Quantum Electronics **36** (3) 235 – 238 (2006)

PACS numbers: 42.55.Ks; 42.60.Lh
DOI: 10.1070/QE2006v036n03ABEH013128

High-pulse-repetition-rate HF laser with plate electrodes

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***Abstract*. A high-pulse-repetition-rate electric-discharge HF laser with inductive–capacitive discharge stabilisation in the active $H_2 - SF_6 - He$ mixture is studied. The multisectional discharge gap with a total length of 250 mm is formed by pairs of anode – cathode plates arranged in a zigzag pattern. The width of the discharge gap between each pair of plates is ~ 1 mm and its height is ~ 12 mm. The laser-beam cross section at the output cavity mirror is ~ 9 mm $\times$ 11 mm. The maximum laser pulse energy and the maximum laser efficiency for the $H_2 - SF_6$ mixture are 14.3 mJ and 2.1%, respectively. The addition of He to the mixture reduced the laser pulse energy by 10 % – 15 %. The maximum gas velocity in the gap between the electrodes achieves 20 m s^{-1}. The limiting pulse repetition rate f_{lim} for which a decrease in the laser pulse energy is still not observed is ~ 2 kHz for the $H_2 - SF_6$ mixture and ~ 2.4 kHz for the $H_2 - SF_6 - He$ mixture. The average output power ~ 27 W is obtained for a pulse repetition rate of 2.4 kHz.**

Keywords: *electric-discharge HF laser, plate electrodes, inductive – capacitive stabilisation, input energy distribution, preionisation, pulse repetition rate.*

1. Introduction

Electric-discharge gas lasers with a high pulse repetition rate (1 – 5 kHz) are widely used in microlithography, ecology, medicine, etc.

Excimer lasers pumped by a self-sustained volume discharge with a pulse repetition rate of several kHz are characterised by a small discharge width (~ 3 mm) and a high gas flow velocity (no less than 50 m s^{-1}) in the electrode gap [1]. Excimer lasers with a pulse repetition rate $f \approx 4$ kHz are used in microlithography [2].

The development of a chemical DF laser with a pulse repetition rate $f = 1.2$ kHz was reported in [3]. A high pulse repetition rate was achieved in the laser with a discharge width ~ 8 mm by using powerful blowers providing a gas velocity of about 30 m s^{-1} in the discharge gap.

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Received 25 November 2005
Kvantovaya Elektronika **36** (3) 235 – 238 (2006)
Translated by Ram Wadhwa

A high pulse repetition rate in an electric-discharge excimer XeF laser [4] was achieved at a relatively low gas circulation velocity by using a new electrode unit [5] based on multisectional plate electrodes with inductive-capacitive discharge stabilisation. Formation of an extremely narrow discharge gap of width ~ 1 mm in this laser made it possible to achieve a pulse repetition rate up to 4 – 5 kHz at a moderate circulation velocity of the active gas (~ 19 m s^{-1}).

Excitation of the active medium of chemical HF(DF) lasers by narrow multisectional discharges located in a single plane, as in [4], leads to considerable diffraction losses in the cavity because the wavelength of such lasers is much longer (by a factor of 10 – 15) than for excimer lasers. These losses can be avoided if the discharge is formed by using plate electrodes in which pairs of anode – cathode plates are located in planes forming an angle α with the optical axis. Such a construction of the electrode assembly was first used in [6] for obtaining the desired laser beam profile in the near-field zone.

If the electrode plates are oriented at a small angle to the optical axis of the laser ($\alpha \leqslant 30°$), the gas-mixture change factor $K = v\cos\alpha/(fb)$ (where v is the gas velocity and b is the width of the plasma cluster) will be determined mainly by the plasma cluster width ($b/\cos\alpha \approx b \sim 1 - 1.5$ mm). The laser beam width D determined by the projection of plasma region onto the plane perpendicular to the optical axis may be quite large ($D \geqslant 10$ mm). Such an arrangement of electrode plates considerably reduces the diffraction radiation losses and allows the development of IR lasers with a pulse repetition rate up to several kilohertz and the beam width in the near-field zone $D \geqslant 10$ mm for moderate values (10 – 20 m s^{-1}) of the gas flow velocity. Such an approach was first proposed in [5].

In this paper, we studied a high-pulse-repetition-rate HF laser with an active volume of 12 mm $\times$ 10 mm $\times$ 250 mm based on plate electrodes arranged at an angle to the optical axis. The gas mixture circulation system provided a flow velocity up to 20 m s^{-1} in the electrode gap.

2. Experimental setup

The gas flow laser was assembled on the basis of a CL-5000 laser chamber [4] (commercially produced at the Physical Instrumentation Centre, General Physics Institute, Russian Academy of Sciences, Troitsk) and a new electrode assembly with a multisectional discharge gap [5].

The aluminium housing of the chamber had a length of 430 mm. The cavity mirrors were fastened to the end flanges of the chamber. The cavity was formed by a spherical goldplated copper mirror ($R \approx 5$ m) and a plane output mirror on a CaF_2 substrate with a reflectance of 60 %. The highly reflecting mirror was protected from damage by a CaF_2 plate. The separation between the cavity mirrors was 50 cm. A diametrical blower rotated by the magnetic clutch of a dc motor and a heat exchanger were installed inside the chamber. The upper part of the chamber contained the electrode assembly with the laser pump source.

Figure 1 shows schematically the electrode assembly of the laser. The discharge gap was formed by pairs of anode–cathode plates inclined at an angle α to the optical axis of the laser. The working edge of each plate had a Stepperch profile. The height and total length of the discharge gap along the optical axis were 12 and 250 mm, respectively.

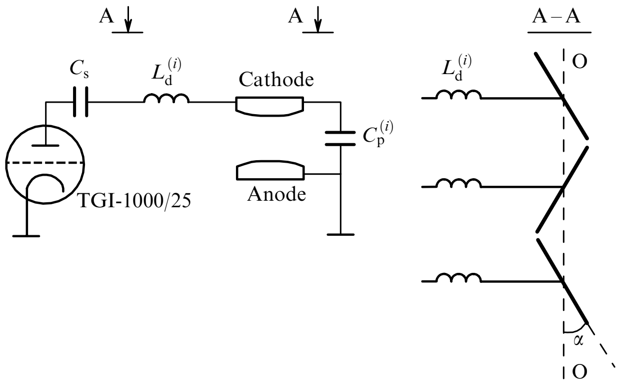

Figure 1. Scheme of the electrode assembly for an HF laser (O-O is the optical axis of the laser).

Preionisation was initiated by spark discharges on both sides of the discharge gap. The pulse pump circuit of the laser contained a storage capacitor C_s (2.8 nF), a peaking capacitor C_p (2.4 nF) and a preionisation capacitor C_{pr} (0.43 nF). In order to achieve inductive–capacitive decoupling, a peaking capacitor $C_p^{(i)}$ was connected to each pair of electrode plates and was charged through a decoupling inductance $L_d^{(i)}$ (Fig. 1).

A pulsed source was used as the power supply for the laser. The storage capacitor C_s was charged for 240 μs with the help of a resonance-diode circuit. A 0.22-μF filtering capacitor was used. The highest charging voltage across the storage capacitor in the pulse-periodic regime of laser operation was 22 kV. A limiting pulse repetition rate of 4 kHz was ensured by the resonance-diode-charging circuit.

When a TGI-1000/25 thyratron was switched on, the peaking capacitor was charged by the storage capacitor in the $C - C$ circuit (see Fig. 1). For a certain voltage across the peaking capacitors, a breakdown was observed in the spark gaps of the preioniser which resulted in charging of its capacitors. After the attainment of breakdown voltage across the peaking capacitors, a volume discharge was formed in the electrode gap. Figure 2 shows typical oscillograms of the voltage pulse across the peaking capacitor and of the laser pulse. For a pulse amplitude of 10–15 kV, the voltage pulse rise front before the electrode gap breakdown was $\sim$ 40 ns.

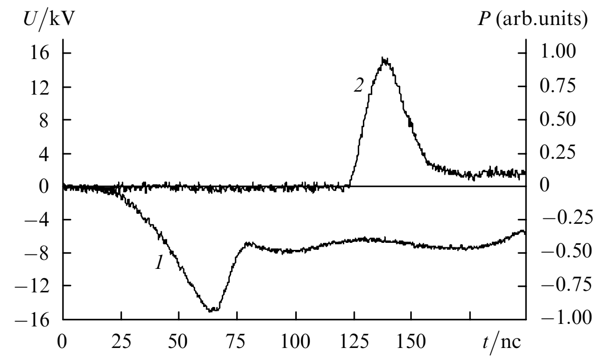

Figure 2. Oscillograms of the voltage pulse U across the peaking capacitor [curve (*1*)] and the generation pulse P [curve (*2*)] for the gas mixture $H_2 : SF_6 = 9.5 : 66.5$ Torr for a storage capacitor charging voltage of 22 kV.

3. Experimental results

Figure 3 shows the optical scheme for measuring the parameters of a high-pulse-repetition-rate HF laser. Distribution of the specific pump power in the cross section of the active volume was determined, as in [6], from the discharge emission intensity in the visible spectral range. The discharge emission was recorded with Olympus C-4040 digital camera (*1*). Highly reflecting resonator mirror (*3*) was replaced with a quartz plate while photographing the discharge. In order to remove parallax errors, photography was done in parallel beams from lens (*4*) whose focal plane coincided with the centre of the discharge gap.

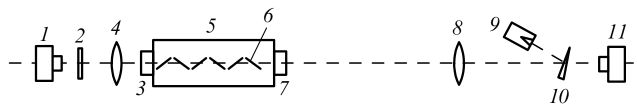

Figure 3. Optical scheme for measuring the optical parameters of the HF laser: (*1*) digital camera; (*2*) optical filter; (*3*) highly reflecting mirror; (*4*) lens; (*5*) laser chamber; (*6*) plate electrodes; (*7*) output mirror; (*8*) CaF_2 lens; (*9*) photodetector; (*10*) optical wedge; (*11*) thermocouple calorimeter.

Figure 4 shows the photographs of discharge emission and its intensity distribution over the discharge width. In all regimes, streamers were clearly observed in the vicinity of the cathode. An increase in the specific energy input to the active volume leads to an increase in the streamer size. For operating at a pulse repetition rate of 2 kHz (Fig. 4a), the discharge width slightly increases due to averaging over 30 pulses and the dip in the central region becomes a bit shallower. Thus, the discharge emission intensity in the middle of the active volume is about 60 %–70 % of its maximum for electrodes with Stepperch profile (Figs 4a, b), and the characteristic width of the discharge emission region is $\sim$ 10 mm.

To increase the laser beam intensity in the central part of the active volume, we used a complex version of the electrode assembly in which all anode plates with a Stepperch profile were replaced by electrode plates with a cylindrical working edge. In this version of the electrode assembly, the emission intensity distribution did not display

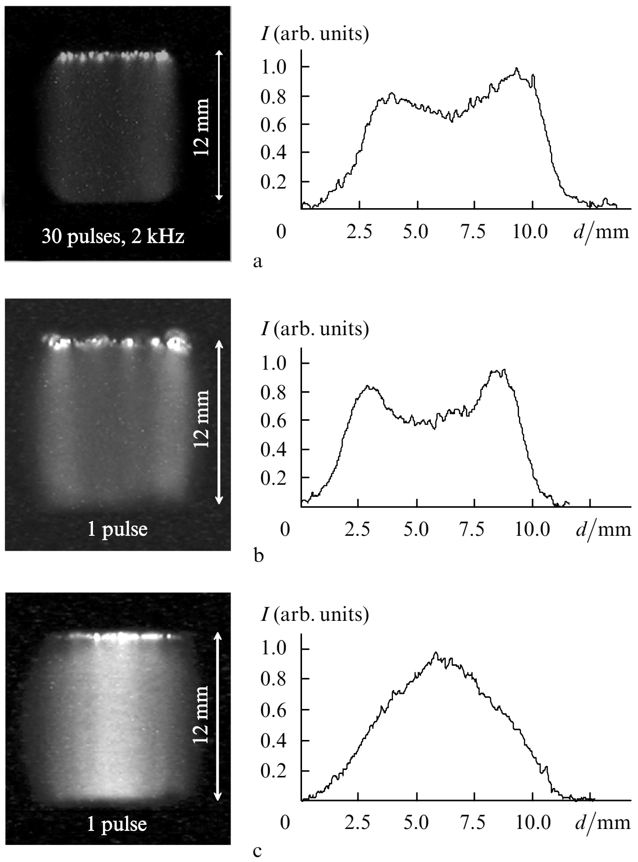

Figure 4. Photographs of the HF laser discharge emission and profiles of glow intensity distribution over the discharge width d for electrode plates with Stepperch profile (a and b) and combined profile consisting of Stepperch profile and a cylindrical surface (c). The active mixture had a composition $H_2 : SF_6 : He = 7 : 49 : 75$ Torr (a, b) and 12.6 : 77.8 : 75 Torr (c) for a pulse repetition rate of 2 kHz (a) (b and c are solitary pulses), charging voltage 22 kV and a gas circulation velocity of 18 m s^{-1}.

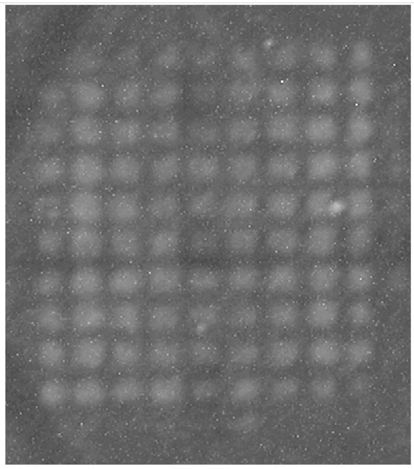

Figure 5. Imprint of a laser beam on photographic paper using an electrode with Stepperch profile. The spacing of the mesh in the near-field zone is 1 mm.

a dip in the central region of the discharge (Fig. 4c). A laser radiation intensity distribution profile with a flatter peak can be obtained by replacing some, and not all, of the anode plates by plates with a cylindrical working edge. The same result can be obtained by using anode plates with a larger radius of the working edge. Thus, the desired laser beam profile can be realised with the help of various combinations of electrode plates.

It was shown in [6] that the profiles of HF laser radiation intensity distribution in the near-field zone and the discharge emission intensity in the visible spectral range are nearly identical in shape. Figure 5 shows the imprint of a laser beam on photographic paper with a diminished image of the output laser mirror (to the scale 1 : 7). To facilitate the interpretation of experimental results, a wire mesh with a 1-mm spacing was installed near the output cavity mirror. The laser beam had a cross section of ~ 11 mm $\times 9$ mm. The radiation intensity near the beam edges (to the left and right) was found to be higher than in the central part of the beam, which qualitatively agrees with the results of investigations of the discharge emission profile (Figs 4a, b).

The laser radiation energy was measured with an ORIEL No. 70263 thermocouple head having a time constant of 2.5 s. Experiments were mainly carried out using $H_2 - SF_6$ and $H_2 - SF_6 - He$ mixtures as the active medium. The highest lasing energy equal to 14.3 mJ was achieved in a mixture $H_2 : SF_6 = 1 : 6$ at a total pressure of 90 Torr and a charging voltage of 22 kV (with a laser efficiency $\eta \approx 2.1\,\%$ relative to the stored energy). Addition of He (75 Torr) to the $H_2 - SF_6$ mixture lowered the lasing energy by $10\,\% - 15\,\%$.

Optimisation of the efficiency η of an electrode-plate chemical HF laser was carried out in [7]. The highest efficiency of a laser with an electrode assembly with an electrode gap of 10 mm was 2.9 % under a total pressure of 110 Torr ($H_2 : SF_6 = 1 : 12$) and a storage capacitor charging voltage of 28 kV. The charging voltage in our experiments did not exceed 22 kV which turned out to be insufficient for operation with higher active volume pressures that are optimal for such an electrode gap. In [3], the efficiency of a DF laser with an electrode separation of 10 mm was found to be $\sim 2\,\%$ under a high total pressure of 120 Torr ($D_2 : SF_6 = 1 : 6$). The laser was pumped by using the Fitch circuit with voltage doubling to 36 kV.

The energy E_N of a packet of N laser pulses (dozens of pulses as a rule) was measured in a calorimeter for a high pulse repetition rate ($f \lesssim 2.5$ kHz). The average pulse energy $E_{av}(f) = E_N(f)/N$ was then determined for various values of f.

In a high-frequency KrF excimer laser, the position of preioniser sparks considerably affects the stability and energy of laser pulses [1]. Hence, we studied the dependence of the average pulse energy on the position of the preioniser spark gaps along the flow (upstream or downstream) and on the pulse repetition rate.

Figure 6 shows the dependences $E_{av}(f)$ for various versions of preionisation. These dependences were used for determining the limiting pulse repetition rate f_{lim} for which the value of $E_{av}(f_{lim})$ does not differ significantly from the average energy in low pulse repetition regime. Note that for a low pulse repetition rate, the pulse energy varies insignificantly (by $10\,\% - 15\,\%$) for various positions of the preioniser spark gaps. For clarity, the energy is shown in arbitrary units in Fig. 6; for each version of preionisation, the value of energy in the single-pulse radiation regime was taken as the unit of measurements.

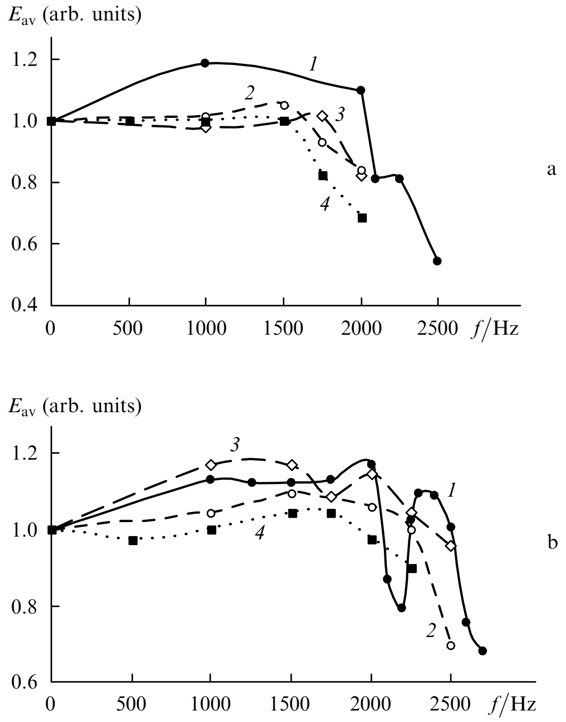

Figure 6. Dependence $E_{av}(f)$ without preionisation [curve (*1*)], for sparks arranged downstream [curve (*2*)] and upstream [curve (*3*)], as well as on both sides of the discharge gap [curve (*4*)] . The composition of the active mixture is $H_2 : SF_6 = 9.5 : 66.5$ Torr (a) and $H_2 : SF_6 : He = 9.5 : 66.5 : 75$ Torr (b) for a gas mixture velocity of 18 m s^{-1} in the electrode gap and a charging voltage of 22 kV.

Figure 6a shows the dependence $E_{av}(f)$ for a charging voltage of 22 kV in the mixture $H_2 : SF_6 = 9.5 : 66.5$ Torr. For a downstream or both sides of the discharge gap arrangement of preionisation sparks, $f_{lim} = 1500$ Hz. For an upstream arrangement of sparks and in the absence of preionisation, the value of f_{lim} increases and amounts to 1750 and 2000 Hz respectively.

The pulse repetition rate in a chemical DF laser was increased in [3] by adding He to the active mixture. An addition of 450 Torr of He led to an increase in f_{lim} from 400 to 1000 Hz. In the present research, the addition of even a small amount of helium (75 Torr) led to a substantial increase in the pulse repetition rate (Fig. 6b). The laser efficiency decreased considerably upon an increase in the helium pressure to several hundred Torr. For an upstream and downstream arrangement of preionisation sparks, the value of f_{lim} increased to 2250 Hz. For arrangement of sparks on both sides of the discharge gap, the value of f_{lim} was 1750 Hz, and in the absence of preionisation its value increased to 2400 Hz.

The resonance character of curves (*1*) and (*3*) in Fig. 6b is due to the evolution of acoustic perturbations in the discharge gap. Such perturbations were also observed in [3] and are manifested most clearly in the absence of preionisation [curve (*1*)]. The dependence $E_{av}(f)$ is smoother in the case of preionisation.

The diametrical blower assembly was subsequently modified and the gas circulation velocity in the electrode gap was increased from 18 to 20 m s^{-1}. As a result, for arrangement of sparks on both sides, the value of f_{lim} increased to 2400 Hz in the mixture with helium (the average laser radiation power was $\sim$ 27 W), while its value was 1750 Hz in the mixture without helium.

To verify the stability of the laser pulse energy, a series of 100 pulses with a pulse repetition rate of 2 kHz was recorded on an exposed and developed photographic paper. The photographic paper was fastened to a rotating disk. The rotational velocity was chosen in such a way that imprints of adjacent pulses did not overlap. The near-field generation zone was projected on the photographic paper. No perceptible difference was observed between the prints of laser pulses obtained by using an active mixture $H_2 : SF_6 = 9.5 : 66.5$ Torr (for a storage capacitor charging voltage of 22 kV).

4. Conclusions

The use of plate electrodes arranged at an acute angle to its optical axis in an electric discharge HF chemical laser made it possible to achieve a record-high pulse repetition rate (2400 Hz) for a low velocity ($\sim$ 20 m s^{-1}) of gas flow in the electrode gap. The laser beam width in the near-field zone ($\sim$ 9 mm) is about an order of magnitude larger than the discharge width for an anode–cathode pair. Our investigations show that the limiting pulse repetition rate is not affected significantly for an upstream or downstream arrangement of preioniser sparks. A further increase in the pulse repetition rate to 3–4 kHz can be realised by increasing the helium pressure in the active mixture.

An increase in the discharge gap voltage is necessary for working with such mixtures.

The use of a new electrode assembly is also quite promising for developing CO_2 lasers with a high pulse repetition rate. The formation of a homogeneous diffusive discharge in the active mixture of the CO_2 laser for a pulse repetition rate of up to 4 kHz is a prerequisite for this purpose.

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