Вісник Харківського національного університету імені В. Н. Каразіна.
Серія "Радіофізика та електроніка". № 983, випуск 19, 2011. С.3-10

УДК 535.8

THE XECL LASER WITH THE ADJUSTABLE SHAPE AND DURATION OF GENERATION PULSE

S.S. Anufrik, A.P. Volodenkov, K.F. Znosko
Yanka Kupala State University of Grodno, 22, Ozheshko Street, 230023, Grodno, Belarus,
e-mail: a.volodenkov@grsu.by

Paper received 10 October 2011

Исследованы генерационные параметры XeCl лазера с системой возбуждения на основе LC контура при использовании смеси Ne–Xe–HCl. Разработана компьютерная модель для нахождения генерационных параметров. Модель дает возможность рассчитывать осциллограммы тока, напряжения и мощности генерации для всех параметров системы возбуждения. Программа по моделированию XeCl лазера позволяет также рассчитывать концентрации электронов, атомов и молекул и энерговклад в активную среду. Скоростные коэффициенты реакций с участием электронов определяются при помощи программы Bolsig +. Показано, что возможна генерация коротких (20 нс) и относительно длинных (60 нс) импульсов излучения путем изменения параметров LC контура. Энергия генерации достигает максимума при использовании обострительных емкостей во много раз меньше накопительной емкости.

КЛЮЧЕВЫЕ СЛОВА: LC контур, XeCl лазер, система возбуждения, энергия генерации, длительность импульса.

Досліджено параметри генерації XeCl лазера з системою збудження на основі LC контура при використанні суміші Ne–Xe–HCl. Розроблено комп'ютерну модель для знаходження генераційних параметрів. Модель дає можливість розраховувати осцилограми струму, напруги і потужності генерації для усіх параметрів системи збудження. Програма по моделюванню XeCl лазера дозволяє також розраховувати концентрації електронів, атомів і молекул і енерговклад в активне середовище. Швидкісні коефіцієнти реакцій за участю електронів визначаються за допомогою програми Bolsig+. Показано, що можлива генерація коротких (20 нс) і відносно довгих (60 нс) імпульсів випромінювання шляхом зміни параметрів LC контура. Енергія генерації досягає максимуму при використанні загострюючих ємностей які у багато разів менші накопичувальної ємності.

КЛЮЧОВІ СЛОВА: LC контур, XeCl лазер, система збудження, енергія генерації, тривалість

The generation parameters of LC-contour excitation system are studied for electro-discharge excimer XeCl laser using a Ne–Xe–HCl mixture. A computation model is developed for finding the generation parameters. It has allowed us to calculate current, voltage and generation power oscillograms for all parameters of the electrical excitation system. The program of XeCl-laser modeling enables to calculate an electrons, atom and molecule concentrations, specific energy deposition in active medium also. By means of program Bolsig + calculation of rate coefficients of reactions with participation of electrons is executed. It is shown that generation of short radiation pulses (20 ns) and relatively long pulses (60 ns) is possible due to changing of LC- contour parameters. Energy of generation reaches a maximum at use of small values of peaking capacity, which are significantly smaller then value of storage capacity.

KEY WORDS: LC- contour, XeCl laser, excitation system, generation energy, pulse duration.

SIMULATION METHOD

Modeling of electro-discharge excimer XeCl-lasers is enough a difficult physical and mathematical problem. The model should take into account and describe processes which occur both in the active environment, and in system of excitation of the volume discharge. Generally the computer model includes the following modules and databases, which are submitted on fig. 1.

1) The module of the decision of Boltzmann equation for the electron energy distribution function (EEDF) [1, 2]. This module on composition of a mixture, on value of a degree of ionization and set *E/N* (*E* - intensity of an electric field in an interelectrode gap; *N* - full concentration of particles) allows to find EEDF and accordingly to define rates of plasma-chemical reactions with participation of electrons, and also to define electron mobility.

Rate factors of reactions with participation of electrons were obtained by averaging on EEDF expressions of next type.

$$k = \left\langle \sigma(\varepsilon) \cdot \sqrt{2\varepsilon/\mathrm{m}} \right\rangle \quad (1)$$

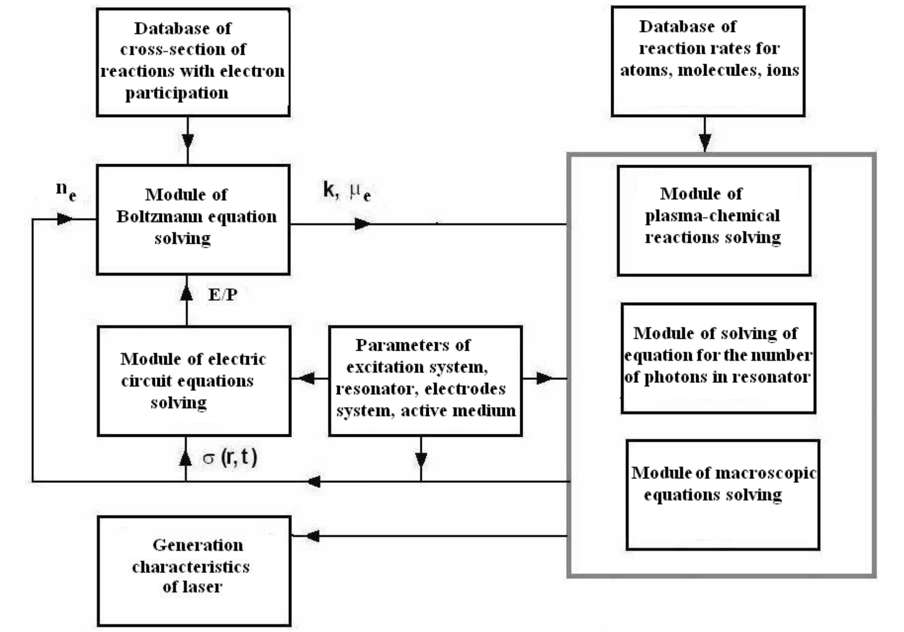


Fig. 1. Schematic diagram of method of modeling of XeCl-laser.

For the solving ready program Bolsig + [1, 2], which automatically calculates rate factors of reactions, is used.

2) The module of the decision of system of the equations of plasma-chemical reactions [3]. This module allows to find the time dependence of concentrations of electrons, ions, atoms and molecules in various energy levels in plasma. The module allows to determine various local characteristics of plasma.

In simplest case the next plasma-chemical reactions must be taken into account.

Ionization and excitation

$Xe + e \rightarrow Xe+ + e + e;\ (ki);\ \ Xe + e \rightarrow Xe^* + e;\ (ke1);\ \ Xe^* + e \rightarrow Xe+ + e + e;\ (ks1)$

Vibration excitation of HCl

$HCl(vi)+e \rightarrow HCl(vj)+e\ (kij)\ ;$

Dissociative attachment

$HCl(0) + e \rightarrow Cl^- + H;\ (k0a,);\ HCl(1) + e \rightarrow Cl^- + H;\ (k1a,\ );\ HCl(2) + e \rightarrow Cl^- + H;\ (k2a)$

Production of XeCl-molecules

$Xe^* + HCl(\mathrm{v}) \rightarrow XeCl^* + H\ (k_{harp})\ ;\ Xe+ + Cl- + M \rightarrow XeCl^* + M;\ (\beta_{rec})$

Quenching of XeCl- molecules

$XeCl^* + e \rightarrow Xe + Cl + e;\ (kq);\ XeCl^* + N \rightarrow Xe + Cl + N;\ (\tau q)$

Emission of XeCl- molecules

$XeCl^* \rightarrow Xe + Cl + h\nu;\ (\tau_{sp});\ XeCl^* + h\nu \rightarrow Xe + Cl + 2\ h\nu;\ (\sigma_{in})$

Absorbtion on wavelength of generation

$Cl- + h\nu \rightarrow Cl+e;\ (\sigma_{abs})$

3) The module of the decision of system of the equations of photochemical reactions [3-4]. Generally this module should include the equation of radiation transfer. In the elementary case it is an equation for number of photons in the resonator.

$$\frac{dQ}{dt} = \left(c\sigma_{in} \cdot \frac{V_a}{V} \cdot \left[XeCl^* \right] - \frac{1}{\tau_{ph}} - c\sigma_{absz} \cdot \frac{V_a}{V} \cdot \left[Cl^- \right] \right) \cdot Q \tag{2}$$

V_a - volume of the active medium; V - volume of the resonator; τ_{ph} - time of a life of a photon in the resonator; $[XeCl^*]$ concentration of excimer molecules; $[Cl^-]$-concentration of ions of chlorine; σ_{in} – cross-section of induced radiation; σ_{abs} - cross-section of absorption by ions of chlorine.

Intensity of radiation of the laser is determined by next expression.

$$I = \frac{Q \cdot h\nu}{S \cdot \tau_{ph1}};\ \frac{1}{\tau_{ph1}} = \frac{c \cdot \left(-\ln R_1 \right)}{2L} \tag{3}$$

τ_{ph1} - finite time of a life of a photon in the resonator due to transmission of the first mirror, the second mirror is counted to be totally reflecting mirror. R_1 is factor of reflection of the first mirror; L - length of the resonator; S- the aperture of a beam of generation.

4) The module of the decision of the macroscopic equations of medium [3-4]. Generally this module allows to define spatial and time dependence of local characteristics of plasma, for example for electron concentration. In the elementary case at modeling plasma can be considered to be spatially homogeneous.

5) A database on dependence of cross-sections of reactions with participation of electrons from their energy (file Siglo.sec from Bolsig+), a database on rates of plasma-chemical reactions with participation of atoms, ions, molecules and photons [1-7].

6) The module of the decision of the equations of an electric circuit [3-4]. This module describes work of system of excitation of the volume discharge in an interelectrode gap. On the total resistance of plasma this module allows to define time dependence of a voltage formed by excitation system on interelectrode gap.

As the system of excitation of the laser, a LC-contour contains storage capacity C1 and peaking capacity C0, being consistently included through inductance L1 (fig. 2).

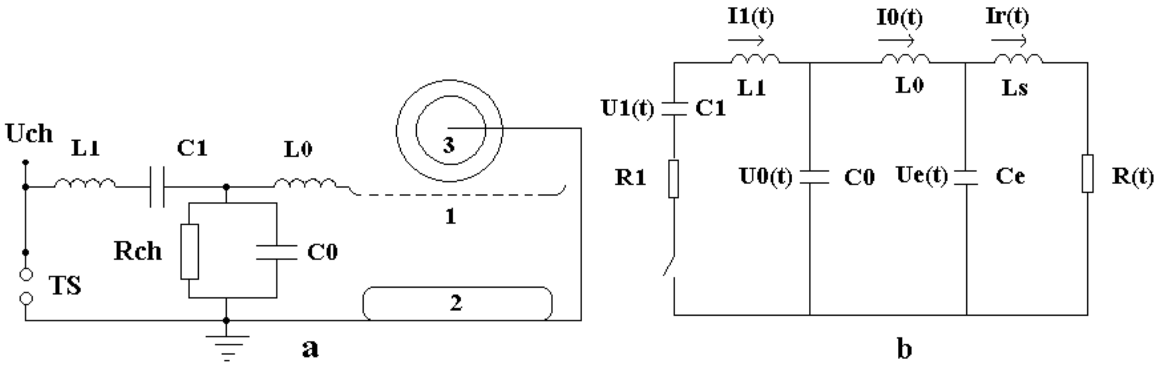


Fig. 2. The constructive circuit of the laser (a) and an equivalent electric circuit (b).

The next designations are used on Fig. 2: C1 - storage capacity; C0 - peaking capacity; L1, L0, Ls - contour inductance; Rch - charging resistance; a Uch - charging voltage; (1, 2) - the basic electrodes; 3 - preionization electrode ; TS - triggered switch; R1-resistance of triggered switch; Ce - capacity of an interelectrode gap; R(t) - resistance of a discharge gap; U1(t) - a voltage on storage capacity; U0(t) - voltage on peaking capacity; Ue(t) - a potential difference on electrodes of the laser; I1(t), I0(t) and Ir(t) - contour currents.

As C1 is recharged on C0 through the switchboard, which possesses the active resistance comparable to resistance of plasma in an interelectrode gap, the significant part of the energy reserved in C1 is lost on it. Hence, one of ways of increase in efficiency and output energy of generation is reduction of losses by the triggered switch. The following characteristic operating modes of a LC-contour are possible [8].

A. At small values of peaking capacities C0 its basic function will consist in formation of the volume discharge. It is charged from storage capacity C1 up to a voltage about double charging voltage, and then quickly run down on an interelectrode gap. At such high overvoltage (5 кV/(cm atm) and sharp front of a pulse of excitation the homogeneous volume discharge is formed. Itself peaking capacity C0 is unloaded at a stage of breakdown, when resistance of discharge plasma is highly enough. The basic energy input in the discharge in this case is carried out from storage capacity C1.

B. At increase of peaking capacities C0 (at simultaneous increase L1) its role changes. Alongside with formation of the discharge it carries out energy input in the discharge. And its power is comparable with power of energy input from C1.

C. If the value of peaking capacities C0 becomes one order with storage C1 the operating mode with full recharging is possible. In this case all energy stored in C1 passes in peaking capacity C0, and in such mode maximum efficiency of the laser is provided as a rule [8].

We had been created the computer program of calculation of idle and working operating modes of system of excitation on the basis of a LC-contour. Under the analytical model on fig. 1, the following system of the equations would be made:

$$\begin{gathered}\frac{dI1}{dt}=\frac{U1-I1\cdot R1-U0}{L1};\ \frac{dI0}{dt}=\frac{U0-Ue}{L0};\\ \frac{dIr}{dt}=\frac{Ue-Ur}{LS};\ \frac{dU1}{dt}=-\frac{I1}{C1};\\ \frac{dU0}{dt}=\frac{I1-I0}{C0};\ \frac{dUe}{dt}=\frac{I0-Ir}{Ce}.\end{gathered}\tag{4}$$

Where *Ir* is current through discharge and *Ur=IrR(t)* is voltage on laser electrodes. In the analytical model (fig. 2b) interelectrode capacity *Ce*, resistance of discharge *R(t)* and own inductance of discharge *Ls* is entered.

These three values model an impedance of the discharge. Intensity of an electric field $\vec{E}$ in the discharge has two components

$$\vec{E} = -\nabla\varphi - \frac{\partial \vec{A}}{\partial t} \tag{5}$$

The first component in (5) is strength of the electrostatic field caused by charges. The second component is caused by variable magnetic field. In quasi-stationary approach the vector potential $\vec{A}$ is determined by currents flowed in the system, therefore the second component depends on speed of change of currents and it is possible to write down

$$Ur = Ir \cdot R = Ue - Ls \cdot \frac{dIr}{dt} \tag{6}$$

7) A database which describes system of excitation, electrode system and the resonator of the laser, and partial pressure of composition agents [3-4].

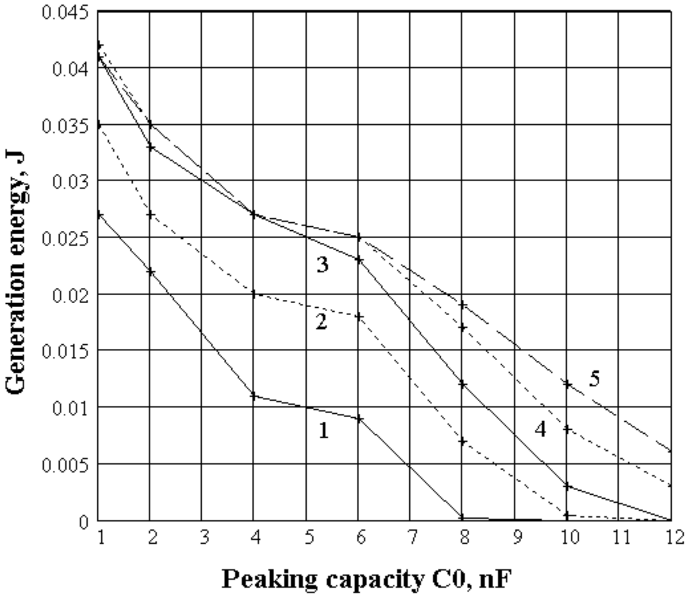
It is necessary to note, that the computer model should provide the simultaneous and self-consistent decision of systems of the equations described by modules and databases (1-7).

RESULTS

Calculations were carried out at the following composition of a gas mix: partial pressure of HCl was equaled 1,5 Torr; partial pressure of Xe was equaled 30 Torr; buffer gas a neon at the total pressure 3,5 atm. For calculations the following parameters of a radiator have been used: length of electrodes L=20 cm; interelectrode distance h=2 cm; width of the discharge b=0,5 cm. It was considered, that the resonator of the laser has been formed by mirrors which were on distance D=25 cm from each other and their factors of reflection were equaled 100 % and 33 %.

At modeling the following fixed parameters of system of excitation have been used: storage capacity C1 = 12 nF; resistance of triggered switch R1=0,15 Ohm; inductance of a contour of the discharge of storage capacity on peaking capacity L1=20 nHn. Calculations were carried out at the following variable parameters of system of excitation: C0=1 - 12 nF; L0=5 - 40 nHn; charging voltage Uch=20 - 30 kV.

On Fig. 3 dependence of energy of generation on value of peaking capacity is submitted.



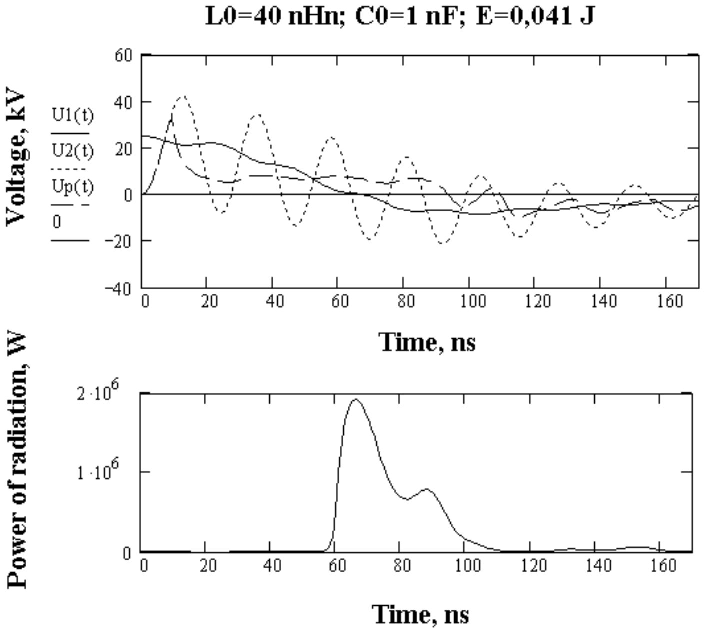
1 – L0=5 nHn; 2 – L0=10 nHn; 3 – L0=20 nHn; 4 – L0=30 nHn;
5 – L0=40 nHn

Fig. 3. Dependence of energy of generation from value of peaking capacity (Uch=25 kV).

From the dependences submitted on Fig. 3 follows, that energy of generation reaches a maximum at use of small values of peaking capacity C0 <<C1. Basic function C0 will consist in formation of the glow discharge. It is charged from storage capacity C1 up to a voltage about double charging voltage, and then C0 is quickly unloaded on an interelectrode gap. At so high overvoltage and abrupt front of a pulse of excitation the homogeneous volume discharge is formed. Itself peaking capacity C0 is unloaded at a stage of breakdown, when

resistance of discharge plasma is highly enough. The basic energy input in the discharge in this case is carried out from storage capacity C1.

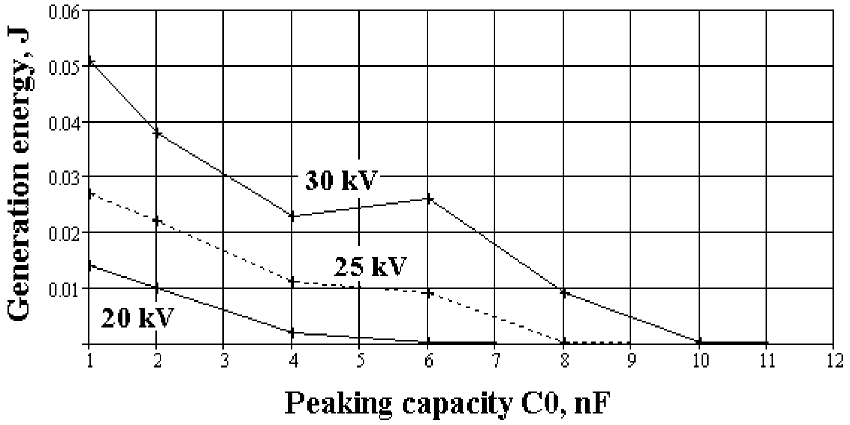
On Fig. 4 typical oscillograms for this case are submitted.



L0=40 nHn; C0=1 nF; E=0,041 J

Fig. 4. Calculation oscillograms of pulses of a voltage and power of generation (Uch=25 kV).

On Fig. 5 dependence of energy of generation on value of peaking capacity is submitted for different charging voltage Uch.



1 – L0=5 nHn; 2 – L0=10 nHn; 3 – L0=20 nHn; 4 – L0=30 nHn;
5 – L0=40 nHn

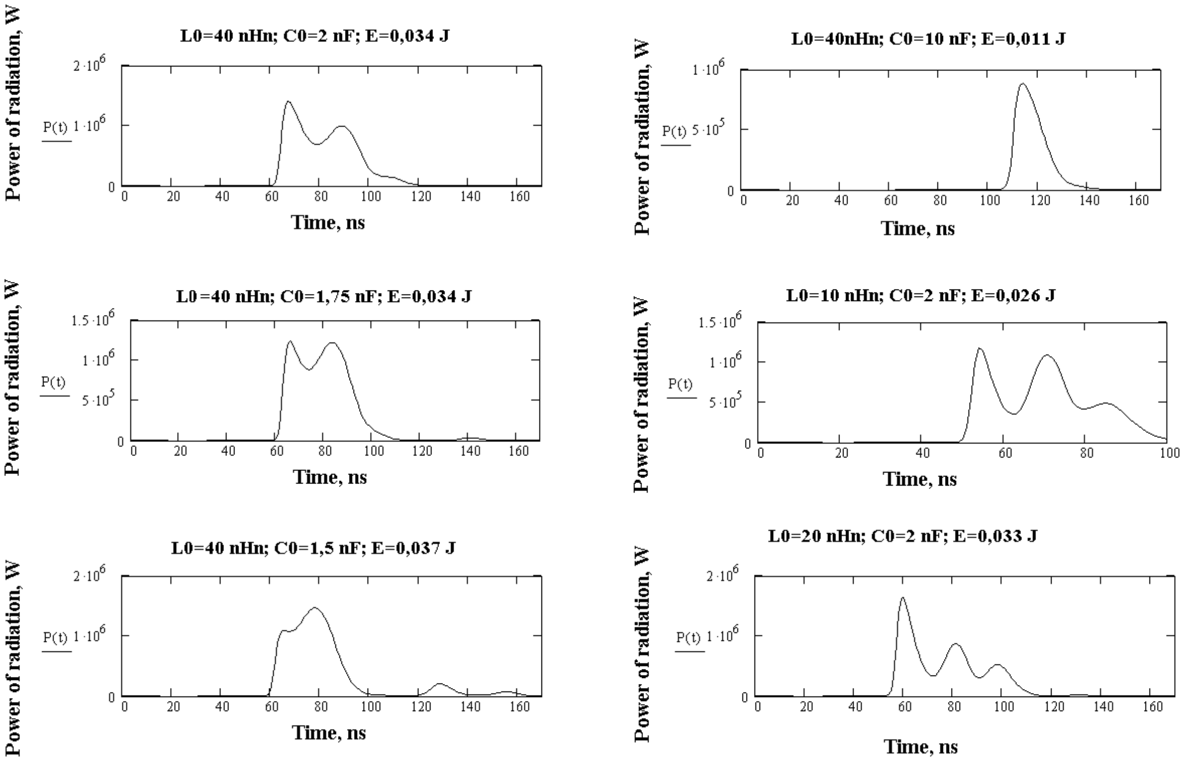
Fig. 5. Dependence of energy of generation from value of peaking capacity (L0=5 nHn).

From the dependences submitted on Fig. 5 follows, that energy of generation reaches a maximum at use of small values of peaking capacity C0 <<C1 for Uch=20-25 kV. For Uch=-30kV energy of generation reaches a maximum at use of small values of peaking capacity and for C0 ~ 6nF.

The possibility to control the pulse duration and amplitude of excimer lasers is very important in many applications. The duration of UV pulses generated by electric-discharge excimer lasers can vary from 10 to 50 ns. The use of quasi-stationary pumping provides generation of laser pulses with the duration over 100 ns. Most electric-discharge excimer lasers are known to produce pulses of duration ~ 20 ns. It is difficult for a single laser to generate both short (<10 ns) and long (>100 ns) pulses.

It is necessary to note, that the form of a pulse of generation essentially depends on parameters of system of excitation. This dependence can be used to carry out purposeful management of the form of a pulse of generation, and also its duration.

On Fig. 6 calculation oscillograms of dependence of power of generation from time which have been received at different values of peaking capacity and inductance L0 are submitted.


L0=40 nHn; C0=2 nF; E=0,034 J

L0=40nHn; C0=10 nF; E=0,011 J

L0=40 nHn; C0=1,75 nF; E=0,034 J

L0=10 nHn; C0=2 nF; E=0,026 J

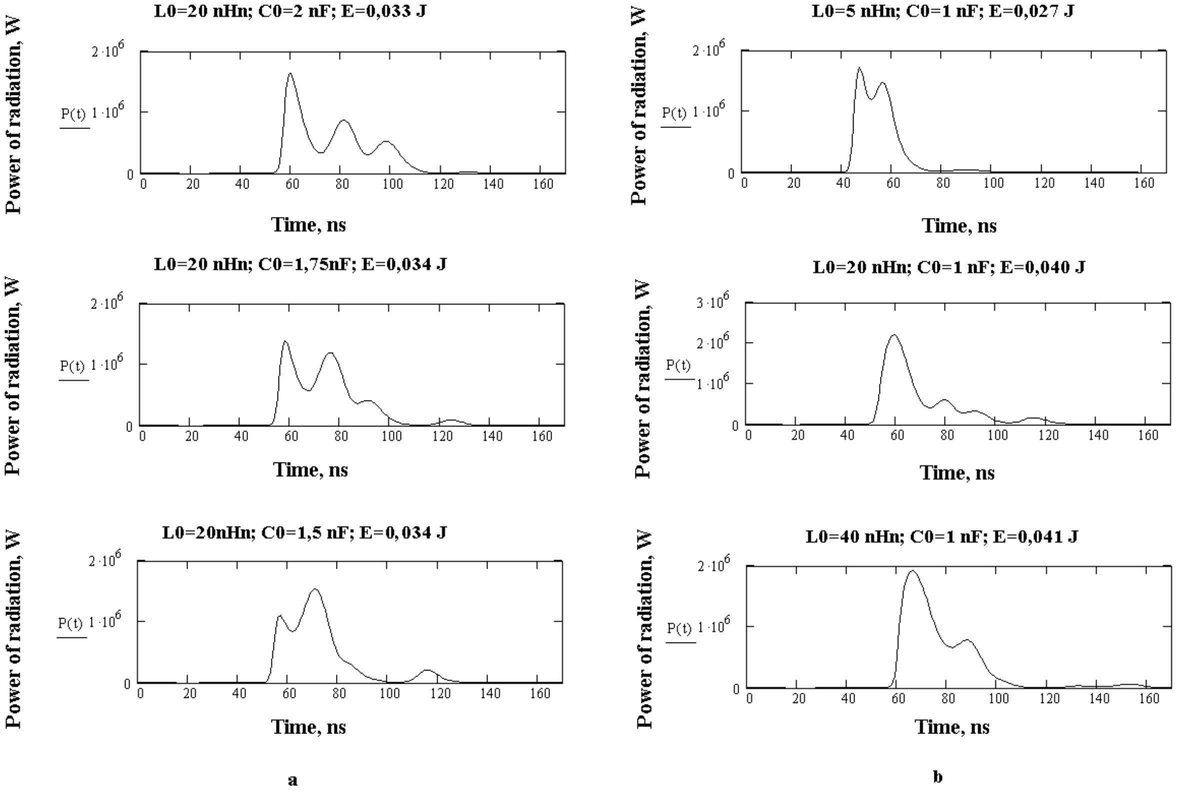
L0=40 nHn; C0=1,5 nF; E=0,037 J

L0=20 nHn; C0=2 nF; E=0,033 J

Fig. 6. Calculation oscillograms of power of generation (Uch=25 kV).

From the dependences submitted on Fig. 6 follows, that shape of pulse of generation depends on value of peaking capacity C0, while duration of generation pulse remains approximately constant and equal 40 ns.

On Fig. 7 calculation oscillograms of dependence of power of generation from time which have been received at different values of peaking capacity and inductance L0 are submitted.


L0=20 nHn; C0=2 nF; E=0,033 J

L0=5 nHn; C0=1 nF; E=0,027 J

L0=20 nHn; C0=1,75nF; E=0,034 J

L0=20 nHn; C0=1 nF; E=0,040 J

L0=20nHn; C0=1,5 nF; E=0,034 J

L0=40 nHn; C0=1 nF; E=0,041 J

a

b

Fig. 7. Calculation oscillograms of power of generation (Uch=25 kV).

From the dependences submitted on Fig. 7a follows, that shape of pulse of generation depends on value of peaking capacity C0.

If value of peaking capacity C0=2 nF, the pulse of generation has 3 maximum. Moreover, the value of first maximum is significantly greater, than values of other maximums.

If value of peaking capacity C0=1,75 nF, the pulse of generation has 3 maximum. Moreover, the value of first maximum is approximately such, as value of second maximum.

If value of peaking capacity C0=1,5 nF, the pulse of generation has 3 maximum. Moreover, the value of second maximum is significantly greater, than values of first maximums.

From the dependences submitted on Fig. 7b follows that shape of pulse of generation and generation energy depend on value of inductance L0.

CONCLUSIONS

The computational model for two-contour excitation systems of XeCl lasers has been developed. On the basis of this methods simulation of generation characteristics of the XeCl-laser with systems of excitation such as a LC-contour is executed at various composition of active medium, parameters of excitation system and charging voltage. Computational model has allowed us to calculate current, voltage and generation power oscillograms for all points of the electrical excitation system. Results of simulation correspond to the experimental data received at research of these lasers [8]. The duration and the shape of output pulses can be varied of the discharge current with insignificant changes in the excitation system parameters. We have shown the excitation system under study provides multi-pulse generation of both short (20 ns) and long (60 ns) laser pulses.

From calculated dependences we have the next conclusions.

1. The energy of generation has achieved maximum value at using of small values of peaking capacitance C0<<C1.
2. Maximum value of generation energy has obtained at some optimal value of L0 (in our case 30 nHn).
3. The main function of peaking capacitance C0 consists in forming of glow volume discharge.
4. In this case the main energy input in discharge is due to storage capacitance C1.
5. The kind of curve of dependence of energy of generation from value of peaking capacity essentially depends on value of charging voltage.
6. Change of value of peaking capacitance C0 allows to govern by duration and form of pulse of generation.
7. Change of value of contour inductance L0 allows to govern by duration and form of pulse of generation.

Our model contains one basic lack. Width of the discharge was taken from experiment. The technique of modeling of the XeCl-laser in view of a profile of electrodes allows to define distribution of intensity of generation under the aperture of a laser beam [9]. Besides the effective width of the discharge and its dependence on parameters of system of excitation, electrodes of the laser, the active medium and charging voltage is determined. Modeling was carried out for the electro-discharge laser which electrodes represented cylinders of radius R=6 cm which axes were on distance D=14,8 cm from each other. For finding of an electric field in such electrode system it is convenient to use following conformal transformation.

$$Z(U,V)=\frac{2\sqrt{\left(\frac{D}{R}\right)^{2}-R^{2}}}{1-e^{-iW(U,V)\cdot\frac{2a\cosh\left(\frac{D}{2R}\right)}{\Delta V}}} \qquad (7)$$

Thus a band in plane W=U+iV (a rectangular in the size ΔUxΔV) is displayed on appearance of two cylinders of electrodes in plane Z=X+iY.

Dependence of width of a beam of generation on composition of a laser mix without taking into account a volume charge has been theoretically investigated. These results did not correspond to experimental data which have been received for the laser with such electrode system in work [10].

To remove this contradiction in settlement model the field formed by a volume charge which arises owing to non-uniform ionization of an interelectrode interval and drift of electrons has been taken into account. In this case we have a good agreement between calculated and experimental data.

REFERENCES

1. Hagelaar G.J.M., Pitchford L.C. Solving the Boltzmann equation to obtain electron transport coefficients and rate coefficients for fluid models // Plasma Sources Sci. Technol. – 2005. Vol. 14. №1. – P.1-12.
2. http://www.codiciel.fr/plateforme/plasma/bolsig/bolsig.php.
3. Anufrik S., Volodenkov A., Znosko K. Kinetic model for XeCl-lasers // LFNM'2006, – 2006. Kharkov,

Ukraine, P.80-83.

4. Ануфрик С.С., Ануфрик А.С., Володенков А.П., Зноско К.Ф. Модель активной среды XeCl-лазера // Материалы VI Международной конференции «Лазерная физика и оптические технологии», – 2006. Гродно, Беларусь, Часть1, С.168-170.
5. Oihong Lou The effect of specific input energy on the performance of an X-ray preionised XeCl discharge laser // Optics Communication. – 1988. Vol. 65-1, P. 26-32.
6. Багинский В.М., Головинский П.М., Данилычев В.А. и др. Динамика развития разряда и предельные характеристики лазеров на смеси He-Xe-HC1 // Квант. электрон., – 1986. Т. 13-4. С. 751–758.
7. Christov Ch.G., Chaltakova N.G. Simplified discharge model for excimer lasers // Bul. J.Phys. – 1988. Vol. 15–5. P. 497–506.
8. Ануфрик С.С., Зноско К.Ф. Влияние параметров LC-контура на энергию генерации XeC1-лазера // Квантовая электроника. – 1989. Т. 16. №11. С.2228-2231.
9. Ануфрик С.С., Володенков А.П., Зноско К.Ф. Методика моделирования XeCl-лазера с учетом профиля электродов и объемного заряда в межэлектродном промежутке // Материалы VIII Международной конференции «Лазерная физика и оптические технологии». – 2010. Минск, Беларусь. С.46-49.
10. Panchenko Yu. N., Losev V. F., Yastremsky A. G., Anufrik S. S. Formation of discharge spatial structure in XeCl laser // Abstacts of IX International Conf. Atomic and Molecular pulsed lasers. – 2009. Tomsk, Russia, P.9.