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Non-stationary absorption in a XeCl* eximer nuclear pumped laser excited by a pulsed nuclear reactor

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The sources of non-stationary losses that occur in a XeCl* excimer laser with nuclear pumping excited by a pulsed nuclear reactor are considered. Experimental studies of the spectral and temporal characteristics of the luminescence of Ar-Xe-CCl_4 gas mixtures of various compositions were conducted in the wavelength range of $200 - 1100$ nm when excited by the products of the neutron nuclear reaction ^{235}U(n,f). The main losses of the *B*-*X* band radiation of the XeCl* molecule ($\lambda_{max} = 308$ nm) occurred due to the effect of the nuclear reactor's instantaneous gamma radiation on the laser's active medium and optical elements. The maximum value of the measured coefficient of non-stationary absorption of the active medium of the XeCl* excimer laser at a wavelength of 308 nm at the moment of the gamma radiation pulse action was $2.5 \cdot 10^{-2}$ cm^{-1}. Self-absorption at the B-level of the *B*-*X* radiation of the XeCl* molecule ($\lambda_{max} = 308$ nm) led to the appearance in the luminescence spectrum of a new *B*-*X* band of the XeCl* molecule ($\lambda_{max} = 236$ nm). The non-stationary intra-cavity refractive index of the Ar-Xe-CCl_4 gas mixture for the *B*-*X* band of XeCl* (308 nm) has been determined to be $n_{res} = 1.1176$. A new method has been proposed for determining the gain characteristics of the active medium of a nuclear-pumped excimer laser over the entire time range of the pump pulse.

Keywords: nuclear pumping, excimer laser, gamma radiation, non-stationary absorption, pulsed nuclear reactor.

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Introduction

Nuclear-pumped lasers directly convert energy of nuclear reactions into light radiation and operate in the wavelength range from IR to near UV [1–4]. The first laser of such type was launched in 1972 in the All-Russian Research Institute for Experimental Physics (Sarov, USSR) [5]. In the USA the generation from nuclear pumping was achieved in 1973 in one year [6,7]. Currently the coefficient of nuclear energy conversion into laser radiation is several percent from the pumping energy contributed to gas, and the achieved level of beam energy in the pulse mode exceeds 500 J with generation pulse duration of 400 μs [8]. The feature of operation of nuclear-pumped lasers using neutron radiation of a nuclear reactor to initiate nuclear reactions, is the considerable reduction in the coefficient of amplification of the laser active medium for the duration of the pulse pumping [2] (see pages 35, 42, 164). This effect is especially strong in excimer media [9,10]. For example, when Ar-Xe-CCl_4-gas mixture is pumped with the products of tne neutron nuclear reaction ^{235}U(n,f), the low-threshold generation that started with high amplification coefficient at *B*-*X*- and *C*-*A*-transitions of excimer molecule XeCl* ($\lambda = 308$, 352 nm) in 50 μs was moderated significantly, which further prevented development of generation even when the maximum energy deposition level was achieved. Fig. 1 shows the time oscillograph chart of the typical generation mode for *B*-*X*-transition of molecule XeCl* ($\lambda_{max} = 308$ nm). Its appearance is explained by the formation of non-stationary absorption sources related to the features of the gamma neutron radiation of the nuclear reactor in the active medium of the laser at the moment of the pumping pulse being in effect.

The products of neutron exothermic nuclear reactions ^{3}He(n,p)^{3}T, ^{10}B(n,α)^{7}Li, ^{235}U(n,f), used to excite the active medium of the nuclear-pumped laser create a special type of plasma — the so called track plasma [11]. This plasma

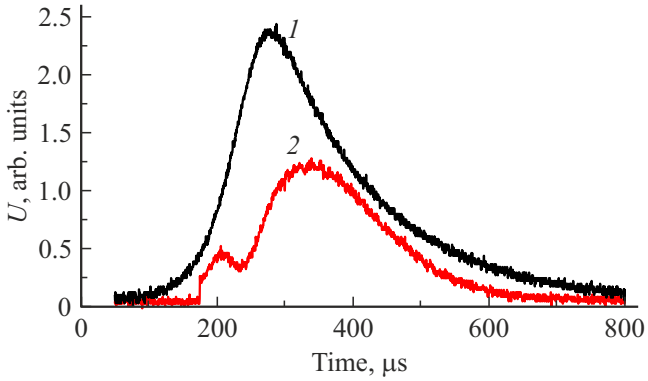

Figure 1. Typical oscillograph charts of the pulse of thermal pumping neutrons (*1*) and generation of excimer XeCl*-laser at wavelength of 308 nm (*2*). Mixture composition: Ar — 780 Torr, Xe — 20 Torr, CCl_4 — 50 mTorr, the resonant cavity output mirror has the transmittance of $T = 0.4\%$ at the wavelength of 308 nm, the generation starts at the specific capacity of the energy deposition of fission fragments into gas ~ 200 W/cm^3.

is characterized by the constancy of the composition, is spatially inhomogeneous (consists of separate tracks of particles), and all major plasma-chemical reactions happen directly in the track volume. The nuclear reactions are initiated in the laser's active medium by radiation of the pulse nuclear reactor. This radiation consists of the pulse of gamma quanta with the average energy of $E_\gamma = 0.9$ MeV and a fast neutron pulse with the average energy of $E_n = 2$ MeV. Both radiation components coincide in time. To improve the effectiveness of the nuclear pumping reaction of the laser active medium, fast neutrons are moderated down to thermal energy ($E_{\text{thermal.neutron}} = 0.025$ eV), and a time shift occurs between the pulse of the thermal pumping neutrons and the pulse of the prompt gamma rays of the reactor (Fig. 2). The interaction of the gamma rays with the materials of the design and the active medium of the laser causes formation of the secondary electrons and additional homogeneous ionization of the laser gas medium. In the track plasma created by the products of nuclear reactions this causes unwanted effects of excimer molecule quenching, and the impact of electrons at the optical materials causes formation of the color centers and additional absorption of excimer radiation.

This paper considers the sources of non-stationary losses occurring at the moment of action of the gamma neutron pumping pulse related to the changes in the properties of the excimer nuclear-pumped laser active medium and with radiation resistance of the optical elements in its design.

The purpose of this paper was to study experimentally the processes of formation of excimer molecules $XeCl^*$ with nuclear pumping of dense gas mixtures Ar-Xe-CCl_4 by mixed gamma neutron pulse radiation and to study the mechanisms of amplification and absorption of radiation from B-X-band of the excimer molecule $XeCl^*$ ($\lambda_{\max} = 308$ nm) under such conditions.

Causes for non-stationary losses in Ar-Xe-CCl_4-gas mix when pumped with nuclear reactor radiation

The composition of the track plasma depends mainly on the components of the gas medium and the initial energy of the nuclear particle and hardly depends on the pumping level to the moment of track overlapping, which occurs at the specific energy deposition into gas exceeding 10 kW/cm^3. The quantity of ions produced in the track, excited atoms and delta-electrons is determined by the semi-empirical Platzman's formula [12]:

$$W = E_0/N_i = E_i + (N_{\text{ex}}/N_i)E_{\text{ex}} + E_e = 1.7I. \quad (1)$$

Here W — energy spent by a charged particle with energy of E_0 to form one pair of buffer gas ions; N_i, N_{ex} — number of ions formed in the track and excited atoms; E_i, E_{ex}, E_e — average energy of ion, excited atom and secondary subthreshold electron; I — potential of buffer gas ionization.

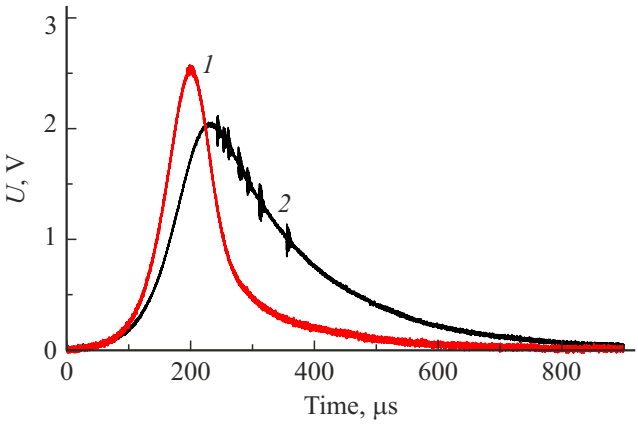

Figure 2. Pulse of prompt gamma-rays from the nuclear reactor (*1*) and the pulse of thermal pumping neutrons (*2*) on the axis of the cell in the center of the polyethylene neutron moderator.

For the fission fragments for all inert gases $N_{\text{ex}}/N_i = 0.53$, $E_i = 1.06I$, $E_{\text{ex}} = 0.85I$, $E_e = 0.31I$ [2]. At atmospheric pressure of the gas mixture the concentrations of positive ions and electrons at the initial moment of track formation are $\sim 10^{14} - 10^{15}$ particles/cm^3 [11].

All main plasma-chemical processes happen within the track volume. Excimer molecules $XeCl^*$ and Xe_2Cl^* mostly form from the reaction of ion-ion recombination of ions Xe^+, Xe_2^+ and Cl^-:

$$Xe^+(Xe_2^+) + Cl^- + (Xe, Ar) \rightarrow XeCl^*(Xe_2Cl^*) + (Xe, Ar). \quad (2)$$

The donor of Cl atoms in the paper instead of the pure Cl_2 was a chemically inert compound CCl_4, which prevented the change in the composition of the active medium of excimer laser due to the chemical interaction of molecules Cl_2 coated with ^{235}U and design elements of the laser cell.

Track electrons are quickly captured, for the time of ~ 1 ns, by CCl_4 molecules forming negative ions Cl^- [13] and nearly electron-free plasma by dissociative attachment:

$$CCl_4 + e \rightarrow CCl_4^- \rightarrow CCl_3 + Cl^-. \quad (3)$$

Optimal concentration of CCl_4 in Ar-Xe-CCl_4-mixture of atmospheric pressure is $10^{15} - 10^{16}$ mol/cm^3. Low value of the concentration depends on the track structure of plasma: due to the absence of the free electrons in the track, the increase in partial pressure of CCl_4 in the mix (above 300 mTorr) does not result in the increase of the number of negative ions Cl^- in the track, but causes strong collision quenching of excimer molecules [14]:

$$XeCl^* + CCl_4 \rightarrow \text{ products}. \quad (4)$$

Gamma rays of the nuclear reactor from the photoelectric effect and Compton scatter are the additional source of electrons that is unbalanced in accordance with the equation (1). When interacting with the active medium of the laser and walls of the laser cell, gamma rays create

practically homogeneous ionization of the entire gas volume. Therefore, the balanced (nearly electron-free) track plasma containing excimer molecules $XeCl^*$ and Xe_2Cl^* formed by the uranium fission fragments is exposed to the external bombardment with secondary photoelectrons and Compton electrons generated by the reactor gamma rays. These electrons in the tracks of particles damage the excimer molecules in superelastic collisions:

$$XeCl^*(B, C) + e \rightarrow Xe + Cl + e' \qquad (5)$$

and in dissociative attachment of low energy electrons (~ 1 eV and above) [10,15]:

$$XeCl^*(B, C) + e \rightarrow Xe(Xe^*) + Cl^-. \qquad (6)$$

This causes lower population of B- and C-states of the excimer molecule $XeCl^*$ at the moment of the gamma rays pulse being in effect. Speed constants of reactions (5) and (6) are in the range from $2 \cdot 10^{-7}$ to $4 \cdot 10^{-7}$ cm^3/s.

The exposure of quartz windows and substrates of mirrors at powerful gamma rays also causes weakening of radiation from B-X-band of the $XeCl^*$ molecule due to the change in the optical transmittance of these parts. Under pulse radiation the induced absorption contains fast and slow components, besides, the absorption coefficient in a fast component is considerably higher than in the slow one, and increases with the reduction in the wavelength of the probing radiation. In the KV quartz in process of pulse radiation, a band of induced absorption occurs with the maximum at wavelength 300 nm, and in KI quartz — bands with maximum of 215 nm and wide bands at 300 and 500 nm. Specific values of induced absorption coefficients of quartz glasses at the wavelength of 400 nm at the absorbed dose capacity of 10^6 Gr/s for quartz KI are 0.6 cm^{-1}, for KV — 0.36 cm^{-1} and for KU-1 — 0.07 cm^{-1} [2]. For shorter wavelengths the coefficients of induced absorption will be substantially higher.

The category of non-stationary losses of active medium of $XeCl^*$-laser not related to the exposure to the gamma pulse includes self-absorption of radiation of B-X-band ($\lambda_{max} = 308$ nm) into „continuum“ of highly excited states of molecule $XeCl^*$ [16]:

$$XeCl^*(B, C) + 308\,\text{nm} \rightarrow XeCl^{**}. \qquad (7)$$

In process of collisional relaxation, D-level is populated:

$$XeCl^{**} + e \rightarrow XeCl^*(D) + e', \qquad (8)$$

which disintegrates spontaneously with emission of radiation of D-X-band of molecule $XeCl^*$:

$$XeCl^*(D) \rightarrow Xe + Cl + 236\,nm. \qquad (9)$$

Processes (7)–(9) are present always and are especially well-observed at high populations of B-, C-states of molecule $XeCl^*$ (Fig. 3). As a result, in the emission spectrum the D-X-band ($\lambda_{max} = 236$ nm) of high brightness arises, which has not been observed there previously.

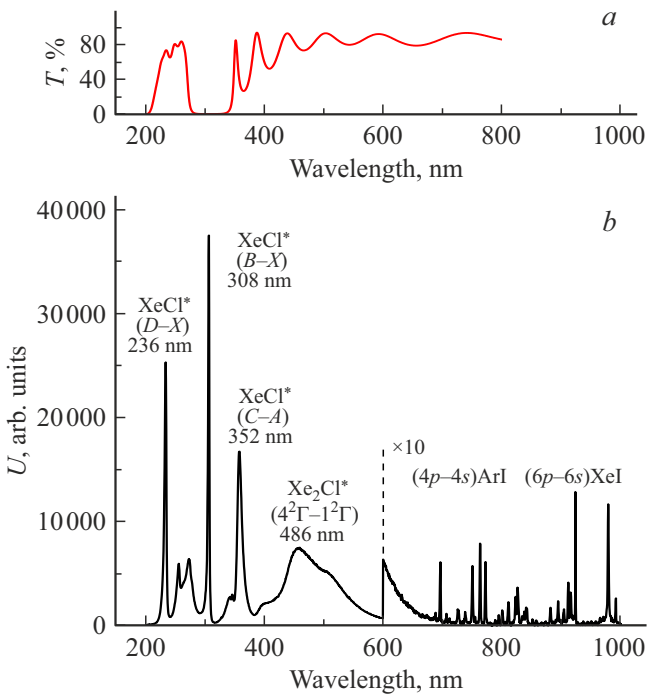

Figure 3. Luminescence spectrum of Ar-Xe-CCl_4-ga mixture in the generation mode when pumped with uranium 235 (b) fission fragments and transmission coefficient T of the output mirror of the laser cell (a). The scale along axis Y is changed 10 times in the interval of the wavelengths 600 – 1000 nm. Intracavity intensities of B-X- and D-X-bands of molecule $XeCl^*$ ($\lambda_{max} = 308$, 236 nm) with account of transmittance of the output mirror ($T_{236nm} = 73.11\,\%$, $T_{308nm} = 0.14\,\%$) are equal to $25320/0.7311 = 37633$ a. u. (236 nm) and $37542/0.0014 = 26816400$ a. u. (308 nm).

The process is accompanied with the effect of abnormal dispersion for B-X-transition of the radiating molecule $XeCl^*$ causing significant change of the medium refractive index at the wavelength of 308 nm and accordingly to the change of focusing or defocusing of the generated output beam.

All three factors are the sources of the non-stationary absorption of radiation of B-X-band of excimer molecule $XeCl^*$ ($\lambda_{max} = 308$ nm) when pumped with the mixed gamma-neutron radiation of the nuclear reactor.

Experimental setup

Studies of luminescence of the dense gas mixtures Ar-Xe-CCl_4 were carried out in a pulse nuclear reactor with medium pumping with uranium-235 fission fragments with energy $E_f = 70$ MeV and duration of pulse of thermal pumping neutrons $T_p = 240\,\mu$s at half maximum. The block diagram of the experimental setup is shown in Fig. 4. The laser cell of window-free design $\varnothing 27 \times 1000$ mm with the

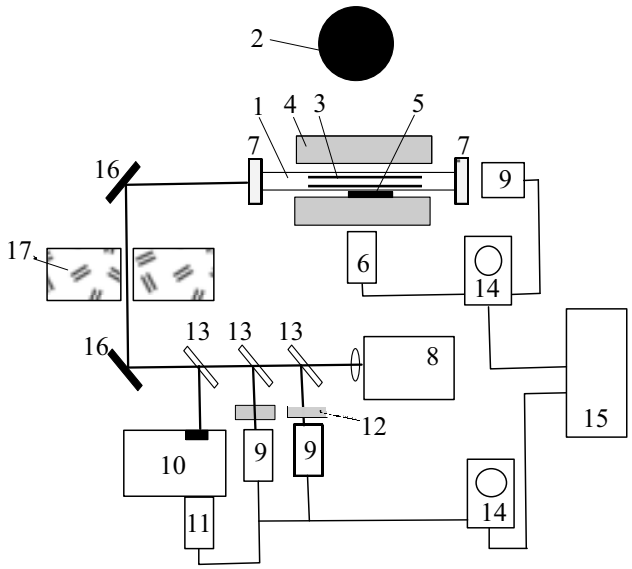

Figure 4. Block diagram of experimental setup: *1* — laser cell, *2* — nuclear reactor core, *3* — layer $^{235}U_3O_8$ with thickness of 3 mg/cm^2, *4* — polyethylene moderator, *5* — neutron chamber KNT-5, *6* — photocell F-22, *7* — resonant cavity mirror, *8* — spectrometer MAYA-2000Pro, *9* — p, *10* — spectrometer MDR-9, *11* — multiplier tube, *12* — optical filter, *13* — beam-splitting plate, *14* — digital oscilloscope, *15* — computer, *16* — aluminum mirror, *17* — biological shield.

studied gas mixture was placed near the reactor core and radiated with a flux of thermal neutrons $\sim 10^{15}$ n/cm^{2}s. Inside the cell, an aluminum tube-insert $\varnothing 25 \times 700$ mm was installed with a layer of uranium oxide with thickness of ~ 3 mg/cm^2 applied on the inner surface. The specific capacity of energy deposition of fission fragments into gas was around $2 \cdot 10^3$ W/cm^3. Since the energy spectrum of neutrons in a nuclear reactor is not thermal, to increase the pumping efficiency, a laser cell was located inside a polyethylene neutron moderator, with the help of which the spectrum of pumping neutron was formed in the cell, being close to the thermal one with energy of ~ 0.025 eV. The neutron pumping pulse shape was recorded by a vacuum small-sized fission chamber KNT-5, installed inside a polyethylene moderator. When carrying out lasing experiments, the cell was sealed with two narrow-band mirrors with multilayer dielectric coatings or with a laser mirror and a quartz window — when carrying out luminescent studies. Gas mixtures Ar-Xe-CCl_4 of different composition were driven into the cell without additional purification. Light emission was registered by a spectrometer MAYA-2000Pro and two multiplier tubes (FEU-106 and FEU-100) installed at the distance of 18 m from the output window of the cell in the area protected against the exposure to the gamma-neutron radiation of the nuclear reactor. Narrow-band optical filters (glasses of grade UFS-2 were placed in front of multiplier tubes to separate UV radiation and grades BS-8 and KS-19 for separation of a long-wavelength area of the spectrum), and quartz discs with thickness of 8 mm were used as beam-splitting plates (13). Time signals were recorded with a fast digital oscilloscope RIGOL DS-5022 ME. Spectral measurements were carried out in the range of wavelengths 200 – 1100 nm with resolution of 1 nm. It should be noted that the spectra recorded by the MAYA-2000Pro spectrometer characterize the integral luminescence of the gas mixture during the action of the pumping pulse.

Experimental results

To evaluate the non-stationary absorption of the active medium of the excimer laser, the experimental studies were carried out with Ar-Xe-CCl_4-gas mixtures of various composition — 50 – 1520 Torr Ar, 4 – 580 Torr Xe, 0.05 – 0.3 Torr CCl_4. In all cases, regardless of the composition of the mixture, the reduction of the light signal was observed at the moment of action of gamma radiation signal even at lower energy depositions into the gas medium.

Self-absorption of radiation of B-X-band of molecule XeCl* ($\lambda_{max} = 308$ nm)

Fig. 5 shows the hardware specter of spontaneous radiation of Ar-Xe-CCl_4-gas mixture when excited by products $^{235}U(n,f)$ of the nuclear reaction for a cell with the output quartz window instead of the mirror. Mixture composition: Ar — 760 Torr, Xe — 20 Torr, CCl_4 — 20 mTorr. The emission spectrum consists of a bright B-X-band ($\lambda_{max} = 308$ nm), C-A-band ($\lambda_{max} = 352$ nm) and a weak D-X-band ($\lambda_{max} = 236$ nm) of molecule XeCl*, a broad

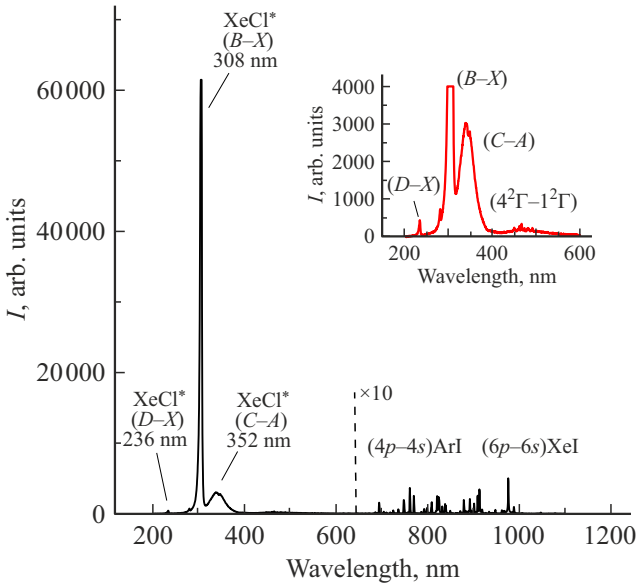

Figure 5. Luminescence spectrum of Ar-Xe-CCl_4-gas mixture for a cell with an output quartz window instead of a mirror. The insert shows a part of the spectrum 200 – 600 nm in the form increased 10 times along axis Y. In the interval of the wavelengths 650 – 1000 nm the intensities of the buffer gas lines are also increased 10 times.

$4^2\Gamma$-$1^2\Gamma$-band of molecule Xe_2Cl^* ($\Delta\lambda = 400 - 600$ nm) and a group of atomary lines of buffer gases that belong to transitions $4p - 4s$ ArI and $6p - 6s$ XeI. If there is a resonant cavity, intensities of B-X- and D-X-bands increase many times (Fig. 3). Formation of a D-X-band is not related to direct exposure of the active medium to the gamma radiation, but causes a change in focusing or defocusing of the generated output beam as a result of the change of the active medium refractive index.

In luminescence spectra of Ar-Xe-CCl_4-gas mixtures (Fig. 3, 5) the occurrence of D-band of molecule $XeCl^*$ ($\lambda_{max} = 236$ nm) happens from self-absorption of radiation of $XeCl^*$ band ($\lambda_{max} = 308$ nm) at B- and C-levels. Let us evaluate the coefficient of this self-absorption in the geometry of the remote source of light (a spot source). The intensity of radiation in the laser active medium in this case is determined as $I(\lambda)/\tau(\lambda)$, where $I(\lambda)$ — externally registered intensity of B-X-band ($\lambda_{max} = 308$ nm), and $\tau(\lambda)$ — transmittance of the output mirror (or window) of the cell at wavelength of $\lambda = 308$ nm. For the spectrum (Fig. 3) of the cell with the resonant cavity the B-X (308 nm) and D-X (236 nm) band intensities will respectively be equal to: $I_{308nm} = 26816400$ ($T_{308nm} = 0.14\,\%$) and $I_{236nm} = 37633$ ($T_{236nm} = 73.1\,\%$), and for the spectrum (Fig. 5) of the cell with the output quartz window — respectively $I_{308nm} = 62778$ a. u. ($T_{308nm} \sim 99\,\%$) and $I_{236nm} = 436$ a. u. ($T_{236nm} \sim 98\,\%$). Therefore, reduction of population of B-level due to self-absorption of radiation of B-X-band is $0.1 - 0.7\,\%$ $(37633/26816400) - (436/64778)$, which is low, however, this effect causes strong changes in the refractive index of the medium at wavelength of 308 nm.

Self-absorption of excimer molecule radiation at B-level is similar to the effect of abnormal dispersion described in papers [17–20]. Explicitly the dependence of the refractive index $n(\lambda_i)$ at abnormal dispersion for the absorption line λ_i is described by Zellmeyer's formula [21]:

$$n(\lambda_i) - 1 = e^2/4\pi m_e c^2 \lambda_i^3/(\lambda - \lambda_i)^2 N_i f_{ik}. \qquad (10)$$

Here e and m_e are the charge and mass of electron; c — light velocity; N_i, f_{ik}, λ_i — population, oscillator force and wavelength of the absorption line. We use the known ratio between the oscillator force f_{ik} and spontaneous emission coefficient A_{ik} [22]:

$$A_{ik} = 8\pi^2 g_i/g_k e^2 f_{ik}/(m_e c \lambda_i^2). \qquad (11)$$

Substituting into (10) the value f_{ik}, we get

$$n(\lambda_i) - 1 = 1/32\pi^3 g_k/g_i \lambda_i^5/(\lambda - \lambda_i) A_i N_i. \qquad (12)$$

In Ar-Xe-CCl_4-medium the product of $I_i = A_i.N_i$ describes the intracavity intensity of spontaneous radiation B-X- and C-A-transitions of the excimer molecule $XeCl^*$. Let us designate n_{res}, I_{res} and n_0, I_0 — refractive index and intensity coefficient of the excimer band with the wavelength of $\lambda_i = 308$ nm in the cell with the resonant cavity (n_{res}, I_{res}) and in the cell without the resonant cavity (n_0, I_0). Then from (12) we find

$$(n_{res} - 1)/(n_0 - 1) = I_{res}/I_0. \qquad (13)$$

Numerical values I_{res} and I_0 for $\lambda = 308$ nm can be obtained from optical spectra of lasing experiments executed with the cells with laser mirrors (I_{res}) (Fig. 3) and quartz windows (I_0) (Fig. 5), and n_0 we take from tables [23] for Ar as the main buffer gas. Substituting into (13) the numerical values for Ar-Xe-CCl_4-gas mixture from Fig. 3 and 5 ($\lambda_i = 308$ nm, $I_{res} = 37542/0.0014 = 26816400$; $I_0 = 62778$), we get the value of intracavity refractive index Ar-Xe-CCl_4-gas mixture averaged for the time of the pumping pulse action:

$$\begin{aligned} n_{res} &= 1 + (n_0 - 1) I_{res}/I_0 \\ &= 1 + 0.000284 \cdot 26816400/62778 = 1.1176, \end{aligned} \qquad (14)$$

which is significantly higher than the tabular values for Ar under normal conditions. The value of the refractive index in the maximum of neutron flux may exceed this value.

Quenching of excimer molecules XeCl* by photoelectrons and Compton electrons

The effect of the prompt gamma rays at the active medium and elements of the laser structure causes formation of fast electrons, which destroy the excimer molecules $XeCl^*$ and Xe_2Cl^* in collisions. The paper [10] evaluated this effect on the basis of the comparison of luminescence signals recorded at the same pumping levels at different moments of time — with presence and absence of the pulse of gamma rays (Fig. 6, *a*). Application of this method is limited to the initial area of pumping pulse growth and will not make it possible to consider the entire time range of the pumping level change. This limitation is caused by a small value ($35\,\mu$s) of the time shift between the pulses of prompt gamma rays and the pulse of thermal pumping neutrons when the hydrogen-containing moderator of neutrons is used from polyethylene (Fig. 2).

Analysis of the shape of time signals of luminescence of (B-X)-band $XeCl^*$ and pulse of thermal pumping neutrons shows that there is a linear dependence between the logarithmic values of these signals. Fig. 6, *a*, *b* shows time oscillograph charts of pumping pulses $I_{thermal.neutron}$ and intensities of I_{308nm} luminescence of B-X-band of excimer molecule $XeCl^*$ ($\lambda_{max} = 308$ nm) in linear (Fig. 6, *a*) and logarithmic coordinates along axis Y (Fig. 6, *b*). Figure 6, *b* shows that at the initial time area of pumping the logarithmic signals of these values linearly depend on time t:

$$\ln I_{308nm} = at + b, \qquad (15)$$

$$\ln I_{thermal.neutron} = ct + d, \qquad (16)$$

where a, b, c, d — constants determined from the curve. Ratios (15) and (16) make it possible to establish the linear dependence between $\ln I_{thermal.neutron}$ and $\ln I_{308nm}$:

$$\ln I_{308nm} = K \ln I_{thermal.neutron} + M, \qquad (17)$$

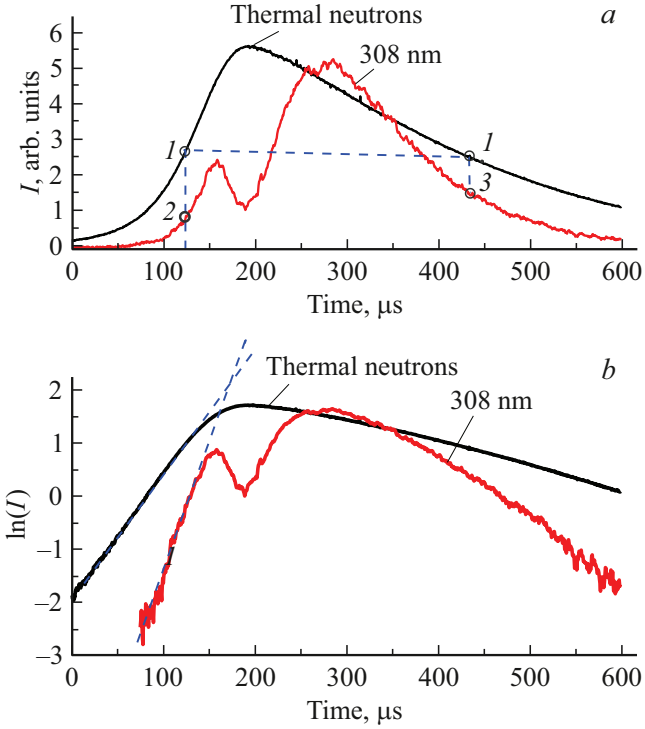

Figure 6. Time oscillograph charts of thermal pumping electron pulses $I_{\text{thermal.neutron}}$ and luminescence of B-X-band of excimer molecule $XeCl^*$ ($\lambda_{\max} = 308$ nm) I_{308nm} in linear (Fig. 6, a) and logarithmic coordinates along axis Y (Fig. 6, b). Gas mixture composition: Ar — 292 Torr, Xe — 20 Torr, CCl_4 — 50 mTorr; the resonant cavity has the front mirror with transmittance $T(308\,\text{nm}) = 1.55\,\%$ and the rear mirror with reflection of $R(308\,\text{nm}) = 98.97\,\%$. Points *2* and *3* note the luminescence signals for the arbitrary moment of time recorded at the same pumping levels (two points *1*).

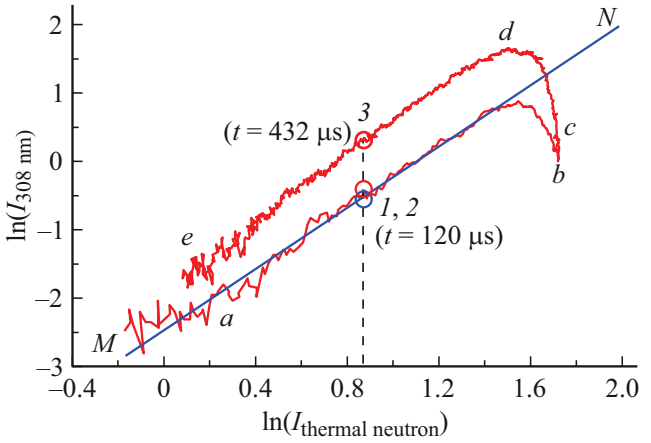

Figure 7. Extrapolation chart of luminescence signal of B-X-band of molecule $XeCl^*$ ($\lambda_{\max} = 308$ nm) when pumping Ar-Xe-CCl_4-gas mixture with uranium fission fragments. Straight line MN is described by equation $\ln I_{308nm} = 2.223 \ln I_{\text{thermal.neutron}} - 0.89$. Points *1* and *2* specified in accordance with Fig. 6, a, and in straight line MN and in the curve abc are practically the same.

where $K = a/c$, $M = b - d/c$.

Linear dependence between $\ln I_{\text{thermal.neutron}}$ and $\ln I_{308nm}$ is only maintained in the absence of the amplification or nonstationary absorption in the active medium, and deviations from linearity indicate the amplification or absorption process occurrence in the medium. Using the linearity property, you can determine the nonstationary absorption or amplification of the laser active medium by joint processing of signals in the entire time range of pumping, and also to determine the absorption caused by the exposure to the gamma rays of the nuclear reactor.

Fig. 7 shows the chart of dependence of the signal amplitude of luminescence excited by the uranium fission fragments in Ar-Xe-CCl_4-gas mixture at B-X-transition of molecule $XeCl^*$ (308 nm) depending on the amplitude of the pulse of thermal pumping neutrons. The chart is built using data of Fig. 6, b in the logarithmic scale along axes X and Y. Straight line MN reflects the linear nature of dependence between the logarithmic values of Fig. 6. The chart is a closed curve (abcdea points). The lower branch abc relates to the initial time range of pumping ($0 - 190\,\mu$s), and the upper branch $cdea$ — to the end one $190 - 600\,\mu$s (Fig. 6,a and Fig. 7). Straight line MN, passing through the points of the lower branch abc, is extrapolation of equation (17) on the entire pumping area — from 0 to maximum amplitude of pumping (at 190 μs, Fig. 6, a) and from the maximum value of amplitude to zero ($cdea$, Fig. 7) and characterizes the luminescence signal corresponding to the amplification-free mode in the absence of the nonstationary absorption in the medium. In respect to this figure, this straight line is described by equation

$$\ln I_{308nm} = 2.223 \ln I_{\text{thermal.neutron}} - 0.89. \qquad (18)$$

It should be noted that building curve $abcdea$ is only possible when the single timing is arranged between the pulses of thermal pumping neutrons and luminescence, at which the experimental values are recorded at the same moments of time. Such timing, for example, is provided by simultaneous recording of both signals by two-channel (or multi-channel) oscilloscope.

The difference between the real signal of luminescence (curve $abcdea$) and linear extrapolated signal (straight line MN) makes it possible to determine the coefficient of nonstationary absorption (or amplification) in the entire time range of pumping.

Let us consider the arbitrary moment of time t, related to the time range of pumping growth or drop. In Fig. 7 this moment corresponds to point *1* in the straight line MN (extrapolated amplification-free signal of luminescence with pumping growth or drop) and points *2* and *3* in curves ab and de for the really measured signals at pumping growth (ab) or drop (de). Let us designate the intensities of these signals as $I_0(t)$, $I_1(t)$, $I_2(t)$. If $\alpha(t)$ — coefficient of amplification (or absorption) at the moment of time t for

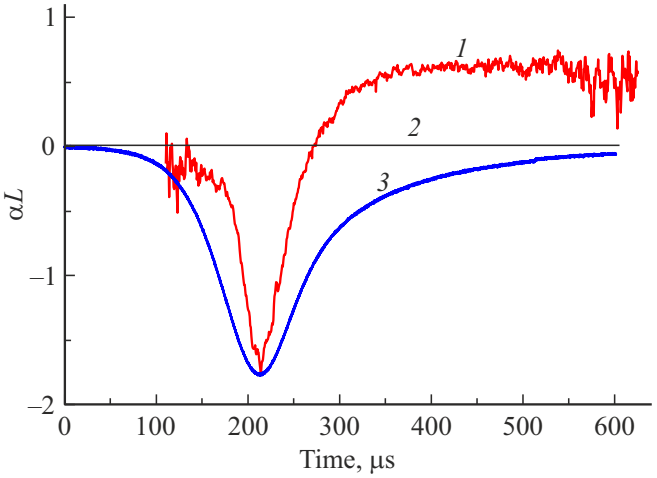

Figure 8. Time dependence of coefficient of nonstationary absorption of B-X-band of excimer molecule XeCl* ($\lambda_{max} = 308$) (*1*) and pulse of prompt gamma rays of nuclear reactor (*3*). Amplitudes of curves (*1*) and (*3*) were normalized without the change in the position of the curves in axis t. The line (*2*) determines the zero level of amplification of luminescence of Ar-Xe-CCl_4-gas mixture in pumping. Powder mixture: Ar — 292 Torr, Xe — 20 Torr, CCl_4 — 50 mTorr.

this pumping level, then

$$I_1(t) = I_0(t)\exp(\alpha(t)L). \tag{19}$$

Here L — cell length. Then

$$\alpha(t) = (\ln I_1(t) - \ln I_0(t))/L. \tag{20}$$

Values $\ln I_0(t)$ and $\ln I_1(t)$ are taken from chart of Fig. 7.

Performing the calculations using formula (20) for the range of the pumping amplitude change in Fig. 7 for the lower curve *abc* and upper curve cdea and rebuilding the produced results in coordinates $x =$ time, $y = \alpha(t)$, we obtain the time dependence of the amplification or absorption coefficient change, since each value of pumping amplitude in the lower (and upper) curve of Fig. 7 corresponds to the strictly determined moment of time (Fig. 6, *a*).

The values of nonstationary absorption and amplification in Ar-Xe-CCl_4-active medium XeCl* of excimer laser produced in this manner are shown in Fig. 8 together with the pulse of gamma rays of the nuclear reactor. Duration of the pulse of nonstationary absorption is $\sim 90\,\mu$s. Correlation is observed between oscillograph charts, which indicates the effect of gamma rays of the nuclear reactor at the development of the nonstationary absorption in the active medium of excimer XeCl*-laser as a result of bombardment of the track plasma with Compton electrons and photoelectrons. In the maximum of the pulse of gamma rays the value of coefficient of nonstationary absorption is $\alpha_{max} \sim 2.5 \cdot 10^{-2}\,\text{cm}^{-1}$. Calculations using this method, which were performed for the Ar-Xe-CCl_4-gas mixtures of various composition studied in this paper demonstrated that the coefficient a varies in the range from 0.02 to 0.04 cm^{-1}. It seems that the nonstationary absorption of B-X-band of molecule XeCl* may be strongly reduced or excluded at all in the case of usage instead of hydrogen-containing moderator of neutrons, the moderator of special design made on the basis of graphite and heavy elements. This will make it possible to weaken the value of impact of the pulse of prompt gamma rays at the active medium of laser due to absorption of gamma rays with heavy elements of the moderator and will move the moment of formation of the laser pulse from the pulse of prompt gamma rays of the reactor at the expense of the increased time of moderation of fast neutrons in graphite compared to the hydrogen-containing medium.

Optics transmittance

The equipment we used prevented separation of the processes causing radiation damage to optical parts with gamma rays and damage to molecules with XeCl* electrons. Therefore, the values $\alpha(t)$ obtained in the experiment characterize the total coefficients of losses related to these two processes. The maximum value of the measured absorption coefficient in this case was $\alpha L = 1.75$, which indicated considerable weakening of radiation of B-X-band of XeCl*. The total dose of gamma rays on the surface of the laser cell for the time of action of pumping pulse ($240\,\mu$s) was 37 Gr, which corresponded to the absorbed dose rate of $\sim 1.5 \cdot 10^5$ Gr/s. Such strong gamma fields started showing non-stationary effects of formation of short-lived color centers in the windows and substrates of laser mirrors caused by radiation exposure. For quartz of grade KV, from which the cell windows and substrates were made, this complied with the appearance of the absorption bands in the UV range of wavelengths 215 and 300 nm [2].

Conclusion

Experimental studies were carried out for the amplification coefficient of the active medium XeCl* of the excimer laser with nuclear pumping excited by mixed gamma neutron radiation of the pulse nuclear reactor. The studies were conducted with boxAr-Xe-CCl_4-gas mixtures of various compositions, and in all cases, regardless of the composition of the mixture, the reduction of the light signal was observed at the moment of action of gamma radiation signal (even at lower energy depositions into the gas medium). It was found that the nonstationary absorption of radiation of B-X-band of molecule XeCl* ($\lambda_{max} = 308$ nm) at the moment of action of gamma rays pulse arises due to the damage to the excimer molecules XeCl* by electrons formed from interaction of gamma quanta with the active medium and materials of laser design, and also as a result of the radiation exposure from gamma rays to

windows and substrates of laser mirrors from quartz glass of KV grade. For our experimental conditions (absorbed dose rate $\sim 1.5 \cdot 10^5$ Gr/s), the maximum value of the loss coefficient is achieved at the moment of the maximum gamma-quanta flux action and is equal to $\alpha L = 1.75$. Duration of the pulse of nonstationary absorption on the base is 90 μs. The coefficient α is not a constant value, but depends on the population of the operating level, when the process of direct destruction of excimer molecules by electrons begins. At the wavelength of 308 nm the value is measured for the intracavity refractive index of Ar-Xe-CCl_4-gas mixture averaged for the time of action of the neutron pumping pulse:

$$n_{\text{res}} = 1 + (n_0 - 1)I_{\text{res}}/I_0$$
$$= 1 + 0.000284 \cdot 565967/54778 = 1.1176.$$

In the maximum of the neutron flux n_{res} will be much higher.

Conflict of interest

The work was conducted in the initiative manner without raising grant funds or any special funding. The authors declare that they have no conflict of interest.

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