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High-power pulse repetitive HF(DF) laser with a solid-state pump generator

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Abstract. **Operation of a repetitively pulsed electric-discharge HF(DF) laser with an all-solid-state pump generator based on FID switches is demonstrated. The energy stored in the pump generator capacitors was 880 J at an open-circuit voltage of 240 kV and a discharge pulse repetition rate of 25 Hz. The specific energy extractions were 3.8 and 3.4 J L^{-1} for the HF and DF lasers, respectively. The possibilities of improving the output laser characteristics are discussed.**

Keywords: *repetitively pulsed laser, electric-discharge HF(DF) laser, solid-state switches, FID switches.*

1. Introduction

In recent years, much attention has been paid to the development and investigation of electric-discharge HF(DF) lasers [1 – 18]. Interest in these systems is explained by a wide range of their possible applications, in particular, as high-power radiation sources in lidars for atmospheric monitoring [2, 13, 19]. Electric-discharge HF(DF) lasers are ecologically safe sources with high peak and average powers and a beam divergence close to the diffraction limit in the practically important spectral range $\lambda = 2.6 - 4.2$ μm. These lasers are of undoubted interest not only for atmospheric monitoring but also for studying the interaction of IR radiation with liquids and gases [20 – 24], as well as for optical pumping of solid-state [25 – 29] and gas [30] IR lasers.

To date, the maximum energies of pulsed electric-discharge HF (400 J) and DF (320 J) lasers were achieved in [18]. In recent years, considerable progress has also been achieved in the development of repetitively pulsed electric-discharge HF(DF) lasers with a high energy in a single pulse. The authors of [6] achieved a HF laser pulse energy of 20 J at a pulse repletion rate of 12 Hz. The volume self-sustained discharge (VSD) in the working medium of the laser was initiated by the radiation of a distributed barrier discharge. In [7], a HF laser pulse energy was 16 J at a pulse repetition rate up to 100 Hz. The VSD was stabilised using a cathode based on an anisotropically resistive material. The authors of [2] created a DF laser with a pulse energy of 40 J and a pulse repetition rate of 10 Hz. The laser electrodes were made as a set of blades connected in series to inductors in order to increase the VSD stability [1]. In [15], the energy of a HF laser pulse was as high as 67 J at a pulse repetition rate of 20 Hz. The VSD was ignited in the gap between solid metal electrodes without additional measures for its stabilisation.

The possibilities of increasing the laser parameters of repetitively pulsed HF(DF) lasers (as well as of other gas-discharge lasers) are limited by some technical problems of switching high energies in repetitively pulsed regimes and by problems of achieving a needed gas flow rate in large discharge gaps in the presence of filters absorbing HF(DF) in the gas channel [31]. As a rule, in pump generators [2, 6, 7, 15, 18] one uses gas-discharge switches (mainly spark gaps). The insufficient service life of these switches is one of the main factors restricting the development of electric-discharge lasers and narrowing the field of their application even in the case of using advanced spark gaps [32] and thyratrons with an unheated cathode [33]. Therefore, it seems important to search for alternative commutation methods, preferably based on solid-state switches, which ensure longer service life of generators.

To form pump pulses for repetitively pulsed gas lasers in the case of switched electric energy up to several tens of joules and an output generator voltage up to 100 kV, one successfully uses relatively low-voltage solid-state switches in combination with step-up transformers [34], bipolar transistors with an isolated shutter [35] and thyratrons [36]. A high-voltage pulse produced after turning on the switch is usually shortened by magnetic compression systems in order to achieve the parameters required for VSD ignition [34, 36]. There are also schemes of high-voltage pulse formation with simultaneous use of a gas-discharge switch and a semiconductor current breaker (SOS diodes) in an inductive storage [37]. It is obvious that the possibilities of using these methods to produce kilojoule pulses with a voltage exceeding 100 kV and a current up to hundreds of kiloamperes, which is needed for pumping repetitively pulsed HF(DF) lasers with a high output pulse energy, are limited.

The creation of a high-power pulsed HF laser with an all-solid-state pump generator based on FID switches [38] was reported for the first time in [17]. The electric energy stored in the generator capacitors reached approximately 1 kJ at the open-circuit voltage of 240 kV. The aim of the present work is

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to study a high-power repetitively pulsed HF(DF) laser with an all-solid-state pump generator.

2. Experimental setup

The principal scheme of the experimental setup is shown in Fig. 1. The VSD was ignited between two identical duralumin electrodes with the interelectrode gap of 13 cm. No special measures were taken to initiate or stabilise the discharge. The laser cavity was formed by a plane Al mirror and a plane-parallel CaF_2 plate. The radiation energy was measured by a Coherent J-50 MB-HE pyroelectric sensor. The pulse profile was controlled by a photodetector from Vigo System Ltd. with a time resolution of about 1 ns. The working media were the SF_6-H_2 and SF_6-D_2 gas mixtures with the pressure $p = 0.07-0.1$ atm. The gas mixture was pumped through the discharge region with a ventilation unit. The HF(DF) exhaust molecules were absorbed by cassette filters placed in the gas-dynamic channel.

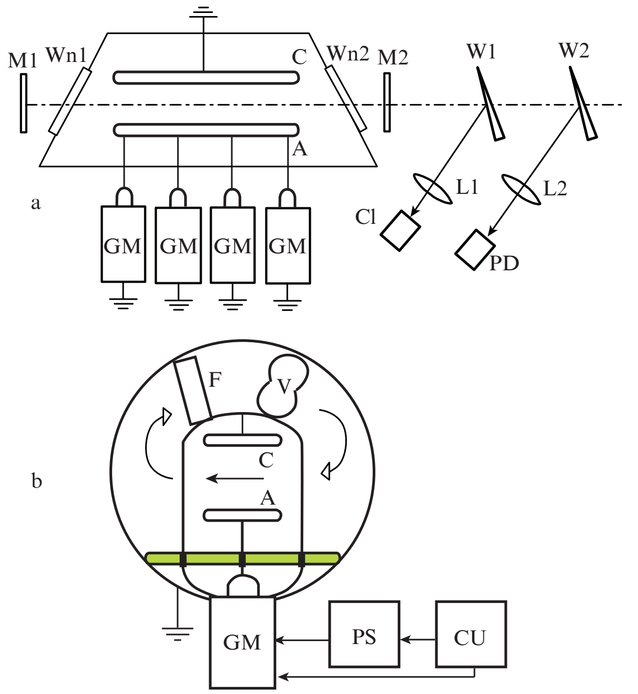

Figure 1. Optical scheme of the experimental setup (a) and scheme of connection of the generator module (GM) to electrodes (b): (M1, M2) cavity mirrors; (Wn1, Wn2) antireflection-coated CaF_2 windows; (W1, W2) CaF_2 wedges; (L1, L2) lenses; (Cl) calorimeter; (PD) photodetector; (C) cathode; (A) anode; (F) filter; (V) ventilation unit; (PS) primary power source; (CU) control unit.

The pump generator (Fig. 1) developed and fabricated at the FID-Technology Research and Production Association (St. Petersburg) consisted of three main units, namely, primary power source AC ⇒ DC with an average power of 25 kW, a control unit and a pulsed high-voltage pump generator, which, in turn, consisted of four generator modules (GMs) connected parallel to the gas-discharge electrodes as shown in Fig. 1a. Figure 1b shows the connection scheme of an individual GM. The module was connected via high-voltage contacts in the dielectric lid of the discharge chamber. The cathode inside the chamber was connected by copper bars so that their inductance was minimal and they were transparent to the gas flow.

The GMs were designed according to the Arkad'ev–Marks 54-cascade generator circuit (the generator used in [17] had 80 cascades) based on solid-state FID switches with the switching time no longer than 1 ns [38]. The temporal instability of the GM switching with respect to the external triggering did not exceed 0.2 ns for the GM output voltage from 100 to 240 kV. The GM was triggered by a voltage pulse with an amplitude of 50 V and a duration of 100 ns. The total intrinsic resistance of the FID switches at a working voltage of 240 kV and a current of about 10 kA in one GM did not exceed 1 Ω. The service life of the FID switches in this regime was longer than 10^9 pulses. The generator capacitance on fire of each of four GMs was 7.6 nF. Similar to [17], the GMs were placed in 125 × 35 × 14-cm metal housings filled with transformer oil. However, in laser scheme we did not use peaking capacitors connected in parallel to the discharge gap as was done in [17] to decrease the current pulse duration. A decrease in the number of cascades in the GMs allowed us to decrease the inductance of the discharge circuit so that the stable VSD in the SF_6-H_2 and SF_6-D_2 mixtures was obtained upon direct connection of the pump generator to the electrodes.

The maximum electric energy stored in the pump generator capacitors was 880 J at the maximum output voltage of 240 kV and the maximum allowable current of 80 kA (in the short-circuit regime). The pump generator was designed to operate for a long time at a discharge pulse repetition rate up to 25 Hz.

In the course of the experiments, we controlled the voltage across the discharge gap U and the discharge current I using a calibrated resistive voltage divider and a small-inductive shunt, respectively (not shown in Fig. 1). The shunt was inserted into the ground conductor.

3. Experimental results and discussion

Figure 2 presents the photograph of VSD in the discharge chamber in the regime of single pulses in the SF_6-H_2 mixture at the pressure $p = 0.09$ atm.

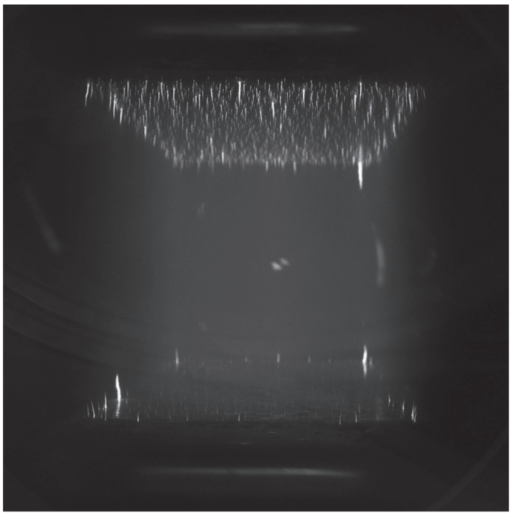

Figure 2. Photograph of the VSD region at the GM open-circuit voltage $U_g = 240$ kV and the SF_6-H_2 mixture pressure $p = 0.09$ atm. The cathode is at the top and the anode is at the bottom.

One can see that the VSD structure is rather homogeneous except for some uncompleted plasma channels no longer than 2 cm. The VSD shape in the repetitively pulsed regime visually does not significantly change from the discharge shown in Fig. 2 because the gas flow rate was high enough for multiple replacement of gas in the discharge region between pulses at their repetition rate of 25 Hz.

Figure 3 shows the oscillograms of the discharge gap voltage U, of the current through the gap I, and of the laser pulse P at the GM open-circuit voltage U_g = 240 V and the SF_6-H_2 mixture pressure $p = 0.09$ atm. The high-frequency oscillations on the voltage and current oscillograms are caused by the presence of parasitic capacitances in the circuit (in the GM itself and mainly in the regions of the GM connection to the high-voltage inlets into the chamber). The parasitic capacitance also broadens the leading edge of the discharge gap voltage, while the shunt records the parasitic capacitance charge current simultaneously with the voltage pulse beginning (at the initial stage, the current oscillogram in Fig. 3 is distorted by electric noise). The durations of the discharge current and the laser pulse at, respectively, 0.1 and 0.5 of the maximum amplitudes are 290 and 180 ns.

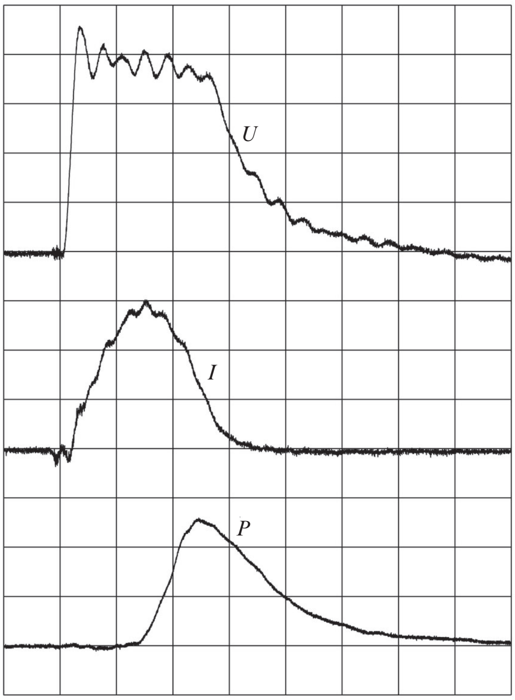

Figure 3. Oscillograms of the discharge gap voltage U, discharge cap current through the gap I, and the laser pulse P at U_g = 240 kV and the SF_6-H_2 mixture pressure p = 0.09 atm. The voltage U is 27 kV div^{-1}, the current I is 15 kA div^{-1}, P is given in arbitrary units, and the sweep is 100 ns div^{-1}.

At U_g = 240 kV, the gas pressure p = 0.09 atm, and the optimum concentration of the components [17], the specific energy extraction was 3.8 J L^{-1} for the HF laser and 3.4 J L^{-1} for the DF laser.

In this set of experiments, the setup did not include a system of compensation of the decrease in the initial mixture components dissociating in the volume discharge plasma. Therefore, in the case of $SF_6-H_2(D_2)$ mixtures with the optimal (with respect to the laser energy) concentration ratio of the components [17] and the pulse repetition rate of 25 Hz, the laser operated only by short (10 s) cycles because the laser energy rapidly decreased with increasing number of pulses due to increasing concentration ratio of SF_6 to $H_2(D_2)$ and to the corresponding deviation of this ratio from optimal. The laser operation with a duration up to 90 s was possible in the case of mixtures with an increased concentration of $H_2(D_2)$. This case is illustrated in Fig. 4, which presents the dependences of the output laser energy W on the discharge pulse number N for mixtures with increased concentration of D_2 at a pulse repetition rate of 25 Hz. As is seen from Fig. 4, the laser energy at first increases with increasing N, which is related to the approach of the concentration ratio of the mixture components to the optimal value due to their dissociation. The sharp decrease in the energy at larger N is explained by a mismatch of the pump generator with the plasma load due to a decrease in the VSD burning voltage caused by a decrease in the concentration of SF_6 and simultaneous accumulation of less-electronegative products of its dissociation.

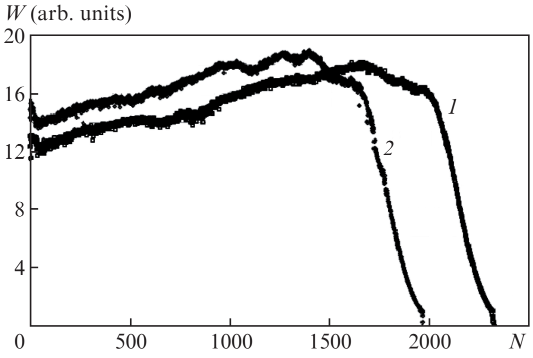

Figure 4. Dependences of the laser energy W on the discharge pulse number N for the mixtures with increased D_2 concentration at a pulse repetition rate of 25 Hz and the gas pressure p = 0.1 atm for (1) $SF_6:D_2$ = 7.5:2.5, U_g = 225 kV and (2) $SF_6:D_2$ = 7:3, U_g = 240 kV.

In conclusion, note that the modular structure of the pump generator allows one to increase the repetitively pulsed laser energy simply by increasing the number of GMs with a corresponding increase in the discharge gap volume.

4. Conclusions

Thus, we have demonstrated for the first time the operation of a high-power repetitively pulsed electric-discharge HF(DF) laser with an all-solid-state pump generator. It also seems promising to use these generators for pumping electric-discharge lasers of other types.

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