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Solid-state laser-pumped high-power electric-discharge HF laser

S.D. Velikanov, S.G. Garanin, A.P. Domazhirov, V.M. Efanov, M.V. Efanov,
S.Yu. Kazantsev, B.E. Kodola, Yu.N. Komarov, I.G. Kononov, S.V. Podlesnykh,
A.A. Sivachev, K.N. Firsov, V.V. Shchurov, P.M. Yarin

***Abstract*. We report the possibility of creating high-power nonchain electric-discharge HF lasers with an all-solid-state pump source. The maximum energy stored in the pump source capacitors based on solid-state FID-switches is 990 J for the open-circuit voltage of 240 kV. The pulse energy of 30 J is obtained in the hydrogen-containing SF_6 mixture at the electric efficiency of the order of 3%.**

Keywords: *nonchain HF laser, solid-state switches, FID-switches, volume self-sustained discharge.*

At present, a volume self-sustained discharge (VSD) is widely used to excite the active media of pulsed and repetitively pulsed gas lasers [1 – 3]. The time during which the discharge exists in the form of a VSD is extremely limited due to the development of plasma instabilities [3, 4]. Therefore, to obtain a maximally uniform VSD and to achieve the optimal conditions for exciting the medium, it is necessary to fulfil stringent requirements to the parameters of a high-voltage pulse produced by the laser pump generator. These requirements include the leading edge duration and the voltage amplitude as well as the amplitude and the limiting duration of the discharge current. An important parameter determining the possible applications of repetitively pulsed lasers is the service life of the pump generator components. The limiting current pulse duration given by the time of the plasma instability development [2, 4] depends on the working mixture composition, specific energy input into the discharge plasma and the measures taken to suppress the plasma instability. However, even in nonchain HF(DF) lasers, where the VSD is realised rather simply [5] (compared, for example, to excimer lasers [6]), the current pulse duration should not exceed several hundreds of nanoseconds [7]. The possibilities to achieve so small durations of the electric energy input to the gas-discharge plasma at large discharge voltages and currents are mainly determined by the parameters of switches used in pump generators. The problem of the switches, including their service life, is one of the main factors restricting the development of high-power electric-discharge lasers and limiting the scope of their applications. For the switching electric energy of up to several tens of joules and the pulsed voltage of up to 100 kV at the generator output, pump pulses in repetitively pulsed lasers are successfully produced by relatively low-voltage solid-state switches in combination with step-up transformers [6], bipolar transistors with an isolated shutter [8] and thyratrons [9]. The high-voltage pulse produced after turning on the switch is usually shortened by the magnetic compression systems in order to achieve the VSD parameters required for ignition [6, 8]. For obvious reasons requiring no commentaries, these methods are unsuitable if, for pumping a laser, it is necessary to produce a pulse with the electric energy of several kilojoules, the voltage of hundreds of kilovolts and the current of hundreds of kiloamperes as, for example, during the initiation of the chemical reaction in high-power electric-discharge HF(DF) lasers [5, 7, 10, 11]. In such laser systems, switching is performed by gas-filled spark gaps [10, 11], which, while passing to the frequency operation regime, is accompanied by a number of problems related to the insufficient service life of switches even when the most advanced spark gaps [12] and non-filament thyratrons [13] are used. Therefore, the search for new switching principles is quite urgent, preferably on the basis of solid-state switches in order to produce reliable pump generators for high-power electric-discharge lasers.

In this paper we present the first results of investigations on the possibility of fabricating a high-power nonchain electric-discharge HF laser with a pump generator based on solid-state FID-switches [14].

The schematic of the experimental setup is presented in Fig. 1. The VSD was ignited between two identical duralumin electrodes whose working surface profile was calculated in accordance with Stappaerts' recommendations [15]. The cathode surface was sandblasted to deposit small-scale inhomogeneities, which facilitate the VSD development in the form of a self-induced volume discharge [16]. The dimensions of the discharge gap measured 10 × 11× 80 cm (electrodes were spaced by 10 cm). Note that in the

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S.D. Velikanov, S.G. Garanin, A.P. Domazhirov, B.E. Kodola, Yu.N. Komarov, A.A. Sivachev, V.V. Shchurov Research Institute of Laser Physics, Federal State Unitary Enterprise 'Russian Federal Nuclear Center – The All-Russian Research Institute of Experimental Physics', prosp. Mira 37, 607190 Sarov, Nizhnii Novgorod region, Russia;
e-mail: velikanov@otd13.vniief.ru, adom@pisem.net, hvadim45@mail.ru;
V.M. Efanov, M.V. Efanov, P.M. Yarin 'FID Technology' Research and Production Association, ul. Gzhatskaya 27, 195220 St. Petersburg, Russia; e-mail: vlad@fidtech.com, mike@fidtech.com;
S.Yu. Kazantsev, I.G. Kononov, S.V. Podlesnykh, K.N. Firsov A.M. Prokhorov General Physics Institute, Russian Academy of Sciences, ul. Vavilova 38, 119991 Moscow, Russia;
e-mail: kazan@kapella.gpi.ru, k_firsov@rambler.ru

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setup being described, any sources initiating the VSD are absent. An increase in the generation energy of compact HF lasers with a small discharge current duration (less than 150 ns) [17, 18] observed under UV or X-ray illumination of the gap is caused, as shown in [19], by stabilisation of the delay time and the amplitude of the electric breakdown voltage of the gap as well as by equalization of the current density distribution over the cathode surface due to the photoeffect on the cathode. At large discharge gaps and, hence, rather large discharge current durations there is no need in initiating the VSP in SF_6-based gas mixtures, in particular, in working media of HF lasers. Under such conditions the VSD develops in the form of a self-initiated volume discharge, including in the gaps with high electric field edge enhancement in the presence of small-scale inhomogeneities on the cathode surface [5, 7, 16, 20]. The electrodes were placed in the middle of a cylindrical dielectric chamber 120 cm in length and 50 cm in internal diameter. The laser resonator was formed by an aluminium mirror with a curvature radius $R = 20$ m and plane-parallel BaF_2 plate mounted directly on the end faces of the discharge chamber. The laser energy was measured with an E-60 calorimeter matrix mounted in the direct laser beam. The laser pulse shape was controlled with a PD3-10.6 photodetector. The working mixtures were $SF_6{:}C_2H_6 = 20{:}1$ and $SF_6{:}H_2 = 9{:}1$ gas mixtures.

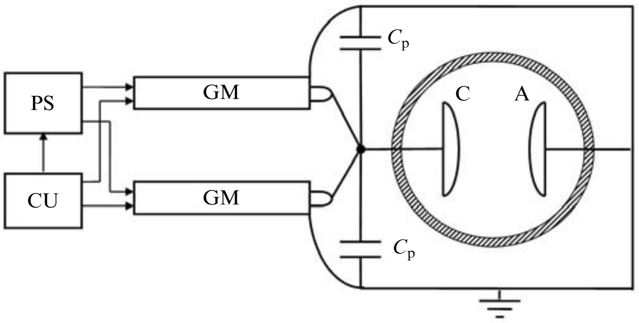

Figure 1. Scheme of the experimental setup: (A) anode; (C) cathode; (PS) power source; (CU) control unit; (GM) generator module; (C_p) 7.5-nF peaking capacitor.

The pump generator developed and fabricated at the FID-Technology Research and Production Association (St. Petersburg) consists of three main units: primary power source with the average power of 25 kW, control unit, and a pulse high-voltage pump generator, which in turn comprises four generator modules connected parallel to the discharge gap electrodes (see Fig. 1; for simplicity only two modules are shown).

The generator modules were designed in accordance with the Arkad'ev – Marks generator circuit based on non-inductive polypropylene capacitors (with the specific density of stored energy of up to 0.1 J cm^{-3}) and solid-state FID-switches with the switching time of no more than 1 ns [14]. The temporal instability of the generator-module switching with respect to the external triggering does not exceed 0.2 ns and does not change with changing the generator module output voltage from 100 to 240 kV. The generator module was triggered by a positive polarity voltage pulse with the amplitude of 50 V and duration of 100 ns. The total intrinsic resistance of the FID-switches at the working voltage of 240 kV and current of $\sim$ 10 kA in one generator module was no more than 1 Ω. The service life of FID-switches in this regime exceeds 10^9 pulses. Each generator module has its own impedance of $\sim$ 11 Ω for the discharge capacity $C_0 = 8.6$ nF. The generator modules were placed in 125 × 35 × 14-cm metal housings filled with the transformer oil.

The maximum electric energy stored in the pump generator capacitors was 990 J for the maximum output voltage of 240 kV and maximum permissible current of 80 kA (in the short-circuit regime). The pump generator was designed to have long service life at a pulse repetition rate of 25 Hz. The present run of the experiments was performed in the single pulse regime because the discharge chamber used here did not allow one to change rapidly the working mixture in the discharge gap.

In the course of the experiments the voltage across the discharge gap and the discharge current were controlled with the help of a resistive voltage divider and small-inductive shunts, respectively (not shown in Fig. 1). The shunts were embedded into the ground conductor lines. To decrease the discharge current duration the system allows installation of 7.5-nF small-inductive peaking capacitors C_p connected in parallel to the discharge gap. The total capacitance of the peaking capacitors was 30 nF.

Figure 2a presents the VSD voltage and current oscillograms in the $SF_6 - C_2H_6$ mixture at the total pressure of 85 Torr and output voltage of 240 kV, which were recorded in the case of direct connection of the generator modules to the discharge gap (the peaking capacitors were not connected). One can see that in this regime the discharge current duration exceeds 400 ns due to the large inductance of the discharge contour (about of 900 nH together with the intrinsic inductance of the generator modules). At these current durations, the discharge in the hydrogen-containing mixture is unstable. According to calculations based on the voltage and current oscillograms, the energydeposited in the VSD plasma is $\sim 70\,\%$ of that stored in the generator module capacitors. Taking into account the low intrinsic resistance of the FID-switches, we can assume that the main energy losses in the discharge gap are caused by the insufficient Q factor of the capacitors used in the experiments.

Connection of the peaking capacitors to the discharge gap allowed us to obtain the VSD in the $SF_6 - H_2$ mixture in the entire range of variations in the generator module voltages, up to the maximum value of 240 kV. Figure 2b shows the typical voltage oscillogram across the discharge gap and the discharge current oscillogram recorded in the scheme with peaking capacitors. One can see that compared to the scheme with the direct connection of the generator modules to the discharge gap, the current duration decreased approximately twofold. Figure 3 presents, as an illustration of the pump uniformity, the VSD photograph in the $SF_6 - H_2$ mixture for the 240-kV voltage of the generator modules in the scheme with peaking capacitors.

The maximum lasing energy was 30 J with the technical efficiency of $\sim 3\,\%$ in the $SF_6 - H_2$ mixture and 28 J with the efficiency of $\sim 2.8\,\%$ in the $SF_6 - C_2H_6$ mixture. The laser pulse had a bell-like shape typical of nonchain HF lasers, the FWHM pulse duration being 140 ns. Note that in present experiments the $SF_6 - H_2$ laser efficiency proved higher than that in the laser operating in the $SF_6 - C_2H_6$ mixture. A similar situation is usually observed at low

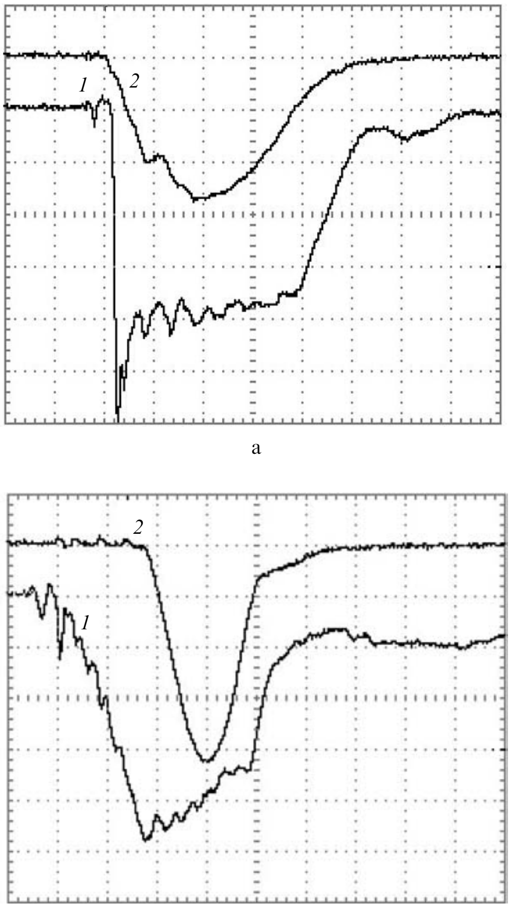

Figure 2. Oscillograms of the VSD voltage across the discharge gap (*1*) and of the VSD current (*2*) for the 240-kV output voltage of the generator in the case of direct connection of the generator to the discharge gap: the $SF_6:C_2H_6 = 20:1$ mixture at a pressure of 85 Torr (a) and the scheme with peaking capacitors with the $SF_6:H_2 = 9:1$ mixture at a pressure of 88 Torr (b). The voltage is 24.6 kV div.$^{-1}$, the current is 8.4 kA div.$^{-1}$, the sweep is 100 ns div.$^{-1}$.

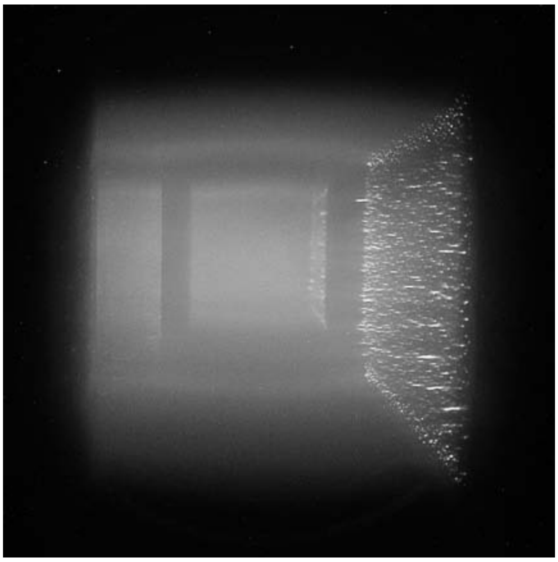

Figure 3. The VSD photograph in the $SF_6:H_2 = 9:1$ mixture at a pressure of 88 Torr and output voltage of 240 kV.

specific inputs of the electric energy into the discharge plasma and short current pulses (see, for example, [17, 21]); in our experiments the specific energy deposition also did not exceed 90 J L^{-1} for the $\sim$ 250-ns current pulse duration in the hydrogen-containing SF_6 mixture. Under these conditions the VSD in hydrogen containing mixtures is stable. In this case, as was found in [21], the efficiency of the atomic fluorine production in them is higher than in ethane-containing SF_6 mixtures. At large energy inputs and current pulse durations, the VSD in hydrogen-containing mixtures becomes unstable and the efficiency naturally decreases compared to the efficiency of the laser operating in the hydrocarbon-containing SF_6 mixtures [5, 7, 21], where the VSD stability margin with respect to the energy input and current pulse duration is significantly larger [7, 20].

Thus we have demonstrated the operability of a high-power pulsed nonchain HF laser with an all-solid-state pump generator based on FID-switches. The obtained results allow one to rely on the ability of this generator to be used in the repetitively pulsed laser, which will be the subject of future research. Note in conclusion that the pump generators can be used not only in HF lasers but also in many gas-discharge lasers operating in other active media [6, 8, 9].

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