Nitrogen UV-laser pumped by a transverse discharge capable of emitting dual pulses

A.N. Panchenko, V.F. Tarasenko, and A.E. Telminov

Institute of High-Current Electronics,
Siberian Branch of the Russian Academy of Sciences, Tomsk

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We present the study of the emission and discharge characteristics in a nitrogen laser pumped by the transverse discharge from the generator with inductive energy storage and SOS-diodes. It is shown, that in the N_2–NF_3 mixture it is possible to form the emission pulses at the wavelength of 337.1 nm, consisting of two pulses spaced from each other by 12 ns time gap and by 25 ns interval between the pulse maxima. Radiation energy of 23 mJ per pulse was obtained.

Introduction

The nitrogen UV-lasers (second positive system, electronic bands $C^3\Pi_u$–$B^3\Pi_g$, the strongest transitions 0–0, $\lambda = 337.1$ nm and 0–1, $\lambda = 357.7$ nm) with the transverse discharge allow obtaining radiation energy of units to tens of millijoules. The maximum radiation energy at excitation by a self-maintained discharge is achieved if adding electronegative gases (SF_6, NF_3, F_2) into the working gas mixture, and at pumping from generators with an inductive energy storage (see Refs. 1 to 4 and references therein). In Ref. 4 it has been shown, that at large SF_6 concentration it is possible to obtain dual laser pulses at $\lambda = 357.7$ nm. Time lag between the maxima of the emission pulse was equal to 23 ns, simultaneously in the first peak, the generation at $\lambda = 337.1$ nm was observed with higher energy. The total duration of the radiation pulse at zero level is ~ 40 ns, total energy of radiation at two lines $\lambda = 337.1$ nm (single-peak generation) and at $\lambda = 357.7$ nm (two-peak generation) made up about 6 mJ. Radiation energy per pulse was three times lower as compared with the radiation energy achieved with the optimal mixture. The occurrence of the second peak has been explained in Ref. 4 by the increase of the E/p parameter (E is the electric field strength in the gap, p is the nitrogen pressure) during the pumping caused by the electronegative gas sticking to SF_6. However, no studies of this mode have been carried out. Note, that usually a single generation peak is observed in the nitrogen UV-lasers.

The purpose of this study was to investigate the working conditions of the nitrogen electro-discharge lasers excited by the transverse discharge at which the generation pulses consisting of two separate peaks are formed, and to obtain the maximum energy of radiation per pulse.

1. Experimental setup and techniques

In the experiments, we used a laser with excitation by the transverse discharge and preionization system from the spark gaps similar to the laser used in Ref. 4. The setup allowed us to form a volume discharge at an increased pressure and optimum parameter values of E_0/p (E_0 is the maximum strength of the electric field in the gap before its breakdown). For pumping, we used the universal generator, enabling the excitation to be performed both from an inductive and the capacitive energy storage (Fig. 1).

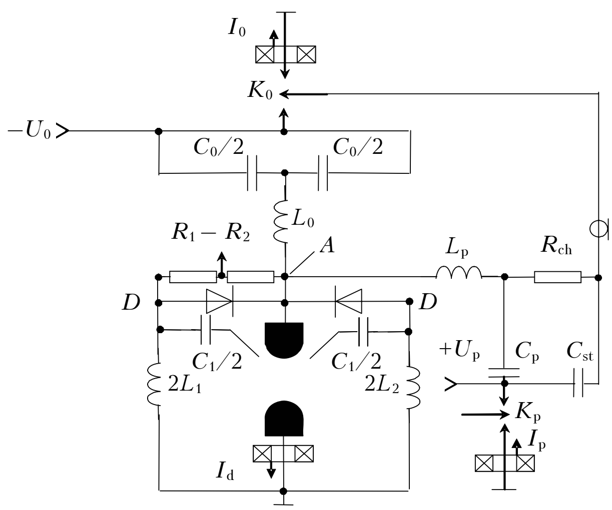

Fig. 1. The electric circuitry of the N_2 laser pumped from an inductive energy storage: K_0, K_p are the spark gaps; C_0 is the primary capacitive storage; C_1 are the peaking capacitors; C_p is the pumping capacitor of the SOS-diodes D in the forward direction; C_{st} is the starting capacitor; L_0, L_1, L_p are the inductances; U_0, U_p are the charging voltage; R_1–R_2 is the voltage divider; I_0, I_d, I_p are Rogowski loops.

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Preionization of the discharge gap was carried out with 72 spark gaps uniformly distributed along both sides of the anode. The capacities and inductances were the following: $C_0 = 70$ nF, $C_1 = 2.45$ nF, $C_{st} = 1.5$ nF, $C_p = 36$ or 10 nF, $L_0 = 24.5$ nH, $L_1 = 11$ nH and $L_p = 0.87$ or 3.13 mH. At pumping from an inductive storage, the discharge current duration was about 200 ns, and at pumping from the capacitive storage C_0 (in this case, C_p and L_p were disconnected at the point A, Fig. 1) the pulse duration of discharge current grew up to ~ 250 ns. The laser had an active volume of 4×0.6–1.5×72 cm^3.

The beam-forming electrodes essentially reducing the heterogeneities of the electric field (local field amplification on the electrodes and in the discharge gap) were used in the laser. The electrodes were made from stainless steel. The interelectrode gap d was equal to 4 cm. The active volume in various experimental conditions varied by varying the width of the discharge area that depended on the charging voltage, composition, and pressure of the gas mixture. Discharge and generation characteristics were studied in pure nitrogen and nitrogen mixtures with NF_3 at pressures of 10–150 Torr.

Radiation energy was measured with a calorimeter OPHIR equipped with FL-250A and PE-50BB sensor heads. For recording the time profile of the radiation pulses, we used a PEC–22 SPU vacuum photodiode by directing a portion of laser radiation with the help of the beam-splitting plate. The spectrum of the nitrogen laser emission was recorded with a StellarNet EPP2000-C25 spectrometer with the resolution of 2 nm. For attenuation of laser and spontaneous radiation, a special optical arrangement was used. Radiation of nitrogen laser was reflected by two aluminum mirrors to increase the distance from the discharge area and after additional attenuation it was directed into the spectrometer. The attenuation was carried out with the help of metal meshes and dielectric mirrors. Such an optical arrangement allowed recording to be performed of the laser radiation only.

Discharge current and the voltage applied to the laser electrodes were determined with the help of the voltage divider and Rogowski loop. Electric signals were monitored with TDS-220 or TDS-224 oscilloscopes. In order to cut off the noise component in the signal, the oscilloscopes were placed in a shielded room. The line supply of the oscilloscopes was performed using an isolating transformer.

2. Experimental results and discussion

First, we have optimized the pulse energy of laser radiation by varying the composition and pressure of gas mixture. The maximum energy has been obtained at nitrogen pressure of ~ 75 Torr and NF_3 ~ 3 Torr. In the further experiments, the working mixture N_2/NF_3 = 75/3 Torr was usually used. The basic results are presented in Figs. 2 to 4.

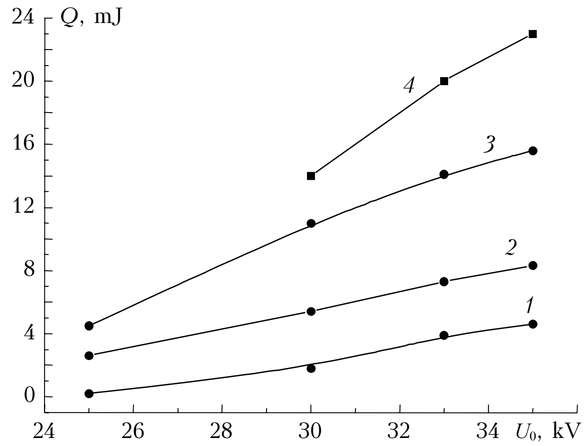

Fig. 2. Dependence of output energy of nitrogen laser on the discharge voltage: curve *1* presents data obtained in pure nitrogen at pumping from generator with a capacitive storage; curve *2* presents data obtained in pure nitrogen at pumping from generator with an inductive storage with C_p = 36 nF and U_p = 20 kV; curve *3* presents data obtained in the mixture $N_2 + NF_3$ at pumping from the generator with an inductive storage with C_p = 36 nF and U_p = 20 kV; curve *4* presents data obtained in the mixture $N_2 + NF_3$ at pumping from an inductive storage with C_p = 10 nF and U_p = 20 kV.

Increasing voltage led in all the mixtures to an increase in the pulse energy of the emission both in the case of a capacitive (curve *1* in Fig. 2) and inductive (curves *2* to *4* in Fig. 2) energy storage. The use of inductive energy storage, instead of the capacitive one allowed increasing considerably the pulse energy of the laser emission (curves *1* and *2*). Use of the admixture of an electronegative gas, as compared to pure nitrogen, yielded an additional twofold growth of the pulse energy (curves *2* and *3*). The maximum energy per pulse of 23 mJ was obtained with the inductive energy storage in the mixture of nitrogen with NF_3 and at a decrease of the capacitance of the C_p capacitor (curve *4*).

Figure 3 shows the oscillograms of voltage pulses, discharge current, and generation pulses recorded under optimal excitation conditions. It is seen, that for generators of both types, the emission pulses consist of two peaks. Delay between the maxima of the two pulses was up to 25 ns. In the given experiments, in contrast to those in Ref. 4, the pause between separate pulses was observed. The pause duration was about 12 ns. Besides, the optimization performed in this study made it possible to obtain two-peak lasing with maximum energy, realized at the highest charging voltages while using optimum working gas mixture. Decreasing the discharge voltage, made the ratio of amplitudes of the first generation peak to the second one to increase and at low voltages the second peak disappeared at all.

Analysis of current and voltage oscillograms presented in Fig. 3, as well as observations of the discharge, showed that use of inductive energy storage has allowed us to improve the discharge homogeneity and made it possible to work with gas mixtures with a higher partial pressure of NF_3, up to 7.5 Torr.

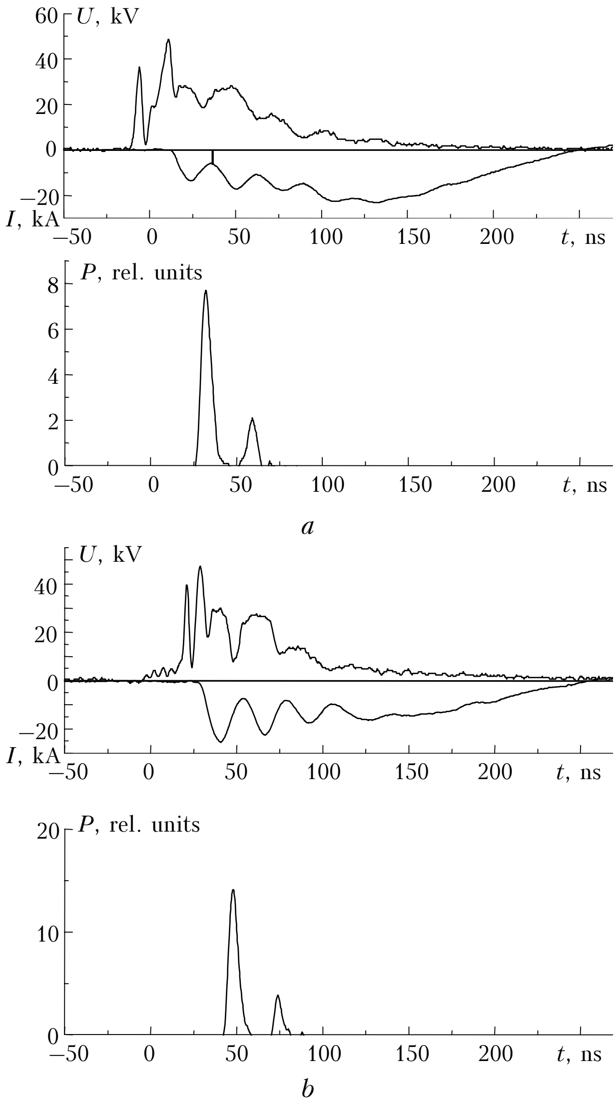

Fig. 3. Oscillograms of the voltage pulses at the discharge gap, discharge current, and laser pulse: the mixture is $N_2/NF_3 = 75/3$ Torr; $C_p = 10$ nF; $C_0 = 70$ nF; $C_1 = 2.45$ nF; $U_p = 27$ kV; $U_0 = 35$ kV; (*a*) is the laser with the capacitive energy storage; (*b*) is the laser with the inductive energy storage.

In this mode, the laser pulse had only one peak while the pulse energy decreased only down to 15.5 mJ. However, at high concentration of NF_3 the discharge current terminated in 40 ns and a part of energy remained in the capacitor C_0, that decreased the energy pumped into the gas discharge. The lasing efficiency estimated based on the amount of energy deposited into the discharge in this mode was about 0.17%. This is quite high efficiency for the nitrogen laser because usually it does not exceed 0.1%. We didn't carry out experiments at high concentration of NF_3 in the mixture because of a strong decrease in the pulse energy, the absence of the gap breakdown, and/or the discharge contraction.

Figure 4 shows the spectrograms of the pulsed laser emission. Under conditions of this experiment, in contrast to those in Ref. 4, the emission mainly occurred at the wavelength of 337.1 nm. It is seen, that more than 95% of the laser radiation energy was emitted at this wavelength. Weak emissions at $\lambda = 357.7$ and $\lambda = 316$ nm (1–0 lasing transition) were also observed.

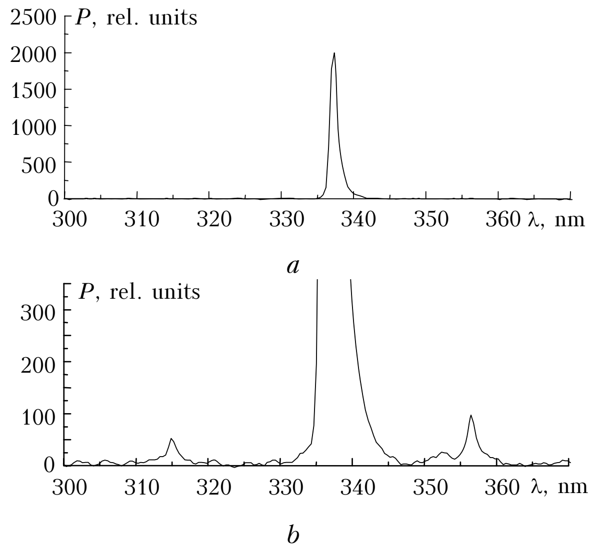

Fig. 4. Emission spectrum of nitrogen laser pumped with the generator with an inductive energy storage: the mixture is $N_2/NF_3 = 75/3$ Torr, $U_0 = 35$ kV, $U_p = 25$ kV, $C_p = 10$ nF, (*a*) attenuated by 250 times; (*b*) with the attenuation by 50 times.

Due to the optimum pressure of working mixture and application of the beam-shaping electrodes (expanding the discharge area at the increasing voltage) it was possible to keep the optimum excitation power and to realize generation mainly at $\lambda = 337.1$ nm. As shown in Ref. 4, generation at $\lambda = 357.7$ nm appears at higher pump power and at increased concentration of the electronegative gas, SF_6, in the mixture.

The nitrogen laser refers to the class of lasers on the self-terminated transitions and demands rather high average electron energy, necessary for the effective excitation of the upper lasing level (> 11.7 eV). Therefore, pulse voltage is applied to the gap that exceeds by several times the static breakdown voltage. Thus, the optimum value of E_0/p should be 150 to 200 V/(cm·Torr) (see Ref. 3). However, the avalanche breeding of electrons at high voltages makes the value of E/p to rapidly decrease after the gap breakdown and lasing terminates. The admixtures of the electronegative gases decrease the voltage decrease rate in the gap and thus enable one to increase the duration of the generation pulse.[1–4]

Use of NF_3 in the laser described, increased the sticking coefficient at the increasing E/p ratio,[5] and modulation of the net discharge current by the current of peaking capacitor C_1, enabled formation of two peaks, at $E/p > 90$ V/(cm · Torr), in the voltage pulse, as seen in Fig. 3. Increasing the E/p ratio in this generator yielded an increase in the discharge current. This value of the E/p ratio was sufficient for electron heating up to the energy necessary for the preferred excitation of the upper lasing level, and the increase in the discharge current made the pump power sufficient for the repeatedly exceeding the lasing threshold.

Conclusion

Thus, in this paper, we have realized the mode of two-peaked lasing at the wavelength of 337.1 nm in the gas discharge pumped both from the generator with an inductive and a capacitive energy storage. It is shown that the second pulse occurs both due to the recurring increase in the E/p ratio during the pump pulse and due to modulation of the net discharge current by the current of the peaking capacitor. Such an operation mode of the nitrogen laser can find practical application in the works demanding the influence of two pulses of UV-radiation on an object under study.

Acknowledgments

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