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A repetitively pulsed HF laser with a large discharge gap operating on the $F_2 - H_2$ mixture

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***Abstract*. An efficient repetitively pulsed (RP) HF laser pumped by a barrier electric discharge with a 10-cm discharge gap is developed. A specific output energy $E/V = 3$ and 23 J L^{-1} and a technical efficiency η equal to 3.4 % and 26 %, respectively, were obtained in the single-pulse regime for non-chain and chain processes. An average output power of 43 W ($E/V \sim 10$ J L^{-1} and $\eta = 11.3$ %) was obtained in the RP mode of the laser with a pulse repetition rate of 10 Hz for a depleted fluorine – hydrogen mixture (20 % F_2, 5 % H_2). Numerical simulation of laser operation under the conditions corresponding to the RP regime for an active medium length of about 0.5 m showed that a specific output energy of 15 J L^{-1} and a technical efficiency right up to 20 % can be attained in a single pulse. A specific output energy $\sim$14 J L^{-1} attained under such conditions in the single-pulse mode for an active medium length of 0.37 m is found to be in good agreement with the theoretical values.**

Keywords: *pulsed HF laser, nonchain and chain reactions, barrier discharge, specific output energy.*

1. Introduction

A repetitively pulsed (RP) regime of laser operation broadens the possibilities of its application for various scientific and technical purposes (e.g., for processing of materials, in medicine, for controlling atmospheric pollution, and for developing a laser rocket engine) compared to the single-pulse and cw regimes. The development of a chemical chain-reaction laser (operating on a chemical chain reaction) with a large discharge gap and a high efficiency in the RP regime is a topical problem. The use of the chemical chain reaction $\{F - H_2 \rightarrow HF(\upsilon) - H,\ H - F_2 \rightarrow HF(\upsilon) - F\}$ in an electric discharge laser leads to an eightfold increase in the specific output parameters as compared to nonchain-reaction process [1].

The high specific output parameters of an HF/DF pulsed chemical laser (PCL) are attained due to a high ($\sim$130 kcal mole^{-1}) energy yield of the $F_2 - H_2$ (D_2) chemical reaction ensuring pumping rotation – vibration levels of the emitting molecules right up to levels with $\upsilon = 6$ (8). Recharging of the waste mixture in the RP regime is carried out by organising a directional gas flow. The energy liberation in the active volume and gas path leads to the emergence of periodic pressure and temperature peaks so that shock waves, acoustic perturbations and the combustion front propagate upstream and downstream. These effects create a number of problems affecting the stability of operation of a repetitively pulsed chemical laser (RPCL). It was assumed earlier that the addition of heavy gaseous diluents SF_6, CF_4 and CO_2 to the hydrogen-fluorine mixture must lower the combustion rate as well as the peak values of the temperature and pressure after the initiation of emission. An analysis of the combustion rate revealed that the replacement of monatomic diluent gases (He, Ar) by polyatomic (SF_6, CF_4) gases lowers the combustion rate from detonation (about 2 km s^{-1}) to subsonic velocities (units and tens of m s^{-1}) [2].

Calculations show that the combustion rate is practically independent of pressure and may be equal to 1 – 10 m s^{-1} for mixtures with active components $F_2 - H_2$ (D_2) ensuring a high value of the output parameters of the RPCL (Fig. 1). With this circumstance in view, we proposed a method of

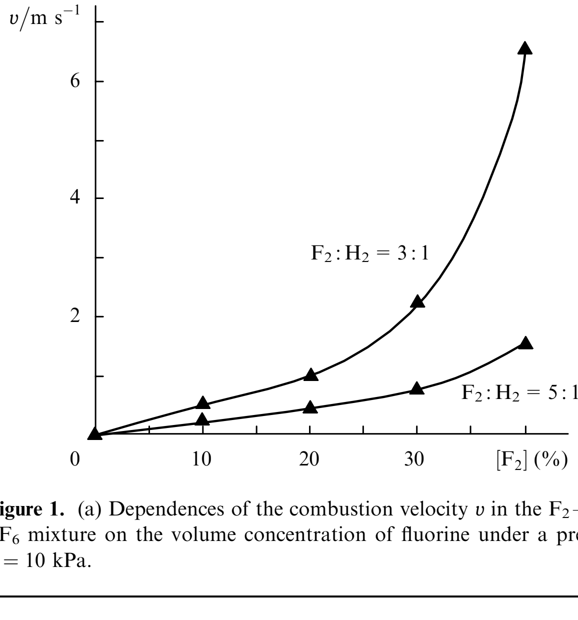

Figure 1. (a) Dependences of the combustion velocity υ in the $F_2 - H_2 - SF_6$ mixture on the volume concentration of fluorine under a pressure $p = 10$ kPa.

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replenishing the working mixture in the active volume of a RPCL by entraining the combustion front by the fresh gas flow at a velocity exceeding that of the combustion front. This method makes it possible to attain a high pulse repetition rate f since, in contrast to the other technique based on an interruption of hydrogen (deuterium) supply, it is independent of the speed of response of valve-type devices [3, 4].

In order to attain the anticipated efficiency, the gas path of the RPCL must have smooth walls and must be free from the protruding elements of the initiating system. Elements like flash lamps, electrodes used for preionisation, and multielectrode board may cause a premature ignition of the mixture and also obstruct the suppression of acoustic perturbations from the active laser volume.

We developed and studied an effective technique for triggering electric-discharge in an HF(DF) RPCL by using stabilising barrier electrodes made of semiconducting ferroelectric ceramics. The electrodes are found to be simple and reliable in operation, do not require any precise adjustment, and ensure a high energy input (up to 100 J L^{-1}) to the homogeneous discharge.

A small-scale barrier-discharge-triggered F_2-H_2 mixture HF RPCL with $f \lesssim 50$ Hz and an active volume of $1.4 \times 3.3 \times 12$ cm (1.4 cm is the size of the discharge gap) was demonstrated in [5]. In this paper, we present the results of investigations of a barrier-electric-discharge HF RPCL with $f = 10$ Hz and a discharge gap extended to 10 cm.

2. Experimental setup

The experimental setup used in this research consisted of the following main systems. The gas system ensured the supply of laser mixture components with preset composition and flow rate to the laser device and created conditions for gas-flow laser operation in chain-reaction and non-chain-reaction mixtures. Preliminary gas mixtures (oxidising mixture $F_2-SF_6-O_2$, gas mixture SF_6-N_2 for spark gaps in the triggering system and for blowing round the windows and electrodes in the discharge chamber) were prepared beforehand in separate containers. The maximum gas flow velocity in the laser channel was 2.5 m s^{-1}, and the flow rate of the main components of the gas mixture was 4 L s^{-1}. A high voltage from the charging unit was supplied to the triggering system. A capacitive pulse generator with voltage quadrupling was used (Fig. 2).

To lower the inductance of the discharge circuit, the pulsed voltage generator (PVG) was prepared from two blocks each of which consisted of two capacitors and one spark gap. The PVG was mounted on both sides of the discharge chamber and functioned as follows.

The storage capacitors are charged from a bipolar source to a voltage of, say, ±45 kV as shown in Fig. 2. After instruction from the triggering device, both spark gaps are triggered simultaneously and voltage pulses with an amplitude ±90 kV relative to the Earth, formed at the electrodes of the discharge chamber, initiate a discharge in the active volume. Using barrier electrodes made of semiconducting ceramic, a homogeneous discharge can be initiated in laser gas mixtures under pressures up to 12 – 13 kPa.

The highest energy content of a PVG formed by four low-conductivity capacitors of capacitance 9.52 nF each was equal to 38.5 J. The charge of the capacitors in the repetitively pulsed regime was monitored with the help of a low-frequency voltage divider. The pulse shape and the discharge current were measured by using shunts and resistive voltage dividers. The energy input in the discharge volume was calculated from the current and voltage oscillograms.

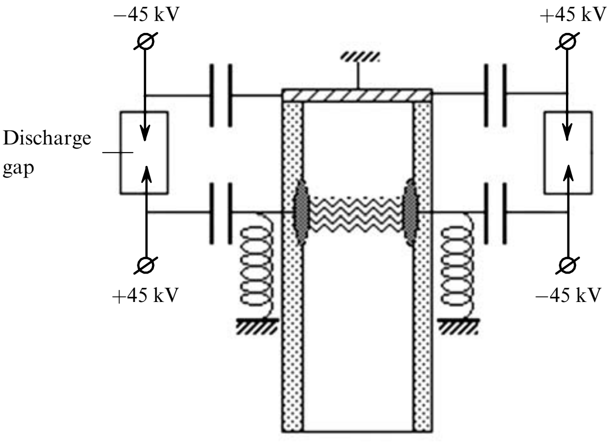

Figure 2. Scheme of a pulsed voltage generator.

The diagnostic system provided the measurement of all the main parameters of laser operation: pressure and temperature, current and voltage pulses of the PVG, energy and time dependences of the laser radiation pulses, and characteristics of the synchronisation system.

The laser device used in our experiments is shown schematically in Fig. 3. The active laser volume is equal to $4.1 \times 10 \times 11$ cm (10 cm is the size of the discharge gap and 11 cm is the length of the medium along the optical axis). The distance between the cavity mirrors (output mirror and totally reflecting mirror with reflection coefficients ~0.30 and ~0.96, respectively) was equal to 0.7 m.

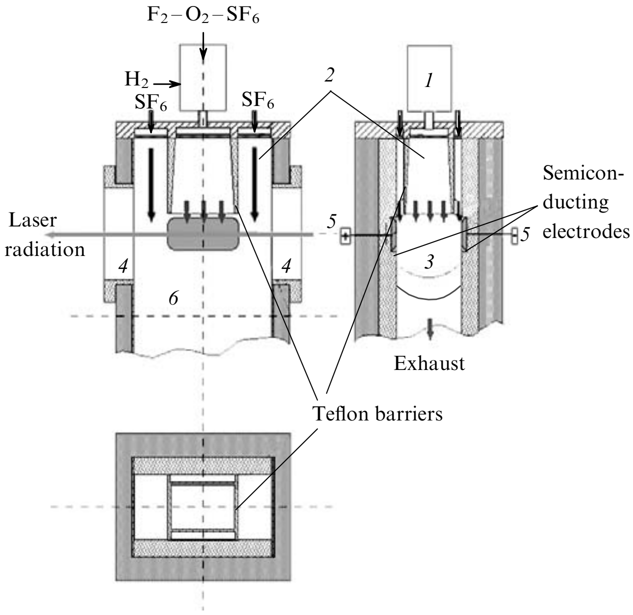

Figure 3. Scheme of a barrier-discharge-initiated laser: (*1*) mixer; (*2*) gas distribution heads with a porous gas distributor; (*3*) discharge chamber with built-in barrier discharge electrode panels; (*4*) fluorite windows for radiation extraction; (*5*) PVG terminals; (*6*) shockwave and acoustic perturbation damper.

The laser windows and the lateral surfaces of barrier electrodes were blown by SF_6 gas.

3. Experimental results

According to calculations presented in [6], the combustion rate strongly depends on the hydrogen concentration in the laser mixture. Thus, in order to determine the mixture composition, we must study the effect of hydrogen on the laser pulse energy E for a fixed concentration of fluorine. Such a dependence was obtained for a fixed concentration of fluorine and a specific energy input $W = 61$ J L^{-1}. One can see from Fig. 4 that for a twofold increase in the hydrogen concentration (from 4 % to 8 %), the energy varies by just 20 % – 30 %. Hence, the gas mixture acceptable for the operation of a RPCL may contain the minimum quantity of hydrogen.

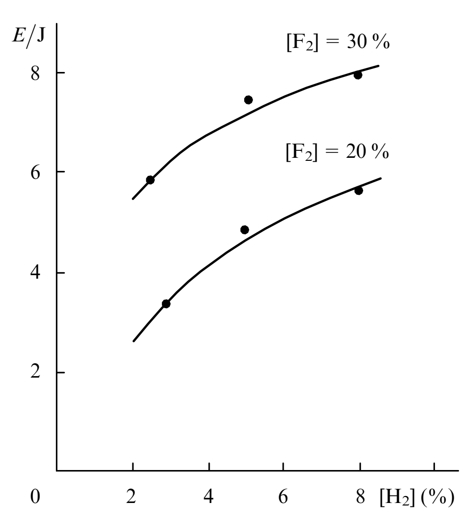

Figure 4. Dependence of the laser pulse energy E on the volume concentration of hydrogen in the gas mixture $F_2-H_2-O_2-SF_6$ for $p = 10$ kPa, $W = 61$ J L^{-1} and $[F_2] = 20$ % and 30 %.

Experiments in the RP regime were first carried out in a nonchain-reaction mixture of composition $SF_6 : H_2 = 9 : 1$ for $f = 10$ Hz. In this case, the average laser power was 13 W. Experiments on chain-reaction mixtures were carried out for a gas flow velocity of about 2.5 m s^{-1}, while the volume concentration of fluorine varied right up to 30 %. The hydrogen concentration was maintained within the interval 4 % – 5 %. One can see from Fig. 5 that the average laser power increases to 43 W for a fluorine concentration of about 20 %, but a further increase in the concentration leads to a sharp decline in the laser power.

A good reproducibility of laser pulses in the series (Fig. 6) and homogeneous prints on photosensitive paper exposed to RPCL radiation were obtained only for fluorine concentrations not exceeding 20 %. It is well known (see Fig. 1) that an increase in the fluorine concentration in the gas mixture leads to a sharp increase in the combustion rate and hence to a number of problems associated with the removal of combustion products from the active laser volume. Under these conditions, the residual HF contained in the active volume may be responsible for a decrease in the average laser power. The simplest way of avoiding this effect is to increase the velocity of the gas flow.

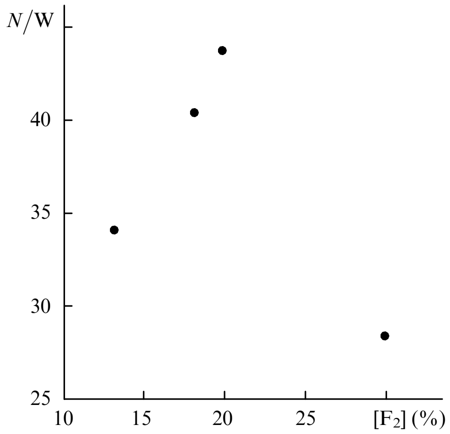

Figure 5. Dependence of the average power N of a RPCL on the volume concentration of fluorine in the gas mixture for $p = 9$ kPa, $[H_2] = 5$ % and $f = 10$ Hz.

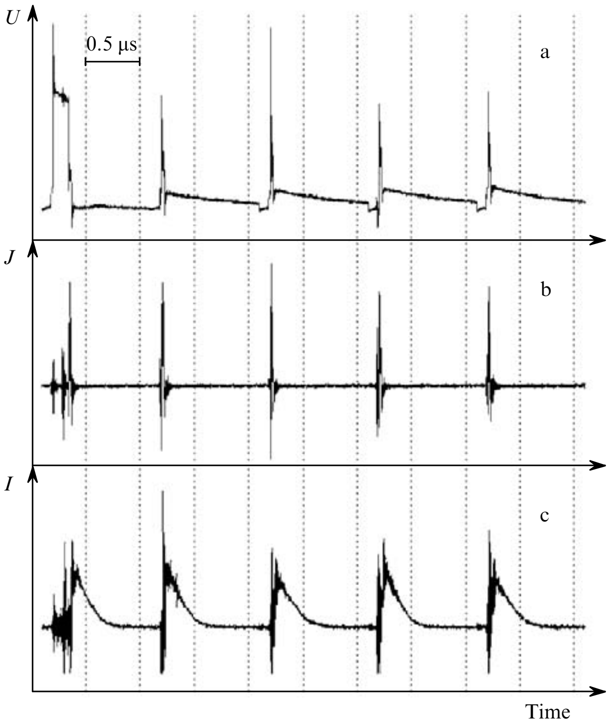

Figure 6. Oscillograms of the discharge voltage U, discharge current J and laser radiation intensity I in a series of five laser pulses (parts of the time scale between pulses are omitted) for the gas mixture $F_2-H_2-O_2-SF_6$ for $p = 10$ kPa, $[F_2] = 18$ %, $[H_2] = 5$ % and $f = 10$ Hz (the value of each division is 0.5 μs).

4. On the possibilities of increasing the laser parameters

The experimental results presented in the previous section were obtained for a comparatively short length of the active medium ($L_{act} = 0.11$ m). Earlier, it was shown that the specific energy output E/V (output radiation energy extracted from a unit volume of the active medium) for a photoinitiated chain-reaction pulsed HF(DF) laser with an active medium pressure of 1.12 atm [7] increases with L_{act} in a certain range. The increase in the lasing efficiency is explained as follows. A decrease in the lasing threshold

K_{th} leads to the involvement of additional rotation–vibration transitions in the process of stimulated emission since the small-signal gain for these transitions becomes equal to or larger than K_{th}. The lasing threshold is defined by the formula $K_{\text{th}} = -\ln(R_1R_2)/(2L_{\text{act}})$, where R_1 and R_2 are the reflection coefficients of the cavity mirrors. Hence, an increase in the value of L_{act} leads to an increase in the specific energy output in the laser. It should be interesting to find out whether the value of E/V increases for an electric-discharge-initiated HF laser under a much lower pressure (0.1 atm).

The partial pressure of F_2 molecules in a photo initiated HF(DF) laser is an order of magnitude higher than in a laser initiated by an electric discharge. However, in view of a lower efficiency of photoinitiation, the total concentration of H and F atoms in the former laser is several times lower than in the latter. Accordingly, the rate of the chemical chain reaction and the small-signal gain in a photoinitiated HF(DF) laser is lower, and the increase in the lasing efficiency upon an increase in the active medium length is obviously manifested in a wider range, i.e., over several metres.

The mathematical model of the processes occurring in the active medium of a pulsed chain-reaction HF laser is analogous to the model that was used earlier for numerical calculations in the case of photoinitiation [7]. Since the small-signal gain in the active medium of an electric-discharge-initiated HF laser is much higher than the lasing threshold K_{th}, a considerable increase in the specific energy output occurs only for $L_{\text{act}} < 0.5$ m (Fig. 7). For $L_{\text{act}} > 0.5$ m, this increase is insignificant. The small-signal gain in the most powerful laser transitions is much larger than 10 m^{-1}, while the lasing threshold $K_{\text{th}} = 1.22\ \text{m}^{-1}$ for $R_1 = 0.98$, $R_2 = 0.3$ and $L_{\text{act}} = 0.5$ m.

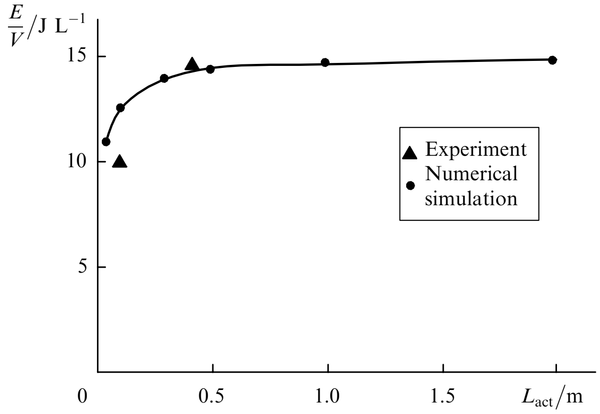

Figure 7. Dependence of the specific energy output E/V of a laser on the active medium length L_{act} for the gas mixture $F_2:H_2:O_2:SF_6 = 20:5.3:1.4:73.3$ for $p = 11.5$ kPa, $R_1 = 0.98$ and $R_2 = 0.3$.

A laser chamber with an active medium length $L_{\text{act}} = 0.37$ m was tested during investigations of a barrier-discharge-initiated HF(DF) RPCL. The experiments revealed a good stability and homogeneity of the barrier discharge. A specific energy output of ~ 14 J L^{-1} was obtained in the single-pulse operation regime of a RPCL (20 % F_2, 5 % H_2), which is in good agreement with the numerical predictions.

5. Conclusions

An efficient repetitively pulsed laser with an 11-cm-long active medium and a pulse repetition rate of 10 Hz, initiated by a barrier electric discharge with an electrode gap of 10 cm has been developed. A 120-ns barrier electric discharge exhibits a high stability, reliability and homogeneity under a specific energy input up to 60 J L^{-1}.

An average output power of 43 W was obtained in the RP regime of the laser with a pulse repetition rate of 10 Hz for a depleted fluorine-hydrogen mixture (20 % F_2, 5 % H_2) ($E/V \sim 10$ J L^{-1} for a laser pulse, which is lower than the corresponding value obtained in the single-pulse regime [8]).

Numerical simulation predicts an increase in the output energy with the active medium length under conditions corresponding to the conditions of our experiment for $f = 10$ Hz. The possibility of obtaining a specific energy output of the laser exceeding 15 J L^{-1} and a technical efficiency right up to 20 % – 25 % can be realised under actual conditions for a barrier-discharge-initiated laser device with an active medium length of about 0.5 m. If an active medium with optimal composition for the RP mode (20 % F_2, 5 % H_2) is used, a specific energy output of ~ 14 J L^{-1} is obtained in the single pulse mode for an active medium length of 0.37 m, which is in good agreement with the theoretical predictions.

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