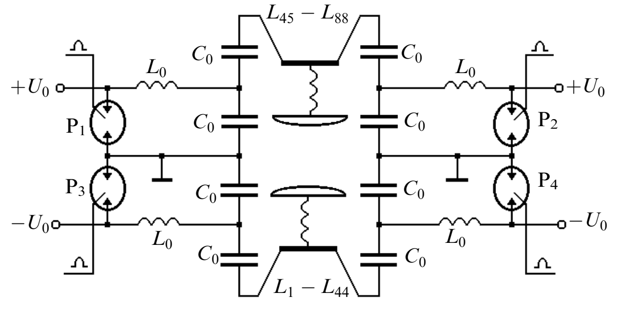

Figure 1. Electric circuit of a chemical laser.

In a wide range of pressures of the active mixtures, a homogeneous diffuse spark-free discharge was excited, without the preionisation of the active volume. A side view of the discharge revealed individual barrel-shaped diffuse plasma formations between the anode and cathode plates located in one plane and overlapping in the central part of the discharge.

Fig. 2 presents typical oscillograms of the voltage pulses across an interelectrode gap of 50 mm and of the discharge current in an $H_2:SF_6=1:12$ mixture at an overall pressure of 68 Torr and for a discharge voltage $U_0=\pm22$ kV. The discharge resistance in the maximum current region was 6 – 7 Ω.

The dependence of the output energy on the gas pressure of an $H_2:SF_6=1:10$ mixture is shown in Fig. 3 for an interelectrode gap of 50 mm at a discharge voltage $U_0=\pm22$ kV. At a total working-gas pressure of 68 Torr, the maximum output energy was 1.2 J and the technical efficiency was 3.5%. In this regime, the cross section of the laser beam in the near-field zone was ~49 mm × 25 mm, the specific input energy was ~0.1 J cm^{-3}, and the average specific output energy was approximately 3.5 mJ cm^{-3}. At minimal pressures, spark formation was not observed in the discharge, but individual faint sparks appeared on increase in pressure above 120 Torr.

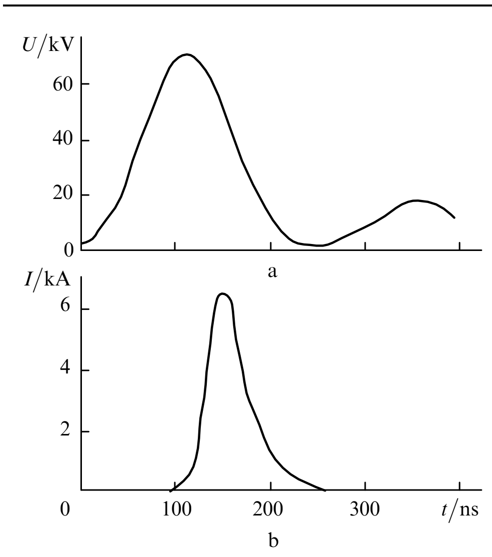

Figure 2. Oscillograms of the voltage pulses across the discharge gap (a) and of the discharge current (b).

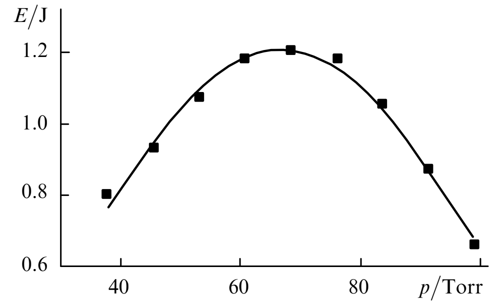

Figure 3. Dependence of the output energy on the pressure of the active mixture for an interelectrode distance of 50 mm.

Data on the change in the efficiency resulting from doubling of the input energy by reducing the length of the active volume by a factor of 2 were obtained. Each electrode was assembled from three batches of electrode plates at 3.25 mm intervals. In each batch, there were 15 plates and the distance between the batches was 45 mm. In this version of the electrode module, the output energy and the efficiency decreased by approximately 30%.

The input energy deposited in the active medium was also increased by reducing the discharge gap to 30 mm by retaining the 6.25 mm interval between the plates. The region of the overlap of discrete plasma formations shrunk appreciably, the cross section of the laser beam in the near-field zone was ~28 mm × 21 mm, the average specific input energy was ~0.2 J cm^{-3}, while the average specific output energy was approximately 6 mJ cm^{-3}. The maximum input and output energies were approximately 1.5 – 2 times greater (0.3 – 0.4 J cm^{-3} and 9 – 12 mJ cm^{-3}, respectively) when account was taken of the discrete nature of the plasma formations. The maximum output energy (1 J) was obtained in this version for a mixture of the composition $H_2:SF_6=1:13$ at a pressure of 106 Torr and with a technical efficiency of 3%.

The satisfactory operation of the electrode module with the plate structure and with inductive stabilisation of the discharge in a discharge gap of 120 mm was tested in a cylindrical discharge chamber made of a dielectric material. The high-voltage pump pulse generator was based on two *LC* oscillators which could be charged to a voltage of ±80 kV and a peaking spark gap. A stable diffuse discharge was generated in an H_2-SF_6 mixture. The resulting efficiency of the chemical laser was up to 3.5% and the specific output energy was up to 5 mJ cm^{-3}.

An electrode module with an interelectrode distance of 10 mm was assembled to test the efficiency of the plate electrode module of a chemical laser with a small interelectrode gap and to check the stability of the frequency regime without circulation of the active medium. The total number of plates on each electrode was increased to 100. The distance between the plates was 1.2 mm and their thickness was 0.3 mm, which corresponded to an interval of 1.5 mm. The length of the active component of the electrode was 150 mm and the radius of the working edge of the plate was 120 mm. Each plate was connected to a common bus with the aid of a $\sim$200 mH inductance. The discharge in the interelectrode gap was excited by a high-voltage generator assembled on the basis of a two-circuit ($C-C$) oscillator with an RU-73 spark gap. A 2.7 nF peaking capacitor, assembled from KVI-3 capacitors (0.68 nF $\times$ 20 kV), was placed directly inside the working chamber near the electrode plates. A 3 nF storage capacitor was placed outside the working chamber and the charging voltage on the storage capacitor was varied in the range 26 – 30 kV.

The working chamber was filled with an $H_2 : SF_6 = 1:12$ active mixture. The laser beam in the near-field zone was $\sim$9 mm high and $\sim$8 mm wide. The dependence of the output energy on the pressure of the active mixture is illustrated in Fig. 4. The maximum output energy of 38 mJ and the specific output energy of $\sim$3.4 mJ cm^{-3} were obtained for a pressure of the active mixture of 114 Torr and a storage capacitor charging voltage of 30 kV, whereas the maximum technical efficiency obtained at the optimum pressure of the active mixture for each charging voltage was 2.7% (26 kV), 2.9% (28 kV), and 2.8% (30 kV). The technical efficiency remained constant on increase in the specific input energy to 0.1 J cm^{-3}. A further increase in the pump energy as a result of an increase in the storage capacitance to 4 nF (charging voltage 30 kV) reduced the efficiency to 2.5%.

In the latest version of our chemical laser, a repetitively pulsed regime was achieved without circulation of the active mixture. A homogeneous diffuse discharge was observed visually up to a pulse repetition rate of $\sim$20 Hz, indicating a high discharge stability.

Comparison of the experimental results obtained in the present study with those of Ref. [9], where the energy characteristics of lasers with solid electrodes and spark preionisation of an $H_2 - SF_6$ mixture were investigated, would be of interest. The maximum technical efficiency of the DILAN device with an active volume of 1 cm $\times$ 1 cm $\times$ 20 cm was 2.2% for a specific input energy less than 0.05 J cm^{-3}, whereas for a specific input energy of $\sim$0.1 J cm^{-3}, the efficiency fell to $\sim$1.5%. The efficiency on the LIDA device with an active volume of 2.5 cm $\times$ 1.1 cm $\times$ 60 cm was 1.6% for an output energy of 1.2 J and a specific input energy of $\sim$0.4 J cm^{-3}. The efficiency of the lasers with the interelectrode distances of 10 and 30 mm and inductive stabilisation of the discharge exceeded almost by a factor of 2 the efficiency of the DILAN and LIDA lasers for specific input energies deposited in the active medium of lasers similar to those used in the present study.

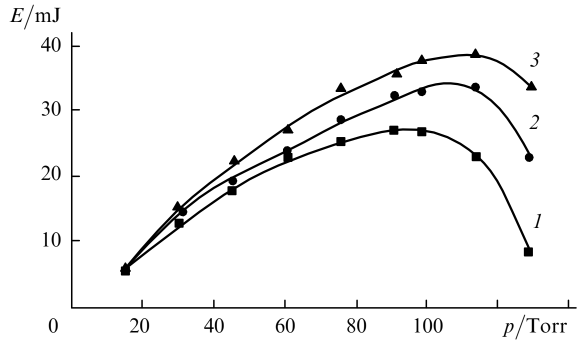

Figure 4. Dependences of the output energy on the pressure of the active mixture for an interelectrode distance of 10 mm at charging voltages of 26 kV (*1*), 28 kV (*2*), and 30 kV (*3*).

The use of plate electrodes in combination with inductive discharge stabilisation thus makes it possible to construct highly efficient chemical lasers which are simple and easy to make. A significant advantage of the proposed electrode module is the feasibility of circulation of the working gas through the electrodes. In this version of the laser, it is possible to employ a discharge circuit with a minimal inductance, placing the pump source on both lateral sides of the discharge gap. This is important in the design of large-volume chemical lasers with a considerable input energy. The interelectrode distance with such an electrode design is determined by the characteristics of the pump source (its inductance and working voltage) and may reach 300 mm or more for a voltage of about 500 kV. Assembly of the laser pump source from individual sections, as specified in Ref. [8], makes it possible to increase linearly the laser energy by a reasonable increase in the length of the discharge gap.

Moreover, the high stability of the discharge and circulation of the gas through the electrodes should make it possible to operate with a near-unity clearance ratio of the working gas, which is especially important in the operation of a laser at a high repetition rate.

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