LASERS

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Wide-aperture electric-discharge nitrogen laser

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***Abstract*. The parameters of a wide-aperture nitrogen laser pumped by a generator with the inductive energy storage and a SOS diode opening switch or a generator with the capacitive energy storage are studied. The gas preionisation was performed by soft X-rays. The size of the active volume of the laser was $10 \times 6 \times 100$ cm. The output energy and power obtained at the 337.1-nm $C\,^3\Pi_u - B\,^3\Pi_g$ transition are maximal for electric-discharge nitrogen lasers. The output energy in the second positive system of nitrogen in the $N_2 - SF_6$ mixture achieved 110 mJ for a peak power of 6 MW. Due to an increase in voltage across the laser gap in nitrogen mixtures with NF_3, the generation of $\sim$ 35-mJ, 100-ns pulses was obtained in the quasi-stationary stage of the discharge.**

Keywords: *UV nitrogen laser, $N_2 - SF_6$ and $N_2 - NF_3$ mixtures, inductive and capacitive energy storages, maximum output energy and power.*

1. Introduction

An electric-discharge laser on transitions of a nitrogen molecule (the $C\,^3\Pi_u - B\,^3\Pi_g$ band with the strongest lines at 337.1 and 357.7 nm) developed in 1963 was the first source of high-power coherent UV radiation [1] and was extensively studied both theoretically [2, 3] and experimentally [3 – 7] before the advent of exciplex lasers. Nevertheless, the nitrogen laser still attracts the attention of researchers due to its low-cost and nontoxic active medium, a simple design and high reliability [8 – 11]. The 337.1-nm wavelength of the nitrogen laser is very convenient for many medical and biological applications [12, 13]. For this reason, the increase in the energy and power of the 337.1-nm radiation is of scientific and practical interest.

Note that the manufacturing of a high-power nitrogen laser is a rather complicated technological problem. This laser belongs to self-contained lasers, and comparatively high average electron energy (more than 11.7 eV) is required to excite efficiently the upper laser level. Because of this, the optimal value of the reduced electric field strength E/p at the instant of the laser-gap breakdown should be 150 – 200 V cm^{-1}Torr^{-1} [11]. However, due to a rapid multiplication of electrons at high voltages, the parameter E/p rapidly decreases after the breakdown. For this reason, the inversion at the $C\,^3\Pi_u - B\,^3\Pi_g$ transition exists only for a short time ($\sim$ 10 ns), and a considerable specific energy ($\sim$ 100 J L^{-1}) should be supplied to the active medium. Because of this, lasing at the $C\,^3\Pi_u - B\,^3\Pi_g$ transition is achieved, as a rule, by using high-voltage generators with capacitive energy storages based on strip lines or *LC* circuits with a low wave impedance, which form short discharge-current pulses. The cross section of the discharge gap of a nitrogen laser is usually a few square centimetres to reduce its inductance, although the interelectrode gap can achieve 10 cm [4]. The specific output energy of the nitrogen laser does not exceed, as a rule, 0.1 J L^{-1} [3, 11].

A simple increase of the active volume and storage capacity of the nitrogen laser leads to the increase in the discharge-circuit inductance and pump duration and usually does not result in the increase in the output power at 337.1 nm. The increase in the discharge-gap inductance can be partially compensated by adding electronegative gases such as SF_6 and NF_3 to the active medium of the nitrogen laser, which slow down the rate of voltage decay on the laser gap. This allows one to increase the time of efficient pumping and the inversion lifetime at the $C\,^3\Pi_u - B\,^3\Pi_g$ transition, which results in the increase in the output energy and efficiency of the nitrogen laser [5, 7, 10, 14 – 16].

Due to these specific features of lasing on nitrogen molecules, only five papers have been published for almost half a century of studies which reported the output energy of the N_2 laser exceeding 20 mJ upon pumping by capacitive-storage generators [5, 14 – 17]. Some parameters of these lasers are presented in Table 1. The maximum output energy at 337.1 nm was 40 mJ [15] and the maximum peak power ($\sim$ 5 MW) was obtained in 4-ns pulses [16].

We showed earlier that the pumping of gas lasers by a generator with the inductive energy storage (IES) improved their radiation parameters [18]. The use of the IES generator considerably reduces the pump pulse duration and increases the pump power. The output energy and power of the nitrogen laser especially noticeably increased with increasing the discharge gap. In different IES pump regimes and the discharge aperture 2×4 cm, the output energy and power at 337.1 nm increased by 3 – 5 times compared to those obtained upon pumping by the capacitive energy storage. The UV energy and power achieved 25 mJ and 3.2 MW,

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Table 1. Parameters of nitrogen lasers pumped by capacitive and inductive energy storages.

Energy storage	V/cm^3	Mixture composition	Q/mJ	$t_{1/2}/\text{ns}$	P_{max}/MW	References
Capacitive	$1.2 \times 0.5 \times 120$	$N_2:SF_6 = 100:10$ Torr	20	8.5	2.5	[5]
	$3.8 \times 1 \times 100$	$N_2:SF_6 = 28:3$ Torr	30	19	1.5	[14]
		N_2, 31 Torr	18	14	1.3	
	$4 \times 4 \times 25$	$N_2:SF_6 = 75:30$ Torr	40	16	2.1	[15]
	$2.5 \times 3.5 \times 50$	$He:N_2 = 740:60$ Torr	20	4	5	[16]
		$He:N_2:NF_3 = 740:60:2$ Torr	25	8	3.1	
	$4 \times 1 \times 65$	N_2, 60 Torr	20.5	13	1.5	[17]
IES with SOS diodes	$4 \times 2 \times 70$	$N_2:SF_6 = 75:9$ Torr	25	7.5	3.25	[10]
	$4 \times 2 \times 70$	$N_2:NF_3 = 75:3$ Torr	25	7.5	3.25	
	$4 \times 2 \times 70$	$N_2:NF_3 = 30:1$ Torr	10	40	0.25	

Notes: V is the active laser volume (height ×width × length); $t_{1/2}$ is the radiation pulse FWHM; Q and P_{max} are the laser energy and maximal power.

respectively, for the laser pulsed duration up to 40 ns [10]. These values of the output energy and power of the N_2 laser are close to the maximum values obtained upon pumping by capacitive storages (see Table 1).

The aim of this paper is to study a wide-aperture nitrogen laser pumped by a generator with the IES and SOS diode opening switch or with the capacitive energy storage.

2. Experimental

We used in experiments a transverse-discharge-pumped laser of design close to a wide-aperture XeCl laser [19]. The gas preionisation in the active volume was performed by soft X-rays. The volume discharge in nitrogen was produced at high pressures and optimal values of the parameter E_0/p (E_0 is the maximum electric field strength in the discharge gap before its breakdown).

The gas volume excited in a cylindrical laser chamber of length 150 cm had a length of 100 cm, an aperture of 10×6 cm and was limited by two profiled electrodes. An anode was connected through an isolator with the pump generator. A thin-wall cathode was mounted on the output window of a vacuum photodiode – a source of soft X-rays [20]. The design of the isolator and a reverse conductor provided the inductance of the discharge gap $L_1 = 20$ nH. X-rays were injected into the gas through a 80-μm-thick titanium foil. The duration of an X-ray pulse with the maximum of the energy distribution in the region of 25–30 keV was 500 ns. The X-ray exposure dose in the active volume achieved 0.15 P. The initial electron concentration produced by X-rays in the laser chamber filled with pure nitrogen at a pressure of 55–75 Torr was 10^7 cm^{-3}. The linear absorption coefficient of X-rays in the mixture of nitrogen with NF_3 and SF_6 increased by a factor of 4–8, however, the initial electron concentration did not exceed 10^6 cm^{-3} due to the attachment of electrons to halogen-containing molecules.

Pumping was performed by a universal generator which provided excitation both from the inductive and capacitive energy storages. The scheme of the laser with the pump generator is presented in Fig. 1. The pump generator

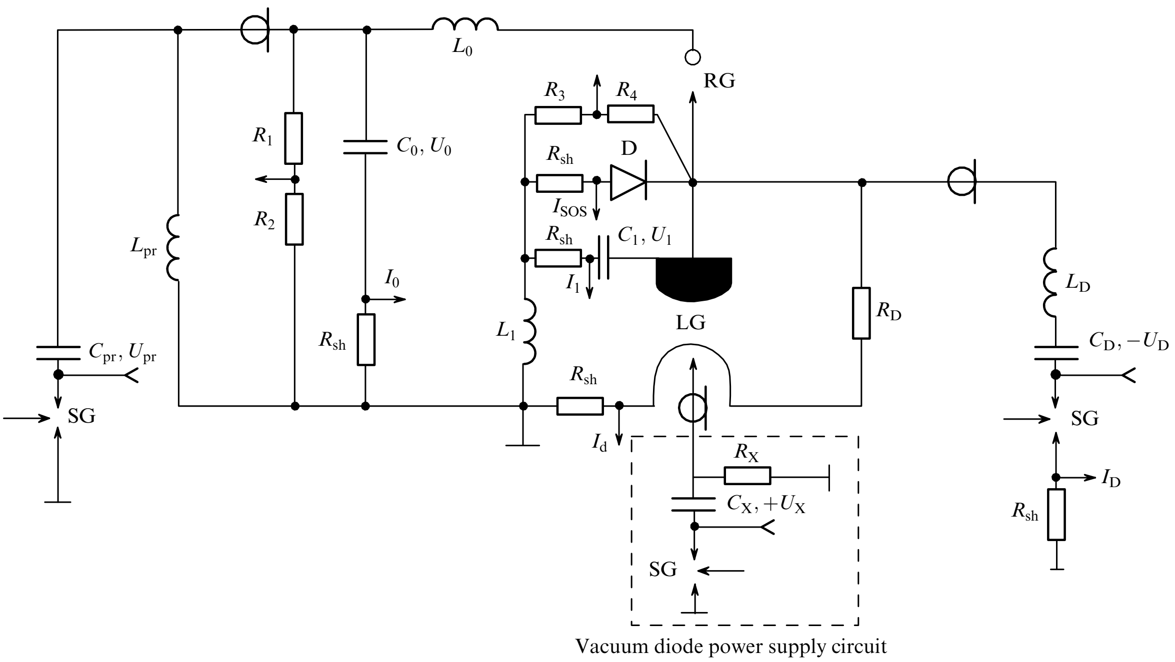


Figure 1. Electric circuit of a wide-aperture nitrogen laser: LG: laser gap; D: SOS diodes; RG: rail gap; SG: spark gap; $R_1 - R_2$ and $R_3 - R_4$: voltage dividers; R_{sh}: current shunts.

contained the main and auxiliary circuits. The main circuit consisted of the storage capacitor $C_0 = 45$ nF, the inductance $L_0 = 100$ nH, and the peaking capacitor $C_1 = 4.27$ nF. The capacitor C_0 was charged from the capacitor $C_{pr} = 100$ nF for the time ~ 1 μs and then was connected to the laser gap trough a rail gap.

The auxiliary circuit formed a direct current pulse through diodes and consisted of capacitors $C_D = 8.3$ nF, a spark gap, and inductance $L_D = 2.4$ μH. In the laser, 12 or 14 SOS-120-4 diodes connected in parallel with the peaking capacitor C_1 were used. The generator could operate with the IES or in the regime of pulsed charging of the peaking capacitor C_1. In the first case, a part of energy stored in the capacitor C_0 was transferred to the inductance L_0 of the main circuit. In the second case, the auxiliary circuit with the capacitor C_D was not used. The volume-discharge-current pulse duration was ~ 150 ns.

The parameters of the volume discharge and lasing were studied in the laser chamber filled with pure nitrogen and mixtures of N_2 with NF_3 and SF_6 at a pressure of 100 Torr. A plane aluminium-coated mirror was used as the highly reflecting mirror in the optical resonator, and a plane–parallel quartz plate was used as the output mirror.

The output energy of the laser was measured with an OPHIR calorimeter with an FL-250A sensor head. The laser radiation from the entire aperture of the discharge was collected on the measuring head with a telescope consisting of two quartz lenses. The radiation pulse shape was measured in the far-field zone with a FEK-22 SPU vacuum photodiode on which a part of laser radiation reflected from the external lens of the telescope was directed. To provide the operation of the photodiode in a linear regime, the incident radiation was weakened by a set of metal grids.

Currents I_0 and I_1 in the discharge circuits of the storage and peaking capacitors and currents I_{SOS} and I_d through SOS diodes and the laser gap were measured with the help of shunts R_{sh}. Voltages U_0 and U_1 across capacitors C_0 and C_1 and SOD diodes were measured with the help of resistive voltage dividers $R_1 - R_2$ and $R_3 - R_4$. Electric signals were recorded by using digital TDS-220 and TDS-3014 oscilloscopes.

3. Experimental results and discussion

The first experiments were performed by using pure nitrogen as the active medium. At a nitrogen pressure of 55–75 Torr, a homogeneous volume discharge with the aperture up to 10×7 cm was obtained; however, the radiation energy did not exceed 1–2 mJ due to insufficient discharge current density. The additions of electronegative gases to the active medium reduced the width of the discharge region by 1–1.5 cm and increased the discharge-gap breakdown voltage. As a result, the pump power and output energy increased. These results are presented in Figs 2–4. Figure 2 shows the dependences of the output energy of the laser on the charging voltage across the storage capacitor C_0 for different pump regimes. For the same charging voltages and pumping the laser by the IES generator, the output energy at 337.1 nm noticeably increased compared to that obtained upon pumping by using the LC circuit. However, due to a large inductance between the SOS diodes and the discharge gap, the duration of the voltage pulse on SOS diodes exceeded the admissible value, and as a result, they failed after a few tens of pulses.

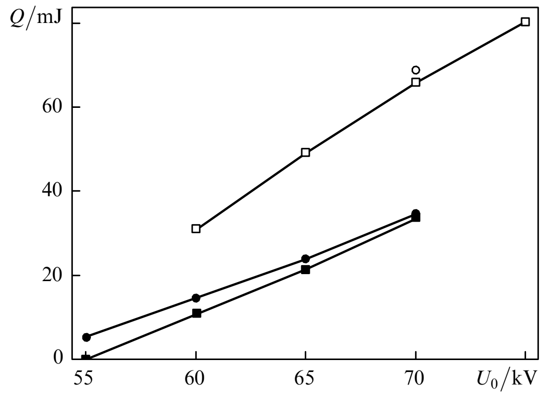


Figure 2. Dependences of the output energy Q of the nitrogen laser on mixtures $N_2:NF_3 = 55:1.5$ Torr (■, ●) and $N_2:SF_6 = 55:3$ Torr (□, ○) on the voltage U_0 across the capacitor C_0. Pumping by a capacitive (■, □) or an inductive (●, ○) energy storage.

For this reason, experiments with maximal charging voltages were performed by using only the capacitive energy storage.

The output pulse energy for the $N_2 - NF_3$ mixtures was 35 mJ. The laser pulse energy for the $N_2 - SF_6$ mixture achieved 80 mJ. The total laser pulse duration was 30 ns and its full-width at half maximum was 14 ns. This corresponds to the peak radiation power ~ 6 MW. In this case, the nitrogen laser efficiency with respect to the energy stored in the capacitor C_0 achieved 0.065 %.

Figures 3 and 4 present the typical oscillograms of voltage pulses on the peaking capacitor, the discharge current, and radiation at 337.1 nm. The oscillograms were obtained upon pumping the nitrogen laser by generators both with capacitive and inductive energy storages. The use of the IES leads to an increase in the breakdown voltage of the laser gap, the discharge current at the stage of the voltage decay in the gap after the discharge ignition, and the laser pulse duration. These factors cause the increase in the output energy and power of the nitrogen laser pumped

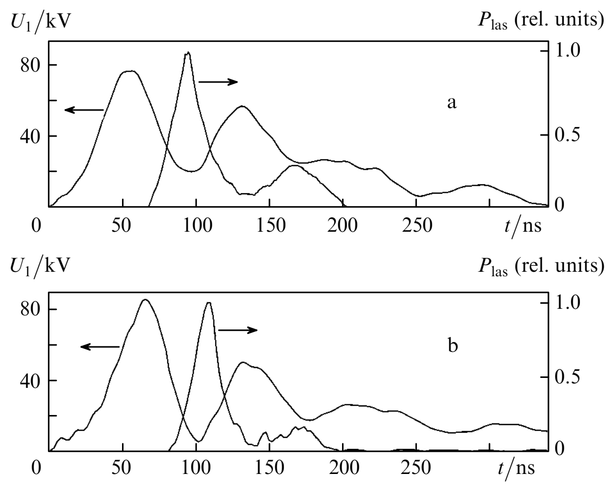


Figure 3. Oscillograms of voltage pulses U_1 on the peaking capacitor and laser pulses P_{las} at 337.1 nm obtained by using pump generators with capacitive (a) and inductive (b) energy storages. The $N_2:NF_3 = 55:1.5$ Torr mixture, $U_{pr} = 45$ kV.

by the IES. This effect was most noticeable at low charging voltages across the storage capacitor C_0. This is explained by the fact that the opening current in SOS diodes in our experiments was ~ 10 kA, whereas the discharge current achieved ~ 50 kA for the maximal charging voltage U_0. Because of this, as the value of U_0 increased, a lower fraction of energy was transferred to the inductive storage, reducing its influence on the output parameters of the nitrogen laser.

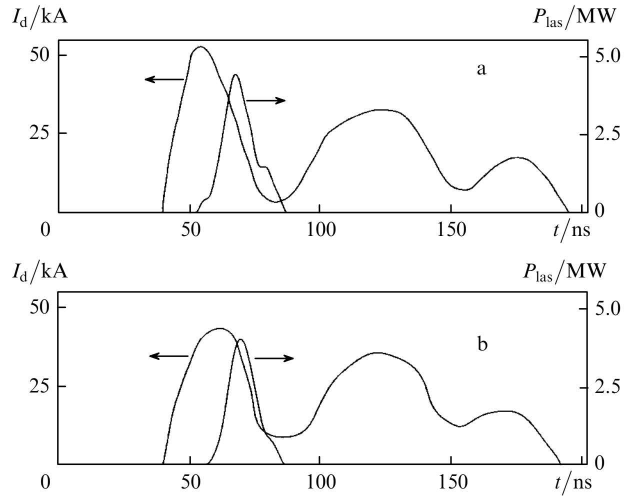
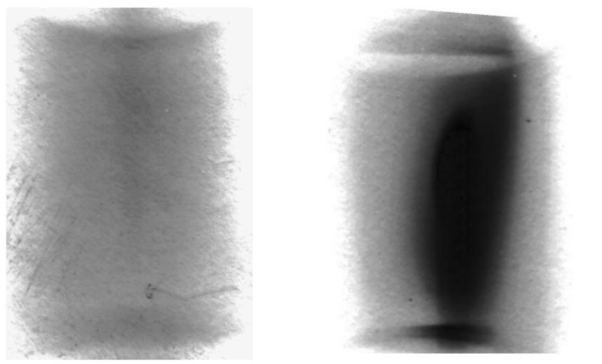


Figure 4. Oscillograms of volume-discharge current pulses I_d and laser pulses P_{las} at 337.1 nm obtained upon pumping the nitrogen laser by generators with capacitive (a) and inductive (b) energy storages. The $N_2:SF_6 = 55:3$ Torr mixture, $U_{pr} = 55$ kV.

The characteristic feature of the operation of the laser on the mixture of nitrogen with NF_3 is a noticeable increase in the laser pulse duration compared to its duration in usual operation regimes of the N_2 laser (see Fig. 3 and Table 1). Earlier, we observed a 337.1-nm laser pulse consisting of two peaks with the total duration of ~ 50 ns in mixtures with NF_3 for a discharge aperture of 2×4 cm and pumping by an IES [10]. As the discharge aperture was increased, a laser pulse was observed which also consisted of two peaks, but its duration exceeded 100 ns. The increase in the laser pulse duration is caused by a considerable increase in the voltage across the laser gap in the quasi-stationary stage of the volume discharge due to a high rate of attachment of electrons to the NF_3 molecules. In addition, voltage oscillations occur across the laser gap in the quasi-stationary stage due to energy exchange between capacitors C_1 and C_0. In this case, the value of E/p in mixtures with NF_3 at the second voltage maximum is ~ 100 V cm^{-1} Torr^{-1}, which is sufficient for producing a high population inversion at the $C\,^3\Pi_u - B\,^3\Pi_g$ transition in the active medium of the nitrogen laser. The laser pulse duration in this case is approximately equal to the voltage oscillation period.

The discharge current density in high-power nitrogen lasers usually varies from a few hundreds to ~ 1 kA cm^{-2} [5, 10, 14–17]. In our case, the discharge current density was lower than 100 A cm^{-2} when the width of the discharge region was 5.5–6 cm. Therefore, a decrease in the discharge-region cross section should result in the increase in the output energy at 337.1 nm. The discharge current density can be increased by decreasing the width of the gas region irradiated by X-rays and (or) increasing a peaking capacitor. We performed experiments with a window of width 2 cm for extraction of X-rays and a profiled cathode with a smaller radius of curvature. In this case, the distance between electrodes forming the laser gap decreased down to 8 cm.

Figure 5 shows the photographic autographs of radiation from a wide-aperture nitrogen laser obtained for two different widths of the illuminated region in mixtures of nitrogen with SF_6. For the width of a window for extracting X-rays equal to 5.5 cm, the photographic paper was illuminated rather uniformly over the entire aperture of the laser beam. For the window width of 2 cm, the total width of the illuminated region did not change, but the illumination intensity in the middle of the print caused by laser radiation from the central region of the discharge, where X-rays are emitted, was higher. As the effective width of the discharge region decreased, the output energy of the nitrogen laser increased noticeably. For the charging voltage $U_0 = 75$ kV, the output energy achieved 95 mJ. The increase in the peaking capacitance C_1 up to 8.6 nF resulted in the increase in the output energy up to 110 mJ. The total laser pulse duration was 40 ns, its FWHM was 18 ns, and the peak power was ~ 6 MW. In this case, the nitrogen laser efficiency with respect to the energy stored in the capacitor C_0 achieved 0.09 %.



a b

Figure 5. Photographic autographs of radiation from the N_2 laser for the illuminated-region width 5.5 cm and the interelectrode distance 10 cm (a) and 2 and 8 cm (b), respectively. Pumping is performed from the *LC* circuit. $U_0 = 70$ kV, the $N_2:SF_6 = 55:6$ Torr mixture.

4. Conclusions

The properties of the wide-aperture nitrogen laser have been studied for different pump regime. It has been shown that the use of the IES generator with a SOS diode opening switch results in the increase in the output energy and power at 337.1 nm due to the increase in the breakdown voltage of the laser gap and the discharge current at the voltage decay stage. The output radiation energy and power obtained in experiments have maximal values achieved so far for the electric-discharge nitrogen laser. The output energy in the mixture of nitrogen with SF_6 in the active volume with the cross section up to 6×10 cm achieved 110 mJ for a peak power of ~ 6 MW and the laser efficiency of 0.09 % with respect to the stored energy. Due to the increase of voltage in mixtures of nitrogen with NF_3

in the quasi-stationary discharge stage, the generation of 100-ns, 35-mJ pulses has been achieved.

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