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# Repetitively pulsed operating regime of a high-pressure atomic xenon transition laser

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***Abstract*****. The repetitively pulsed regime of an atomic xenon transition laser pumped by an electron beam with various pulse durations and an electron-beam-initiated discharge is studied experimentally. An average radiation power of 2.5 W has been achieved in a quasi-stationary regime for a pulse repetition rate of 5 Hz in a laser pumped by a radially convergent electron beam of duration 100 μs without circulation of the Ar – Xe working mixture. The average output power for a laser pumped by a planar electron beam in quasi-stationary regime is 2 W. It is shown that for a specific energy contribution not exceeding 50 J $L^{-1}$ and laser excitation by a train of electron-beam pulses at a repetition rate of 50 Hz, the amplitude and duration of the second lasing pulse virtually coincide with those of the first. For a laser pumped by a discharge initiated by a nanosecond electron beam, an average lasing power of 380 mW is achieved under steady-state conditions upon transverse circulation of the working mixture and a pump pulse repetition rate of 25 Hz. Pumping by an electron beam from two accelerators with a pulse duration of a few tens of microseconds under an Ar – Xe mixture pressure of about 1 atm and a specific pump power of 1 – 3 kW $cm^{-3}$ per pulse is proposed for the development of 1.73-μm repetitively pulsed Xe lasers with a high average output power.**

***Keywords***: *repetitively pulsed regime, IR Xe laser, electron beam, electron-beam-initiated discharge.*

## 1. Introduction

The atomic xenon transition laser is the most efficient and powerful gas laser operating in the near IR range (see reviews [1 – 3] and references therein, as well as the recent papers [4, 5]). However, investigations of this laser at elevated (1 atm and higher) pressures in mixtures with argon buffer gas were usually performed using single pulses. In some works, He – Xe mixtures were pumped by a self-sustained discharge using rapid transverse circulation of the working mixture [6, 7]. A linear increase in the average laser power (up to 10 W [6] and 25 W [7]) was found with increasing the pump pulse repetition rate (up to 1.2 and 7 kHz respectively). However, these investigations were made by using short excitation pulses at high initial voltages and mixtures with a high concentration of He (more than 99.5 %). This resulted in lasing mainly at a wavelength of 2.03 μm with a low input energy efficiency (a fraction of one percent). It is known [8 – 11] that under optimal pump conditions (Ar – Xe mixture, $\lambda = 1.73$ μm), the lasing efficiency of the Xe atomic transition laser is 3 % – 5 % of the input energy. The highest efficiency of the xenon laser is attained upon pumping by an electron beam [10, 11] or by an electron-beam-controlled discharge [9].

In recent papers [3, 12], special attention was paid to the repetitively pulsed Xe laser. Estimates made in Ref. [3] (no experiments were performed in the periodic regime) suggest the use of an ArXe mixture at a pressure of ~ 4 atm to build a high-average-power IR Xe laser (~ 1 kW and higher) pumped by an electron-beam-controlled discharge (i.e., by the electroionisation technique). The study of an Ar – Xe mixture Xe laser was reported in Ref. [12]; the laser was pumped by a 40-ns electron-beam pulses with a pulse repetition rate up to 100 Hz. Experiments in Ref. [12] were made without circulation of the working mixture. Because the pump conditions were not optimal (short beam-current pulse, low specific energy contribution, absence of circulation, etc.), the average output power obtained in Ref. [12] under steady-state conditions did not exceed 1.5 mW for a very low power efficiency of the electron beam injected into the laser chamber.

The aim of this research is to study the lasing at atomic transitions in Xe at elevated pressures of the Ar – Xe working mixture in the repetitively pulsed regime upon pumping by an electron beam or an electron-beam-initiated discharge. In addition, an optimal approach is proposed for fabricating a high-average-power Xe laser.

## 2. Experimental setup and measuring technique

We used three setups described in detail in Refs [13 – 15].

Setup 1 [13] consists of an electron accelerator with a plasma vacuum diode based on a plasma grid cathode and a laser chamber separated from it by a foil window of size 10 × 60 cm whose support grid is cooled by running water. The accelerator produced 150 – 200-keV, 10 – 100-μs electron-beam pulses. The electron-beam current was 20 – 100 A and pulse repetition rate was 50 Hz in short-time repetitive regime. The nonuniformity of the current density over the

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beam cross section did not exceed 15 % of the mean value. The electron-beam current was modulated by modulating the current of an arc discharge generating plasma in the electrode system of a plasma grid cathode to which a constant accelerating high voltage was applied. The emission boundary of the plasma was fixed and stabilised by a small-size metal grid covering the emission window of the plasma cathode of size 10 × 60 cm, equal to that of the output foil window. Such a method of obtaining an electron beam and its formation provides high energy efficiency and allows independent variation of the energy of accelerated electrons, as well as the amplitude, duration and repetition rate of beam current pulses over a wide range. The beam extracted through a 40-μm thick aluminium – beryllium foil entered the laser chamber. In our experiments, we used a stainless steel laser chamber of volume 20 L, but its active optical volume was just 6 L and was determined by the size of the mirrors used.

An electron accelerator based on a coaxial vacuum diode with an external plasma grid cathode and an internal foil anode was used in setup 2 [14]. The water-cooled cylindrical support grid of the anode served as a laser chamber of volume ~ 18 L (inner diameter ~ 20 cm, active length 60 cm). The accelerator formed a radially convergent electron beam which was incident on the working mixture of the laser after passing through a foil. This ensured a higher uniformity of pumping over the active cross section of the laser volume than in setup 1 for a laser mixture pressure of 1 – 1.5 atm. For the FWHM current pulse duration of 10 – 100 μms, the current beam density was controlled in the range 0.1 – 0.005 A $\text{cm}^{-2}$ by varying the plasma cathode discharge current for a constant average electron energy behind the foil, which was chosen equal to ~ 170 keV in view of the uniformity of energy contribution to the laser mixture. The beam current pulse repetition rate was determined by the power of the electric supply circuits used in the experiments, as well as by the heating of the laser chamber, and was equal to 5 Hz in the repetitive short-time regime.

The modernised version of setup 3 described in Ref. [15] consisted of an electron accelerator with a plane vacuum diode capable of forming an electron beam behind the divider foil with the following parameters: current amplitude ~ 7 kA, cross section 72 × 3 cm, FWHM current pulse duration 4.2 ns, pulse repetition rate up to 25 Hz, and the peak on the electron energy distribution curve corresponded to ~ 160 keV. The working volume 3 × 3 × 72 cm was excited by a capacitor bank of capacitance 0.19 μF placed in a gas cell. The circulation system for the gas mixture ensured a flow velocity up to 10 m $\text{s}^{-1}$, which made it possible to use the setup in pulse-periodic mode for a long time.

The working gas mixtures were prepared directly in laser chambers. The rated purity of the constituent gases was 99.998 % for argon and 99.9992 % for xenon. Internal plane – parallel cavities made of a copper mirror or a mirror with aluminium or insulator coating (totally reflecting mirror) were used in the experiments. The output mirrors had a reflection coefficient of 99 %, 95 %, 33 %, 27 %, and 6 % at $\lambda = 1.73$ μm. A plane – parallel KRS-5 plate (reflection coefficient ~ 33 %) was used in most experiments. The laser output energy or the average output power was measured with an IMO-2N calorimeter or with a PE-25 pyroelectric sensor (OPHIR Opt.). The laser pulse shape was determined using a FSG-22-3A2 photoresistance. Electric signals were recorded with a TDS-3032 oscillograph.

## 3. Experimental results and discussion

The results obtained previously on setups 1 and 2 using single pulses are described in detail in Refs [4, 5, 13,14]. It was shown that the highest emission efficiency (more than 2 % in Ref. [4] and more than 4 % under identical conditions [10, 11]) was achieved for pump pulse durations of tens of microseconds in the Ar – Xe mixture at a pressure of ~ 1 atm and for a specific pump power of 13 kW $\text{cm}^{-3}$. A partial (~ 50 %) substitution of helium for argon resulted in a change in the radiation wavelength from 1.73 μm to 2.03 μm and in an approximately two-fold decrease in the output energy. However, steady-state operation could be carried out at a higher pulse repetition rate in the repetitively pulsed regime without circulation in mixtures containing ~ 50 % of helium. Apparently, this is due to a higher thermal conductivity of helium, which results in a faster removal of heat to the cooled walls of the laser chamber. For this reason, we performed experiments in the repetitively pulsed regime without mixture circulation for both working mixtures.

### 3.1 Experiments without laser-mixture circulation on setup 1

Figure 1 (curve *1*) shows the dependence of the average radiation power in the Ar – Xe mixture on the repetition rate of the 100-μs beam current pulses with amplitude ~ 40 A. The average output power was measured with an IMO-2 calorimeter in the quasi-stationary regime within ~ 30 s after the starting of the accelerator. One can see that for a pulse repetition rate of 5 Hz, the average output power achieves its maximum value of ~ 2 W. The energy-input efficiency in this regime is ~ 1 % for a pulse repetition rate of 12 Hz and ~ 0.5 % for a pulse repetition rate of 5 Hz. The decrease in the average output power with increasing the pulse repetition rate is due to a heating of the working mixture and a decrease in the accelerator beam current caused by a decrease in the voltage across the vacuum diode. Upon a replacement of 50 % of argon by helium, the highest average output power was observed for a pulse repetition rate of 10 Hz, but was ~ 30 % lower in

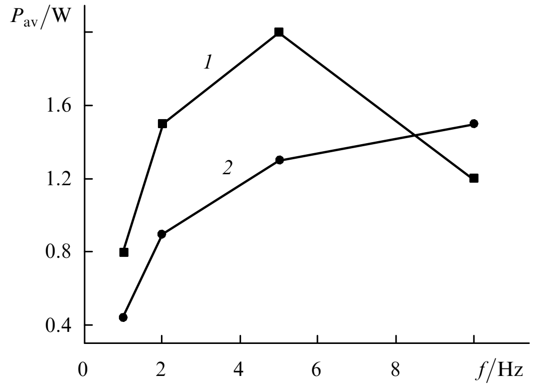

**Figure 1.** Dependence of the average output power $P_{\text{av}}$ in the Ar : Xe = 100 : 1 (curve *1*) and the He : Ar : Xe = 100 : 100 : 1 (curve *2*) mixtures on the pulse repetition rate *f*, obtained on setup 1 at the mixture pressure $p = 1.2$ atm.

magnitude. The energy-input efficiency for a ternary mixture at a pulse repetition rate 1 – 2 Hz decreased to about half compared to the efficiency for a binary mixture and did not exceed ~ 0.5 %. However, the efficiency, as well as the average output power, was higher in a ternary mixture than in a binary mixture for a pulse repetition rate of 10 Hz.

Curve (*2*) in Fig. 1 shows the dependence of the average output power on the pulse repetition rate in a ternary mixture for other parameters of the beam current: the FWHM pulse duration 15 μs and amplitude 230 A. As in the case of a beam current pulse duration of 100 μs, the average output power increases with increasing the pulse repetition rate up to 10 Hz, achieving 1.5 W. As a result of a partial substitution of helium for argon, the maximum average radiation power was observed for a pulse repetition rate of 10 Hz due to a faster removal of heat to the walls of the laser chamber. Temperature measurements for various gases at the centre of the laser chamber (in experiments without lasing) showed that, as expected, the gas temperature in the intervals between pulses decreases most rapidly in pure helium and most slowly in xenon.

The dependences of the average output power for Ar – Xe and He – Ar – Xe mixtures were identical for beam current pulse durations of 15 and 100 μs. The maximum average output power was observed at a pulse repetition rate of 5 and 10 Hz for the first and second mixtures, respectively. The highest average output power for identical pump pulse repetition rates up to 5 Hz was achieved in the binary mixture, but the duration of laser operation for which the highest average radiation power was retained was longer in the ternary mixture. The maximum input energy efficiency in the experiments without circulation of the working mixture was ~ 1 % for a pulse repetition rate of 1 – 2 Hz.

To eliminate the heating of the working mixture and to decrease the voltage across the accelerator diode, the working mixture was excited by pulse trains. The pulse repetition rates in each train consisting of 5 – 10 pulses were 1, 5, 10, 17, 25 or 50 Hz. Under the conditions of these experiments (specific energy input not exceeding 50 J $L^{-1}$), the amplitude of the second pulse and its shape remained virtually unchanged, i.e., the energy and lasing efficiency values were preserved. The amplitudes of the third and subsequent lasing pulses were determined by the beam current density as well as its duration, and began to decrease gradually for high energy inputs. Therefore, in the case of electron beam excitation, at least two pulses can be 'applied' to a portion of the mixture. This allows us to decrease considerably the circulation rate of the working mixture.

Note that if the pumping is performed by a planar electron beam, the distribution of energy input over the laser chamber cross section may be nonuniform in wide-aperture setups. This leads to a decrease in the lasing efficiency and in the energy per pulse; or considerable part of the electron beam is absorbed outside the region covered by the cavity. For this reason, we performed experiments on an accelerator with a radially convergent electron beam.

### 3.2 Experiments on setup 2 without laser-mixture circulation

By using 100-μs beam-current pulses we obtained the average output power of up to 2.5 W in the Ar : Xe = 100 : 1 mixture at a pressure of 1 atm and for a pulse repetition rate of 5 Hz. For the same values of the pressure and pulse repetition rate, the average radiation power in the He : Ar : Xe = 50 : 50 : 1 mixture was 2 W. For a pulse repetition rate of 2 Hz, the average output power in the steady-state regime for these mixtures was 1.8 and 1 W, respectively. The distribution of the radiation power density over the beam cross section was uniform owing to the electron beam injection from all sides. The maximum input energy efficiency was ~ 1.5 % for a pulse repetition rate of 1 – 2 Hz without circulation of the working mixture in setup 2.

However, a slow heating of the working mixture was observed at a pulse repetition rate exceeding 1 – 2 Hz in setup 2, like in setup 1; this heating could not be compensated by water cooling of the laser chamber. Consequently, the temperature of the working mixture and the laser chamber increased, while the lasing efficiency decreased, within a few minutes or a few tens of minutes (depending on the pulse repetition rate, beam current pulse parameters, mixture composition and pressure, design of the laser chamber and the cooling system, etc.).

### 3.3 Experiments on setup 3 with transverse circulation of the laser mixture

Figures 2 and 3 show the dependences of the output energy per pulse on the charging voltage and mixture pressure, while Fig. 4 shows the oscillograms of the discharge current and the lasing pulse. Setup 3 was used for operation at maximum charging voltage that still allowed an enhancement of the radiant energy (see Fig. 2). As in Ref. [8], the increase in the mixture pressure in such a setup led to a rapid growth in the output energy (see Fig. 3). However, the working pressure of the mixture in setup 3 was restricted by the strength of the laser chamber, which did not allow us to work with a pressure of 5 atm as in Ref. [8], where a specific output energy of 0.75 J $L^{-1}$ was obtained and the efficiency with respect to the energy stored in the capacitor was ~ 3 %. The maximum efficiency achieved in our setup did not exceed ~ 0.5 %. The storage capacitor in setup 3 as well as in Ref. [8] was charged by a dc voltage source through an inductance. Pulsed charging of the storage capacitor [3] requires an additional capacitor and a commutation switch, which increases the losses in the laser power supply.

An average output power of 380 mW was obtained in the Ar : Xe = 100 : 1 mixture on setup 3 pumped by an

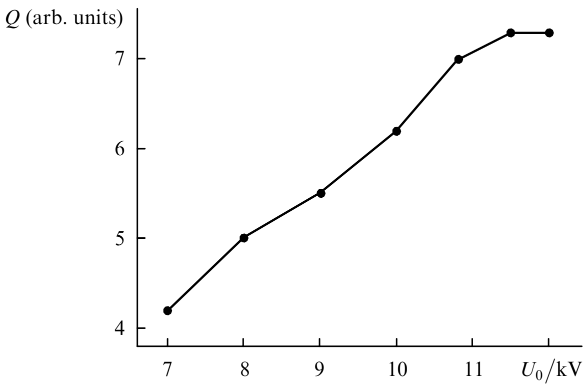

**Figure 2.** Dependence of the pulse energy $Q$ on the capacitor charging voltage $U_0$ at the pressure $p = 1.2$ atm of the Ar : Xe = 100 : 1 mixture obtained on setup 3.

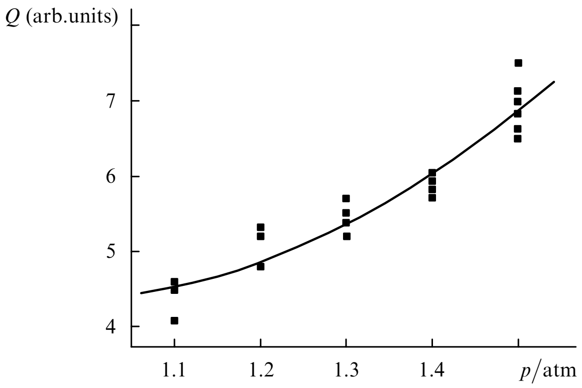

**Figure 3.** Dependence of the pulse energy $Q$ on pressure $p$ of the Ar : Xe = 100 : 1 mixtures for a capacitor charging voltage $U_0 = 7$ kV, obtained on setup 3.

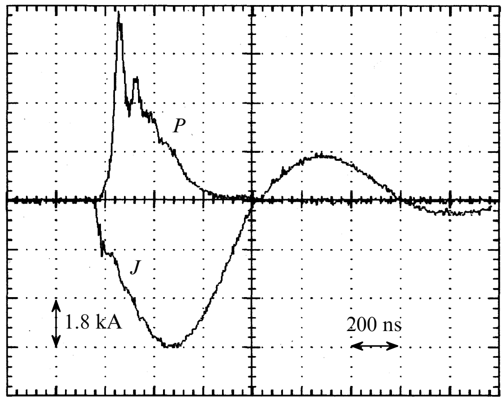

**Figure 4.** Oscillograms of the lasing pulses $P$ for the Ar : Xe = 100 : 1 mixture for a discharge current $J$ at the pressure $p = 1.1$ atm and $U_0 =$ 9 kV, obtained on setup 3.

electron-beam-initiated discharge at a pressure of 1.2 atm and a pulse repetition rate of 25 Hz (Fig. 5). The laser could work in this regime for a long time without a considerable decrease in the average output power. For 10 min of laser operation, the average output power decreased by no more than 20 % after which it remained virtually unchanged. Apparently, the decrease in the average output power is caused by the desorption of molecular gases from the electrodes and the foil, as well as the dust 'rising' from the chamber walls. An increase in the pulse repetition rate due to a circulation of the mixture (Fig. 5) led to a linear increase in the average output power in the steady-state regime. The circulation system ensured at least five replacements of the working mixture in the period between pulses. A decrease in the circulation rate of the mixture for a given pulse repetition rate led to a contraction of the discharge and quenching of lasing (starting from a certain value of the circulation rate). Therefore, the working mixture should be replaced many times (at least five times in setup 3) to obtain a steady-state repetitively pulsed regime upon pumping by a discharge initiated or controlled by an electron beam. It was mentioned above that two pulses can be 'applied' to one portion of the mixture in the case of electron-beam pumping. This allows one to reduce the circulation rate to a replacement of only the working mixture in the interval between pulses.

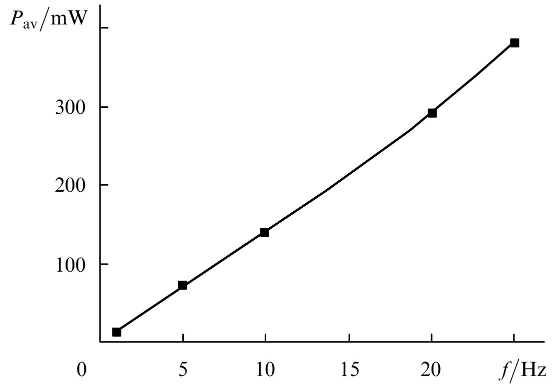

**Figure 5.** Dependence of the average output power $P_{\text{av}}$ for the Ar : Xe = 100 : 1 mixture on the pulse repetition rate $f$, obtained on setup 3 at the mixture pressure $p = 1.2$ atm and $U_0 = 10$ kV.

It must be emphasised that the switching off of the electric field (pumping by an electron beam only) reduces the average output power by a factor of 15. However, the average steady-state output power was an order of magnitude higher than in Ref. [12] even when pumping was carried out by the electron beam only.

## 4. Conclusions

We have studied atomic Xe transition lasers operating in the repetitively pulsed regime at high pressures of Ar–Xe mixture and obtained:

(i) an average radiation power of 380 mW in the steady-state regime for a pulse repetition rate of 25 Hz upon transverse circulation of the working mixture and pumping by an electron-beam-initiated discharge; and

(ii) an average radiation power of 2.5 W without circulation of the working mixture in the quasi-stationary regime upon pumping by a 100-μs electron-beam pulses.

Four different approaches can be used to build a high-average-power IR Xe laser (~ 1000 W and higher):

1. The use of an electron beam for pumping and realisation of the highest lasing efficiency (~ 4 % of the input energy). In this case, the optimal pressure of the Ar–Xe mixture is ~ 1 atm while the specific output energy per pulse is $1-2$ J $\mathrm{L}^{-1}$. The specific pump power and the beam current pulse duration for such a laser must be $1-3$ kW $\mathrm{cm}^{-3}$ and 100–10 μs, respectively. A drawback of this regime is a comparatively low specific output energy.

2. The use of an electron beam for pumping and realisation of high specific output energies ($4-6$ J $\mathrm{L}^{-1}$) due to an increase in the beam current density and the working pressure of the mixture. In this case, the optimal pressure of the Ar–Xe mixture is ~ 4 atm while the efficiency is about 2 %. The drawbacks of this method are a lower efficiency (about half that in regime 1) and a high working pressure, which complicates the circulation system and design of the laser chamber.

3. The use of an electron-beam-controlled discharge for pumping (electroionisation pump technique). This regime was proposed to build a high-average-power IR xenon laser [3]. In this case, the optimal pressure of the Ar–Xe mixture is ~ 4 atm and a high lasing efficiency (about 3 % of the energy stored in the reservoir capacitor) and high specific radiant energies ($4-8$ J $\mathrm{L}^{-1}$) are achieved. The drawbacks

of this method are a high working pressure, which complicates the circulation system and design of the laser chamber, and a high circulation rate of the working mixture (several times higher than in the case of electron-beam pumping). In addition, additional losses appear at the grid installed at the cathode to improve the uniformity of the electron field in the discharge gap and to protect the foil. Note that even a brief contraction of the discharge in this regime (in one or more pulses, which is possible in the repetitively pulsed regime) may damage the foil.

4. Pumping by a self-sustained discharge with UV or X-ray preionisation, a high pulse repetition rate (1 – 10 kHz), and using the He – Xe working mixture. This regime is promising only for obtaining an average output power of a few tens or hundreds watt. Such setups are simpler but the lasing efficiency usually does not exceed a fraction of one percent and the laser operates at 2.03 μm.

In all these cases, a circulation of the working mixture should be used to replace the gas in the active volume during the interval between pulses. In the case of pumping by a single electron beam, one replacement of the working mixture before the arrival of the next pump pulse is sufficient, while the possibility of discharge contraction in the case of pumping by various types of discharge necessitates the replacement of the working mixture about five times in the interval between pump pulses.

On the basis of the results of our investigations and an analysis of the known experimental data, we suggest the first approach for obtaining a high average output power (~ 1000 W and higher) in atomic Xe transition lasers. The Ar – Xe mixture at a pressure of 1 atm is pumped by an electron beam injected into the laser chamber from two directions. The specific pump power and the beam current pulse duration must be about 1 – 3 kW cm$^{-3}$ and 100 – 10 μs respectively. The circulation of the working mixture must ensure its complete replacement in the active volume being excited during the interval between pump pulses.

## References

1. Sereda O.V., Tarasenko V.F., Fedenev A.V., Yakovlenko S.I. *Kvantovaya Elektron.*, **20**, 535 (1993) [*Quantum Electron.*, **23**, 459 (1993)].
2. Karelin A.V., Sinyanskii A.A., Yakovlenko S.I. *Kvantovaya Elektron.*, **24**, 387 (1997) [*Quantum Electron.*, **27**, 375 (1997)].
3. Kholin I.V. *Kvantovaya Elektron.*, **33**, 129 (2003) [*Quantum Electron.*, **33**, 129 (2003)].
4. Tarasenko V.F., Fedenev A.V., Skakun V.S. *Kvantovaya Elektron.*, **26**, 209 (1999) [*Quantum Electron.*, **29**, 209 (1999)].
5. Fedenev A.V., Tarasenko V.F., Skakun V.S. *Kvantovaya Elektron.*, **32**, 449 (2002) [*Quantum Electron.*, **32**, 449 (2002)].
6. Fahlen T.S., Tang R. *IEEE J. Quantum Electron.*, **9** (6), 609 (1973).
7. Kozlov B.A., Ashurkov R.I. *Proc. SPIE Int. Soc. Opt. Eng.*, **4351**, 141 (2001).
8. Losev V.F., Tarasenko V.F. *Kvantovaya Electron.*, **7**, 663 (1980) [*Sov. J. Quantum Electron.*, **10**, 381 (1980)].
9. Basov N.G., Chugunov A.Yu., Danilychev V.A., Kholin I.V., Ustinovsky N.N. *IEEE J. Quantum Electron.*, **19**, 126 (1983).
10. Watterson R.L., Jacob J.H. *IEEE J. Quantum Electron.*, **26**, 417 (1990).
11. Zayarnyi D.A., Semenova L.V., Ustinovskii N.N., Kholin I.V., Chugunov A.Yu. *Kvantovaya Elektron.*, **25**, 493 (1998) [*Quantum Electron.*, **28**, 478 (1998)].
12. Gimatdonov V.R., Karelin A.V., Kuznetsov D.L., Novoselov Yu.N., Simakova O.V., Surkov Yu.S. *Pis'ma Zh. Tekh. Fiz.*, **30**, 66 (2004).
13. Vintizenko L.G., Gushenets V.I., Koval N.N., Mesyats G.A., Skakun V.S., Tarasenko V.F., Fedenev A.V., Shchanin P.M. *Doklady Akad. Nauk SSSR*, **288**, 609 (1986).
14. Bugaev A.S., Koval N.N., Lomaev M.I., Mel'chenko S.V., Ryzhov V.V., Tarasenko V.F., Turchanovsky I.Yu., Fedenev A.V., Shchanin P.M. *Laser and Particle Beams*, **12** (4), 633 (1994).
15. Karpov V.M., Konev Yu.G., Orlovskii V.M., Osipov V.V., Ponomarev V.B. *Kvantovaya Elektron.*, **15**, 465 (1988) [*Sov. J. Quantum Electron.*, **18**, 294 (1988)].