Efficient high-pressure quasi-cw laser using the first negative system of nitrogen

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Experiments show that the rate at which the B state of the N_2^+ ion is depopulated by hydrogen molecules is at least two orders of magnitude lower than the rate at which the X state is depopulated. It has thus been found possible to develop a high-power quasi-cw laser for the near-UV region ($\lambda = 391$ nm) and for the visible region ($\lambda = 428$ nm) with an efficiency up to 2% in electron-beam pumping of the high-pressure $He/N_2/H_2$ mixture. The output energy is observed to increase when the active medium is pumped by an electric discharge.

The solution of the problem of achieving a fast and selective depopulation of the lower working level during lasing on optically allowed bound-bound transitions raises the possibility of achieving efficient quasi-cw lasing in the visible and UV regions. For example, the selective quenching of resonant $3s$ states of Ne was used in Ref. 1 to develop the first efficient laser in the yellow-red region at a specific pump power of only $\cong 10$–10^2 W/cm^3. It was mentioned in that paper that the rapid depopulation of the lower working levels of lasers can also be achieved in other processes which occur with Coulomb cross sections. Of interest in this connection are lasers using allowed ion transitions, in particular, the B-X transitions of the N_2^+ ion, since the $B\,^2\Sigma^+_{uv=0}$ upper working level can be populated highly efficiently.[2] Self-terminating lasing was achieved in Refs. 2 and 3 on the first negative system of nitrogen during pumping of a high-pressure He/N_2 mixture by an intense electron beam.

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The cross sections for induced transitions in molecules, which are two or three orders of magnitude smaller than atomic cross sections, provide speed and selectivity but also impose an additional restriction on the "quenching" process: The $N_2^+(X)$ molecular ions which are produced as a result of the depopulation must not absorb the laser light. Hydrogen is promising here since the N_2H^+ ion, formed in the heavy-particle transition $N_2^+(X) + H_2 \to N_2H^+$, does not absorb light in the first negative system of nitrogen,[4] and the reaction rate for this process is very high,[5] $\sim 2\times 10^{-9}$ cm^3/s. A hydrogen pressure of 2 torr would thus be sufficient to depopulate the lower working level at a rate an order of magnitude higher than the rate of the spontaneous decay of the upper level ($v_{sp} \cong 1.6\times 10^7\ s^{-1}$; Ref. 4). Furthermore, it follows from the relation between the reaction rate constants for the ion-molecule processes[5,6] that at an H_2 density no higher than the N_2 density the efficiency at which the upper working level is pumped decreases only insignificantly. Nevertheless, it would not be possible to develop an efficient laser if, as is usually the case, the more highly excited levels are quenched more rapidly.[6] The feasibility of developing a quasi-cw laser with a high efficiency which operates on the B-X transition of N_2^+ thus depends on the ratio of the rates at which the upper and lower working levels of the H_2 molecules are quenched.

Figure 1 shows the intensity of the spontaneous emission in the transition $B\,^2\Sigma^+_{uv=0} \to X\,^2\Sigma^+_{gv=1}$ of the nitrogen ion ($\lambda = 428$ nm) versus the hydrogen pressure in a mixture consisting of 6 atm of He and 4 torr of N_2/H_2, pumped by an electron beam. At an H_2 pressure of 2 torr, which provides the necessary rate of depopulation of the $N_2^+(X)$ level, the emission intensity decreases 15–20%.

During electron-beam pumping of the He/N_2 mixture, the $B\,(v=0)$ state of the nitrogen ion is filled by two processes: the charge exchange of molecular helium ions,[3] $He_2^+ + N_2 \to N_2^+(B) + 2He$, and the Penning ionization[6] $He^* + N_2 \to N_2^+(B) + He + e^-$, so that we need to determine the ratio of the efficiencies of these two processes in order to evaluate the reaction rate constant for the quenching of $N_2^+(B)$ by hydrogen molecules. At a nitrogen density $\gtrsim 10^{18}$ cm^{-3} the only process that depopulates the $N_2^+(B)$ level is the Penning process.[5] According to Ref. 7, the ratio of

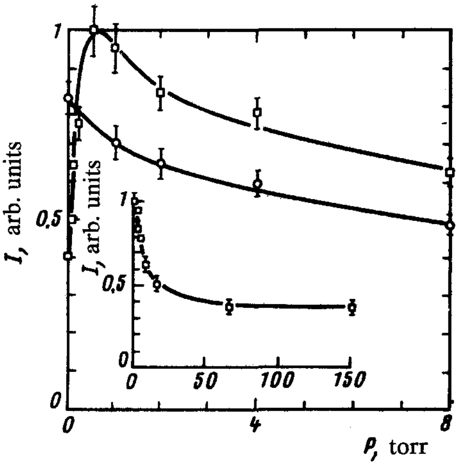

FIG. 1. The luminescence intensity at $\lambda = 428$ nm versus the H_2 pressure (O) and the N_2 pressure (□).

the number of excited He atoms to the number of ions is ≈ 0.53 in the case of electron-beam pumping. Analysis of the asymptotic behavior of the intensity of the spontaneous emission as a function of the nitrogen pressure (Fig. 1) reveals that the probabilities for the formation of the $N_2^+(B,v=0)$ level by the two mechanisms are essentially identical. Making use of this result, we can use the dependence of the luminescence intensity on the hydrogen pressure to estimate the rate at which the $B\,^2\Sigma^+_{uv=0}$ level is quenched by H_2 molecules; we find $<10^{-11}$ cm^3/s. The rate at which the upper working level is "quenched" by hydrogen is thus at least 100 times lower than the rate at which the lower level is quenched.

The apparatus described in Ref. 8 was used in the present lasing experiments. The active medium of the laser is pumped by an electron beam with an electron energy ~ 200 keV, a pulse length $\cong 0.7\ \mu$s, and a current density up to 7 A/cm^2. The volume of the active region of the laser is $\cong 1$ liter. The laser resonator is formed by dielectric mirrors which are selective at $\lambda = 428$ nm, which have dimensions of 8×3.5 cm, and which have transmittances $T_1 \leqslant 0.1\%$ and $T_2 \cong 1\%$.

Most of the experiments on the characteristics of the lasing were carried out at a pressure of 6 atm of the $He/N_2/H_2$ mixture. The experiments show that at a hydrogen pressure of 2 torr the optimum nitrogen pressure is 4 torr. The N_2 density in the mixture is higher than the density (0.5 torr) which maximizes the luminescence efficiency in the case of the He/N_2 mixture (Fig. 1) because of a competition between the pumping of the upper working level and the ionization of H_2.

Figure 2 shows the output energy and efficiency of the laser at $\lambda = 428$ nm versus the current density of the electron beam. The threshold current density of the electron beam is determined by the need to saturate the working transition during the pump pulse, rather than by the condition for steady-state lasing.[9] The decrease in the lasing rise time with increasing pump power is of course accompanied by an increase in the energy and efficiency of the laser. At $j \cong 6$ A/cm^2, for example, the lasing energy is $\cong 0.2$ J (the specific power is 450 kW/liter), with an efficiency $\sim 1.3\%$. When the active medium is instead pumped by the electric-discharge method, the output energy increases, and the threshold beam current density decreases. We believe that the phys-

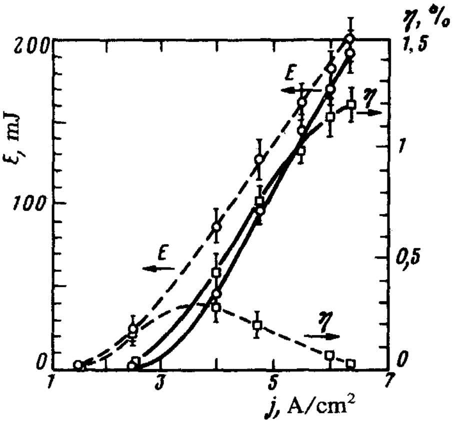

FIG. 2. Output energy and efficiency of the laser at $\lambda = 428$ nm versus the current density during pumping by an electron beam (solid curves) and pumping by the electric-discharge method (dashed curves).

ical reason for the effect of the electric field is a decrease in the rate at which the excited ion states are quenched by electrons as the electrons are heated. An estimate from the van Regemorter formula[10] shows that an increase in the electron temperature from, say, room temperature to 1–2 eV reduces the quenching rate by a factor of seven to ten. The field becomes inconsequential at a high density of secondary electrons (Fig. 2), because of their heating during randomization.[11] In principle, the electric field could act by a different, and more efficient, mechanism: the excitation of metastable helium levels in the discharge, followed by a pumping of the upper working level of the laser through Penning ionization of nitrogen. If this mechanism is to be implemented, the rate of the stepwise excitation of helium would have to be relatively low, so that the electron density would have to be limited to $\lesssim 10^{13}$ cm^{-3} ($j \lesssim 0.1$ A/cm^2).

In the present experiments, the lasing occurs near the "red edge" of the first negative system of nitrogen, not on the $P(7)$ line, which corresponds to the maximum population of the upper working level. The reason is that at a pressure of only a few atmospheres the broadening of the gain contour of a single rotational line of helium becomes substantially greater than the distance between such lines near the edge.[4] As a result, $P(9)$-$P(13)$ transitions, for example, contribute to the gain on the $P(12)$ transition. It follows that an increase in the buffer gas pressure will lead to an increase in the gain during beam pumping; this conclusion is confirmed by experiments carried out by us at a pressure of 10 atm. Under these conditions, the lasing efficiency reaches 2%, due, in particular, to the faster development of the lasing.

When a nonselective resonator (aluminum-coated mirrors) is used, the lasing occurs only in the 0-0 band of the B-X transition in the UV region ($\lambda = 391$ nm), and the length of the output pulse is $\cong$400 ns.

In summary, the selectivity of the depopulation of the B and X states of N_2^+ by hydrogen, which has been observed in the present experiments, has made it possible to achieve, for the first time, intense quasi-cw lasing on the 0-0 and 0-1 bands of the first negative system of nitrogen, with an efficiency up to 2%.

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