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Non-chain pulsed DF laser with an average power of the order of 100 W

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Abstract The design and performance of a closed-cycle repetitively pulsed DF laser are described. The Fitch circuit and thyratron switch are introduced to realize self-sustained volume discharge in SF_6–D_2 mixtures. The influences of gas parameters and charging voltage on output characteristics of non-chain pulsed DF laser are experimentally investigated. In order to improve the laser power stability over a long period of working time, zeolites with different apertures are used to scrub out the de-excitation particles produced in electric discharge. An average output power of the order of 100 W was obtained at an operating repetition rate of 50 Hz, with amplitude difference in laser pulses <8 %. And under the action of micropore alkaline zeolites, the average power fell by 20 % after the laser continuing working 100 s at repetition frequency of 50 Hz.

1 Introduction

Deuterium fluoride (DF) laser radiates several dozen lines in the spectral range 3.6–4.2 μm, which is the infrared atmospheric transparency window covering the absorption peaks of many air contaminants, resulting in its significant application in remote atmosphere ecological monitoring [1, 2]. Besides, non-chain short pulsed HF/DF laser is an ideal pump source for novel Fe:ZnSe laser, whose fluorescent life time is 360 ns at $T = 292$ K, and this process can expand the laser spectrum to 4–5 μm [3–5].

In the past few years, most published works are devoted to improving the output energy, electric efficiency, and repetition rate of non-chain HF/DF laser. Using self-initiated volume discharge, Apollonov et al. [4, 5] realized large volume uniform discharge in SF_6–D_2 gas mixture that allowed increase in the radiation energy up to 325 J at electric efficiency of 3.4 %. By optimizing the mixture composition, specific input energy, and uniformity of electric field, Tarasenko improved the electrical efficiency of non-chain HF/DF laser up to 6.4 % with the output energy over 1 J [6, 7]. Using corona preionizer, Harris et al. [8] enabled HF/DF laser operation up to 1-kHz repetition rate and obtained average laser output power of up to 2.5 W in SF_6–D_2 gas mixture. By diluting working mixture with helium to preserve the conditions of discharge matching, Velikanov et al. [9] reported an atmospheric pressure laser with the output of 33 W, pulse repetition rate up to 2.2 kHz, electrical efficiency of 1.6 %. Using three electric-discharge laser modules of the same type, which are aligned along one optical axis, Aksenov et al. [10] achieved mean laser output power of up to 400 W in SF_6–D_2 gas mixture at 10 Hz. By optimizing gas flowing velocity and adding 3A molecular sieve, Huang reported a closed-cycle, repetitively pulsed HF laser with output power of 18 W at 50 Hz [11, 12]. Using an all-solid-state pump generator based on FID switches, Velikanov demonstrated an electric-discharge HF(DF) laser with repetition rate of 25 Hz, which specific energy extractions were 3.8 and 3.4 J L^{-1} for HF and DF laser, respectively [13]. Above researches show that single pulse energy can be scaled up with discharge volume, but it is difficult to improve output power by scaling up pulse repetition rate with pulse energy of the order of 1 J. The main reasons are as follows: (1) Gas flow inhomogeneity

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throughout the length of the electrode system would fluctuate severely at high repetition rate; (2) gas flow resistance will doubly increase for using scrubber cell, which would cause huge trouble to long-term laser power stability.

In 2012, our group presented the computer modeling and experimental results of non-chain pulsed DF laser. The single pulse energy of 4.95 J and peak power of 33.27 MW was achieved under the optimum conditions with UV-preionized discharge [14]. In this paper, we reported a compact high-repetition-rate non-chain DF laser with an average power of the order of 100 W. Based on the Fitch circuit and thyratron switch, the technology of self-initiated volume discharge is introduced to improve the uniformity of discharge. Centrifugal fun with large flow rate is used to realize high repetition rate basing on optimum design of flow passage. At an operating repetition rate of 50 Hz, a maximum average output power of 150 W is achieved by optimizing the mixture composition and specific input energy. Then, the long-term power stability of this laser is shown under the action of micropore alkaline zeolites.

2 The circuit scheme of laser

Charging voltage source and discharge chamber with electrode system of non-chain DF laser are schematically shown in Fig. 1. TDI-1-50K/50 thyratron is used as circuit switch, parallel-connected capacitors C_1 and C_2 are main storage capacitors, L_1 and L_2 are matching inductors of C_1 and C_2, and A is the test point of voltage between electrodes. The discharging unit adopts a polished anode and frosted cathode, and the electrodes of size 65 cm × 5 cm were rounded off to the radius 1 cm with the separation of 5 cm between plane electrodes. The cathode surface has been subjected to a sand-blasting treatment so as to form volume discharge without UV preionizer. The total capacitance is 120 nF, with stored energy up to 121 J.

Compared with our previous reports about spark pin UV-preionized circuit [14], this self-initiated volume discharge circuit has two obviously advantages in realizing long-time working stability of DF laser:

1. Less working gas will be consumed during single discharge;
2. Arc discharge without preionization will almost disappear in discharge process, and the composition of discharge products is relatively simple.

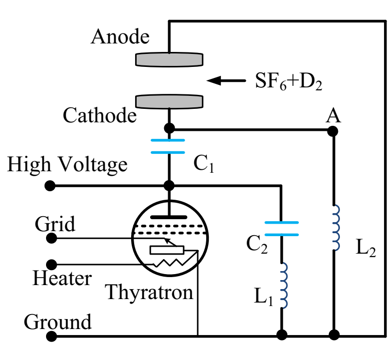


Fig. 1 Circuit scheme of non-chain DF laser

3 Experimental results and discussion

3.1 Single pulse operation

For improving the output energy and electric efficiency of non-chain DF laser, tests were conducted to estimate the best mixture composition, total pressure, charging voltage, and gas temperature.

According to the output capability of our high-voltage source, the charging voltage was selected as 43 kV firstly. Then, we tested the output energy of DF laser at different mixture compositions and total pressures separately, and the results are shown in Fig. 2.

Under the condition of same mixture composition, the energy increases with the growth of total pressure at first, and then when the total pressure is 8.1 kPa, the laser energy reaches maximum, and later, it decreases gradually as pressure continues to increase. The gas resistance and circuit parameters approximately match when the total pressure is 8.1 kPa, which is easy to realize homogeneous glow discharge and prevent their collapse into arcs discharge. At the same total pressure, the laser has the highest output energy when the gas mixture ratio is 8:1. Under this ratio, the number of F-atom produced by SF_6 molecule dissociation

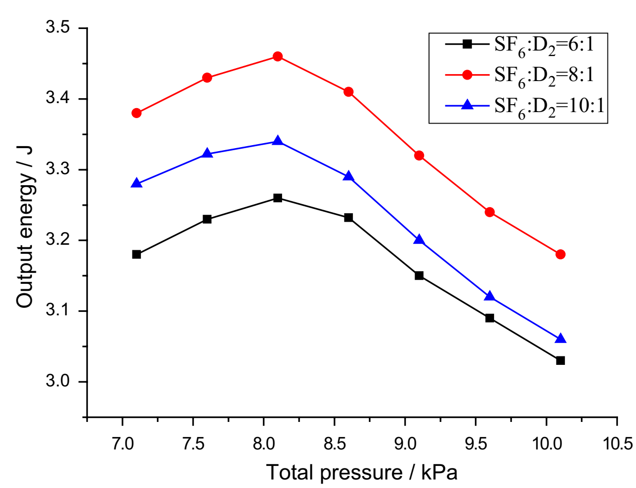
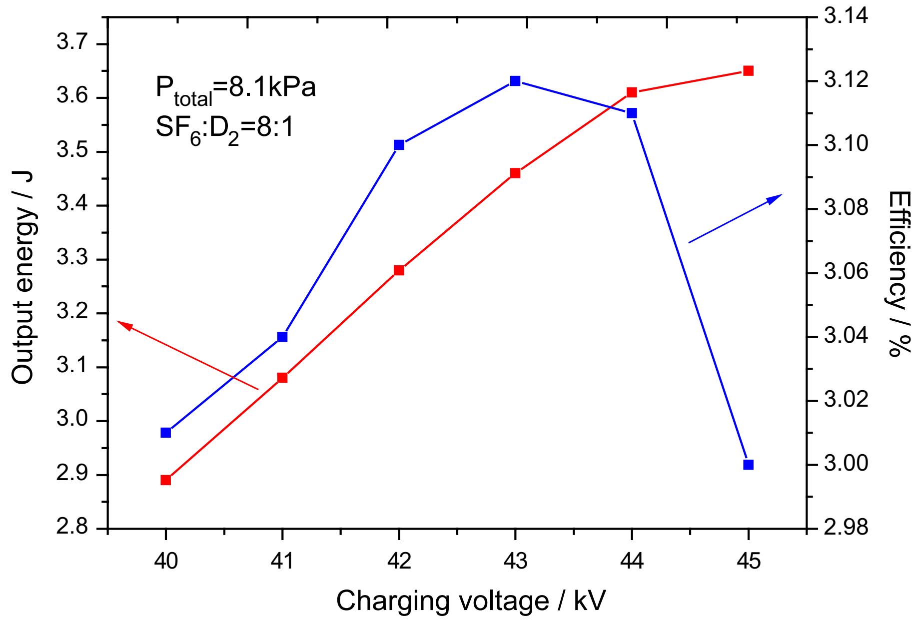


Fig. 2 Single pulse energy versus mixture composition and total pressure

Fig. 3 Single pulse energy and electric efficiency versus charging voltage



matches the D_2 density, which would obviously drop the adsorption of excessive SF_6 to free-electron or the de-excitation effect of excessive D_2 to excited DF molecule at other mixture ratio, so it is conducive to enhancing the energy extraction efficiency.

Under conditions of the optimal gas mixture ratio and total pressure (P_{total} = 8.1 kPa, SF_6:D_2 = 8:1), tests were conducted to study the energy and electric efficiency at different charging voltages, and the results are shown in Fig. 3. Laser energy gradually becomes larger linearly with increasing the charging voltage when the charging voltage is lower than 43 kV. However, as charging voltage continued to increase, the laser energy would further enhance, but the increment would obviously slow down. The highest output energy obtained in our experiment reaches 3.6 J. The electric efficiency increases with the increase in charging voltage at first, and then when the charging voltage is 43 kV, the electric efficiency reaches maximum of 3.12 %, and later, it decreases gradually as the charging voltage continues to increase, which provide a better contrast with the relation between energy and charging voltage. The main reason is the inhomogeneous discharge between the electrode gaps when injecting huge electric energy at a shorter discharging time.

When P_{total} = 8.1 kPa and SF_6:D_2 = 8:1, the discharging voltage waveform is shown in Fig. 4 at charging voltage of 43 kV. One can see that the discharging voltage has a shape which is typical for non-chain DF lasers with glow discharge. The measured discharging width is about 120 ns, and the discharging voltage is bout 38 kV. So the optimum *E*/*P* (*E* is the field strength and *P* is the pressure of working mixture) value is 93.83 V × (m × Pa)$^{-1}$ in our

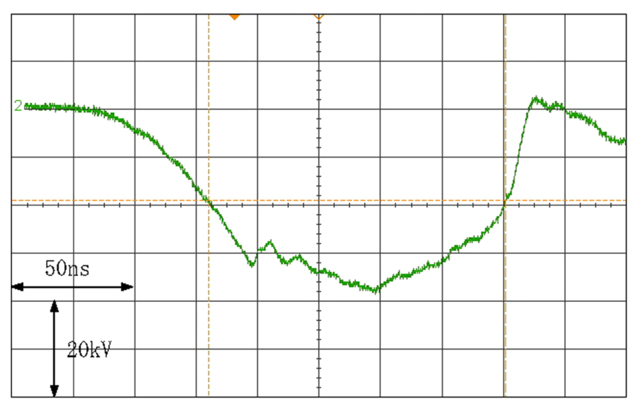


Fig. 4 Oscillograms of discharging voltage at charging voltage of 43 kV

experiments. These results are in agreement with numerical calculations by Ruan et al. [14].

The ablation of electrodes is greatly evidence with phenomenon of inhomogeneous discharging, especially at high repetition rate. To protect electrodes, the laser should work at homogeneous discharge, so the charging voltage would be limited to 43 kV in the experiments of repetition frequency operation.

3.2 Repetition frequency operation

Based on the single pulse operation, the total pressure of mixture gas is optimized to improve the average output power of non-chain DF laser. The output characteristics of DF laser were measured as gas mixture ratio of SF_6:D_2 = 8:1,

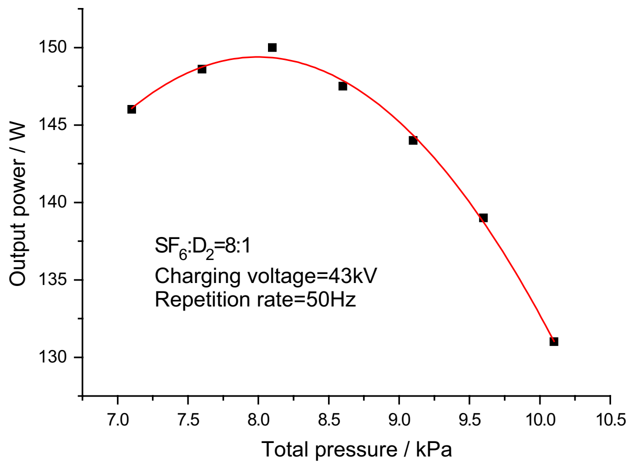


Fig. 5 Average output power versus total pressure

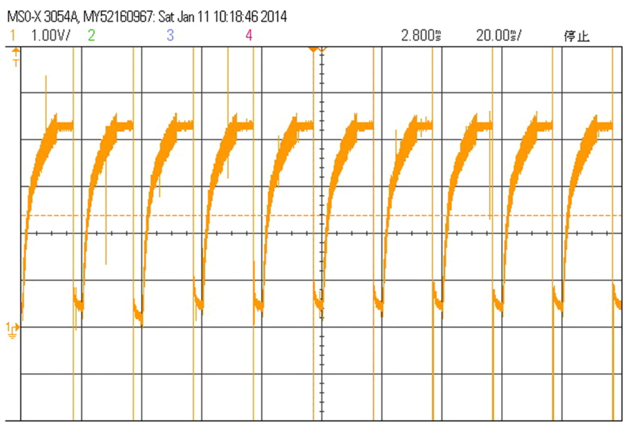


Fig. 6 Charge and discharge waveform of energy storage unit

charging voltage of 43 kV, and operating repetition rate of 50 Hz at different total pressures. The fitted curve of average output power versus total pressure is depicted in Fig. 5.

As shown in Fig. 5, the highest average power is 150 W at the total pressure of 8.1 kPa. But comparing it with Fig. 2, it is easy to find that the relationship between average output power and total pressure is in good agreement with that between energy and total pressure. But, the average output power is obvious below the value by multiplying the single output energy and repetition rate. Firstly, we tested the charge and discharge performance of energy storage unit at operating repetition rate of 50 Hz to check whether the injecting energy was normal. The charge and discharge waveform is shown in Fig. 6. The charge and discharge both are normal, indicating the function of energy storage unit is normal and ruling out the decrease in average output power by storage unit.

The phenomenon that average output power is below the multiplication of single output energy and repetition rate at

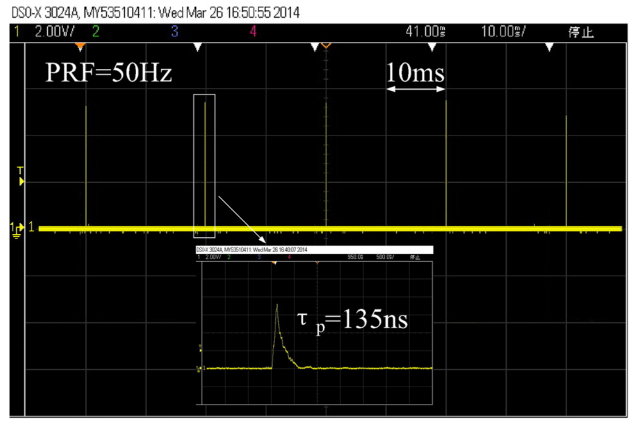


Fig. 7 Pulse trains and typical shapes of DF laser

same mixture gas and charging voltage is universal in the HF/DF laser [8–12, 15]. The main reasons are as follows: (1) More heat can occur on the surfaces of electrodes under continuous high-frequency electrical discharge, which courses gas inhomogeneous temperature distribution from electrode surfaces and in discharge gap, and then emerges local stirring motion between electrode gaps. The local stirring motion would deteriorate the homogeneity and stability of discharge. (2) The mixture density homogeneity is also disturbed by the production of shock waves in pulsed discharges, especially at high repetition frequency. These acoustic waves are reflected from different surfaces of gas-dynamic channel and interact with each other, resulting in local inhomogeneity of mixture pressure and density in discharge gap. (3) It is difficult to forecast the thermal expansion character of mixture gas introduced by discharge. The selected fun could provide two gas changes between shots, but it is hard to avoid the few residual gas produced by previous discharge to participate in second discharge at high repetition frequency.

Pulse trains and typical pulse shapes of non-chain DF laser at 50 Hz are shown in Fig. 7. We can see that the pulse amplitudes jittered, but no loss of pulse was observed, and the amplitude difference in laser pulses is less than ±8 %. The pulse duration of DF laser is 135 ns with single pulse energy of 3.46 J, so the peak power of the DF laser reaches 25.63 MW.

3.3 Testing of laser power long-term stability

Electric-discharge non-chain pulsed DF laser using SF_6 and D_2 as working mixtures has four types of reactions, which are F atoms formation reaction, pumping reaction, de-excitation reaction, and stimulated radiation. F atoms arise from electric discharge decomposition of SF_6, which also produce lower fluoride as SF_5, SF_4, SF_3, and so on. The pumping reaction produces a large number of ground-state

Table 1 Diameter and acid–base character of gases in discharge area [16–18]

Gas	SF_6	SF_5	SF_4	D_2	DF
Diameter (Å)	4.56	3.77	3.6	2.4	2.98
Acid–base property	Neutral	Neutral	Acidic	Neutral	Acidic

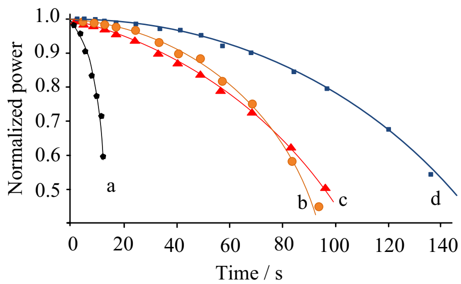


Fig. 8 Normalized output power versus continuous working time at 50 Hz with different zeolites: *a* no adsorbents; *b* 3 Å zeolite; *c* 5 Å zeolite; *d* micropore alkaline zeolite

DF molecules besides excited DF molecules. F atoms formation reaction and pumping reaction just consume a small number of working gases, and there are a lot of SF_6 and D_2 remained in gas storage chamber after each pulse.

The main gases in discharge area after discharge are SF_6, D_2, SF_5, SF_4, SF_3, and ground-state DF, in which ground-state DF molecules have the highest de-excitation effect on excited DF molecules [14], so ground-state DF molecules are the main adsorption objects of zeolite. Table 1 shows the diameter and acid–base character of main gases in discharge area after electric discharge.

Figure 8 shows the relationship between laser powers and continuous working time under different zeolites. Curve *a* represents the running characteristics of DF laser without any adsorbent, in which laser power quickly reduces to 60 % of the initial power. Curves *b*, *c*, and *d* are DF laser operating characteristics with 3, 5 Å, and micropore alkaline zeolites, respectively. The micropore alkaline zeolite is made of micropore zeolite with modification of removing silicon and adding aluminum, and its channel diameter ranges from 0.9 to 2 nm. Curves *b*, *c*, and *d* have the same experiment conditions: The zeolite particle size is 1–2 mm, filling volume is 1 L, and thickness is 30 mm. It's obviously from comparing curves *b*, *c*, and *d* that alkaline micropore zeolite has the best adsorption effect, with which the average power fell by 20 % after laser continuing working 100 s at 50 Hz. There are two reasons to explain this phenomenon. Firstly, the main de-excitation molecules are acidic molecules, so the alkaline zeolite can firmly lock the acidic de-excitation molecules with chemical bonds. Secondly, the diameter of micropore channel is greater than that of gas remained in discharge area, and each single porous wall can adsorb many de-excitation particles and does not affect circulation of working gases. The channel diameter of 3 Å zeolites is close to that of ground-state DF molecules, so the physical adsorption effect of 3 Å zeolites is slightly greater than 5 Å zeolites in the early stages of laser operation. And then, the 3 and 5 Å zeolites have almost same adsorption effect, which shows that the physical and chemical adsorption mechanisms coexist in the zeolites. As time goes on, the adsorption effect of zeolites will decrease because of its lifetime limitation, so it must be replaced timely after adsorption saturation.

4 Conclusion

By using Fitch circuit and thyratron switch, the self-sustained volume discharge of 1.65 L was obtained in SF_6–D_2 mixtures, and the repetition frequency operation of DF laser is presented. In our experiments, the best operational conditions are as follows: total pressure of 8.1 kPa, mixture composition of SF_6:D_2 = 8:1, charging voltage of 43 kV. The optimum single pulse output energy of 3.46 J, pulse duration of 135 ns, and peak power of 25.63 MW are obtained. The average output power of 150 W is recorded at 50 Hz. The de-excitations, harmful to laser output, can be effectively removed by passing the gas through a chemical trap consisting of a rectangular stainless steel box filled with microporous basic zeolites, which is helpful to extend long-term stability of the laser. By using basic zeolites, the average power fell by 20 % after the DF laser continuing operating 100 s at repetition frequency of 50 Hz.

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