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UV lasing in nitrogen pumped by a runaway-electron-preionised diffuse discharge

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***Abstract*. UV lasing is studied in nitrogen and the N_2-SF_6 mixture pumped by a volume discharge initiated by a runaway-electron preionised diffuse discharge (REP DD) produced in an inhomogeneous electric field. It is shown that lasing at a wavelength of 337.1 nm is observed at pressures up to 2.5 atm without any preionisation source. At a pressure of 0.5 atm with the use of blade electrodes and the $N_2:SF_6 = 10:1$ active medium of length ~ 6 cm, the output laser energy of ~ 2 mJ was achieved for the pulse power of 0.55 MW. The REP DD pumping regime is compared with the regime of pumping by a volume discharge produced by a preionisation source.**

Keywords: *volume discharge without a preionisation source, inhomogeneous electric field, nitrogen laser.*

1. Introduction

An important field of applications of various discharges and electron beams is laser technologies [1 – 4]. Volume discharges are used in various fields of science and technology, in particular, for the development of dense-gas pulsed lasers. High-pressure volume (diffusive) discharges in various gases have been investigated in many papers [4 – 10]. Lasers were mainly pumped by discharges in a homogeneous electric field by using the discharge-gap preionisation by an additional source [1 – 4]. Volume discharges at high pressures can be produced in comparatively strong electric fields because in this case a high enough initial electron concentration in the interelectrode gap is achieved [6]. At the given initial electron concentration, the heads of electron avalanches are overlapped to achieve the critical size of the avalanche and formation of a streamer. In strong electric fields the acceleration of a part of electrons in the electron-avalanche heads occurs, which does not restrict the formation of diffusive discharges [5, 10]; in this case, discharges consist of individual diffusive filaments, which lead to the inhomogeneity of the energy input and reduce the lasing efficiency [10].

Volume discharges formed in an inhomogeneous electric field are quite interesting. The possibility of producing a diffusive discharge in helium [11] and air [12] at the atmospheric pressure in an inhomogeneous electric field was first reported in the late 1960s. Nanosecond voltage pulses of amplitude above 100 kV were applied to the discharge gap. Investigations in this direction were stimulated by the fact that X-rays and runaway electron beams were observed during the discharge-gap breakdown (see review [7] and references therein). However, this discharge regime was not used for pumping lasers, and then interest in the investigation of volume discharges in an inhomogeneous electric field at high pressures weakened.

It was shown in recent papers [13, 14] that nanosecond voltage pulses applied to the discharge gap in an inhomogeneous electric field without any additional preionisation source produced a volume (diffusive) discharge in various gases at pressures above the atmospheric pressure. In [13], the record specific power inputs in the volume stage of the discharge were obtained (~ 0.8 GW cm^{-3} at the air pressure of 1 atm). The volume discharge initiated by a runaway-electron-preionised diffuse discharge (REP DD) in an inhomogeneous electric field was produced at the voltage across discharge gaps of different designs equal to 10 – 300 kV and a pulse repetition rate of 160 Hz.

It was found that the volume discharge was produced due to preionisation of the discharge gap by runaway electrons, which are accelerated due to amplification of the electric field in the electrode region and in the discharge gap [13 – 15]. Infrared lasing at atomic transitions of xenon was obtained upon REP DD pumping of the $Ar:Xe = 240:1$ mixture at a pressure of 1.2 atm and the active-medium length of 1.5 cm only [13, 14]. However, the lasing threshold at the second positive system of nitrogen was not achieved under these conditions. It is interesting to obtain lasing in the VUV region in dimers of heavy inert gases pumped by the REP DD [16, 17]. Efficient lasing in these systems was achieved so far only upon excitation by an electron beam [1, 3, 4]. As a rule, the excitation by a self-sustained volume discharge is difficult to perform because of problems related to the formation and maintaining of the volume discharge. To obtain efficient lasing, the volume discharge in heavy inert gases should be produced at high pressures and the active length of the laser of tens of centimetres and more.

Note that the REP DD was earlier realised in heavy inert gases and used to obtain high-power VUV radiation in

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dimers of Ar, Kr, and Xe [18], in particular, at xenon pressures up to 12 atm [19]. At the same time, the REP DD properties relevant to its use for obtaining lasing at transitions in various atoms and molecules remain poorly studied. Therefore, before proceeding to a challenging problem of obtaining lasing in dimers of inert gases, it is necessary to study in more detail the possibilities of using the REP DD to obtain lasing in extended discharge gaps at high pressures. At the initial stage it is reasonable to use gases in which lasing can be obtained comparatively simply upon pumping by a volume pulsed discharge, for example, nitrogen. Ultraviolet lasing in nitrogen was first obtained in 1963 [20]. Later, various types of N_2 lasers were developed which were pumped by longitudinal or transverse discharges from pulsed oscillators with capacitive energy storages of various designs. The spectral parameters of radiation from nitrogen laser were measured, and the influence of parameters of pump pulses, the composition and pressure of a gas mixture on the peak radiation power, pulse duration and energy was determined (see monographs [3, 4] and reviews [21, 22]). The voluminous literature on the study of lasing in nitrogen allows us to compare the known regimes of pumping of nitrogen lasers by a self-sustained discharge with REP DD pumping.

The aim of the present paper is to study the possibility of obtaining lasing in nitrogen and mixtures of nitrogen with other gases upon REP DD pumping.

2. Experimental

We used in experiments RADAN-220 and SLEP-150 nanosecond pulse generators and three discharge chambers. The RADAN-220 generator [23] had the storage line with a wave resistance of 20 Ω and produced a voltage pulse with the amplitude up to 280 kV on a high-resistance load. The pulse duration was ~ 2 ns for the matched load, while the pulse-front duration in the transmission line was ~ 0.5 ns. The SLEP-150 generator [24] formed voltage pulses with the amplitude up to 150 kV on a high-resistance load, the pulse-front duration being ~ 0.3 ns. At the output of the SLEP-150 generator a transmission line with a wave resistance of 100 Ω (when the line was filled with a transformer oil) or 140 Ω (when the line was filled with air) was installed. The FWHM of the voltage pulse in the transmission line of the SLEP-150 generator could be varied from 1 to 0.1 ns with the help of a cutting gap.

Figure 1 shows the design of a laser chamber. The distance between the cathode and anode was 14 mm. The cathode of length ~ 6 cm and anode of length ~ 8 cm were made of a 120-μm-thick stainless steel foil. The two electrodes were blades with rounded edges, which provided a more homogeneous pump energy input over the length of the interelectrode gap. The matter is that the specific pump power in the edge-plane or blade-plane geometry substantially changes along the gap length, achieving the maximum value ~ 800 MW cm^{-3} [13] near the electrode with a small radius of curvature. It was shown earlier [25] that a comparatively uniform energy input along a gap of length 12 – 20 mm was achieved when both electrodes had a small radius of curvature. The authors of paper [25] used needle electrodes, by supplying voltage pulses from an ARINA generator [23] to the discharge gap. The active laser length was increased by a factor of ~ 4 compared to paper [13], where the lasing threshold in nitrogen has not been achieved. In addition, the inductance of leads from the generator to the electrodes of the discharge chamber was reduced, which allowed us to increase the voltage across the discharge gap. On the side walls of the discharge chamber quartz windows or mirrors were mounted. The maximum output powers and energies were obtained by using a low-Q cavity with a quartz plate as the output mirror. Because the laser chamber was not equipped with current and voltage sensors, the electric parameters of the discharge were measured with the help of two additional chambers. The electrodes used with the RADAN-220 generator had a length of 6 cm and were made of a 100-μm-thick foil. With the SLEP-150 generator, we used a plane anode and a cathode in the form of a tube of diameter 6 mm made of a 100-μm-thick foil. All the electrodes with a small radius of curvature were made of stainless steel. Additional chambers were not intended for obtaining and extracting laser radiation; however, they were equipped with current shunts and capacitive voltage dividers. One of the chambers used with the SLEP-150 generator had a side window to photograph the discharge.

Laser radiation was detected with a FEK-22 photocell and an IMO-2N calorimeter. The output signals of FEK-22, the capacitive divider, and the current shunt were recorded with a TDS-3054B oscilloscope (0.5 GHz, five samplings for 1 ns). Experiments were performed with nitrogen and its mixtures with argon, helium, and SF_6 as active media.

3. Formation of a REP DD

As mentioned above, a REP DD can be produced by applying short high-voltage pulses to a discharge gap. We

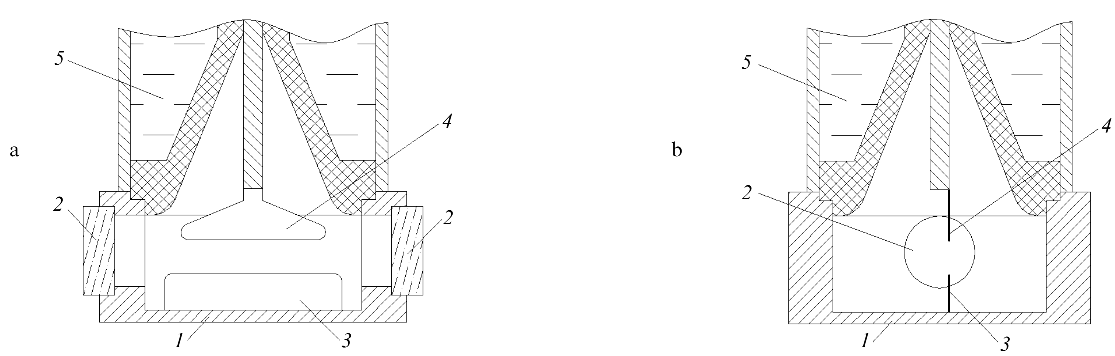

Figure 1. Laser chamber design: cross sections of the chamber along (a) and perpendicular (b) to the optical axis of the cavity. (*1*) laser chamber; (*2*) quarts windows; (*3*) anode; (*4*) cathode; (*5*) high-voltage RADAN-220 generator.

performed preliminary studies of the volt – ampere characteristics of the discharge and its spatial shape in nitrogen, air, and SF_6. Figure 2 presents the characteristic oscillograms of the discharge current in nitrogen and voltage across a capacitive divider obtained by using the above-mentioned additional chamber. In the oscillogram of the voltage pulse, as in the case of formation of a pulsed volume discharge with preionisation from an additional source [3, 8], we can distinguish the pulse front, the stage of the rapid voltage decay and the quasi-stationary stage of duration corresponding approximately to the generator pulse duration. The 'useful' pumping of the UV nitrogen laser, as shown earlier [3, 22], occurs in the region of rapid voltage decay. We managed to increase the voltage across the discharge gap compared to that in [13] by reducing the inductance of leads to the discharge gap and shortening the voltage pulse front. When a mixture of nitrogen with SF_6 is used, the voltage across the discharge gap in the laser under study, as in other nitrogen lasers [22], increases additionally compared to the case of using only nitrogen. This is caused by the increase in the breakdown voltage of the discharge gap and allows one to increase the power of lasing on the second positive system of nitrogen. However, the addition of a working mixture when a common pulsed volume discharge is used does not exceed, as a rule, 0.3 atm. By using REP DD pumping, we managed to obtain conditions close to optimal at high pressures of a mixture of nitrogen with SF_6. Thus, for the voltage pulse duration $\tau_p \sim 2$ ns, the pulse amplitude ~ 150 kV, and the interelectrode gap $d = 10$ mm, the discharge was diffusive even in SF_6 at the atmospheric pressure. The discharge current appeared at the voltage pulse front, and the direction of discharge current did not change. During the REP DD in SF_6, the resistance of the discharge plasma exceeded the wave resistance of the generator. More than 80 % of energy from the generator was supplied to the discharge plasma for ~ 3 ns. In a laser with the UV and X-ray preionisation from spark gaps [26], the maximum pressure at which the discharge remained diffusive did not exceed 0.1 – 0.3 atm. In nitrogen for the interelectrode gap from 12 to 16 mm, the diffusive discharge in a strongly inhomogeneous field was obtained at pressures up to ~ 5 atm (with a RADAN-220 generator). However, as the gap was decreased ($d \leqslant 6$ mm) and the voltage pulse durations were 1 and 2 ns, the discharge in SF_6, air, and nitrogen at the atmospheric pressure contracted. As a whole, the discharge contraction probability increases with increasing the voltage pulse and its leading edge duration, with decreasing the interelectrode gap, and with increasing the gas pressure in the discharge chamber up to several atmospheres.

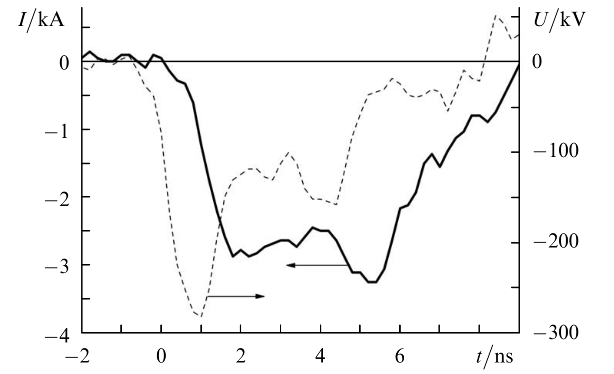

Figure 2. Typical oscillograms of the discharge current and voltage across the capacitive divider for a discharge in nitrogen; nitrogen pressure is $p = 1$ atm.

The FWHM of the voltage pulse produced by the SLEP-150 generator on a matched load was ~ 1, ~ 0.2, ~ 0.15, and ~ 0.1 ns. Depending on the interelectrode gap size, the gas type and its pressure, different discharge regimes were obtained, the diffusive discharge being observed in a broad range of experimental conditions. Figure 3 presents the photographs of emission of the discharge in air for $\tau_p \sim 0.2$ ns in the transmission line and different interelectrode gaps. Bright spots are observed only on a cathode. Because the voltage pulse was shortened, no contraction of the discharge in air at the atmospheric pressure for $d = 4$ mm was observed. As the discharge gap was increased up to 16 mm, a REP DD had no time to appear, and emission was observed only near the cathode, which is typical for a pulsed corona discharge. However, cathode spots were observed in this regime as well. For $d = 12$ mm, the diffusive emission was observed near the entire cathode edge, while the discharge gap was enclosed only by one diffusive 'channel', which was formed near the lower edge of the cathode (Fig. 3b).

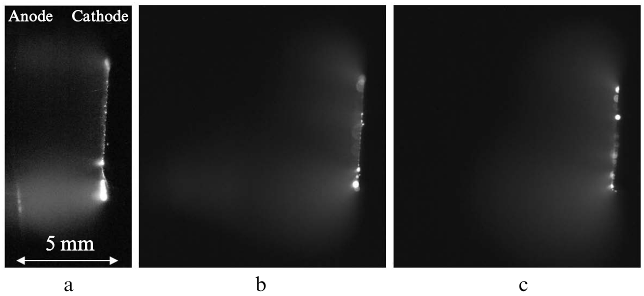

Figure 3. Photographs of the discharge emission in air for a ~ 0.2-ns voltage pulse in the transmission line and interelectrode gaps 4 mm (a), 12 mm (b), and 16 mm (c).

It follows from our experiments that the REP DD is the initial stage of the discharge which is initiated by voltage pulses with a steep leading edge applied to the discharge gap with an inhomogeneous electric field. The first stage of the REP DD is a pulsed corona discharge. The dense diffusive plasma is first produced near an electrode with a small radius of curvature [15]. Then, the dense-plasma front propagates at a high velocity (up to 10 cm ns^{-1}) from the electrode with a small radius of curvature and after some time, less than 1 ns in our conditions, encloses the gap. Ionisation process are developing then in the entire gap, the voltage across the gap decreases, the discharge passes to the quasi-stationary stage and transforms to an anomalous glow discharge. As the voltage-pulse duration is increased, the pulsed glow discharge contracts. During contraction, the emission of the volume stage of the discharge (REP DD) is masked by higher-intensity emission from the spark channel. The volume pulsed discharge produced in lasers by a preionisation source is attributed to a pulsed glow discharge (usually, anomalous).

The main difference of the REP DD is the formation of the diffusive discharge due to preionisation by runaway electrons and X-rays which are generated in the discharge in an inhomogeneous electric field. In this case, the filling of the gap by the dense plasma occurs due to the motion of the front of an ionisation wave from an electrode (electrodes) with a small radius of curvature. Preionisation by runaway electrons allows one to increase considerably the working pressure in the laser gap of a simple design. Of course, a high-pressure volume discharge can be also obtained without using runaway electrons; however, this requires the construction of very complex setups with electron accelerators for preionisation of the discharge gap. Moreover, to obtain UV lasing in nitrogen, it is necessary to inject the electron beam into the discharge gap to which the voltage exceeding the static breakdown voltage by several times should be applied.

4. Measurements of lasing parameters and discussion

During lasing experiments we obtained a diffusive discharge without the preliminary preionisation of the discharge gap both in nitrogen and its mixtures with argon, helium, and SF_6 at pressures up to a few atmospheres. Nanosecond voltage pulses were applied to the discharge gap from the RADAN-220 generator. Figure 4 presents the photograph of luminescence of paper excited by UV laser radiation obtained in the $N_2:SF_6 = 10:1$ mixture. A similar picture was observed for lasing in pure nitrogen. The use of two electrodes with a small radius of curvature provided a more uniform radiation intensity distribution along the discharge gap length compared to the knife-plane electrode configuration. An additional low-intensity emission spot on the right is probably caused by the formation of a low-current discharge in the entire volume of the discharge chamber. Lasing was obtained both in nitrogen and its mixtures with SF_6. Figure 5a presents the oscillograms of laser pulses in pure nitrogen for different pressures. As the nitrogen pressure is decreased, the leading edge of the laser pulse becomes less steep, and the pulse duration increases. A similar result was obtained for lasing in the $N_2:SF_6 = 10:1$ mixture (Fig. 5b). The minimum duration of the laser pulse equal to ~ 1 ns was obtained in nitrogen at pressures 1.2 – 1.6 atm.

Figure 4. Photographs of luminescence of white paper excited by UV laser radiation. The $N_2:SF_6 = 10:1$ mixture, the mixture pressure is $p = 0.5$ atm.

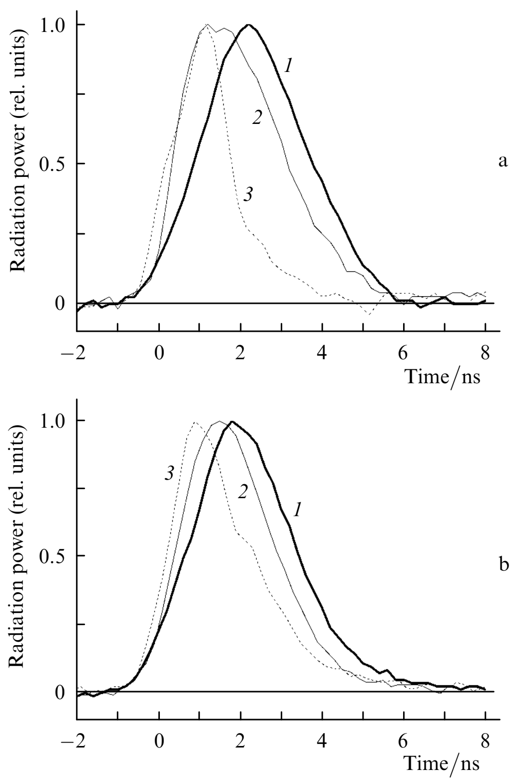

Figure 5. Oscillograms of pulses emitted by the nitrogen laser (a) and the laser based on the $N_2:SF_6 = 10:1$ mixture (b) for $p = 0.4$ atm (*1*), 1 atm (*2*), 1.6 atm (a; *3*) and 2 atm (b; *3*).

The dependences of the laser pulse peak power and FWHM on the nitrogen pressure are presented in Fig. 6a. One can see that the radiation power achieves the maximum value at a pressure of ~ 0.5 atm, while the pulse duration decreases with increasing pressure. The average pulse energy at a nitrogen pressure of 0.5 atm was ~ 0.1 mJ. The radiation energy in mixtures of nitrogen with helium and argon was lower under the same conditions.

The dependences of the laser pulse parameters for the $N_2:SF_6 = 10:1$ mixture on the mixture pressure (Figs 5b and 6b) were similar to those in pure nitrogen. At the same time, the maximum peak radiation power at a mixture pressure of 0.5 atm increased by ~ 16 times compared to that in nitrogen and was ~ 0.55 MW. The laser pulse energy at a pressure of 0.5 atm was ~ 2 mJ, corresponding to the specific energy output of ~ 0.1 mJ cm^{-3}. The lasing efficiency with respect to the energy stored in a forming high-voltage line of the RADAN-220 generator was ~ 0.1 %, which is a high value for a laser with a comparatively small active length (~ 6 cm) and a high mixture pressure. These lasing parameters were obtained in a nitrogen laser of design considerably different from conventional [3, 4, 21, 22]. Thus, for example, the addition of SF_6 to nitrogen in conventional nitrogen lasers leads, as a rule, to the two – three-fold increase in the output radiation energy. Note also that the working mixture has high optimal pressures. This fact can be used for the development of lasers emitting short pulses.

The nitrogen laser emitted at 337.1 nm both in N_2 and the $N_2:SF_6 = 10:1$ mixture. Usually, $N_2:SF_6$ mixture lasers pumped by a transverse discharge also emit at 358 nm [22].

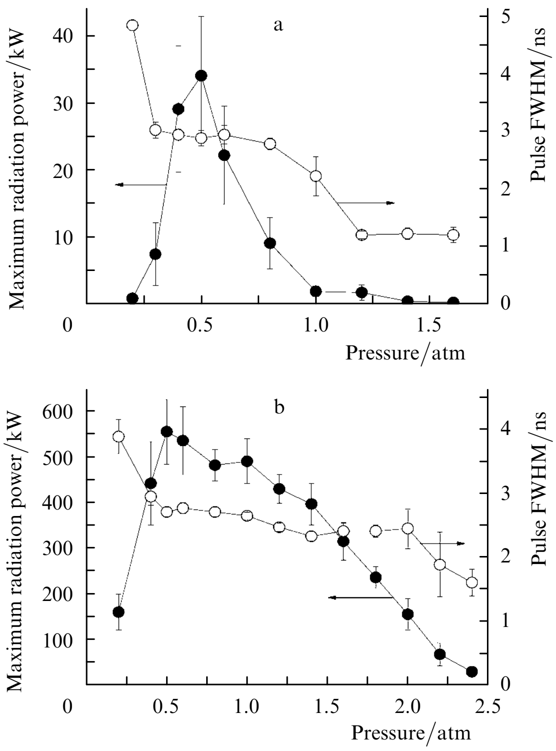

Figure 6. Dependences of the maximum laser radiation power and the laser pulse FWHM on the nitrogen pressure [(a) lasing in pure nitrogen and (b) in the $N_2:SF_6 = 10:1$ mixture].

5. Conclusions

Our study has shown that the REP DD pump power and homogeneity are sufficient for obtaining lasing in nitrogen and the $N_2:SF_6 = 10:1$ mixture at pressures up to 2.5 atm. The specific output energy emitted at 337.1 nm in the second positive system of nitrogen achieved ~ 0.1 mJ cm^{-3}. These results suggest that high-power laser radiation can be obtained upon REP DD pumping of various gaseous media, in particular, dimers of heavy inert gases. For this purpose, we plan to build discharge chambers with of large volumes and large active lengths. Note in conclusion that the formation of the volume (diffusive) discharge, as we have shown in [13–15], is caused by preionisation by runaway electrons, which are generated due to amplification of the electric field near electrodes and in the discharge gap. The use of the REP DD allows one to increase the working pressure of the mixture and simplify the design of the discharge gap. The REP DD pumping eliminates the need to use an additional system for preionisation of the discharge gap.

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