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Original research article

Repetitively pulsed non-chain DF laser with pulse repetition frequency up to 50 Hz

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ABSTRACT

The design and performance of a closed cycle repetitively pulsed non-chain DF laser based on self-initiated volume discharge is presented. In order to effectively solve the problem of large volume uniform glow discharge in non-chain pulsed DF laser, a voltage doubling reverse circuit in the Fitch generator was used. The working mechanism and effects of the voltage doubling circuit was analyzed theoretically according to closed loop equation of RLC circuit, and the results were in good agreement with the experiment. The performance of non-chain DF laser operating in both single pulse mode and repetitive mode was researched. A maximum output energy of 3.65 J and a technical efficiency of 3.12% were recorded in single pulse mode. A laser power of 150 W was obtained at the repetition rate of 50 Hz, the amplitude difference of laser pulse was better than + 8%, and the laser pulse width was about 135 ns.

1. Introduction

Repetitively pulsed non-chain DF laser emitting in 3.5˜4.1 μm wavelength range is useful in laser radar transmitters, laser spectroscopy, atmospheric monitoring and laser-material interaction fields, because this emitting band falls into an important atmospheric transmission window and contains absorption peaks of many atoms and molecules [1–5].

Because of its tremendous prospect in applications, many researches have been carried out on repetitively pulsed non-chain DF/HF lasers. In 1982, Rudko designed a compact cylinder type high repetition rate HF/DF laser system, which applied four high pressure ratio blowers working in parallel, realizing higher than 2 W laser output at a repetition rate of 4 kHz [6]. In 1995, using photo-triggered discharge technique, a large volume homogeneous glow discharge was achieved by Bruent [7], and through replacing D_2 with C_6D_{12} as deuterium donor, the output pulse energy was increased to 8 J and typical average power of 450 W was achieved at a repetition rate of 65 Hz [8]. In 1998, Gorton presented a pipe connected non-chain DF laser, which had an automatic charging and exhausting system, and the average power was maintained at about 3 W after millions of laser pulses at repetition rate of 1 kHz [9]. Russian Federal Nuclear Center has made many researches on improving the performance of repetitive DF lasers, one of whose researches showed that adding He to the working mixture can effectively improve discharge homogeneity in active medium, and an average output power of 25–30 W was achieved for a pulse repetition rate of up to1200 Hz [10]. In 2012, an UV auto pre-ionization capacitive transfer structure circuit was used by Tang Y, realizing 130 mJ stable laser energy at a repetition rate of 50 Hz [11].

In our previous work, the discharge processes and output performance of non-chain pulsed DF laser using UV pre-ionization

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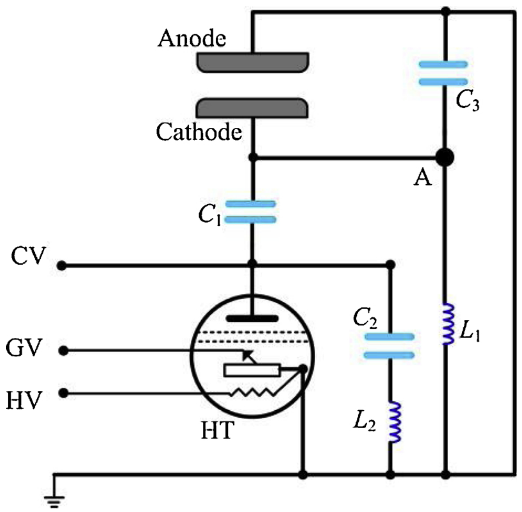

Fig. 1. Schematic diagram of non-chain DF laser.

discharge were studied, and a maximum pulse energy of 4.95 J with 1.96 L discharge volume was attained [12–14]. High repetition rate and large volume homogeneous glow discharge is a technical problem faced by DF lasers due to high electro-negativity of SF_6 molecules, which need high breakdown voltage and increase the demand for charging voltage. In this paper, a repetitively pulsed non-chain DF laser based on self-initiated volume discharge is designed, and the characteristics of voltage doubling reverse circuit in Fitch generator and the output performance of this laser are investigated.

2. Experimental setup

Characteristics of DF laser operating under repetition mode were studied using a close cycle apparatus consisting of three main blocks: a gas circulation and cooling system, which included a discharge chamber with a cavity for generating laser radiation and a heat exchanger for cooling the working gas; an energy storing and discharging system for exciting electric discharge in discharge area, including a high voltage pulse generator and a charging device, applying voltage doubling reverse circuit; a system for charging and exhausting working gas in discharge chamber. The schematic diagram of non-chain DF laser is presented in Fig. 1.

Self-initiated volume discharge (SIVD) was ignited between two aluminum plates with charge distance $d = 5$ cm. Plate dimensions was 65 cm × 5 cm, with plate edges rounded along the perimeter at radius r = 1 cm, and the cathode surface was sandblasted to obtain a homogeneous SIVD. The laser resonator was formed by mirrors of a gold coated concave reflector and a CaF_2 coated plate, providing the reflectivity of the laser emission spectrum of DF˜30%. The charging generator was based on Fitch generator scheme, using a hydrogen thyratron (HT) as its switching element. GV and HV were thyratron grid and cathode resistance heating power supply, respectively. Power was supplied by a high voltage source (CV), which charged capacitor C_1 and C_2 through inductor L_1 and L_2 respectively. Then, under the triggering of the grid ignition voltage, HT turned on, and current flowed through it. Because the inductance of L_2 was far less than that of L_1, voltage reversed on capacitor C_2 and the potential difference of C_1 just had a negligible drop due to loss in the reversal process. After voltage reversal on C_2, the thyratron anode's voltage was too low to maintain the conduction of HT and the series potential difference of capacitor C_1 and C_2 at this moment was two times the charging voltage. The energy stored in C_1 and C_2 was then applied to peaking capacitor C_3 and to the main discharge gap. The electric field in the discharge gap was inhomogeneous after sandblasting on the cathode, and discharge began at sandblasting tip, and expanded rapidly to the whole cathode region to form self-sustained discharge.

Fig. 2 shows the equivalent circuit of voltage doubling reverse circuit, where HT is replaced with variable resistor R. Because R is

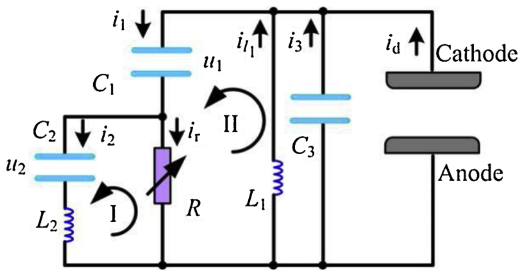

Fig. 2. Equivalent circuit of voltage doubling reverse circuit.

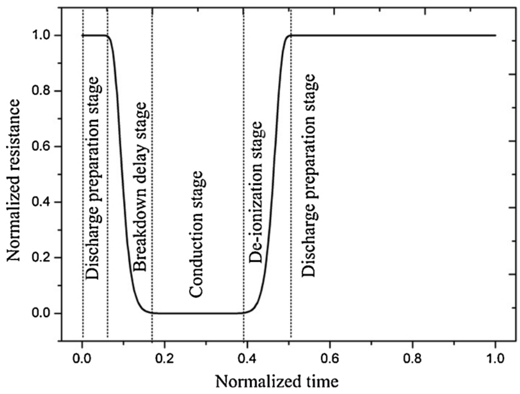

Fig. 3. Resistance across the thyratron versus time.

positively correlated with the voltage drop and the discharge voltage waveform of HT is similar to that described by super-Gaussian function, the resistance can be described by super-Gaussian function:

$$R = \{1 - \exp[-2(t - k_t)/Rn]^4\} \times R_{\max} + R_{\min} \tag{1}$$

where $R_{\max}$ is the resistance of HT without breakdown, $R_{\min}$ is the resistance when HT is turned on, *Rn* is the quantity of turn-on time and k_t is the zero offset of grid trigger signal. The time dependence of the resistance is shown in Fig. 3.

If regards HT as an ideal device and neglects its breakdown delay time and deionization time, the variation of resistance with time can be characterized by a rectangular function:

$$R(t) = rect\left(\frac{t}{a}\right) = \begin{cases} 0.1\Omega, & t < a \\ 1e7\Omega, & t \geq a \end{cases} \tag{2}$$

Here $a = L/R$ is the time constant of the inductor.

The voltage doubling characteristic of the circuit was studied by numerically solving the loops I and II in Fig. 2 according to the closed loop equation of RLC circuit. The circuit parameters used in the calculations were as follows: $C_1 = C_2 = 60\text{nF}$, $U_c = 40\,\text{kV}$, $L_1 = 80\mu\text{H}$ and $L_2 = 30\text{nH}$ (Fig. 4).

Calculation results show that, terminal voltage of Capacitor C_1 in loop *I* rapidly decreases from 40 kV to -38.34 kV once the thyratron is broken down, while the potential difference across C_2 in loop *II* just decreases from 40 kV to 37.42 kV. Then, due to the interruption of thyratron, terminal voltage of capacitors C_1 and C_2 remains unchanged. At this point, capacitors C_1 and C_2 are connected in series (see Fig. 2), and the series capacitance is $C_{12} = C_1C_2/(C_1 + C_2) = 30\text{nF}$. The potential difference across capacitor C_{12} is Vc_1-Vc_2 = 75.76 kV, meaning the circuit realizes voltage doubling. For the same DC charging voltage, this voltage doubling reverse circuit could increase the discharge voltage without increasing the charging voltage, meaning that it can break down discharge electrodes with larger gap and realize large volume uniform glow discharge, so as to improve the output energy of DF laser.

3. Experimental results and discussion

At the first stage of our experiment, we studied the characteristics of DF laser working in single-pulse mode. The performance of voltage doubling reverse circuit in the Fitch generator was tested with a 60 kV high voltage probe. The inter-electrode distance *d* was fixed because of the limitation of the mechanical structure, flow velocity and uniformity of the flow field in our experimental device. In the quasistationary phase of a volume self-sustained discharge in DF laser, the ratio of electric field to gas mixture pressure *E/p* is

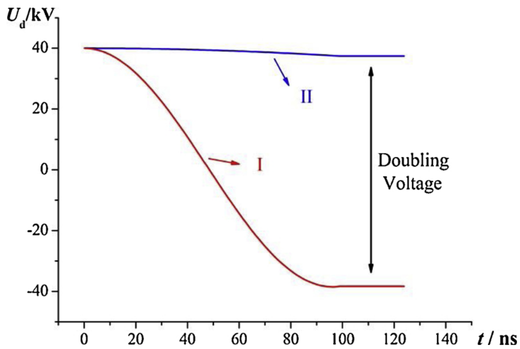

Fig. 4. Loop voltage versus time.

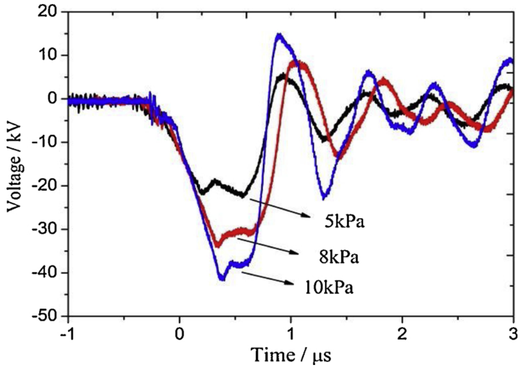

Fig. 5. Discharge voltage waveforms across the electrodes.

constant [15], which means that the required breakdown voltage will gradually increase with the rise of gas pressure when *d* is fixed. So, the discharge characteristics were verified by changing the gas pressure. Fig. 5 shows the discharge voltage waveforms at different gas pressures (p = 5 kPa, 8 kPa and 10 kPa) with charging voltage U_c = 30 kV.

The discharge voltage is 22.3 kV, 33.2 kV and 41.8 kV when working pressure is 5 kPa, 8 kPa and 10 kPa, and the discharge voltage is higher than the charging voltage under 8 kPa and 10 kPa, proving that this voltage doubling reverse circuit has good discharge characteristic. By applying this circuit, a larger volume uniform glow discharge can be achieved without changing the DC charging voltage.

The influence of charging voltage on the laser output energy for different mixture component were investigated at a pressure of the active mixture p = 8.1kPa, with results shown in Fig. 6.

It is seen from the curves that the pulse energy first increases quickly with the charging voltage at $U_c < 43$ kV and then due to the ark discharge in the gap the energy begins to be saturated and finally decreases at high voltage. The maximum energy at different voltage under p = 8.1kPa is reached in the component SF_6: D_2 = 8:1, where the number density of F atoms produced by dissociating of SF_6 matches that of D_2 molecules at SF_6: D_2 = 8:1. However, with further increase of D_2, the de-excitation effects of D_2 and D on excited DF also increase but the density of F deceases, which in turn lead the decline of the inverted population density. The stable maximum energy of E = 3.65 J was reached at U_c = 45kV in the component SF_6:D_2 = 8:1, while the maximum efficiency of 3.12% was reached at U_c = 43 kV. When $U_c > 43$ kV, local inhomogeneous discharge occurs, causing little input energy increment or even energy decreasement. Besides, serious arc discharge at high voltages has obvious ablation effect on electrodes (Fig. 7), which will affect the output performance and operational life span of the laser, so the voltage should be limited within 43 kV in repetitively pulsed regime.

At the second stage of experiments, we studied the characteristics of DF laser operating in repetitively mode. The output power was measured at 50 Hz repetition rate for the SF_6:D_2 = 6:1, 8:1 and 10:1 mixture at p = 8.1kPa and U_c = 43 kV, with results shown in Fig. 8. One can see that, under the same charging voltage and pressure, laser power reaches maximum (P_{out} = 150 W) at SF_6:D_2 = 8:1, which is in agreement with the single pulse operation. The possibilities of further increasing the average power were limited by the de-excitation effect on excited DF molecules in the discharge gap. Two methods can be used to increase the power: adding molecular sieve adsorption system in the discharge chamber or increasing the circulation speed of the working gas.

In the experiments, the pulse stability of repetition mode in one time cycle (20 s) was measured. Fig. 9 presents the typical waveforms of pulse series (a) and single pulse (b). One can see that the laser pulse energy has random fluctuation, but the overall stability is good, and there has little pulse loss. The amplitude difference of laser pulse is better than +8% and the laser pulse width is about 135 ns. All the results prove that the voltage doubling circuit has good discharge stability under repetition mode.

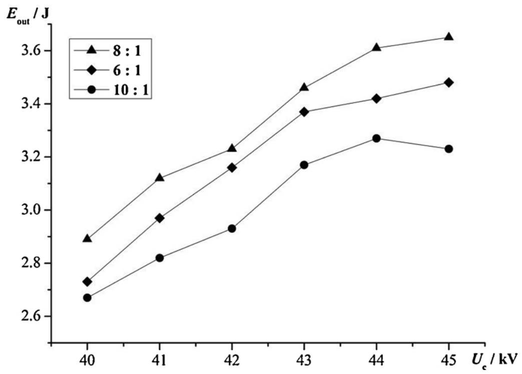

Fig. 6. Dependences of laser output energy E_{out} on charging voltage at total pressure p = 8.1kPa.

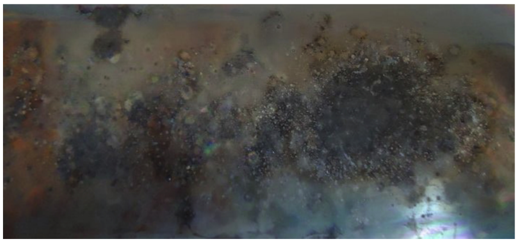

Fig. 7. discharge electrode after ablation by arc discharge.

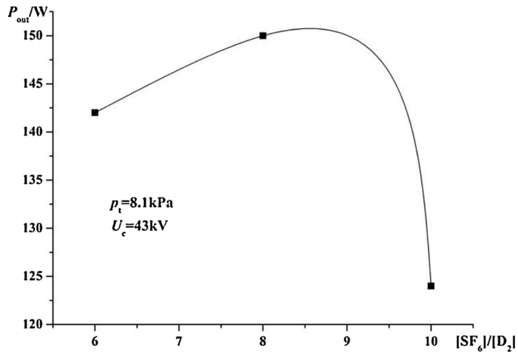

Fig. 8. Output power of DF laser at different mixture ratio.

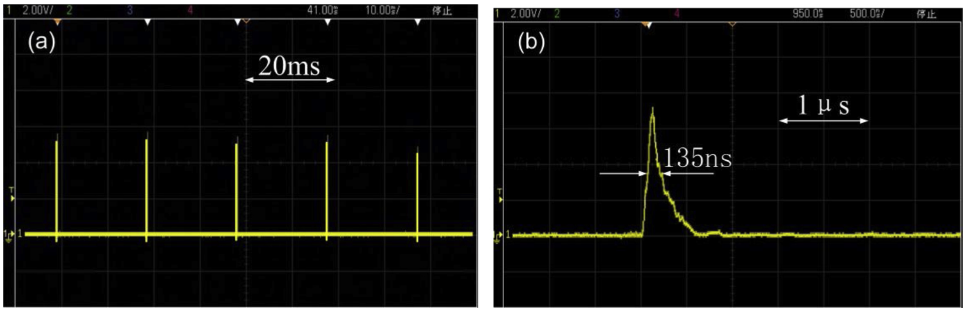

Fig. 9. Laser pulse waveforms.

4. Conclusions

Results of a study of a repetitively pulsed self-initiated volume discharge DF laser operating on SF_6-D_2 mixture are reported. Calculations and experiments were made to analyze and verify the mechanism and effects of the voltage doubling reverse circuit used in the high voltage pulse generator, and both the calculations and experiments prove that this circuit has good performance in double voltage discharge. There is a limitation of the charging voltage ($U_c \leq 43$ kV) for the attainment of the stable output energy and for prolonging the electrode life. A lasing power of 150 W was obtained at a pulse repetition rate of 50 Hz when the total pressure and charging voltage were 8.1 kPa and 43 kV respectively, and the relative technical efficiency at this condition was 3.12%.

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References

[1] J. Altmann, P. Pokrowsky, Sulfur dioxide absorption at DF laser wavelengths, Appl. Opt. 19 (20) (1980) 3449–3452.
[2] P. Pokrowsky, Absorption of H_2S at DF laser wavelengths, Appl. Opt. 22 (14) (1983) 2221–2223.
[3] V.Y. Agroskin, B.G. Bravy, Y.A. Chernyshev, Aerosol sounding with a lidar system based on a DF laser, Appl. Phys. B 81 (2005) 1149–1154.
[4] B.I. Vasilev, O.M. Mannoun, IR differential-absorption lidars for ecological monitoring of the environment, Quantum Elec. 36 (9) (2006) 801–820.

[5] G. Wilson, B.R. Graves, S.P. Patterson, et al., Deuterium fluoride laser technology and demonstrators, SPIE 5414 (2004) 41–51.
[6] R.I. Rudko, Z. Drozdowicz, S. Linhares, High-repetition-rate, recirculating hydrogen fluoride/deuterium fluoride laser, Rev. Sci. Instrum. 53 (4) (1982) 452–457.
[7] H. Brunet, Improved DF performance of a repetitively pulsed HF/DF laser using a deuterated compound, SPIE 3092 (1997) 494–497.
[8] H. Brunet, M. Mabru, F. Voignier, High energy-high average power pulsed HF/DF chemical laser, SPIE 2502 (1995) 388–392.
[9] M.R. Harris, A.V. Morris, E.K. Gorton, A closed-cycle, 1khz pulse repetition frequency, HF(DF) laser, SPIE 3268 (1998) 247–251.
[10] I.L. Butsykin, S.D. Velikanov, P.A. Evdokimov, et al., Repetitively pulsed DF laser with a pulse repetition rate up to 1200 Hz and an average output power of-25W, Quantum Elec. 31 (11) (2001) 957–961.
[11] K. HUANG, A.P. YI, Y. Tang, et al., Discharge pumped non-chain repetitively pulsed HF laser, SPIE 8796 (2013) 879620.
[12] P. Ruan, J.J. Xie, L.M. Zhang, et al., Computer modeling and experimental study of non-chain pulsed electric-discharge DF laser, Opt. Express 20 (7) (2012) 28912–28922.
[13] P. Ruan, L.M. Zhang, G.J. Tan, et al., Experimental study on non-chain electric-discharge pulsed DF laser, SPIE 8796 (2013) 87961P.
[14] Q.K. Pan, J.J. Xie, C.L. Shao, et al., Discharge processes of UV pre-ionized electric-discharge pulsed DF laser, Opt. Commun. 363 (363) (2016) 91–96.
[15] V.V. Apollonov, Discharge Characteristics in a Nonchain HF(DF) Laser, Quantum Elec. 30 (30) (2016) 483.