Electroionization laser using metastable xenon atoms

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A new approach is proposed for developing high-power gas lasers which work on atomic transitions. The idea is to pump the working levels by an externally sustained electroionization discharge from highly excited metastable states excited in the active medium by an external source. An output energy of more than 50 J at the wavelength 1.73 μm has been achieved from an Ar:Xe laser with an active-medium volume of 10 liters.

Gas lasers working on atomic transitions[1] and pumped by a self-sustained electric discharge are known for their extremely low energies and quantum efficiencies. The common helium-neon laser is a good example. We wish to propose a new approach to the development of efficient, high-pressure gas lasers which operate on electronic transitions. The idea is to use as the main working level highly excited metastable states, whose population would be maintained at a sufficiently high level in the active medium by an external excitation source. We have implemented this idea experimentally (Fig. 1) in the quasisteady pumping by an externally sustained electroionization discharge of the well-known $5d$-$6p$ lasing transitions of the Xe atom[2–4] from the metastable (M) Xe*($6s$) states, which are populated in the active medium by a fast electron beam. The pumping from high-lying states makes it possible to achieve a high quantum efficiency from the system and to keep the discharge relatively insensitive to various instabilities.

In the present experiments we used an electroionization laser apparatus with an active-region volume of 10 liters and an aperture of 10×10 cm. An electron beam with an energy $\sim$300 keV and a cross section of 10×100 cm is injected into the cell through a 20-μm titanium foil in the direction perpendicular to the optical axis of the

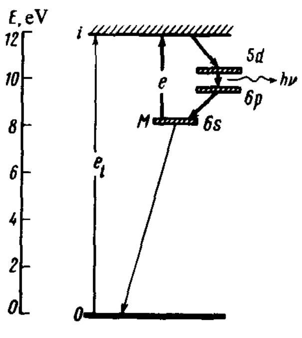

FIG. 1. Scheme for pumping the electroionization laser using xenon metastables.

laser. At a pulse length $\sim 3.5\ \mu s$ at the base, the electron current density beyond the foil is $1.8\ A/cm^2$. The anode of the discharge gap has dimensions of 10×100 cm and lies 10 cm from the foil. The electroionization pumping of the active volume is arranged by discharging a capacitor bank. The discharge is periodic; the length of the first period of the discharge current corresponds roughly to the length of the electron beam pulse. The laser resonator is formed by a plane gold mirror and a stack of two quartz plates. The active medium is a mixture of the gases Ar and Xe with a pressure varied up to 3.5 atm and a composition Ar:Xe = 100:1. Lasing was observed on five $5d$-$6p$ transitions of the Xe atom, with more than 90% of the energy in the line with $\lambda = 1.73\ \mu m$.

Metastable states are excited by the electron beam in ionization reactions followed by a recombination of atoms of the active medium (Fig. 1). The ionization of the xenon involves atoms of the buffer gas in the reactions

$$Ar + e_i \rightarrow Ar^+ + e_i + e, \quad (1)$$

$$Ar^+ + 2Ar \rightarrow Ar_2^+ + Ar, \quad (2)$$

$$Ar_2^+ + Xe \rightarrow Xe^+ + 2Ar \quad (3)$$

(e_i and e are beam electrons and secondary electrons, respectively). The recombination of Xe^+ with electrons in the reactions

$$Xe^+ + 2Ar \rightarrow ArXe^+ + Ar, \quad (4)$$

$$ArXe^+ + e \rightarrow Xe^{**}(5d) + Ar \quad (5)$$

populates the upper working level of the $5d$-$6p$ transition and gives rise to a lasing[5]:

$$Xe^{**}(5d) \rightarrow h\nu(\lambda = 1.73\ \mu m) + Xe^{**}(6p). \quad (6)$$

The relaxation of the lower working level, $Xe^{**}(6p)$, in the active medium results in xenon atoms in metastable states, $Xe^*(6s)$, whose lifetime at a pressure of 2–3 atm is several hundred nanoseconds.

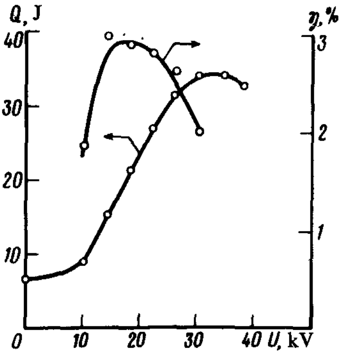

FIG. 2. Output energy Q and efficiency (η) of the electroionization pumping vs the voltage to which the capacitor bank is charged. Here η is defined as the ratio of the output energy due to the discharge to the energy stored in the capacitor bank; the pressure of the active medium is 2.5 atm.

The production of xenon metastable atoms in the active medium is thus accompanied by lasing on these transitions, but because of the low quantum efficiency the physical efficiency of the laser with pumping exclusively by the electron beam does not exceed 1–1.5%. The imposition of an electric field increases the output energy by a factor of five or six (Fig. 2). In this case the working transitions are pumped through the ionization of xenon metastables by conduction electrons in the reaction

$$Xe^*(6s) + e \rightarrow Xe^+ + 2e, \tag{7}$$

followed by a recombination of the Xe^+ ion in reactions (4) and (5). After the emission of a photon and the relaxation, the xenon atom is in its original metastable state, and the process repeats itself. The pumping by the electroionization discharge is thus a quasisteady cyclic process (the thick arrows in Fig. 1). The role played by the electron beam reduces primarily to one of replenishing the loss of metastables through recombination to the ground state in the reactions

$$Xe^*(6s) + Xe + Ar \rightarrow Xe_2^* + Ar, \tag{8}$$

$$Xe_2^* \rightarrow h\nu(\lambda = 0{,}173\ \mu m) + 2Xe. \tag{9}$$

When the power of the external ionization source is reduced, the pumping by the discharge becomes relatively more important. At an electron beam density ~0.02 A/cm^2, for example, the output energy in the case of electroionization pumping exceeds that in the case of pumping exclusively by the electron beam by a factor of nearly 100.

The pumping from metastable states results in a high output efficiency. At a quantum efficiency of about 20% in reaction chain (7)–(4)–(5), and at a physical efficiency of about[6] 5%, the efficiency of the electroionization pumping "from stored energy" reaches 3% in these experiments (Fig. 2). The maximum power output, more than 50 J, was obtained at an active-medium pressure of 3.5 atm.

Because of the good spatial uniformity of the electroionization pumping, it is possible to achieve a high optical quality without resorting to complicated pulse-tailoring arrangements. In our experiments, in which the instability of telescopic resonators was used, the width of the angular distribution of the output in the far zone at half the maximum intensity was 4×10^{-5} rad.

In conclusion we should mention that there are other ways to effectively populate metastable states to produce laser media with specified electrical properties: direct photoexcitation, ionization by an intense x-ray flux, excitation by the products of nuclear reactions, etc. This successful development of a laser using xenon metastables demonstrates the promising outlook for this method and suggests a search for other laser systems with a suitable structure of electronic transitions.

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