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High-power repetitively pulsed electric-discharge HF laser

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***Abstract*. A high-power non-chain electric-discharge repetitively pulsed HF laser based on SF_6 – hydrocarbon mixtures is developed and investigated. A pulse energy $W_g = 67$ J is obtained at a pulse repetition rate of 20 Hz.**

Keywords: *HF laser, self-sustained volume discharge, high-power repetitively pulsed laser.*

1. Introduction

In recent years much attention has been paid to the development and study of pulsed and repetitively pulsed non-chain HF(DF) lasers with initiation of chemical reaction by a self-sustained volume discharge (SSVD) [1 – 12]. The interest in these systems is due to the wide range of their possible practical applications, in particular, as sources of high-power coherent radiation in lidars for ecological monitoring of atmosphere [2, 13, 14]. Currently non-chain electric discharge HF(DF) lasers are the only ecologically safe sources with high peak and average lasing powers and a laser beam divergence close to the diffraction limit in the spectral range $\lambda = 2.6 - 4.2$ μm, which is important for applications. Such sources are of undoubted interest not only for atmospheric monitoring but also for a number of physical experiments on interaction of IR radiation with fluids and gases [15 – 17], and for optical pumping of IR gas lasers of other types [18].

Until 1995 the output energy of SSVD-initiated non-chain lasers hardly exceeded 10 J. Most researchers explained this low value by the difficulties of implementing SSVD in gas mixtures based on SF_6, a gas used in non-chain HF(DF) lasers as a donor of atomic fluorine. At the same time, to efficiently use such lasers, for example, in lidars, laser pulse energy must be increased at least to several tens of joules [2]. In particular, the energy of a chain DF laser in a lidar for measuring aerosol concentrations at distances up to 15 km should be 100 J [19].

The finding of the effect of self-initiated volume discharge in highly electronegative gases [3, 4] made it possible to increase the energy of pulsed non-chain lasers by more than an order of magnitude. Energies of 400 and 320 J at electric efficiencies of 4.3 % and 3.4 % were obtained for HF and DF lasers, respectively [5], and a possibility of further scaling of pulsed non-chain lasers was demonstrated.

The success in the development and design of repetitively pulsed non-chain electric-discharge HF(DF) lasers with a high pulse energy was less significant. Apparently, this is related to a number of technical problems of switching high energies in the frequency regime and to the difficulty of rapidly changing the operating mixture in discharge gaps of large size when the gas channel contains HF(DF) absorption filters [20]. In [7] the HF laser energy was 20 J at a pulse repetition rate of 12 Hz. An SSVD was initiated by a distributed barrier discharge below a planar grid electrode. The second-electrode surface had a profile providing a homogeneous electric field in the discharge gap. An energy of 16 J at a pulse repetition rate up to 100 Hz was obtained for an HF laser in [8], where a cathode made of anisotropic resistive material was used to stabilise SSVD. A DF laser with an energy of 40 J and a pulse repetition rate of 10 Hz, consisting of three identical discharge units, was reported in [2]. An SSVD in units was ignited using a sectioned pump source with common synchronisation. The electrodes in the units were sets of blades, which, as was believed in [1], improved the SSVD stability. Thus, special measures were taken to stabilise SSVD in repetitively pulsed HF(DF) lasers with high output characteristics and, correspondingly, high accumulated electric energy: illumination of the discharge gap, use of a homogeneous electric field [7], application of an anisotropic resistive cathode [8], modular design, and use of shaped blade electrodes [1, 2].

The purpose of this study was to analyse the possibility of obtaining a high output power for a non-chain electric-discharge HF laser with continuous metal electrodes, operating in the repetitively pulsed regime, without additional measures for SSVD stabilisation.

2. Experimental setup

The laser discharge gap was formed by two identical duraluminum planar electrodes, curved along the perimeter ($r = 2$ cm). The flat portion of the electrode surface was 15×100 cm in size. The interelectrode distance d could be varied in the range of 10 – 20 cm, but experiments were performed at $d = 15$ cm. The cathode was sandblasted to form small (~ 50 μm) microasperities on its surface, which,

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as was shown in [4], facilitate the development of self-initiated volume discharge. The electrodes were placed in a glass–epoxy tube 250 cm long, with an inner diameter of 80 cm, symmetrically with respect to its axis. The lasing media were $SF_6:C_2H_6 = 20:1$, $SF_6:C_3H_8(C_4H_{10}) = 30:1$, and $SF_6:H_2 = 9:1$ mixtures with a total pressure of 45–75 Torr. The working medium in the discharge volume was changed via gas circulation in a closed contour using a special ventilation unit, similar to that described in [8]. The gas mixture was blown out along the discharge chamber axis; the flow velocity in the discharge region was 40 m s^{-1}.

The laser resonator was formed by a copper mirror with a radius of curvature $R = 20$ m and a plane-parallel KCl plate. The mirror was installed in the adjusting unit, connected by a bellows with the discharge chamber. The plane-parallel plate was mounted directly on the discharge chamber end face. The lasing power was measured (in the single-pulse regime) by an array (18 × 18 cm in size) of E-60 calorimeters, installed in the direct laser beam at a distance of 1 m from the output window of the discharge chamber.

The pulsed high-voltage generator, used to initiate SSVD, consisted of four identical sections, connected in parallel to the discharge gap electrodes by copper busbar wires. The sections were placed in a metal housing, filled with SF_6 at atmospheric pressure. The electric circuit of a high-voltage generator section is shown in Fig. 1. The generator was designed according to the Fitch circuit, based on low-inductive KMK-100-50 capacitors having a capacitance $C = 50$ nF and a nominal voltage of 100 kV. Controlled dischargers (CDs) [21] were filled with an $SF_6:N_2 = 1:10$ mixture, with an excess pressure up to 6 atm. The dischargers were designed so as to implement laser operation for 60 s at a discharge pulse repetition rate of 20 Hz without replacing gas in them. The charging voltage U_{ch} was varied in the range of 50–75 kV in the experiments. The experimentally chosen inductance L_1 served to match the circuit of voltage reversal on the capacitor C with the discharge circuit. A resistive divider was used to control the pulsed voltage across the discharge gap. A segment (~ 1 m long) of the conducting wire passed through the Rogowski loop (RL). At a large width of conducting wire (~ 1 m) this monitoring technique does not make it possible to exactly measure the discharge current; however, it enables one to determine the time corresponding to current maximum. The synchronising system provides simultaneous (with an error of ±10 ns) triggering of eight dischargers of the high-voltage generator.

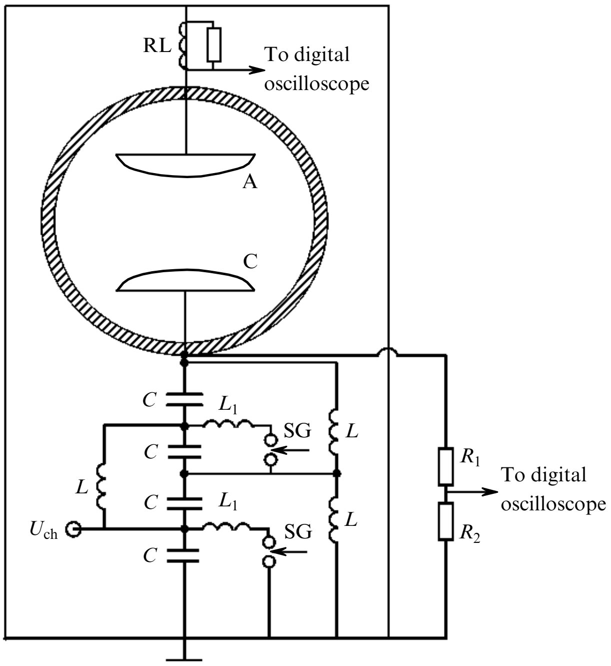

Figure 1. Electric circuit of one of the four sections in the high-voltage generator: (RL) Rogowski loop, (A) anode, (C) cathode, (SG) spark gapr, (L, L_1) inductances, (C) capacitor, and (R_1, R_2) resistors of the high-voltage divider; U_{ch} is the charging voltage.

3. Experimental results and discussion

After matching the voltage reversal circuit in the Fitch generator with the discharge circuit a stable SSVD in SF_6–hydrocarbon mixtures was obtained in the entire range of charging voltage variation ($U_{ch} = 50 - 75$ kV) at a discharge pulse repetition rate up to 20 Hz. The possibilities of further increasing the pulse repetition rate were limited by the rate of working gas circulation in the discharge gap. Figure 2 shows a photograph of SSVD in a $SF_6 - C_2H_6$ mixture at the maximum charging voltage, $U_{ch} = 75$ kV, which demonstrates homogeneity of the self-induced volume discharge at a high edge amplification of electric field, which is characteristic of the discharge gaps used here. Figure 3 presents the coordinate distribution of discharge plasma emission intensity in a plane parallel to the electrode surface; it was obtained by processing the photograph in Fig. 2. This distribution qualitatively corresponds to that of the deposited electric energy over the discharge gap. It can be seen in Fig. 3 that, despite the edge amplification of electric field, the energy supply is maximum at the center of the gap. This is also evidenced by the distribution of cathode spot density over the cathode surface (Fig. 2).

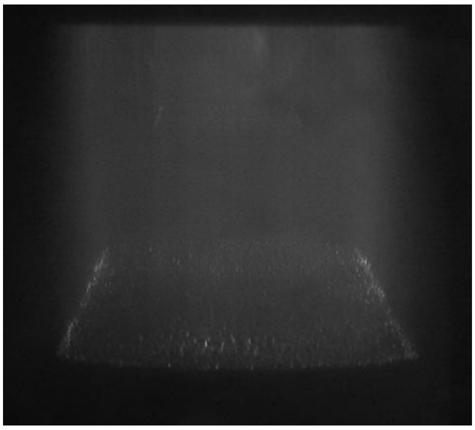

Figure 2. Photograph of SSVD in an $SF_6 - C_2H_6$ mixture with $U_{ch} = 75$ kV.

Figure 4 shows typical oscillograms of voltage across the discharge gap and the discharge current at SSVD ignition in an $SF_6 - C_2H_6$ mixture. Despite the significant distortion of the real shape of voltage pulse by the inductive component (for technical reasons the divider was connected to the discharge gap through segments of conducting wires) and the distortion of the pulse current shape (caused by the same

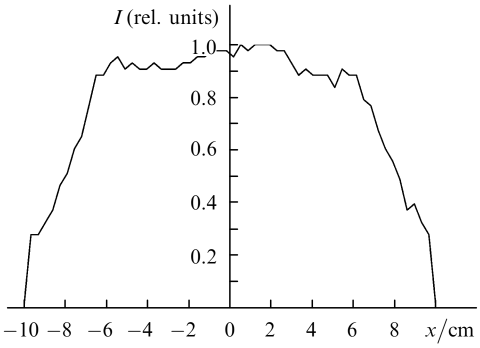

Figure 3. Coordinate distribution of emission intensity I from discharge plasma in a plane parallel to the electrode surface.

factor), these oscillograms make it possible to estimate with a sufficient accuracy the discharge current duration: $\tau \approx$ 320 ns. At this relatively long time of electric energy supply into the discharge plasma in SF_6 – hydrogen mixtures SSVD was stable only at $U_{ch} \leqslant 60$ kV. At the same time, in SF_6 – hydrocarbon mixtures, as follows from the above-mentioned experimental data, SSVD was implemented in the entire range of U_{ch} variation, without any additional measures to stabilise it both in the pulsed and repetitively pulsed regimes.

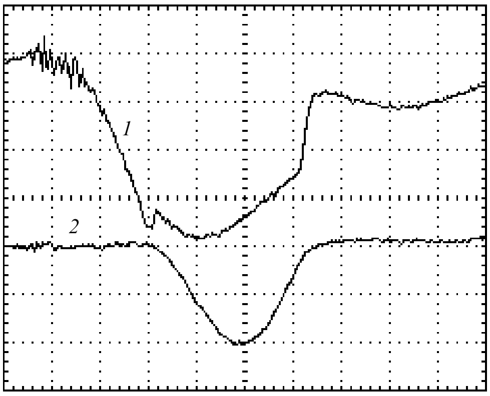

Figure 4. Typical oscillograms of SSVD voltage (*1*) and current (*2*) (scan 100 ns div.$^{-1}$).

The dependences of the HF laser energy W_g on U_{ch} for mixtures with different hydrocarbons are shown in Fig. 5. When measuring these dependences, the mixture pressure was varied in correspondence with the change in the charging voltage to match the plasma load resistance with the discharge circuit wave resistance. One can see that the lasing energy is maximum ($W_g = 67$ J) for the $SF_6 - C_2H_6$ mixture and $U_{ch} = 75$ kV; under these conditions, the electric efficiency (with respect to the energy accumulated in capacitors) is $\sim 3\,\%$. The low efficiency of the laser on SF_6 – hydrogen mixtures is apparently due to the inhomogeneity of volume energy contribution (related to the long duration of discharge current pulse). Note also that the efficiency obtained in this study is below that reported in [5], with similar characteristics of the discharge gap and identical mixture compositions. Apparently, this difference can be attributed to the large electric energy loss in Fitch circuits. In the repetitively pulsed regime the lasing energy per pulse was independent of pulse repetition rate up to 20 Hz, because the ventilation unit at least twice changed working mixture between pulses. This was confirmed by the measurements of the total energy of a train of lasing pulses at short-term (1 s) switchings on of the system. The lasing pulse had a shape typical of non-chain electric-discharge HF lasers (see [15, 16, 22] and references therein), its FWHM was ~ 150 ns, and lasing began at a current close to maximum.

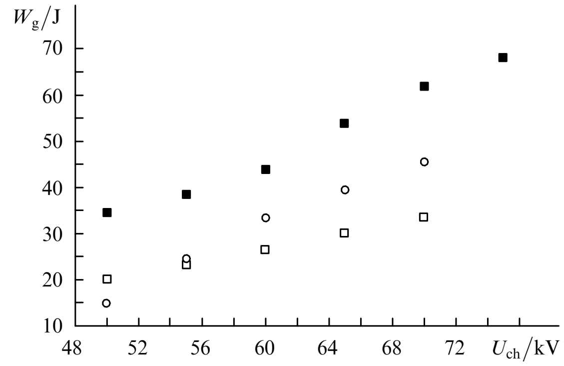

Figure 5. Dependences of the HF laser energy W_g on U_{ch} for mixtures of SF_6 with different hydrogen-containing molecules: (■) $SF_6 : C_2H_6 = 20:1$, (○) $SF_6 : C_3H_8 = 30:1$, and (□) $SF_6 : H_2 = 10:1$.

4. Conclusions

A high-power non-chain electric-discharge repetitively pulsed HF laser was developed and investigated. It was shown that SSVD can be implemented in SF_6 – hydrocarbon mixtures in a discharge gap with a high edge amplification of electric field without additional measures to stabilise discharge in both pulsed and repetitively pulsed regimes. The lasing energy $W_g = 67$ J at a pulse repetition rate of 20 Hz was obtained. To design a DF laser, C_6D_{12} molecules can be used as deuterium donors. The SSVD stability in mixtures of SF_6 with carbon deuterides is known to be no worse than in mixtures with hydrocarbons, and the lasing energy of DF laser (at the same energy contributions to the discharge plasma) is ~ 0.8 of the HF laser energy [22].

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