

PACS numbers: 42.55.Lt; 42.60.Lh; 52.80.– s
DOI: 10.1070/QE2006v036n05ABEH013239

Efficient electric-discharge XeF laser pumped by a generator with an inductive energy storage

A.N. Panchenko, V.F. Tarasenko, E.A. Tel'minov

***Abstract*. The parameters of discharge and laser radiation in an Ne – Xe – NF_3 mixture excited by a double discharge from a generator with an inductive energy storage and a current interrupter based on semiconductor SOS diodes are studied. It is shown that a high-voltage prepulse formed by a generator with inductive energy storage increases considerably the stability and duration of volume discharge in mixtures with NF_3, and also increases the emission energy and pulse duration of laser radiation at the $B - X$ transition of XeF^* molecules. In the case of spark preionisation, radiation pulses with a total duration of up to 200 ns and the full width at half-maximum up to 100 ns are obtained. The maximum output energy of an XeF laser ($\lambda = 348$, 351 and 353 nm) was 0.5 J for the electric efficiency up to 1.6 %.**

Keywords: *stable volume discharge, XeF laser, efficient excitation, inductive energy storage.*

1. Introduction

An increase in the pulse duration of electric-discharge exciplex lasers is important both from practical and scientific points of view. On the one hand, a decrease in the radiation pulse power leads to a considerable increase in the pulse energy and the average power of the radiation transmitted along an optical fibre. On the other hand, an increase in the number of round trips in the cavity allows an effective control of laser radiation parameters such as the laser line width and divergence, which is important for various technological applications of electric-discharge exciplex lasers.

The radiation pulse duration was increased for the first time in a XeCl excited by a transverse self-sustained discharge. The duration of 308-nm laser pulses upon pumping by a pulse-forming line achieved ~ 200 ns [1]. The transient pumping of gas lasers proposed in [2] made it possible to increase the pulse duration of a XeCl laser to 1 μs by using intense preionisation with the help of plasma electrodes. This pump regime proved to be quite versatile, and pulses with a total duration of up to 0.4 μs were obtained from a XeF laser. However, the efficiency of energy supply to the active medium of an exciplex laser was low in [1, 2] due to the mismatch of impedances of a pulse generator and discharge. To increase the efficiency of electric-discharge pumping, quite complicated schemes of double discharge excitation involving spark switches or magnetic switches based on saturable chokes [3 – 5] were developed. The pump oscillator first formed a high-voltage prepulse initiating a discharge in the laser gap, and then the main storage capacitor or forming line supplied the main part of stored energy to the active laser medium in the impedance matching regime. The pulse duration of lasers excited by a double discharge was increased up to ~ 1.5 μs [4], and the electric efficiency was increased up to 4 % – 5 % [3, 5].

In lasers based on inert gas fluoride molecules, the discharge contraction occurs sooner than in an XeCl laser, and strongly restricts the laser pulse duration [6]. Usually, the pulse duration of an electric discharge XeF laser is 20 – 30 ns for the output energy of ~ 100 mJ [7 – 10]. The use of plasma electrodes [11] provided the increase in the radiation energy for lasers based on excited XeF^* molecules to ~ 0.8 J, and in the pulse duration to ~ 50 ns. In these experiments, the electric efficiency η_0 of the XeF laser relative to the energy stored in the capacitive storage did not exceed 1 %.

By pumping mixtures with a low concentration of the fluorine donor NF_3 by a double discharge with X-ray preionisation, the authors of paper [12] obtained laser pulses with the full width at half-maximum (FWHM) up to 212 ns. The efficiency of the XeF laser relative to the energy stored in the main storage was higher than 1.2 % [13]. However, because of large energy expenditures on prepulse formation and generation of illuminating X-rays, the laser efficiency was below 1 %.

Earlier, we proposed a method of laser medium pumping by a double discharge with the prepulse formation using an inductive energy storage and a current interrupter based on SOS diodes [14]. We also reported the fabrication of a long-pulse XeCl laser emitting up to 1.5 J with $\eta_0 = 2$ % [15]. Preliminary experiments showed that a generator with an inductive energy storage also allows one to increase the pulse duration of electric-discharge KrF and XeF lasers [16]. However, optimal pump conditions for the XeF laser were not achieved in this work.

In this paper, we report the fabrication of an efficient long-pulse XeF laser pumped by an oscillator with an inductive energy storage and a semiconductor current

A.N. Panchenko, V.F. Tarasenko, E.A. Tel'minov Institute of High Current Electronics, Siberian Branch, Russian Academy of Sciences, prosp. Akademicheskii 2/3, 634055 Tomsk, Russia;
e-mail: alexei@loi.hcei.tsc.ru, VFT@loi.hcei.tsc.ru

Received 15 March 2006
Kvantovaya Elektronika **36** (5) 403 – 407 (2006)
Translated by Ram Wadhwa

interrupter. By using spark preionisation, we obtained radiation pulses with a total duration up to 200 ns and a 0.5 J energy emitted by XeF^* molecules (at 348, 351 and 353 nm) for an electric efficiency $\eta_0 = 1.6\,\%$.

2. Laser design and measuring technique

We used in experiments a transverse-discharge-excited laser and a simple system for preionisation by spark gaps. The design of the laser was similar to that described in [14–16]. The device allowed the formation of a volume discharge at elevated pressures in the $Ne-Xe-NF_3$ mixtures. Figure 1 shows the electrical circuit of the laser. The pump oscillator consists of the main and auxiliary circuits. The main circuit is formed by a storage capacitor $C_0 = 38$ or 70 nF, an inductance L_0, and a spark gap SW_0. The auxiliary circuit was intended for preliminary pumping of SOS diodes D in the forward direction and consisted of a capacitor $C_D = 10$ or 36 nF, a spark switch SW_D and an inductance L_D. The laser used 10 SOS-50-2 diodes connected parallel to peaking capacitors. Preionisation of the discharge gap was performed by radiation from the spark gaps arranged uniformly on both sides of the anode and actuated by pulse charging of peaking capacitors $C_1/2$ ($C_1 = 2.45$ nF).

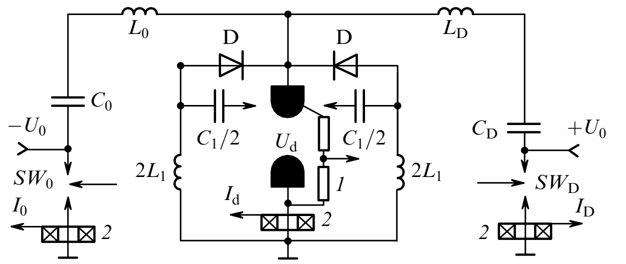

Figure 1. Electric circuit of the XeF laser pumped by the inductive energy storage: SW_0, SW_D – spark gaps; C_0 – primary storage capacitor; $C_1/2$ – peaking capacitors; C_D – capacitor for pumping SOS diodes D in forward direction; $L_0 = 24.5$ nH, $L_1 = 11$ nH, and $L_D = 0.87$ or 3.13 μH – inductances of the circuits; U_0 and U_D – charge voltages; (1) voltage divider, (2) Rogowski loops.

The oscillator could operate in the inductive energy storage regime, or as an ordinary capacitive generator. In the latter case, the capacitor C_D was not used. The discharge current pulse duration in these regimes was 150–250 ns. The active laser volume V under various experimental conditions was $4 \times (0.8 - 1.2) \times 72$ cm and varied with the width of the discharge region, which depended on the discharge voltage U_0 of the main storage, the composition and pressure of the mixture.

Profiled electrodes used in the laser reduced considerably the electric field inhomogeneities (local field amplification at the electrodes and in the discharge gap). The electrodes were made of stainless steel. The interelectrode distance d was 4 cm. Discharge and lasing characteristics were studied in $Xe : NF_3 = 4 : 1$ mixtures using neon as a buffer gas at a nitrogen trifluoride pressure of 1.5 or 0.75 Torr. The total pressure in the mixture was 2–3.5 atm. The rear mirror was an aluminium or dielectric-coated plane mirror, and the output mirror was a plane mirror with the reflectivity $R = 30\,\%$ at $\lambda \sim 350$ nm.

The laser output energy was measured with an OPHIR calorimeter with a FL-250A sensor head. The pulse shape was recorded in the far-field zone with a FEK-22 SPU vacuum photodiode on which a part of the laser radiation was directed with the help of a beamsplitter. The emission spectrum of the XeF laser was recorded with a StellarNet EPP2000-C25 spectrometer with a spectral resolution of 0.75 nm and the instrument function half-width of 1.5 nm. To obtain a linear operation regime of the photodiode and the spectrograph, the incident radiation was attenuated by metal grids.

We measured the current I_d through the discharge gap, discharge current I_0 through the storage capacitor, current I_D through SOS diodes, and the voltages U_{SOS} and U_d across SOS diodes and the laser electrodes with the help of Rogowski loops and a resistive voltage divider, respectively. The electric signals were recorded with TDS-220 or TDS-224 digital oscillographs.

3. Experimental results and discussion

Figure 2 shows the pump oscillator operation in the inductive storage regime. During the first 500 ns after switching the spark switch SW_D, current starts flowing in the forward direction through the semiconductor diodes. The voltage across the diodes, which amounts to hundreds of volts, decreases during the forward pumping phase. The spark gap SW_0 is activated at the instant of reversal of the current I_{SOS}, and a pulse of opposite polarity is fed to the diodes from the capacitive storage, while a part of the energy stored in C_0 is supplied to the inductance L_0 of the circuit. After about 30 ns, the resistance of SOS diodes starts to increase sharply, resulting in a rapid interruption of the current I_0. The time spread for activation of various diodes connected in parallel in the generator did not exceed a few nanoseconds. SOS diodes had a very high stability, reliability, and a long service life, and could withstand multiple current and voltage overloadings.

At the instant of interruption of current I_0, the inductive storage forms a prepulse with the amplitude up to $U_{max} = L_0 dI_0/dt \sim 70 - 80$ kV (dI_0/dt is the rate of current interruption in the diodes) and a build-up time of about 20 ns. After breakdown of the laser gap, the inductive

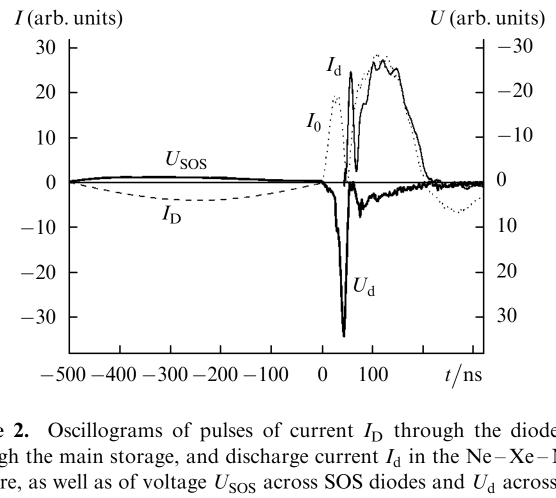

Figure 2. Oscillograms of pulses of current I_D through the diode, I_0 through the main storage, and discharge current I_d in the $Ne-Xe-NF_3$ mixture, as well as of voltage U_{SOS} across SOS diodes and U_d across the laser gap for the oscillator operation in the inductive energy storage mode.

storage together with the peaking capacitors ensures a rapid growth of the discharge current I_d, forming a short high-power pump pulse. The combined action of factors such as a high breakdown voltage and a sharp increase in the discharge current (when the inductive energy storage is used) leads to a considerable increase in the discharge homogeneity of mixtures in exciplex lasers and improves the discharge stability [2, 17]. The main part of energy is then supplied to the active medium of the XeF laser during discharge of capacitor C_0. A mismatching of the impedance of capacitor C_0 with the discharge resistance may be observed for large values of U_0. However, the reverse current flows through the SOS diodes, which reduces the electrode erosion and enhances the reliability of laser operation both with the inductive and capacitive generator.

The double-discharge pumping by an oscillator with the inductive energy storage is analogous to the diode mode excitation in circuits with magnetic switches [5, 13]. However, the inductive oscillator does not require pulsed charging of storage capacitors and an exact synchronisation of switching of the prepulse generator and the X-ray source. Moreover, diode mode operation of the laser frequently results in the emergence of a pause between the laser gap breakdown and the onset of pumping from the pulse-forming line, which may lead to discharge inhomogeneities. No such 'current pause' is observed when the inductive storage is used.

The interruption current I_{int} in diodes and the energy transferred to the circuit inductance L_0 were determined by the energy or the charge stored in the capacitor C_D, as well as by the charge voltage of the main storage (Fig. 3). In our experiments, diodes were activated at $I_{int} \sim 28$ kA, while the fraction of energy transferred to the inductance for the prepulse formation did not exceed 20 %. Note that, on the one hand, an increase in the interruption current raises the prepulse amplitude and the rate of increase in the current through the laser gap, thus improving the conditions for discharge formation. On the other hand, an increase in I_{int} leads to a sharp increase in the energy loss in the SOS diodes during current interruption [18], thus causing a decrease in the energy supplied to the active medium and hence a deterioration of the working characteristics of the XeF laser. The dependence of the output energy of the XeF laser on the charge accumulated in the capacitor C_D is shown in Fig. 4. The maximum output energy was obtained for $C_D = 10$ nF and $U_D = 15$ kV, which corresponds to an energy of about 1 J spent on direct pumping of the SOS diodes.

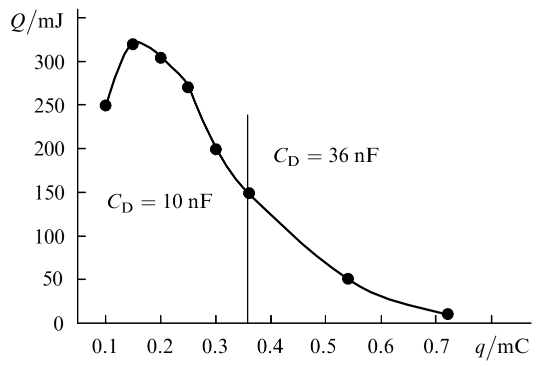

Figure 4. Dependence of the XeF laser energy on the charge stored in the capacitor $C_D = 10$ or 36 nF for a gas mixture $Ne : Xe : NF_3 =$ 2.5 atm : 6 Torr : 1.5 Torr for $C_0 = 70$ nF and $U_0 = 30$ kV.

Figure 5 shows integrated photographs of the discharge emission and Fig. 6 shows the oscillograms of voltage pulses across the laser gap and lasing pulses for various excitation regimes. A slow build-up of voltage across the laser gap and a low breakdown voltage for an XeF laser pumped by a capacitive storage violate the discharge homogeneity. Wide diffusion channels associated with bright cathode spots are observed against the volume emission background. The inductive storage enhances the rate of increase in voltage across the gap and the breakdown voltage for the discharge gap by a factor of 1.5 – 2. In this case, the discharge emission becomes much more homogeneous and the cathode spots and channels almost disappear. An improvement in the quality of discharge formed with the help of an inductive oscillator leads to a considerable increase in the pulse duration of the XeF laser. Laser pulses with a total duration up to 120 ns and the FWHM above 50 ns were obtained under the experimental conditions of Fig. 6. A decrease in the mixture pressure led to an increase in the FWHM lasing pulse duration to 75 ns, as in [13].

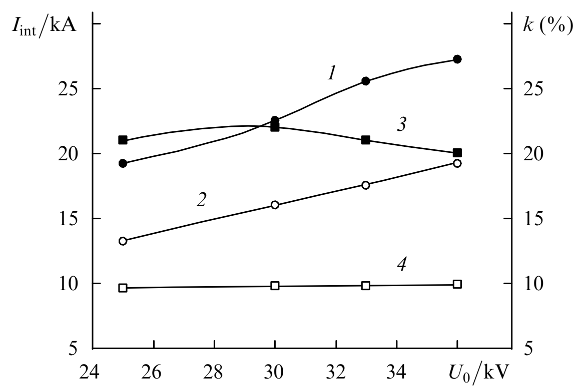

Figure 3. Dependence of the interruption current I_{int} [curves (*1*) and (*2*)] and the fraction of energy $k = L_0 I_{int}^2 (C_0 U_0^2)^{-1}$ [curves (*3*) and (*4*)] transferred from the main storage capacitor C_0 to the inductance L_0 on the charge voltage U_0 of the capacitor $C_0 = 70$ nF, $C_D = 36$ nF [curves (*1*), (*3*)] and 10 nF [curves (*2*), (*4*)], $U_D = 20$ kV.

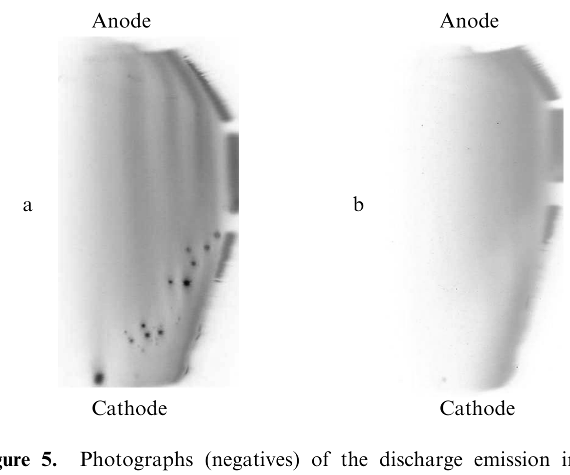

Figure 5. Photographs (negatives) of the discharge emission in the $Ne : Xe : NF_3 = 2.5$ atm : 6 Torr : 1.5 Torr mixture pumped by (a) capacitive and (b) inductive oscillators for $C_0 = 70$ nF, $U_0 = 30$ kV, $C_1 = 36$ nF, and $U_D = 15$ kV.

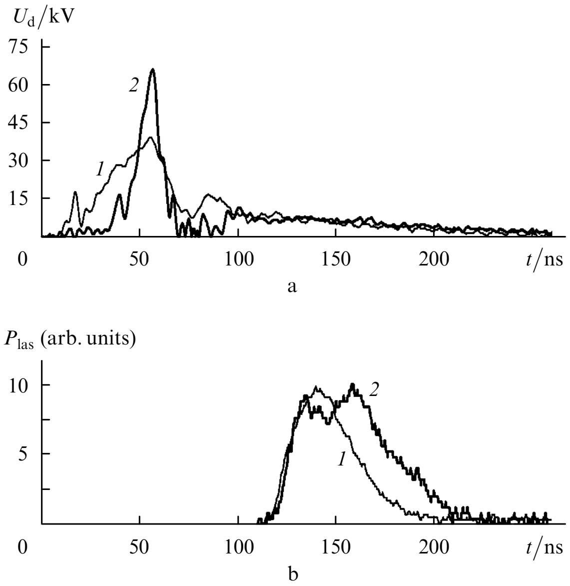

Figure 6. Oscillograms of (a) voltage pulses across the discharge gap and (b) laser radiation, obtained by pumping from capacitive [curve (*1*)] and inductive [curve (*2*)] pump oscillators for the Ne : Xe : NF_3 = 2.5 atm : 6 Torr : 1.5 Torr mixture, $C_0 = 70$ nF, $U_0 = 30$ kV, $C_1 =$ 36 nF, and $U_D = 15$ kV.

Figure 7 shows the emission spectra of the XeF laser obtained at various neon pressures. Three laser bands, whose intensity varied with the buffer gas pressure, were observed at $\lambda \sim 348$, 351 and 353 nm. As the pressure was increased, the intensity of the 353-nm band sharply increased due to an increase in the collision relaxation rate of XeF^* molecules [9, 19].

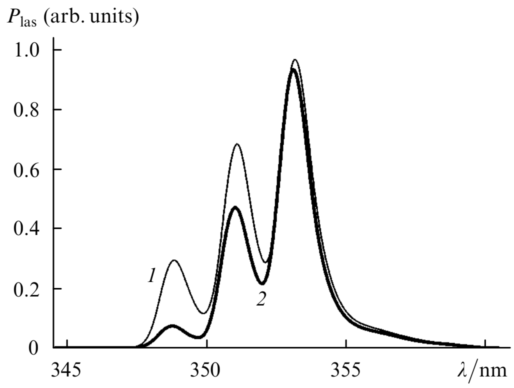

Figure 7. Laser radiation spectrum for the Xe : NF_3 = 6 Torr : 1.5 Torr mixture at a neon pressure $p = 2$ atm [curve (*1*)] and 2.5 atm [curve (*2*)], pumped by an inductive storage, $C_0 = 70$ nF, $U_0 = 33$ kV.

Note that upon pumping by a storage capacitor, the laser pulse duration was slightly shorter than the pump pulse duration at a high concentration of NF_3 in the gas mixture. It was mentioned above that this may be due to the formation of microchannels (filaments) in the discharge gap [4, 6, 17], which cannot be seen in the integrated photographs. The probability of filament formation decreases with halogen concentration in the mixture. Figure 8 shows the characteristic oscillograms of voltage across the laser gap, discharge current and lasing pulse in a mixture with a low concentration of nitrogen trifluoride. In our experiments, the reduction of the partial pressure of NF_3 in the mixture from 1.5 to 0.75 Torr upon increasing the resonator Q factor led to an increase in the total pulse duration up to 200 ns and in the FWHM up to 100 ns, which is close to the results obtained in [12] under analogous conditions using an X-ray preionisation and a complex magnetic-switch-based double discharge generator. A radiation energy of up to 150 mJ was obtained, and the efficiency η_{int} of the XeF laser with respect to the input energy was up to 1.5 %.

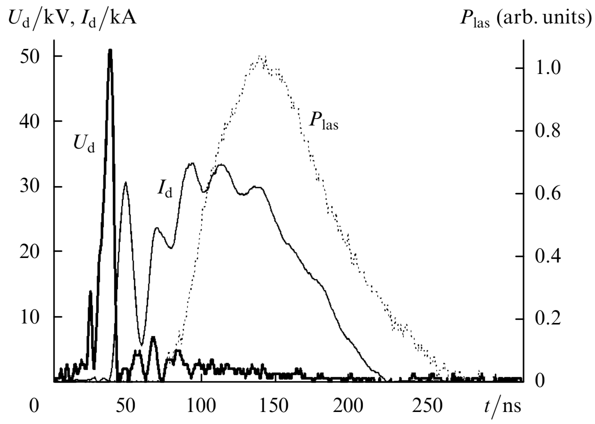

Figure 8. Oscillograms of the voltage pulse across the discharge gap (U_d), current (I_d) and output power (P_{las}) pulses for the XeF laser, obtained in the Ne : Xe : HCl = 2.5 atm : 3 Torr : 0.75 Torr gas mixture pumped by the inductive storage for $C_1 = 10$ nF, $U_D = 20$ kV, $C_0 = 70$ nF, $U_0 = 36$ kV. The output mirror had the reflectivity $R = 80$ %.

When an inductive storage with $C_0 = 70$ nF was used in a mixture containing NF_3 at a pressure of 1.5 Torr, the radiation energy increased with the buffer gas pressure, and achieving 0.5 J at $p = 3.5$ atm, corresponding to the specific laser energy ~ 1.8 J L^{-1} and an electric efficiency $\eta_0 =$ 1.1 %. The internal efficiency η_{int} of the XeF laser (with respect to the energy supplied to the active medium) was more than 2 % in this case. When the inductive storage was switched off, the radiation energy decreased by 30 % – 50 %.

Figure 9 shows typical oscillograms and dependences of the radiation energy and efficiency of the XeF laser pumped by inductive and capacitive oscillators, obtained by reducing the capacitance C_0 to 38 nF. A decrease in the storage capacitance led to a drop in the discharge current pulse duration to ~ 150 ns. When an inductive oscillator was used, the radiation pulse resembled the discharge current pulse in shape and terminated simultaneously with the excitation pulse. In this case, the laser pulse duration (120 ns at the pulse base and 50 ns at the FWHM) remained almost the same as for $C_0 = 70$ nF. The highest electric efficiency of the XeF laser was 1.6 % under the conditions of our experiments. Such a high efficiency was obtained earlier only in an XeF amplifier pumped by a fast discharge due to a decrease in energy loss for the achievement of the threshold [20]. The output energy up to 0.36 J was obtained, and the efficiency η_{int} of the induction-storage-pumped XeF laser with respect to the energy supplied to the active medium was 3 %. Close values of the internal efficiency of the XeF laser were obtained by exciting Ne – Xe – NF_3 mixtures by an electron beam, which provides a high

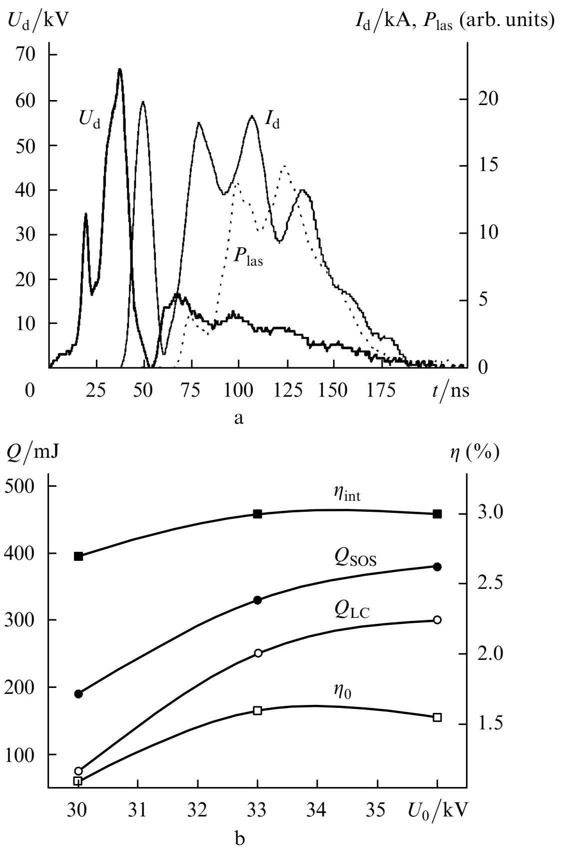

Figure 9. (a) Oscillograms of the voltage pulse U_d in the discharge gap, discharge current (I_d) and lasing power (P_{las}) pulses, obtained by using the inductive storage for $U_0 = 36$ kV; (b) the radiation energy (Q_{SOS}), internal efficiency (η_{int}) and electric efficiency (η_0) of the XeF laser pumped by the inductive storage oscillator, as well as the output energy (Q_{LC}) upon pumping by the capacitive storage as functions of the charge voltage of capacitor C_0. The mixture $Ne : Xe : NF_3 = 2.5$ atm : 6 Torr : 1.5 Torr, $C_0 = 38$ nF, $C_1 = 10$ nF.

uniformity of the input energy and solves the problem of discharge contraction [21–23]. The output energy and the radiation pulse duration decreased considerably when the inductive storage was switched off.

The results obtained in this study show that an oscillator with inductive storage can excite a stable volume discharge of duration 150–200 ns in mixtures with nitrogen trifluoride. In turn, a high quality of discharge considerably enhances the output energy and lasing efficiency, as well as the pulse duration of the XeF laser.

4. Conclusions

We have studied the lasing parameters of the $Ne-Xe-NF_3$ mixtures excited by the double discharge from an oscillator with the inductive energy storage and the current interrupter based on semiconductor SOS diodes. Unlike other double discharge oscillators, the inductive oscillator does not require pulse charging of storage capacitors or an exact synchronisation of their triggering. The time spread for actuation of individual SOS diodes connected in parallel in the generator did not exceed a few nanoseconds. The oscillator provided a high stability of the generated pulses, in particular in the repetitively pulsed regime.

We have shown that a high-voltage prepulse formed by an oscillator with the inductive storage considerably enhances the stability and duration of the volume discharge in mixtures with NF_3, and also increases the energy and the duration of the pulse generated at the B–X transition of XeF^* molecules. Laser pulses with a total duration of up to 200 ns at the FWHM of 100 ns were produced. The output emission energy of XeF^* molecules (at 348, 351 and 353 nm) achieved 0.5 J for the electric efficiency of the XeF laser up to 1.6 %. The internal efficiency η_{int} was close to that of electron-beam-pumped XeF lasers and achieved 3 %.

Based on the experiments reported in the paper, we have fabricated the efficient long-pulse electric-discharge XeF laser with a simple and reliable spark preionisation, pumped by an oscillator with the inductive storage and the current interrupter based on semiconductor SOS diodes.

Acknowledgements. This work was supported by the ISTC (Grant No. 2596).

References

1. Levatter J.I., Robertson K.L., Lin S.C. *Appl. Phys. Lett.*, **39**, 297 (1981).
2. Lomaev M.I., Mel'chenko S.V., Panchenko A.N., Tarasenko V.F. *Izv. Akad. Nauk SSSR. Ser. Fizich.*, **48**, 1385 (1984).
3. Long W.H., Plummer M.J., Stappaerts E.A. *Appl. Phys. Lett.*, **43**, 735 (1983).
4. Taylor R.S., Leopold K.E. *J. Appl. Phys.*, **65**, 22 (1989).
5. Fischer C.H., Kushner M.J., DeHart T.E., MacDaniek J.P., Petr R.A., Ewing J.J. *Appl. Phys. Lett.*, **48**, 1574 (1986).
6. Kuscner M.J. *IEEE Transactions on Plasma Science*, **19**, 387 (1991).
7. Burnham R., Powell F.X., Djeu N. *Appl. Phys. Lett.*, **29**, 30 (1976).
8. Sarjeant W.J., Alcock A.J., Leopold K.E. *Appl. Phys. Lett.*, **30**, 635 (1977).
9. Verkhovskii V.S., Mel'chenko S.V., Tarasenko V.F. *Kvantovaya Elektron.*, **8**, 417 (1981) [*Sov. J. Quantum Electron.*, **11**, 254 (1981)].
10. Kumagai H., Obara M. *IEEE J. Quantum Electron.*, **25**, 1874 (1989).
11. Baranov V.Yu., Borisov V.M., Khristoforov O.B. *Kvantovaya Elektron.*, **8**, 165 (1981) [*Sov. J. Quantum Electron.*, **11**, 93 (1981)].
12. Mei Q.-C., M.Peters P.J., Trentelman M., Witteman W.J. *Appl. Phys. B*, **60**, 553 (1995).
13. Trentelman M., M.Peters P.J., Mei Q.-C., Witteman W.J. *J. Opt. Soc. Am. B*, **12**, 2494 (1995).
14. Baksht E.H., Panchenko A.N., Tarasenko V.F. *Kvantovaya Elektron.*, **30**, 506 (2000) [*Quantum Electron.*, **30**, 506 (2000)].
15. Baksht E.H., Losev V.F., Panchenko A.N., Panchenko Yu.N., Tarasenko V. F. *SPIE Proc. Int. Opt. Eng.*, **4747**, 88 (2001).
16. Baksht E.H., Panchenko A.N., Tarasenko V.F., Matsunaga T., Goto T. *Jap. J. Appl. Phys.*, **41**, 3701 (2002).
17. Makarov M., Bonnet J., Pigache D. *Appl. Phys. B*, **66**, 417 (1998).
18. Rukin S.N. *Prib. Tekh. Eksp.*, (4), 5 (1999).
19. Baranov V.Yu., Borisov V.M., Kiryukhin Yu.B., Stepanov Yu.Yu. *Kvantovaya Elektron.*, **5**, 2285 (1978) [*Sov. J. Quantum Electron.*, **8**, 1287 (1978)].
20. Sadighi-Bonabi R., W.Lee F., Collins C.B. *J. Appl. Phys.*, **52**, 8508 (1982).
21. Mandl A., Litzenberger L. *Appl. Phys. Lett.*, **51**, 955 (1987).
22. Nishida N., Tittel F.K. *Appl. Phys. Lett.*, **52**, 1847 (1988).
23. Mandl A. *J. Appl. Phys.*, **71**, 1630 (1992).