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On the nonuniformity of the output beam power density of a nitrogen laser

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***Abstract*. The distribution of the UV power density in the 337.1-nm $C\,^3\Pi_u - B\,^3\Pi_g$ band over the output beam cross section of a transverse-discharge-pumped nitrogen laser is studied experimentally. It is shown that for the nitrogen pressure up to tens of torr and large laser pulse durations, the radiation power density from the cathode discharge region is lower than that from the rest part of the discharge gap. The potential distribution in the cathode discharge region is analysed theoretically. It is shown that the length of the cathode region with a low radiation power density observed in the experiment corresponds approximately to the length of the dark Faraday space in an anomalous glow discharge.**

Keywords: *UV nitrogen laser, radiation power distribution over the output beam cross section, transverse discharge pumping, simulation of the cathode discharge region.*

1. Introduction

The uniform distribution of the radiation power density over the output beam cross section is very important for the practical application of radiation from different lasers. This distribution is affected by various factors (geometry of the active volume, type of the resonator, duration of the excitation pulse, etc.). In addition, the electric-field strength distribution over the length of the interelectrode distance in the glow discharge (normal and anomalous), which is most often used to excite different lasers, is nonuniform [1]. When pulsed gas lasers are pumped by a transverse discharge, the influence of the nonuniformity of the electric-field strength distribution over the interelectrode distance on the properties of the active medium is especially noticeable at low pressures of the laser mixture, in some cases an increase in the electric field at the cathode being used to form an electron beam [2].

Because the quasi-stationary distribution of the electric field strength over the interelectrode distance is specified during the formation of the glow discharge within the finite time (tens of nanoseconds), this also can affect the distribution of the radiation power density over the output beam cross section at small durations of the output pulses from different lasers. The strongest influence of the nonuniformity of the electric-field strength distribution over the interelectrode distance should appear in lasers with a comparably long duration of the output pulse (tens – hundreds of nanoseconds). During this period a quasi-stationary glow discharge with all characteristic regions has time to form.

The aim of this paper is to study the radiation power density distribution over the cross section of the output beam from a transverse-discharge-pumped UV nitrogen laser. The nitrogen laser was chosen due to its simplicity and possibility of simulating parameters of the cathode region during the discharge in nitrogen. In addition, by varying the nitrogen pressure and excitation conditions, we can obtain output pulses of different durations upon transverse-discharge pumping, which can exceed 100 ns for the $N_2 - NF_3$ mixture [3].

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2. Experimental setup and measurement methods

We used in experiments a transverse-discharge-pumped laser with a spark preionisation described in detail in [4, 5]. 72 pointed electrodes for spark illumination were located near the potential electrode. Pumping was performed by a universal generator allowing excitation both from the inductive and capacitive energy storage. In these experiments we used a generator with capacitive energy storage. The resonator was formed by an aluminum-coated mirror and a quartz plate. The active volume of the laser was $4 \times 2 \times 72$ cm (the length of the discharge gap was $d =$ 4 cm). The width of the discharge gap depended on the nitrogen pressure and the generator voltage. The output energy of the nitrogen laser was measured with an OPHIR calorimeter equipped with FL-250A and PE-50BB sensor heads. The output pulses were detected with a FEK-22 SPU vacuum photodiode to which a part of laser radiation was directed by using a beamsplitter. The laser spectrum was measured with a StellarNet EPP2000-C25 spectrometer with a resolution of 0.75 nm. For the photodiode and spectrometer to operate in the linear regime, radiation at the input was attenuated by a sequence of metal grids.

The distribution of the radiation power density over the beam cross section was determined in two ways. A digital camera recorded the luminescence of white SvetoCopy paper screens excited by laser radiation. If necessary, radiation was attenuated by using NS-7 or NS-8 light filters. Then the densitograms of obtained photographs were made. The radiation power propagated through a diaphragm of diameter 2 mm was simultaneously measured with a FEK-22 SPU photodiode. The diaphragm was displaced in the direction from the cathode to the anode with a step 2 mm.

The discharge current and the voltage across the laser electrodes were measured with a voltage divider and a Rogowski loop. The electric signals were fed to the TDS-220 or TDS-224 oscilloscope.

3. Experimental results

Figure 1 shows the distributions of the radiation power density of the UV nitrogen laser in the direction from the anode to the cathode for the positive voltage polarity across the potential electrode and different pressures of pure nitrogen and in the $N_2 - NF_3$ mixture. Figure 2 presents the oscillograms of voltage pulses across the discharge gap, the discharge current and emission of the nitrogen laser. For the nitrogen pressure of 87 Torr, the pulse FWHM was ~ 6 ns and its delay with respect to the discharge current pulse was ~ 12 ns. Under these conditions, the distribution of the radiation power density along the discharge gap length is relatively uniform and high-power laser radiation is detected on both electrodes. In this case, the laser intensity distributions obtained by different ways differ by no more than 20 %. As the nitrogen pressure was decreased down to 12 Torr, the pulse FWHM increased up to ~ 17 ns, and its delay with respect to the discharge current pulse increased to ~ 29 ns. In this case, the width of the discharge region and the laser beam increased and a region with a significantly lower radiation power density appeared at the cathode. When NF_3 (2 Torr) was added to nitrogen (12 Torr), the pulse duration increased to ~ 26 ns and the delay of the output pulse with respect to the discharge current pulse decreased down to ~ 24 ns. The widths of the discharge region and the laser beam in this case did not change much compared to lasing at the nitrogen pressure of 12 Torr and the length of the cathode region, where a drastic decrease in the output power is observed, decreased. An addition of NF_3 to nitrogen lead also to changes in the emission spectrum. Lasing in pure nitrogen was observed only at 337.1 nm, while additional laser lines at 316.0 and 357.7 nm were observed in the $N_2 - NF_3$ mixtures.

For the negative polarity of the voltage pulse across the potential electrode and the nitrogen pressure of 12 Torr, the shape of the discharge changed. The discharge began to close on the pointed illuminating electrodes. For the nitrogen pressure of 87 Torr, the breakdown on the pointed electrodes was not noticeable and the distribution of the radiation power density of both electrodes was approximately equal as that for the positive polarity of the potential electrode. The FWHM of the output pulse was also ~ 6 ns.

For the mixture of nitrogen (12 Torr) with NF_3 (2 Torr) and also for the positive polarity of the voltage pulse across the potential electrode, a region with a lower density of the radiation power was detected at the cathode. However, the length of this region decreased while the radiation power density in it increased. This behaviour of the radiation power density upon changing the polarity can be explained by the influence of the pointed illuminating electrodes near the potential electrode on the discharge parameter. Note that the discharge between the pointed electrodes and the potential electrode is a source of not only UV and VUV radiation but also of the X-ray radiation [5].

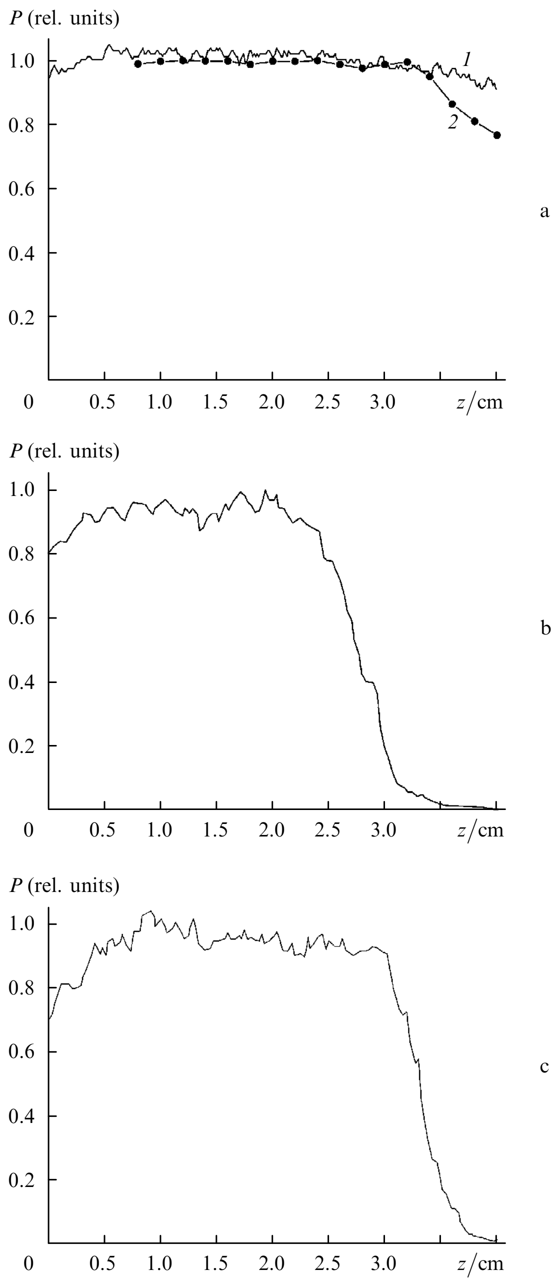

Figure 1. Distribution of the radiation power density P of the nitrogen laser along the discharge gap obtained from photographs of the luminescence 'images' at the pure nitrogen pressure $p = 87$ Torr (*1*, a) and 12 Torr (b) and the N_2:$NF_3 = 12$:2 Torr mixture (c) and upon scanning the diaphragm in the case of pure nitrogen at $p = 87$ Torr (*2*, a). NS-8 (*1*, a) and NS-7 (b, c) filters were used. The point $z = 0$ corresponds to the position of the anode and $z = 4$ cm – to the position of the cathode.

Additionally, the discharge was studied in the discharge chamber with a spherical potential electrode (cathode) of diameter 24 mm and a plane anode for the interelectrode distance of 6 and 12 mm. Voltage pulses were fed to the electrodes from the generator with the wave resistance 20 Ω and the idle voltage 10 – 25 kV. The diameter of the discharge region in these experiments did not exceed 20 mm and the lasing threshold was not achieved for all nitrogen pressures. The experiments showed that for the

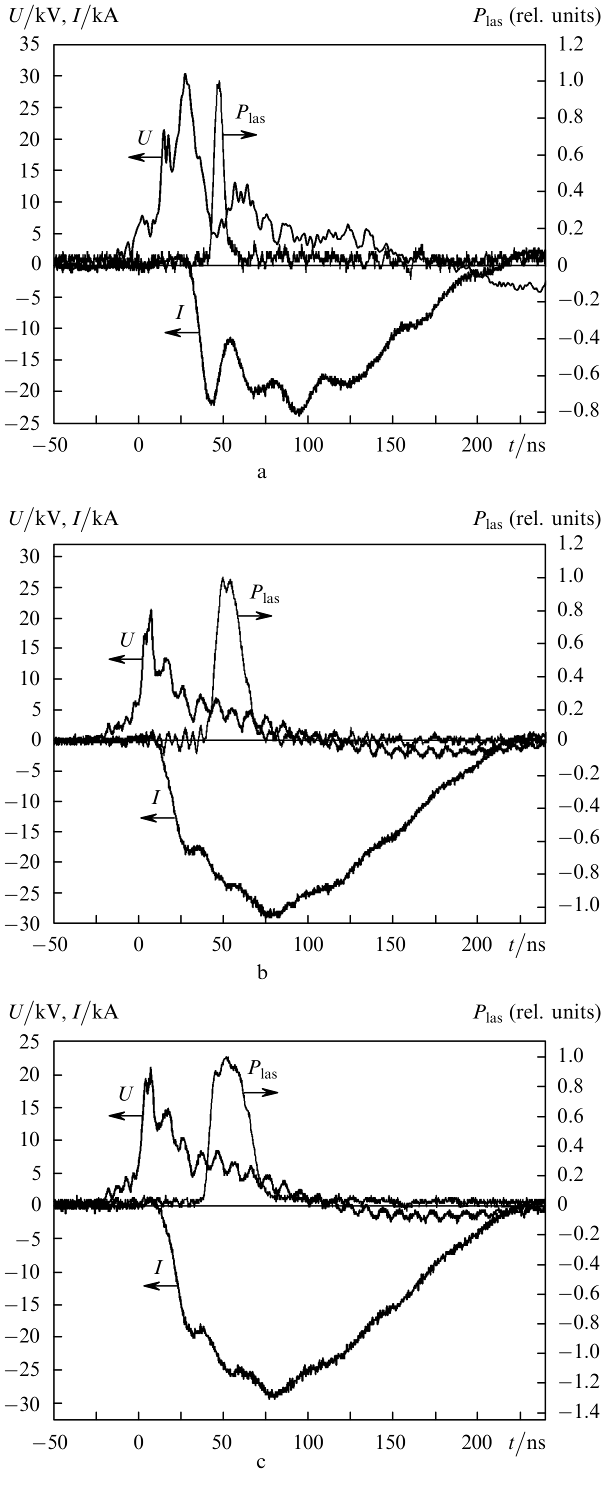

Figure 2. Oscillograms of voltage pulses U across the discharge gap, discharge current I and lasing power P_{las} for the charging voltage of the pump generator $U_0 = 30$ kV, the nitrogen pressure $p = 87$ (a) and 12 Torr (b) and the $N_2 : NF_3 = 12 : 2$ Torr mixture (c).

nitrogen pressure of tens of torr and the duration of the discharge current pulse of 25–90 ns, a dark Faraday space is well seen near the cathode, while for the pressure of ~ 90 Torr it is virtually absent. The longest length of the dark Faraday space, as is well known [1], is realised at low pressures of nitrogen and other gases. Therefore, under these conditions a decrease in the density of UV radiation power at the cathode for the nitrogen pressure of tens of torr is caused, first of all, by an increase in the dimensions of the dark Faraday space.

4. Theoretical estimates of the potential distribution in the discharge gap

Let us determine the type of the discharge in the nitrogen laser at the instant of achieving the maximum power of coherent radiation, when according to Fig. 2b for the gas pressure $p = 12$ Torr the discharge current is ~ 24 kA and the voltage across the discharge gap is $U \simeq 4$ kV. The current density in the discharge is $j \simeq 160$ A cm^{-2}, which corresponds to the reduced density $j/p^2 \simeq 1$ A cm^{-2} Torr^{-2}. This allows us to relate the regime of the observed discharge to a deeply anomalous one because a normal discharge in nitrogen has a substantially lower reduced density: $j/p^2 \simeq 4 \times 10^{-4}$ A cm^{-2} Torr^{-2} [6]. Based on this fact, we will estimate the possible distribution of the electric field in the discharge gap to explain the observed reduced pump power of the active medium of the nitrogen laser in the cathode region. To describe the behaviour of the glow discharge in the cathode region, we will use the stationary theory presented in [7]. It was shown in [7] that a decrease in the potential in the cathode region occurs in the layer of the volume discharge and in the intermediate layer of the quasi-neutral plasma with a strong field.

The initial data for calculating the parameters of the glow discharge in [7] were the reduced mobility μ_{i} of ions and the coefficients A and B approximating the first Townsend ionisation coefficient α. As a result, we obtained

$$v_{\text{i}} = \mu_{\text{i}} \frac{E}{p}, \quad \frac{\alpha}{p} = A \exp\left(-\frac{B}{E/p}\right), \tag{1}$$

where v_{i} is the ion drift velocity and E is the electric field strength.

In the deeply anomalous regime the decrease in the potential in the intermediate layer should be rather small compared to the cathode decrease in the layer of the volume discharge. Therefore, we present expressions allowing the calculation of the reduced current density, the width of the volume discharge region and the cathode decrease in the potential:

$$J(y_{\text{c}}) \approx y_{\text{c}}^2 E_3(1/y_{\text{c}}) \left(\ln \frac{1+\gamma}{\gamma} - \frac{1}{1+\gamma} \right)^{-1},$$

$$a_{\text{c}} = \frac{1+\gamma}{E_3(1/y_{\text{c}})} \left(\ln \frac{1+\gamma}{\gamma} - \frac{1}{1+\gamma} \right), \tag{2}$$

$$u_{\text{c}} = \frac{1}{2} y_{\text{c}} a_{\text{c}} = \frac{y_{\text{c}}^3 (1+\gamma)}{2J(y_{\text{c}})},$$

where $E_3(1/y_{\text{c}})$ is the integral exponential function of the third order and γ is the ion–electron emission coefficient. Here, the dimensionless variables

$$J = \frac{j/p^2}{\varepsilon_0 A B^2 \mu_{\text{i}}}, \quad a_{\text{c}} = A p l_{\text{c}}, \quad u_{\text{c}} = \frac{A}{B} U_{\text{c}}, \quad y_{\text{c}} = \frac{E_{\text{c}}/p}{B} \tag{3}$$

are the reduced current density, the width of the volume discharge layer, cathode decrease in the voltage and the reduced field strength on the cathode surface, respectively; and ε_0 is the permittivity of vacuum.

For nitrogen $A = 12$ cm^{-1} Torr^{-1}, $B = 342$ V cm$^{-1}\times$ Torr^{-1}, $\mu_i = 2.5\times10^3$ cm^2 Torr V^{-1} s^{-1} [1], the coefficient γ taking into account the kinetic mechanism of potential ejection of electrons by ions is reasonable to take equal to ~ 0.2. By using these values we obtain the dimensionless reduced current density $J \simeq 3.2\times10^3 \gg 1$ in the discharge under study. We will determine from the first inequality in (2) the dimensionless reduced field at the cathode: $y_c \simeq 80$ and from the second one – the dimensionless layer width: $a_c = 2.0$. Then, from the last inequality in (2) we obtain taking (3) into account the dimensional estimate of the cathode decrease in the potential: $U_c \simeq 2.3$ kV. This estimate agrees well with the experimental results of Ref. [8] and conclusions of the theory of the anomalous glow discharge [1].

Note that in the mentioned discharge burning regime the cathode decrease in the voltage U_c strongly depends on the efficiency coefficient γ. We set $\gamma = 0.2$ but if we take its minimum value for a discharge in nitrogen equal to ~ 0.01 (it characterises the so-called potential ejection of electrons by ions) [9] the estimate of the cathode decrease in the potential will increase to ~ 10 kV. Therefore, the estimate $U_c \simeq 2.3$ kV should be treated as a rough one.

In the quasi-stationary phase of the glow discharge in nitrogen, the electric field strength E_{st} in the positive column of length d_{glow} approximately corresponds to half the static breakdown voltage, which under our conditions yields the estimate of a decrease in the voltage on the glow column: $U_{glow} \simeq {}^1/_2(E_{st}/p)pd_{glow} = 700$ V. Thus, the estimate of the general decrease in the potential on the discharge gap U_d is ~ 3 kV, which well agrees with the observed values (~ 4 kV), especially taking into account the roughness of the used model to describe the deeply anomalous discharge. These estimates show that a greater part of the input power is deposited into the cathode discharge region and does not contribute into pumping of the laser active medium.

The width of the volume discharge layer is rather small: $l_c = a_c/(Ap) \approx 0.01$ cm. For this reason, a dark region near the cathode of length ~ 0.5 cm observed in the 'images' of laser radiation cannot be interpreted as a dark region of the volume discharge. In our opinion, this region corresponds to some analogue of the dark Faradya space of a stationary glow discharge in which the electric field strength is close to zero. It is difficult to estimate its length in the discharge based on general theoretical assumption, but it is usually an order of magnitude larger than the width of the volume discharge layer.

As a quantitative estimate, we can take the relaxation length of a fast electron with the initial energy ~ 2.5 keV in gas of the corresponding pressure, although in the glow discharge it rather corresponds to the length of the negative glow region. The path length L_c of comparatively fast electrons with the initial energy W_0 in gas can be calculated by the expression

$$L_e \sim \frac{W_0}{W_{ei}}\frac{1}{\sigma_{ion}n_{mol}}, \qquad (4)$$

where $\sigma_{ion} < 5\times10^{-17}$ cm^2 is the effective cross section characterising ionisation of nitrogen atoms and molecules by fast electrons [10]; n_{mol} is the total concentration of nitrogen molecules and atoms; $W_{ei} \simeq 35$ eV is the mean energy of formation of an electron–ion pair in nitrogen. Estimate (4) yields the path length $L_e < 3$ cm for $E_0 =$ 2.3 keV and $p = 12$ Torr. However, this is the estimate of the total path length, while the real path due to electron scattering (the so-called extrapolated path) can be approximately an order of magnitude lower. If we assume that for electron energies of several keV the transport cross section σ^* of scattering and cross sections of inelastic collisions is of the same order, the estimate of the extrapolated path length R_e can be calculated from the relation

$$R_e \sim \frac{1}{n_{mol}}\left(\frac{W_0/W_{ei}}{\sigma_{ion}\sigma^*}\right)^{1/2} \approx \left(\frac{W_0}{W_{ei}}\right)^{1/2}\frac{1}{\sigma_{ion}n_{mol}}. \qquad (5)$$

The calculation by using Eqn (5) yields $R_e \sim 4$ mm under our conditions, which in agreement with the observed length of the dark region in Fig. 1.

A similar calculation can be performed for a discharge at a pressure $p = 87$ Torr. Figure 2a presents for this discharge oscillograms of voltage pulses across the discharge gap, the discharge current and lasing power, where at the instant of achieving the maximum of the output power the discharge current $I \simeq 25$ kA, the voltage across the discharge gap $U \simeq 5-7$ kV, $j/p^2 \simeq 2\times10^{-2}$ A cm^{-2} Torr^{-2} (the reduced current density already approaches the reduced current density of a normal glow discharge). Calculations by using Eqns (2) and (3) yield the cathode decrease in the potential $U_c \simeq 400$ V and the potential decrease on the positive glow column $U_{glow} = 6$ kV. Thus, at a nitrogen pressure of 87 Torr the main decrease in the potential occurs in the region of the quasi-neutral plasma column, while in the cathode region the decrease in the potential is insignificant. It is natural that the length of the dark Faraday space estimated by using (5) turns equal to ~ 0.2 mm.

Taking the above-said into account, we can assume that the cathode region, in which a reduced pump power takes place at low pressures, is the region with reduced field strength typical of the negative glow and dark Faraday space in the glow discharge.

5. Conclusions

The results of the study of the radiation power density distribution over the output beam cross section of a transverse-discharge-pumped UV nitrogen laser have been presented in this paper. It has been shown that at a small duration of the output pulse and increased pressures in this laser, the radiation power density distribution at the cathode and anode differ inconsiderably. When the working pressure is decreased, which under conditions of this experiment leads to the increase in the laser pulse duration and its delay with respect to the current pulse, a region with a lower density of the lasing power appears at the cathode. The length of this region in nitrogen as calculations show, approximately corresponds to the length of the dark Faraday space in the anomalous glow discharge. The peculiarities of the dark Faraday space in the anomalous glow discharge are low electric field strength in it compared to the strength in the region of the positive column and the fact that the main energy input in it belongs to electrons with the energy of hundreds of electron volts. As shown above, the lasing threshold on the second positive nitrogen system is not achieved both at low electric field strength [11] and excitation of nitrogen by an electron beam in the absence of the buffer gas [12]. The addition of NF_3 to nitrogen leads to a decrease in the length of the dark region at the cathode, which can be explained by additional energy losses of electrons upon their collisions with molecules of the heavy gas NF_3.

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