Intense quasi-cw lasing in the visible region in a high-pressure mixture of inert gases

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Intense quasi-cw lasing with an efficiency $\simeq 1\%$ has been achieved for the first time on $3p$-$3s$ transitions of neon during electron-beam pumping of a high-pressure He:Ne:Kr(Ar) mixture. The upper working levels are populated selectively through the dissociative recombination of an electron with a molecular neon ion. An effective depopulation of the lower working levels is achieved in a process involving the liberation of an electron in an interaction of resonant levels of the neon atom with krypton (or argon).

Lasing on self-terminating $np^5\,(n+1)p - np^5\,(n+1)s$ transitions of compressed heavy inert gases (Ar, Kr, Xe) was first achieved by V. P. Chebotaev's group in a fast discharge (pump power $\gtrsim 1$ GW/liter) during excitation of the upper working level by electron impact from the ground state.[1] Another effective mechanism for a selective population of low-lying p states, which operates during electron-beam pumping of high-pressure inert gases, is the dissociative recombination of molecular ions.[2]

The large cross sections ($\gtrsim 10^{-13}$ cm^2; Ref. 3) of the allowed p-s transitions make it possible, in principle, to achieve a quasi-cw lasing in the visible region in the case of a selective depopulation of $np^5(n+1)s$ states. The fast spontaneous decay of the upper working level ($\nu_{sp} \sim 10^8$ s^{-1}), however, requires that the lower level be depopulated at a high rate ($\sim 10^9$ s^{-1}). A depopulation rate of this magnitude should be provided by a "quenching" process with a rate constant $\sim 10^{-9}$ cm^3/s; a rate constant of this magnitude can be achieved, for example, in a process involving ionization of the quenching center. The $3p$-$3s$ transitions of Ne hold promise in this regard, since the $3s$ states of neon lie above the ionization potential of most atoms and molecules, and the wavelengths corresponding to all these transitions lie in the visible region. Heavy inert gases would be preferred as the quenching agents for $3s$ states. In this case the rate constant for charge exchange with Ne_2^+, which competes with the dissociative recombination of Ne_2^+, is relatively small.[4]

In a collision that involves the liberation of an electron, that states which are quenched most rapidly are those which are resonantly coupled with the ground state and are thus selectively depopulated. For example, the rate at which the $2^1P_1^0$ resonant state of He is depopulated in a process involving the ionization of heavy inert gases is one or two orders of magnitude greater than the rates at which the 2^1S_0 and 2^3S_1 metastable states are depopulated.[5] No corresponding experimental data are available in the case of Ne, but estimates based on Ref. 5 show that the $3s'[1/2]_1^0$ resonant state could be depopulated at the necessary rate at a quenching-agent density of only $\sim 10^{18}$ cm^{-3} (for the other resonant level, $3s[3/2]_1^0$, the depopulation rate constant is smaller by a factor of 2.5). The Ne density is limited by a self-quenching of the upper working levels; for the $3p'[1/2]_0$ level, for example, it is $\sim\nu_{sp}/K_q \simeq 100$ torr, where $K_q \simeq 2\times10^{-11}$ cm^3/s is the rate constant for the quenching of this level by neon. The efficiency of the excitation and of the lasing increases when a buffer gas is used; for the case of Ne, this would have to be He. The pump power, which determines the density of "slow" electrons, is limited both by the quenching of the upper working level by electrons[3] and the three-body recombination of He_2^+ involving two electrons.[6] The dissociative recombination of the molecular helium ion occurs slowly, and the rate of charge exchange with He_2^+ is considerably higher for Ne than for Ar, Kr, or Xe (Ref. 4).

These arguments show that we can expect to achieve a quasi-cw lasing on $3p$-$3s$ transitions of Ne by pumping a ternary mixture of high-pressure inert gases with an electron beam.

In the present experiments, a He/Ne/Kr(Ar) mixture is pumped by an electron beam with a current density in the range 10^{-3}–10 A/cm^2, a pulse length in the range 0.5-200 μs, and an average electron energy $\simeq$200 keV. The lasing spectra are measured with an ISP-51 spectrograph. The lasing energy is measured by a calorimeter with a sensitivity of 20 mV/J. The optical volume of the laser is 1 liter.

Figure 1 shows the scheme of $3p$ and $3s$ levels of Ne, along with the lasing transitions that have been observed. Also shown here are densitometer traces of the emission spectra and the mixture compositions, in which the corresponding lines were obtained. At relatively low concentrations of Ne and Kr (or Ar) in the mixture, the only lasing is at $\lambda = 5852.5$ Å (Fig. 1a). The reason for this result is the highly efficient population of the $3p'[1/2]_0$ state during the dissociative recombination of Ne_2^+ (Ref. 2), the depopulation of the $3s'[1/2]_1$ lower resonant level (the fastest depopulation in this system of transitions), and the optimal (for lasing) relations between the statistical weights of these levels. The mixing of $3s[3/2]_1$ and $3s[3/2]_2$ states by neon (through an exchange interaction) and by electrons, on the one hand, and the rapid quenching of the $3s[3/2]_1$ resonant level by krypton, on the other, lead to the appearance of lasing at $\lambda = 7032.4$ Å and $\lambda = 7245.2$ Å as the Ne or Kr pressure is raised (Fig. 1, b and c).[1)] Since the upper working levels for these transitions are the same, the appearance of

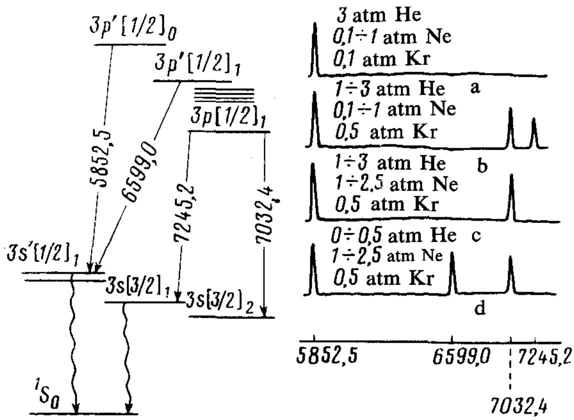

FIG. 1. The neon level scheme and emission spectra.

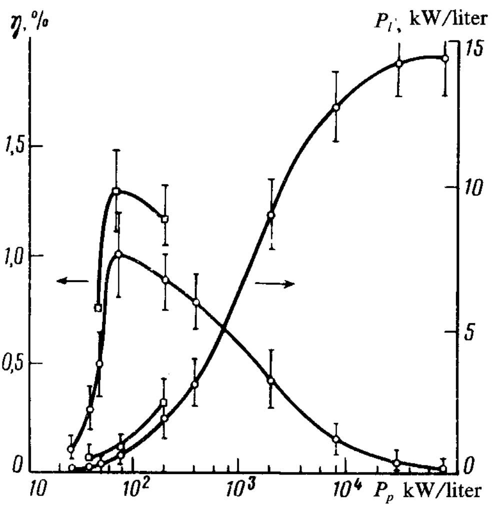

FIG. 2. Lasing power and laser efficiency versus the pump power. ○—He/Ne/Kr mixture; □—He/Ne/Ar mixture.

both lines in the emission spectrum (Fig. 1b) means that at Ne pressures $\lesssim 1$ atm the $3p[1/2]_1 - 3s[3/2]_2$ transition is self-terminating. A further increase in the Ne pressure in the mixture (Fig. 1c) makes it possible to achieve a quasi-cw lasing at $\lambda = 7032.4$ Å (the duration of the pump and the lasing is $\simeq 0.5$ μs). A decrease in the He pressure in the mixture, which retards the exchange between the $3p'$ and $3p$ level groups, is accompanied by the appearance of lasing at $\lambda = 6599.0$ Å (Fig. 1d).

The highest lasing efficiencies η and lasing energies were found for the transition $3p'[1/2]_0 - 3s'[1/2]_1$. Figure 2 shows the efficiency and the specific lasing power P_l at $\lambda = 5852.5$ Å versus the specific pump power P_p. For a fixed beam current density, we optimized the mixture composition at a fixed total pressure of 3 atm, and we also optimized the resonator parameters, since the intensity of the emission in the resonator is limited by the finite rate at which the lower working level is depopulated. At a Kr (or Ar) pressure $\gtrsim 30$ torr, the emission pulse reproduces the pump pulse under all pumping regimes studied, and the maximum duration of the emission reaches 200 μs. The experimental points in Fig. 2 correspond to the maximum values of η and P_l. The optimum efficiency $\simeq 1\%$ is reached at $P_p \simeq 70$ kW/liter, which corresponds to an electron-beam current density $\sim$10–20 mA/cm^2 for the typical mixture composition He/Ne/Kr(Ar) = 50/1, 5/1. The primary reason for the decrease in η with increasing pump power is (as we mentioned earlier) a strengthening of the effect of the quenching of the $3p'[1/2]_0$ level by electrons and of the ternary recombination of He_2^+. Our estimates show that at a specific pump power $\sim$2 MW/liter the rates of these processes are comparable to the rates of the spontaneous decay of the upper working level and of charge exchange with He_2^+ involving Ne, respectively. We also note that over a broad range of the pump power, $P_p \simeq 60$–400 kW/liter, the efficiency changes by no more than 20%. Since the rate of charge exchange with Ne_2^+ involving Kr (this exchange competes with the population of the upper working level by recombination) is roughly an order of magnitude higher than for the charge exchange involving Ar, the replacement of krypton by argon leads to some improvement in the specific lasing characteristics at low pump power levels.

In summary, these experiments demonstrate that it is possible to achieve a rapid ($\lesssim 1$ ns) and selective depopulation of the $3s$ resonant states of Ne in a process involving the liberation of an electron. For the first time, intense quasi-cw lasing has been achieved in the visible region during the pumping of a mixture of compressed inert gases. Lasing has been observed at four lines of the system of $3p$-$3s$ transitions of neon. The maximum efficiency, $\simeq 1\%$, was achieved at $\lambda = 5852.5$ Å.

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[1)]Lasing at these wavelengths was also achieved in Ref. 7.

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