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Efficiency of a nitrogen UV laser pumped by a self-sustained discharge

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***Abstract*. The features of excitation of a nitrogen laser emitting at the second positive system of nitrogen (the $C^3\Pi_u - B^3\Pi_g$ electronic bands at 337.1 nm) are investigated. The results of the papers, which reported the highest UV lasing efficiencies upon pumping by a self-sustained discharge, are analysed and recommendations are given for achieving the high efficiency of a nitrogen laser. The output characteristics of lasers with a pump on the basis of strip lines and ceramic capacitors are given as functions of the pump parameters and the gas pressure.**

Keywords: *nitrogen UV laser, discharge pumping, lasing efficiency.*

1. Introduction

The generation of stimulated UV radiation in molecular nitrogen (the second positive system, the $C^3\Pi_u - B^3\Pi_g$ electronic bands, the 0 – 0 transition at 337.1 nm) has long attracted the attention of many researchers [1 – 16]. In the early 1970s, a nitrogen laser was one of the highest-power sources of coherent radiation in the UV spectral range, which provided megawatt output powers and repetition rates of hundreds of hertz and over. At present, due to the advent and development of a variety of efficient rare-gas halide exciplex (excimer) lasers emitting at different wavelengths in the UV and VUV spectral regions [17, 18], the interest in the nitrogen laser has considerably decreased. Nevertheless, owing to the use of an inexpensive and safe nitrogen gas as the working medium, a relatively simple design, and a high output power at a short duration of the output pulse (0.5 – 10 ns), this laser continues to find practical use and attract the attention of researchers [19 – 21].

However, there is no consensus so far in the literature concerning the maximum efficiency that can be achieved in a nitrogen UV laser pumped by a self-sustained discharge. Earlier, the lasing efficiencies of 6.5 % [3], 3 % [12], 1 % [6], 0.8 % [16], and 0.5 % [14] have been reported. If a nitrogen laser with so high a lasing efficiency is realistic, it is not clear why, with the current state-of-the-art technology, high-efficiency (~ 1 %) nitrogen lasers are not commercially available. Note also that the effect of additions of electronegative gases on the UV lasing characteristics in nitrogen is interpreted differently in different papers [9 – 11].

In this paper, the properties of excitation of an electric-discharge nitrogen laser emitting at the second positive system of nitrogen are studied. Since lasing in nitrogen is possible on different transitions at different methods of pumping, the main attention was paid to obtaining the efficient lasing at 337.1 nm (the highest output power with a discharge pumping was obtained on this transition). This research was also stimulated by Ref. [20], in which it was erroneously stated that the parameter E_0/p ($E_0 = U_0/d$ is the highest electric field intensity across the laser gap d; p is the nitrogen pressure) does not affect substantially the characteristics of a nitrogen laser and that the highest pump power is achieved at the highest voltage across the plasma in the nitrogen laser. In addition, in Ref. [20] an error was made in the determination of the voltage across the discharge gap.

2. Experimental setups and techniques

Experiments were performed using two setups. In the first setup, a pump source was used based on the discharge of ceramic capacitors with a high dielectric constant ε. A pump source used in the second setup was based on strip lines made of lavsan film with a high electric strength and low ε. Fig. 1 shows a scheme of the discharge circuit of a nitrogen laser and the cross section of the nitrogen-laser electrodes and the ceramics-based capacitive storage with a minimal inductance of connection to the electrodes [2]. In Fig. 1a, L, C, ρ, and R_p denote the inductance, the capacitance, the wave impedance of a distributed-parameter line, and the discharge plasma resistance, respectively. The cir-

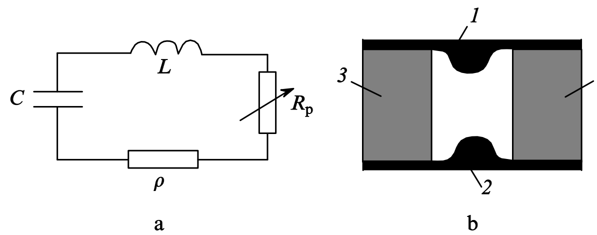

Figure 1. Schematic of the discharge circuit simulating the N_2-laser pumping (a) and the optimal arrangement of the electrodes (*1*, *2*) of the discharge gap with ceramic capacitors *3* (b).

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cuits for charging ceramic capacitors may be different (see, e.g., Refs [2, 4, 7, 15]). In this paper, a two-circuit scheme was used, with the capicitances of the storage and peaking capacitors being equal. A substantial fraction of the inductance of the discharge circuit (Fig. 1b) is accounted for by the discharge gap, this fraction increasing with the gap length.

Fig. 2 shows the second version of the laser with a minimal inductance of connection of the capacitive storage to the laser chamber (strip lines of lavsan film were used). Upon pumping by the discharge of the strip lines, both two lines [6] (Fig. 2), and four lines, arranged symmetrically in pairs and working with a common discharge gap, can be used. The active length of the lasers being tested was 20 cm, the interelectrode distance was varied from 5 to 20 mm, and the discharge width was 3 – 10 mm. Note that the use of a specific pumping scheme to excite a nitrogen laser is significant only from the standpoint of formation of an excitation pulse of the required amplitude, a laser pulse of the optimal duration, and the optimal power (discharge current density) for the selected discharge gap geometry and nitrogen pressure.

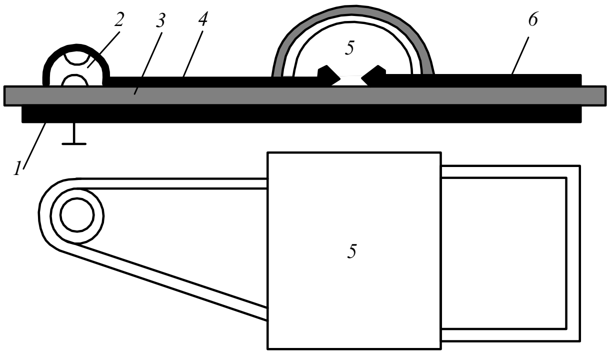

Figure 2. Design of the nitrogen laser with a pump generator based on strip lines: (*1*) grounded electrode; (*2*) spark gap; (*3*) lavsan film; (*4*) triangular electrode; (*5*) laser chamber; (*6*) rectangular electrode.

The output energy was measured with an IMO-2N calorimeter. The radiation pulse shape was recorded with a FEK-22 photodiode whose output signal was fed to a fast oscilloscope. Voltage and current oscilloscope traces were recorded with an ohmic voltage divider and a current shunt.

3. Theoretical model of a nitrogen laser

The output power of a nitrogen laser was calculated from the equations describing the energy input into the active medium during pumping, its distribution between different energy levels, and the development of stimulated emission. Fig. 1a shows the circuit which models the processes in the discharge circuit. For $C = \infty$ and $\rho = \text{const}$, this circuit permits considering the discharge of a distributed-parameter line with a wave impedance ρ.

The theoretical model of this circuit was described in detail in Ref. [7], where the results obtained for a nitrogen laser were also reported. Of chief interest is the investigation of output laser characteristics as functions of the parameters p, ρ, and E_0/p. Fig. 3a shows the calculated time dependences of the voltages across the laser gap and the capacitor, the discharge current, and the intensity of laser radiation. These dependences completely determine the lasing regime, and a set of the results of this kind allows one to study the principal features of pumping and lasing.

4. Results and discussion

4.1 Discharge characteristics of a nitrogen laser

A nitrogen laser belongs to self-terminating lasers and has a high quantum efficiency ($\sim 16\,\%$). However, the efficiency realised in practice is usually two or more orders of magnitude lower. To provide the efficient excitation of the upper laser level, the electron energy should exceed 11.7 eV. The attainment of so high an electron temperature in the quasi-stationary regime is possible by using voltages, pressures, and interelectrode gaps corresponding to the left branch of the Paschen curve. In this case, however, the nitrogen pressures prove to be so low that the lasing threshold is not reached.

For pressures and discharge gaps commonly used in nitrogen lasers, the discharge conditions correspond to the right branch of the Paschen curve, with the initial voltage several times greater than the static breakdown voltage. Since the lifetime of the upper laser level for a nitrogen pressure of ~ 10 Torr is ~ 40 ns and the lifetime of the lower one is ~ 10 μs (the lower level is not depopulated during lasing), a pulsed discharge of short duration is employed to pump a nitrogen laser. In this case, the average electron energy is high enough to efficiently excite the upper laser level only during the transient stage of the discharge, when the voltage drop across the laser gap, due to the initial voltage exceeds by several times the static breakdown voltage [5, 8, 15]. The overvoltage across the laser gap is due to the steep edge of the voltage pulse applied. The type of discharge realised corresponds to an anomalous glow discharge. Different factors (the pump source, the designs of the laser chamber and the preionisation system, the nitrogen pressure, the additions of other gases to nitrogen, etc.) can affect the discharge characteristics.

We shall not discuss the factors of a specific nature, which complicate the consideration of the principal features of the operation of a nitrogen laser. In this paper, we used lasers pumped by a transverse discharge, which were operated at low repetition rates or in the single-pulse mode. In this case, the electron density (the residual density or the one due to preionisation) did not appreciably affect the build-up of the voltage across the discharge gap. The walls of the laser chamber were not in contact with the discharge region and had no effect on the current distribution over the laser-gap cross section, which ensured a uniform pumping. The maximum ionisation of the working gas did not exceed 10^{-3}.

Figs 3b, c show the oscilloscope traces of the current and voltage pulses across the discharge gap obtained both experimentally and by graphical integration and differentiation from the oscilloscope traces of current and the voltage on the capacitor. One can see that the results of calculation by the model of Fig. 3a are in good agreement with the experimental oscilloscope traces (Fig. 3b) and the voltage across the plasma obtained from the current oscilloscope trace. The oscilloscope traces of the voltage across the laser gap are significantly different from those of the voltage on the capacitive storage. One can also see that the radiation pulse is substantially shorter than the current pulse. Our investigations of lasers pumped by a transverse discharge show that the prebreakdown discharge current and the specific energy deposition in gas prior to the drop of the voltage across the laser gap are very low when a duration of the pulse front of the voltage across the gap was over 30 ns. And it is only after the breakdown of the laser gap, as evidenced by the voltage decrease and a significant increase in the current through the gap, that the pump power increased significantly. The authors of Ref. [20] stated erroneously that the pump power under their experimental conditions was maximal when the voltage across the discharge gap was maximal.

The rate of voltage decay in nitrogen depends on the operating pressure and the parameter E_0/p [5, 7, 8]. The plasma (gas) resistance, which far exceeds the resistance of a pump source prior to the breakdown of the discharge gap, becomes several times lower than the resistance of the pump source after a rapid decay of the voltage occurring in several nanoseconds. In this case, the difference between the resistance of the pump source and that of the plasma increases with E_0/p in the quasi-stationary stage of the discharge [5, 8]. For a volume discharge in nitrogen, these resistances match only for $E_0/p \leqslant 70$ V cm^{-1} Torr^{-1}. However, under these conditions the electron temperature is low and the UV lasing does not occur.

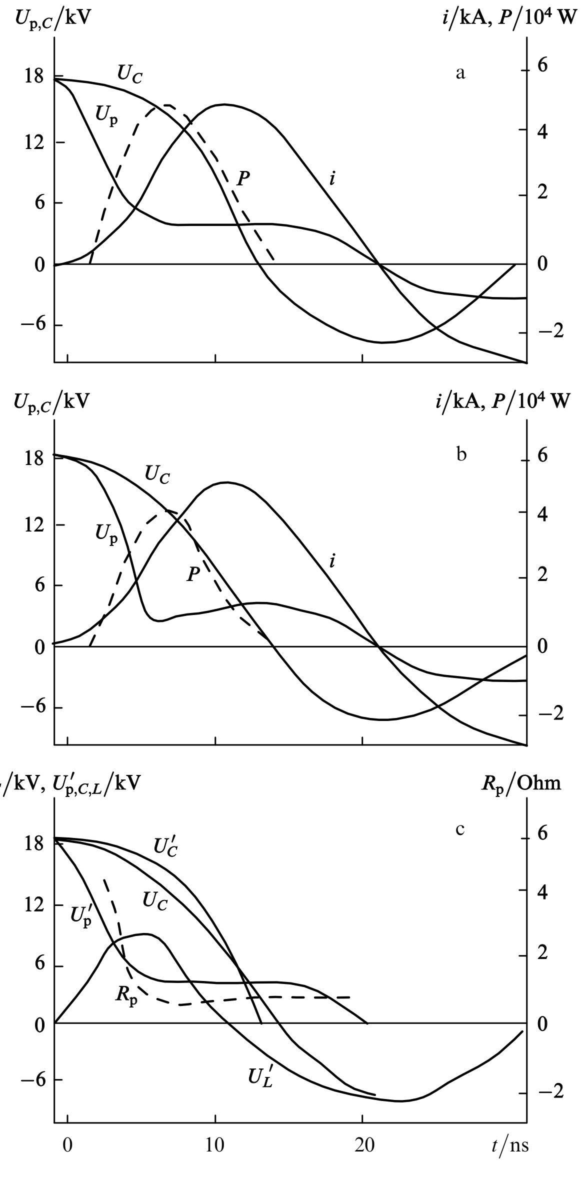

Figure 3. Pulses of the voltage across the capacitor (U_C) and the laser gap (U_p), the current i, and the output laser power P obtained theoretically (a) and experimentally (b); voltage pulses across the capacitor (U'_C), the inductance of connections (U'_L), the laser gap (U'_p); and the resistance of the plasma in the laser gap (R_p) obtained by integrating and differentiating the experimental U_C and i (c) for the laser with a pump involving ceramic capacitors.

4.2 Pumping with a storage based on ceramic capacitors

The main distinction of the lasers that use pump sources based on capacitors made of ceramics with a high dielectric constant is in the significant influence of the unremovable inductance L of the discharge circuit, which consists of connections between the ceramics and the discharge gap, ceramic capacitors, and the interelectrode gap. In this case, the effect of this inductance is stronger than for distributed-parameter strip lines and depends on the design of a specific laser. Usually, L determines the growth rate of the current through the discharge gap.

One can see from Fig. 3 that the duration of the phase of fast voltage decay is two times shorter than that of the leading edge of the current pulse, i.e., a significant fraction of the pump pulse energy is wasted, which lowers the laser efficiency. The efficiency can be partly increased by reducing the inductance L of the discharge circuit and the capacitor capacitance C. However, as follows from Fig. 1b, the discharge gap – capacitors arrangement is optimal and L can be reduced only slightly by replacing the capacitors with ceramic bars.

The second way of shortening the pump pulse – by reducing the capacitor capacity – also does not offer advantages. This is due to an increase in the wave impedance of the discharge circuit and the lowering of the discharge current. By reducing C by 20 % – 50 % relative to its value optimised for maximum output laser energy, it is possible to increase the lasing efficiency, but the output energy decreases in this case.

Fig. 4 shows the pressure dependences of the output laser energy for different voltages U_p across the gap for $C = 4 \times 10^{-9}$ F. One can see that the increase in the voltage results in an increase in the optimal pressure, the optimal ratio $E_0/p \sim 200$ V cm^{-1} Torr^{-1} remaining nearly constant. A twofold increase in the interelectrode gap (the dashed curve in Fig. 4) results in a twofold reduction in the nitrogen pressure, while the optimal value of the parameter E_0/p ~ 200 V cm^{-1} Torr^{-1} is retained. The increase in the output energy and lasing efficiency for $d = 2$ cm is caused by a reduction in the parasitic inductance of the discharge circuit.

Note that an external ioniser is required to obtain a uniform discharge for nitrogen pressures of over 30 Torr. We used the UV radiation of spark gaps as such an ioniser. Fig. 5 presents the pressure dependences of the average output power obtained in nitrogen and in a nitrogen – SF_6 mixture (the content of SF_6 was about 10 %). The FWHM duration of the output pulse was 5 ns in nitrogen and increased to 8 ns in the nitrogen – SF_6 mixture. In this case, the output energy and the efficiency increased by more than a factor of two. Under these conditions, the increase in the efficiency and output laser energy is due to the moderation of the decay rate of the voltage across the laser gap, which

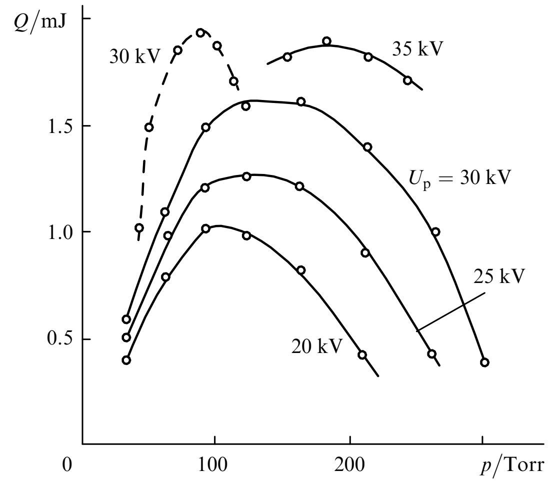

Figure 4. Dependences of the output laser energy on the nitrogen pressure for different voltages U_p across the gap for the nitrogen laser with a pump involving ceramic capacitors with an interelectrode distance of 1 (the solid curve) and 2 cm (the dashed curve).

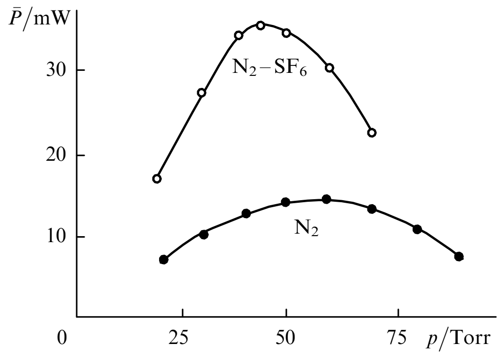

Figure 5. Dependences of the average output power on the pressure of nitrogen and the nitrogen – SF_6 mixture (the SF_6 pressure was 4 Torr) for a pulse repetition rate of 15 Hz.

lengthens the stage of discharge during which the electron temperature is high enough to excite the upper laser level.

Additions of SF_6 may also increase the breakdown voltage and the output energy. However, this effect can be observed only in the lasers where the nitrogen breakdown occurs at voltages across the gap that are lower than the maximum voltage. Note that the effect caused by the addition of SF_6 is highest in lasers with a relatively low lasing efficiency in pure nitrogen and when the leading edge of the current pulse was two or more times longer than the duration of the phase of rapid voltage decay. An investigation of the pump systems based on capacitors with the high ε showed that the real efficiency of such setups usually is, due to the inductance of capacitor leads, about ~ 0.1 %, which agrees well with the efficiency calculated for similar conditions. If L is reduced to the limiting values, which can not virtually be realised, the efficiency in the theoretical model could reach 0.4 %.

4.3 Pumping with a distributed-parameter line

Let us illustrate the effect of the pump pulse duration. Fig. 6 shows the oscilloscope traces of the laser pulses for different pump-pulse durations and the shape of the voltage pulse across the discharge gap obtained by calculations. One can see that, as the duration of the pump pulse increases, the laser-pulse duration at first increases and then, beginning with $t = 5$ ns, remains invariable. Therefore, for a given nitrogen pressure and parameter E/p, the increase in the pump-pulse duration results only in a reduction in the laser efficiency.

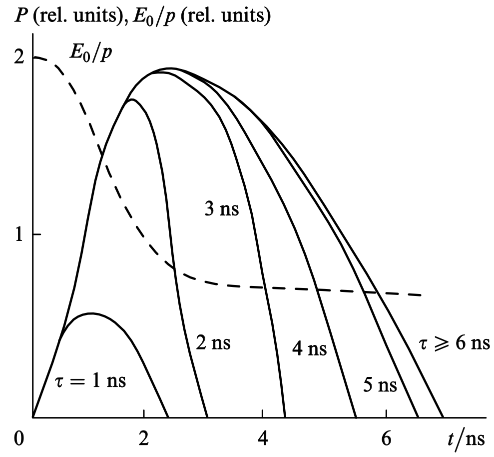

Figure 6. Calculated radiation pulses of the nitrogen laser pumped by a strip line with a wave impedance of 0.5 Ohm for different pump-pulse durations τ, and time dependence of the parameter E/p (the dashed curve).

Fig. 7 shows the dependences of the specific output laser energy, the pulse duration, and the laser efficiency on the parameter E_0/p. The pump duration was taken to be equal to the laser pulse duration. One can see that for $L = 0$ the laser efficiency has a maximum at $E_0/p \sim 150$ W cm^{-1} Torr^{-1}. Some decrease in the optimal value of E_0/p compared to the data of Section 4.2 is due to the fact that the current growth rate is limited only by the conductivity of a gas-discharge plasma. With pumping accomplished by

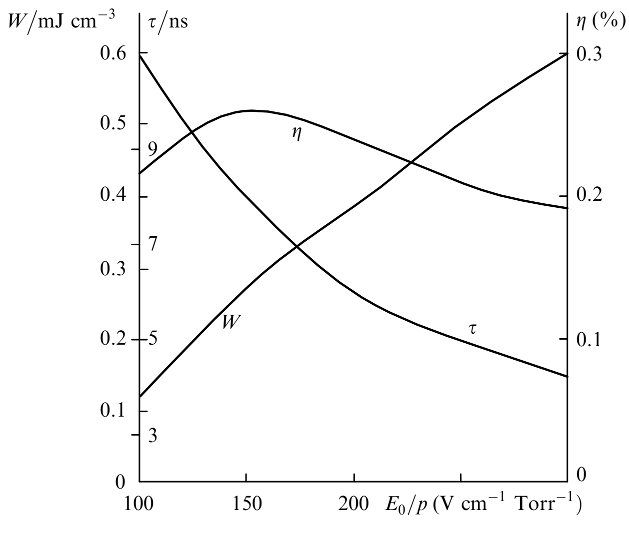

Figure 7. Specific output energy W, duration of the laser pulse τ, and efficiency η of the nitrogen laser calculated as functions of the parameter E_0/p with the pumping by a strip line with a wave impedance of 0.5 Ohm, a nitrogen pressure of 60 Torr, and a parasitic inductance $L = 0$.

strip lines, it is most advantageous to use operating pressures of ~ 100 Torr. An increase in pressure results in a reduction of the pump- and laser-pulse durations. Lowering p to low values is advantageous due to an increase in the pump duration, but this reduces the specific output power.

A comparison of the results of calculations and experimental data in the case of obtaining a high efficiency was made for the nitrogen laser whose parameters are shown in Fig. 3. In this laser, the induction of connection of the discharge gap is minimal, the pump pulse duration is short (~ 3 ns) and does not exceed the short decay time of the voltage across the gap. In this laser, a low-inductance spark gap filled with nitrogen at a pressure of 5.5 bar was used, which enabled the formation of a voltage pulse with a steep edge at low losses in the gap. For a pressure of 90 Torr and an interelectrode distance of 9 mm, the output energy was ~ 1 mJ for an efficiency of 0.2 % – 0.27 %. Calculations by the theoretical model yielded, assuming the same conditions, an efficiency of 0.29 %. In accordance with the investigations conducted, the user of highest-efficiency lasers is recommended to exploit the 50 – 150 Torr operating pressure range, the $E_0/p = 150 - 200$ V cm^{-1} Torr^{-1} region, a pump-pulse duration of 2 – 4 ns, the power supply with a minimal wave impedance, and the minimal parasitic inductance between the laser chamber and the power supply.

To reduce the losses in the spark gap and obtain a current pulse with a nanosecond edge, of critical significance is also the current switched by the spark gap, which should not exceed 10 kA. Accordingly, the active laser length should be relatively short (20 – 30 cm) or several spark gaps should be used. Moreover, losses due to amplified spontaneous emission should be reduced. For this purpose, an output beam with a nearly square cross section should be used, the interelectrode distance not exceeding 5 – 10 mm; in addition, a travelling excitation wave should be used [6] (see Fig. 2). Note that additions of an electronegative gas to nitrogen do not increase the efficiency and the output energy of a nitrogen laser when the pump-pulse duration in a nitrogen discharge and the laser gap are optimally matched.

The achievement of a nitrogen laser efficiency of over 0.5 % was reported in Refs [3, 6, 12, 14, 16]. According to our results, the maximum practical efficiency of a UV nitrogen laser pumped by a self-sustained discharge, calculated relative to the energy stored in the capacitive storage, cannot exceed ~ 0.3 %. It is likely that errors were made in the efficiency determination in the above-mentioned papers. Note that the laser designs described in Refs [6,14,16] are close to the optimal ones, and the laser efficiencies achieved for them should be close to the limit (~ 0.3 %).

4.4 Pumping with an inductive energy storage

The application of inductive energy storage devices allows an increase in the pump power, a reduction of the effect of inductance of the discharge circuit, the formation of short single-pole excitation pulses, and an increase in the maintenance period of high E/p parameter values during the excitation pulse [19, 22]. However, attempts to take full advantage of all the above merits of inductive energy-storage generators for UV nitrogen laser pumping using modern current interrupters, have not met with success so far. Nevertheless, our study showed that the efficiency of an electric-discharge UV nitrogen laser, which was calculated relative to the energy introduced into the gas during the laser pulse, was 0.2 % [19], while the base duration of the laser pulse amounted to 50 ns upon pumping by a transverse discharge [22]. The laser pulse duration can also be increased by lengthening the maintenance time of high electron plasma temperature by pumping by a microwave discharge. For a microwave pump duration of 50 ns in Ref. [13], the laser-pulse duration was also 50 ns.

5. Conclusions

Therefore, experimental and theoretical investigations show that a high-power and relatively efficient lasing in a nitrogen laser at 337.1 nm is realised only during the transient stage of discharge. The average electron energy is relatively high during this time period, ensuring a higher excitation rate for the upper laser level than for the lower one. The duration of the transient discharge stage for pressures of tens and hundreds of Torr is several nanoseconds and shortens with increasing nitrogen pressure and electric field intensity. The increase in the operating pressure results in the shortening of the laser pulse due to a faster decay of the voltage across the laser gap (due to the shortening of the maintenance time of high electron temperature).

Additions of electronegative gases (SF_6, NF_3) to nitrogen slow down the decay of voltage across the gap and increase the useful pump duration. In this case, it is possible to increase the pulse duration and energy in those lasers whose current-pulse duration exceeds the optimal one. The maximum efficiency of a nitrogen laser (~ 0.3 %) pumped by a transverse discharge is achieved in the pressures range from tens to hundreds of Torr for short pump pulses, a low wave impedance of the supply system, and a low inductance of the discharge circuit. Nitrogen lasers with a nearly square section of the output laser beam, an interelectrode distance of 5 – 10 mm, a pump pulse of no longer than several nanoseconds (2 – 4 ns, depending on the operating pressure), the parameter $E_0/p = 150 - 200$ V cm^{-1} Torr^{-1}, and a low wave impedance of the strip line of the pump generator provide the maximum efficiency. In this case, low-loss switches providing a high rate of current growth should be used.

The above-listed parameters are extremely hard to realise, and the limiting lasing efficiencies of no higher than 0.3 % have been only obtained in a few papers [6, 7, 14, 16] to date. The maximum output energy is realised in lasers with a relatively large interelectrode distances and with additions of electronegative gases to nitrogen. As the interelectrode distance increases, the effect of inductance of the pump source-to-laser chamber connection weakens and the voltage across the laser gap rises.

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