Research of 30 ns Discharge XeCl Laser[1]

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Abstract - Results of experimental and theoretical investigations of discharge XeCl laser with 30 ns (FWHM) radiation pulse duration are presented. Laser generates the laser energy of 0.38 J with 2.4% total electric efficiency. Calculated laser radiation parameters and discharge parameters have a good agreement with experimental results. Influence of basic plasma-chemical processes in discharge on laser output and efficiency is shown. Maximal laser efficiency relatively pumping power amounts to 4%.[1]

1. Introduction

The studies devoted to XeCl-laser with pulses of short duration of 20÷40 ns are long-term ones. There are many publications devoted to such lasers and their characteristics. At present, such laser parameters as energy, power, or efficiency obtained in various researches works are rather different. The influence of initial parameters of pumping on lasing characteristics is not sufficiently revealed as well.

In paper [1], influence of pumping power on radiation efficiency is discussed. It is shown that the highest efficiency of 2.3 % is being reached at the pumping power value of 1.0 MW/cm^3. Laser efficiency reduces up to 1.6 % with pumping power increasing by three times. In [2] the electric circuit design with magnetic spike circuit was used. At pumping power of ~1.5 MW/cm^3 the efficiency made (1.5–2)% with respect to the energy stored in peaking capacitors. Radiation energy of 0.12 J was obtained in gas medium volume of 84 cm^3. In [3] active medium volume was equal to 116 cm^3, laser output energy was 280 mJ (2.4 mJ/cm^3) and pulse duration was 20 ns. At pumping power of 3.77 MW/cm^3 high efficiency of 2.9 % has been reached. The paper [4] reports on obtaining of the minimal (7 ns) duration pulse. The volume of active medium is 52 cm^3, the length is 26 cm, width is 1 cm, and inter-electrode space is 2 cm. At pumping power of 4.7 MW/cm^3, the efficiency of 1.6 %, radiation energy of 28 mJ (0.53 mJ/cm^3), and output power of lasing as 4 MW were obtained. In [5] it is reported on the results of study of the laser having the least volume of gas medium as 3,8 cm^3.with the length of 14 cm, width of 0,3 cm, and inter-electrode space of 0,9 cm. While possessing very high pumping power of 45 MW/cm^3 radiation energy obtained is 40 mJ (10.5 mJ/cm^3), output lasing power is 1.3 MW, and radiation pulse duration is 30 ns. Laser efficiency reached 0.8 %, defined as the ratio of radiation power and pumping power. Note that the highest radiation energy per unit volume as 10.5 J/l has been achieved in this work.

Lasing characteristics obtained in various works rather differ by their values. Such data give general representation of energy characteristics the laser possesses, as well as the mechanism consisting in that the maximal efficiency is being realized at definite pumping power is shown. In order to understand the influence of the initial parameters of pumping on lasing characteristics, as well as to select optimal parameters of pumping, it is necessary that physical processes taking place in active medium were studied in a more detail.

Earlier we reported about development of XeCl laser with output energy of 0.21 J and laser pulse duration at FWHM of 25 ns [6]. The laser total electric efficiency of 1.9 % has been achieved. It has been shown that increase of laser efficiency requires increasing of pumping power but it increases the electron density and leads to increase in the rate of excimer molecules quenching. Therefore it is very important the optimal selection of pulse length and value of pumping power.

This paper presents the results of subsequent experimental and theoretical research of short pulse XeCl laser with the object to obtain the maximal lasing efficiency. For it the pump power and pulse duration was somewhat increased.

2. Experimental equipment and mathematical model

For laser pumping the typical charge–transfer electric circuit was used (Fig.1). The storage capacity C_1 = 66 nF is charged from constant-voltage source up to U_0 = 22 kV. The thyratron of TGI-1000/25 is used as a switch. Inductance of the first circuit L_1 = 100 nH was selected as optimal proceeding from two conditions: operation reliability of thyratron and obtain of maximum radiation energy. The discharge capacity of the second circuit C_2 = 52.3 nF is pulsed charged and then

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it discharges providing pumping of active medium..

The discharge electrodes had length of 59 cm. Inter-electrode distance was 2.24 cm. Discharge effective width was 0.6-0.7 cm. Gas operating mixture Ne/Xe/HCl = 770/8/1 was used in experiments with total pressure of 3.6 bar. The length of resonator was 100 см, reflection mirrors were R_1 = 0.85 and R_2 = 0.07.

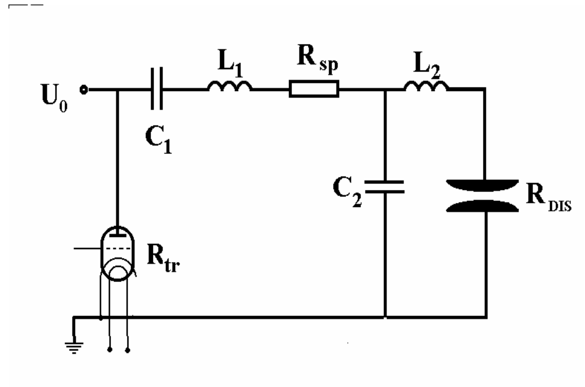

Fig.1. Schematic diagram of setup and excitation circuit. C_1= 66 nF; C_2=52.3 nF; L_1=100 nH; L_2=4 nH, R_{sp} – sparks resistance; R_{DIS} – discharge plasma resistance; R_{tr} – thyratron resistance; U_0=22 kV.

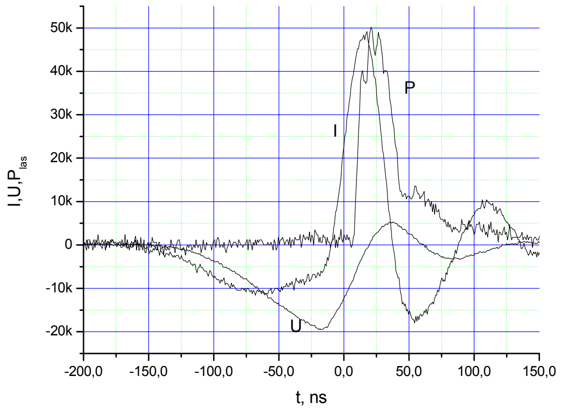

Fig.2. Experimental temporal evolutions of capacitor C_2 voltage U, current I and lasing power (P).

Measurements of the laser radiation energy and laser pulse in the experiment carried out by means of the calorimeters IMO- 2H and FEK22-SPU, accordingly. Electric pulses registered by means of the oscilloscope TDS-3014.

For study of physical processes in laser the numerical model of the laser has been created on the assumption of spatially uniform discharge. Model includes the decision of the Boltzmann equation for electron, a system of equations describing time variation of electron concentration, positive and negative ions, active media atoms and molecules being in electron- and vibration-excited states; equations describing electric circuit, and equations describing formation of laser radiation in resonator. 1D code was used for distribution calculation of the flow intensity of laser radiation on length of the resonator

The change at time a resistances of thyratron and spark gaps in electrical circuit taken into account by R_{sp} resistance. The value of R_{sp} was chosen by experimental way. Kinetic processes in model are taken into account on base data of paper [7]. For gas mixture Ne/Xe/HCl following levels of the molecules were used. Neon: Ne (ground state), Ne* (3s state), Ne** (all other excited levels), ion Ne+. The Xenon: Xe (ground state), Xe*(6s state), Xe**(6s, 6p and 5d states), Xe*** (all other excited states), ion Xe+. Four vibration excited levels of molecule HCl (v = 0,1,2,3), two dissociative levels HCl(A) and HCl(B+C), as well as ion of the molecule HCl+ were taken into account. For molecule XeCl the lower ground level XeCl(X), upper excited level XeCl**, as well as levels XeCl(B, v ≥ 0), XeCl(C, v ≥ 0, 1) were considered. From the other particles of the plasma were considered following: atoms H and Cl, excited atom Cl*, molecule H_2, excited molecules Ne_2* and Xe_2*, Xe_2Cl^*, molecular ions Ne_2+, Xe_2+ and NeXe+, negative ion Cl^- , as well as electrons, photons of stimulated and spontaneous radiation. The model included 320 kinetic processes in plasma.

3. Research results and discussion

The experimental laser radiation parameters are 0.38 J output pulse energy with 28 ns (FWHM) pulse duration. Laser can work with 10 Hz pulse repetition rate. The laser electric efficiency of 3.5 % calculated from storage energy in discharge C_2 capacity and output peak power of 12.5 MW have been achieved.

Measured and predicted temporal evolutions of capacitor C_2 voltage, capacitors current, as well as lasing power are shown in Fig.2. From comparison of simulation and measured data it follows that they are well agreed. The calculations have shown that maximum pumping power (Fig.3) is 270 MW and specific power of the pumping is 3.1 MW/cm^3. Rise time of pumping powers is 30 ns. Time delay between the generation and pump power pulses is 27 ns. So the generation begins to develop in the time range of pumping power maximum. Herewith maximum of generation power (P=10 MW) delays relatively maximum of pumping on ~10 ns.

During of pumping power rise time making the plasma occurs. The energy is accumulated on exited and ionized states of xenon atoms. Also the growing of XeCl(B,C) excited molecules concentration occurs. Growing of the XeCl (B, v = 0) molecules concentration leads to increase gain factor of active medium. Simultaneously with accumulation of the energy in plasma the energy losses in process of the excited states quenching, elastic collisions, spontaneous radiation and other processes occur. From the general physical presentations follows that for increase of laser efficiency, under small duration of the pumping particularly, it is necessary to reduce the generation time delay comparatively pump beginning.

According to our simulations the energy accumulated in the first capacitor is 15.9 J, the pump energy of discharge is 10.5 J. The energy of laser radiation is 0.38 J. Laser efficiency relatively pump energy is 3.6% and relatively energy stored in first capacitor is 2.4%. Efficiency of the laser defined as attitude of the maximum powers of generation and pumping is 4%. If the specific power of the pumping at given duration of the pulse will be reduced that the efficiency and energy of the radiation will sharply decreases too. And vice versa if the specific pump power will be increased that the efficiency and energy of the radiation will increase.

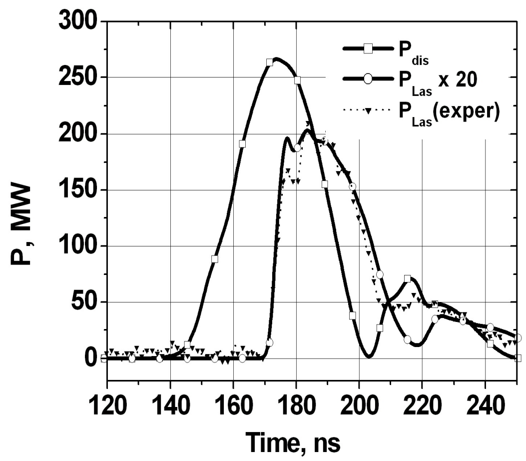

Fig.3. Experimental and calculated temporary behavior of laser radiation power and calculated pumping power.

In Fig.4 are shown the temporary dependencies of a concentration: electron, excited atom of the xenon Xe*, Xe** and Xe***, the molecules of HCl on ground and on three vibration excited states, as well as a concentration of laser radiation photons. For time ~20 ns from discharge beginning the electron concentration reaches $2x10^{15}$ cm^{-3}. In the same time the voltage on plasma falls with 20 kV before 7 kV. In this period of time the concentration of excited xenon atoms is greater, than electron concentration. Then the deceleration of the excited atoms growing occurs but the electron concentration continues to increase. The direct ionization changes to step-ionization. In conditions of strong reduction of the voltage on electrode the further growing of electron concentration is provided completely by step-ionizing.

The initial concentration (Fig.4) of the HCl molecules was $1{,}26x10^{17}$ cm^{-3}. The growing of the excited HCl(v) molecules concentration occurs in plasma. Accordingly, the attachment velocity of the electron to molecule HCl(v) increases. The following situation realizes in plasma when increase of the velocities both step- ionizing and dissociative attachment with growing of the electron concentration occur. The interaction of these processes defines the features of the plasma which much powerfully depends from initial HCl concentration. During the first half-cycle of discharge current a total HCl concentration fell before $0.8x10^{17}$ cm^{-3}, a consumption of the HCl molecules was $0.46x10^{17}$ cm^{-3}. In case a more full use of the HCl molecules that can be reached for longer pumping pulse duration the energy of the laser radiation will increase. Herewith a deterioration of discharge homogeneity can be. On this drawing a temporary dependency of photon concentration of laser radiation is shown, its maximum concentration is $4x10^{14}$ cm^{-3}.

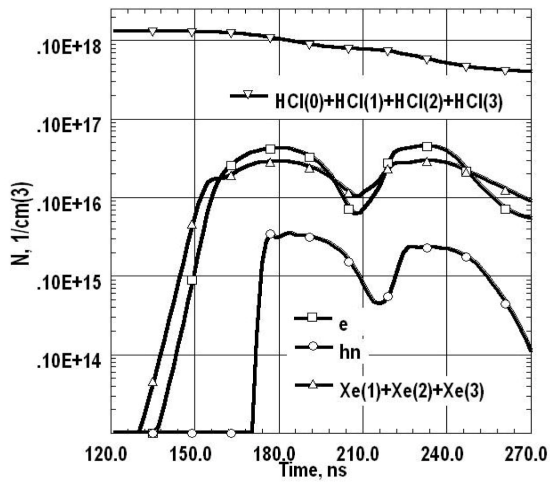

Fig.4. Temporary dependencies of plasma particles concentration.

In Fig.5 velocities of the following processes are shown: making XeCl** molecules, quenching of excimer molecules by electrons and heavy particles, stimulated and spontaneous radiation. The presented dependencies persuasively show that a strong quenching of excimer molecules first of all by electrons obstructs the development of generation and reduces an efficiency of the laser. At moment of 170 ns corresponding the beginning of the generation development the velocity of the molecules XeCl** making is $6{\cdot}10^{23}$ $cm^{-3}s^{-1}$. In this moment the quenching velocity of this molecules by electrons, the rest particles and velocity of the spontaneous radiation, accordingly, are: $3.5x10^{23}$ $cm^{-3}s^{-1}$, $1.0{\cdot}10^{23}$ $cm^{-3}s^{-1}$ and $0.5x10^{23}$ $cm^{-3}s^{-1}$. More than 80% from created excimer molecules is perished in reaction of the quenching and less than 20% of excited XeCl molecules converse to laser photons. So, the strong quenching slows the growing of $XeCl(B_0)$ molecules concentration, accordingly, increases the delay time of generation relatively of pumping beginning. In maximum of generation the situation improves the velocity of XeCl** molecules making is $7.5x10^{23}$ $cm^{-3}s^{-1}$ but the velocity of photons creation of laser radiation increases before $5x10^{23}$ $cm^{-3}s^{-1}$. Here to moment the quenching velocity of electrons falls before $2x10^{23}$ $cм^{-3}$ c^{-1}. In maximum of laser flow power in resonator an efficiency of conversion of excited XeCl molecules to laser photons increases up to 66%.

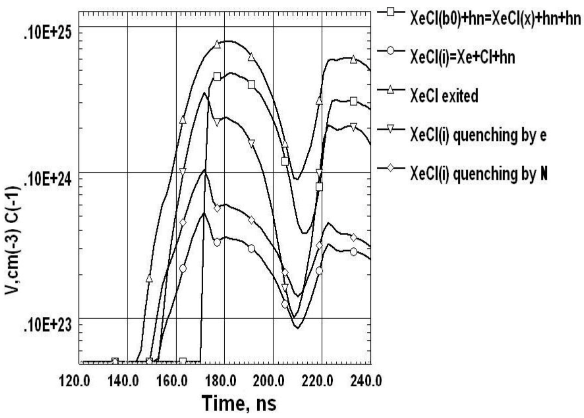

Fig.5. Creation and quenching velocities of excited XeCl molecules by electrons, heavy particles, stimulated and spontaneous radiation.

4. Conclusion

XeCl laser with output energy up to 0.38 J, the pulse duration at FWHM of 28 ns and 10 Hz pulse repetition rate has been created. The laser peak power of 10 MW, the energy density of 4.4 J/l and the total laser efficiency of 2.4 % have been achieved. Laser efficiency relatively pump energy was 3.6%. Efficiency of the laser defined as attitude of the maximum power of laser generation and pumping power was 4%.

Calculation results show that laser efficiency to a greater extent depends by time delay of laser pulse relatively to pump pulse. A main reason of time delay is high quenching of excited XeCl molecules by electrons in discharge plasma. More 80% created in plasma of excited XeCl molecules are destroyed in quenching reactions. The threshold of laser generation reaches only in pump pulse maximum and laser pulse are formed in pump decrease condition. During this time a high efficiency of conversion of excited XeCl molecules to laser photons of 66% realizes.

An efficiency and energy of laser radiation can be increased in case using of a pump mode having a more shot front rise time of a pumping power and relatively long back rise time.

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