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Electric-discharge xenon laser with weak external ionization

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A laser utilizing infrared transitions in Xe, operating in the radiation field of a continuously operating nuclear reactor, was constructed and investigated for the first time. The maximum energy characteristics of the laser (specific output energy ~0.1 J/liter, efficiency ~0.1–0.2% of the energy deposited in the gas) were obtained for a mixture of the Ar:Xe = 100:1 composition at a pressure of 2 atm when the gas was ionized by ^{235}U fission fragments. The laser could be operated at temperatures up to 650 °C.

INTRODUCTION

Much work has been published on high-pressure lasers utilizing infrared transitions in xenon.[1–7,15] It was reported in Ref. 6 that a nuclear-pumped xenon laser was constructed using a pulsed reactor capable of supplying neutron fluxes of densities 10^{13}–10^{14} neutrons$\cdot$cm$^{-2}\cdot$s^{-1}, typical of continuously operating nuclear reactors. Direct nuclear pumping[6,7] can be used to excite efficiently large-volume active media, but the specific power deposited in lasers excited directly by continuously operating nuclear reactors is relatively low ($\sim$1–10 W/cm^3). Therefore, direct nuclear pumping of high-power lasers requires creation of large cavities in the active zone of the reactor, which results in deterioration of the critical parameters of the reactor.

We constructed and investigated an electric-discharge laser utilizing transitions in Xe I in which a gas mixture was ionized by radiation from a continuously operating nuclear reactor. Strong continuous ionization of a gas and the presence of an ionization source inside the laser make it possible to achieve a high pulse repetition frequency and, consequently, a high average output power in the form of laser radiation. The power needed to pump a laser by an electric discharge can be provided by the same nuclear reactor which ionizes the active medium.[8]

APPARATUS

Our experiments were carried out on three lasers using a VVR-K continuously operating nuclear reactor.[9] Each laser chamber contained two separate pairs of rounded electrodes and two resonators. Laser radiation from the first resonator passed along an internally polished tube 11 to a recording system comprising an FD-9É111A photodiode and an S8-13 oscilloscope. Coherent radiation of the second resonator was reflected by a mirror 7 and reached a calibrated calorimeter 6. Each resonator consisted of a nontransmitting gold mirror 4 with a radius of curvature 5 m and a flat sapphire plate 5.

Voltage pulses were generated by a bank 10 consisting of K15-10 storage capacitors with a total capacitance 40 nF charged from a high-voltage rectifier. A controlled discharge gap 9 transferred the voltage from the storage capacitors along a waveguide 8 to peaking capacitors 3 and inner electrodes 1. The waveguide consisted of two metal tubes, with diameters 34 and 20 mm and the gap between which contained desalinated reactor water. The KVI-3 peaking capacitors had a total capacitance of 4 nF and were located inside the laser chamber, i.e., within the active zone of the reactor. Voltage pulses were recorded using a Rogowski loop and an S1-75 oscilloscope.

Each of the three investigated lasers differed in respect of the construction set by the design requirements. In the case of lasers Nos. 2 and 3 there were no peaking capacitors 3, so that it was possible to operate at high (up to 10^{14} neutrons$\cdot$cm$^2\cdot$s^{-1}) neutron flux densities and high temperatures. In lasers Nos. 1 and 3 the gas mixture was ionized by products of the ^{3}He$(n,p)T + 0.76$ MeV nuclear reaction. In the case of laser No. 2 we used helium-free gas mixtures, so that the active medium was ionized by ^{235}U fission products generated by a layer of uranium 235 deposited on outer elec-

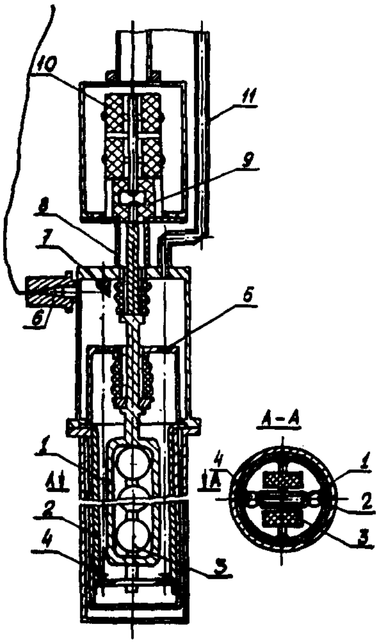

FIG. 1. Section through the apparatus.

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trodes 2 in the form of a continuous layer of ~ 10 mg/cm^2 density.

The presence of a double jacket in laser No. 3, with the outer side of the jacket cooled by the reactor water and the inner subject to radiation heating, made it possible to vary the temperature of the active medium by altering the ^{4}He pressure in this jacket. This temperature was monitored by a Chromel–Alumel thermocouple.

Before loading in the reactor we checked the laser and the recording system using radiation from a ^{4}He–N$_2$ laser emitting at 337 nm. The dimensions of the discharge gap were $0.9\times0.6\times50$ cm (and the width of the discharge gap was determined using the $\lambda = 337$ nm radiation). The investigated laser was placed in the central channel of the reactor zone in such a way that the center of the discharge region coincided with the center of the active zone.

EXPERIMENTAL RESULTS

A preliminary optimization of the active medium was carried out using an electric-discharge laser with preionization by ^{210}Po α particles.[10,15] The highest output energy was obtained from a mixture of the ^{4}He:Ar:Xe = 100:50:1 composition and in this case a considerable fraction of the output radiation (~40%) was emitted at the wavelength of 1.73 μm.

1. The first reactor experiments were carried out using laser No. 1 and a mixture of the composition ^{3}He:Ar:Xe = 100:50:1 at a pressure of 1.5 atm; in this case the thermal neutron flux density was within the range 10^{11}–10^{13} neutrons·cm^2·s^{-1}. Figure 2 shows the dependences of the laser radiation energy on the charging voltage obtained for different neutron fluxes. The observed reduction in the laser radiation energy (~ 15%) on increase in Φ from 10^{12} to 10^{13} neutrons·cm^2·s^{-1} was clearly due to a change in the laser parameters (peaking capacitance and others), because of heating by the reactor radiation.[11] The maximum laser efficiency was achieved at low values of E/N ($\sim 5\times10^{-17}$ V·cm^2). An increase in the charging voltage increased the importance of the multistage ionization processes, which limited the concentration of the Xe atoms in the 5d state. The specific energy deposited in the three-dimensional discharge reached 50 J/liter, whereas the maximum efficiency of the Xe I laser was achieved at a pumping rate an order of magnitude less.[5]

It is clear from the results obtained that the minimum neutron flux density Φ needed for the operation of an Xe laser is 10^{11} neutrons·cm^2·s^{-1}. A calculation of the energy losses experienced by the products of the ^{3}He $(n, p)T$ reaction in the gaseous mixture showed that the electron density in the mixture was $n_e \approx 2\times10^{10}$ cm^{-3} when the neutron flux density was $\Phi = 10$ neutrons·cm^2·s^{-1}. The value of n_e needed to initiate a volume discharge in a gas was known to be governed by the rate of rise of the voltage across the discharge gap dU/dt. The measured value of dU/dt reached 500 V/ns, i.e., the critical value $n_e \approx 2\times10^{10}$ cm^{-3} was in agreement with the experimental results reported in Ref. 12.

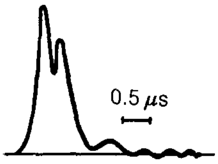

FIG. 3. Oscillogram of an output pulse obtained from an active mixture of the Ar:Xe = 100:1 composition at $p = 2$ atm.

2. The characteristics of an electron-beam-controlled laser using atomic transitions in xenon after ionization of the active medium by an electron beam with a current density $j = 0.013$–1.7 A/cm^2. We demonstrated the feasibility of operation of such a laser at lower current densities ($j < 1$ mA/cm^2).

Experiments on laser No. 2 were carried out using a mixture of the Ar:Xe = 100:1 composition at a total pressure of 2 atm. Figure 3 shows an oscillogram of an output radiation pulse obtained from this laser as a result of the 5d–6p transition in Xe I emitting at $\lambda = 1.73\,\mu$m. It is clear from this figure that lasing occurred during the first and second half-periods of the discharge current which should be compared with the report in Ref. 3, where ionization by an electron beam resulted in lasing only during the first half-period.

The dependence of the output energy of the laser at $\lambda = 1.73\,\mu$m on the charging voltage applied to the storage capacitors when the neutron flux densities were 10^{14} and 3×10^{13} neutrons·cm^2·s^{-1}, corresponding to an ionization energy input by an electron beam of density ~ 1 and 0.3 mA/cm^2, respectively, is plotted in Fig. 4. Clearly, when the active medium was ionized by a neutron flux of 3×10^{13} neutrons·cm^2·s^{-1} density the output radiation energy reached saturation at a charging voltage of 20 kV. The maximum value of the specific output energy obtained in this case for a neutron flux density of 10^{14} neutrons·cm^2·s^{-1} under a charging voltage of 20 kV was ~0.1 J/liter at an efficiency of ~0.1–0.2% of the energy deposited in the gas. Therefore,

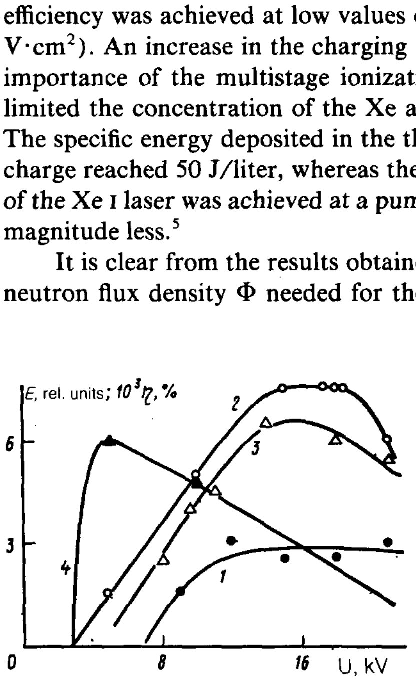

FIG. 2. Dependence of the output radiation energy (1–3) and the efficiency (4) of a laser on the voltage applied to the storage capacitors, obtained for different neutron flux densities Φ (neutrons·cm^{-2}·s^{-1}): 1) 10^{11}; 2), 4) 10^{12}; 3) 10^{13}.

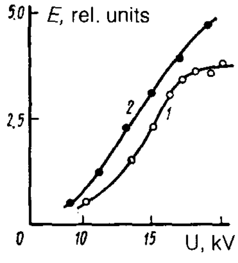

FIG. 4. Dependences of the output radiation energy on the charging voltage applied to the storage capacitors used to excite a mixture of the Ar:Xe = 100:1 composition at $p = 2$ atm, obtained for different neutron flux densities Φ (neutrons·cm^2·s^{-1}): 1) 3×10^{13}; 2) 10^{14}.

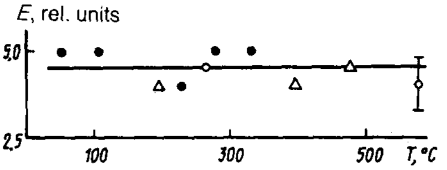

FIG. 5. Output energy characteristics of a laser employing a mixture of the ^4He:^3He:Ar:Xe = 50:50:50:1 composition at $p = 1.5$ atm, when the charging voltage applied to the storage capacitors was 20 kV, and the neutron flux density had the following values Φ (neutrons$\cdot$cm$^{-2}\cdot$s^{-1}): ●) 10; △) 2×10^{13}; ○) 3×10^{13}.

the use of a helium-free mixture and an increase in the duration of pumping made it possible to improve the energy characteristics of the laser by 1.5 orders of magnitude.

3. In various practical applications of lasers emitting as a result of atomic transitions in rare gases it would be of interest to know the influence of temperature on the operation of a laser. We investigated the operation of our electric-discharge xenon laser in a fairly wide range of temperatures from 50 to 650 °C.

These experiments were carried out on laser No. 3. Figure 5 shows the results of measurements of the output characteristics of this laser when the composition of the mixture was ^4He:^3He:Ar:Xe = 50:50:50:1, the total pressure in the mixture was 1.5 atm, and the charging voltage applied to the storage capacitors was 20 kV. An increase in temperature to 650 °C had no influence on the operation of the laser (within the limits of the experimental error). This was due to the fact that lasing occurred as a result of high-energy ($\sim$10 eV) transitions in the xenon atom.

CONCLUSIONS

We constructed the first infrared laser utilizing transitions in Xe I emitting in a radiation field of a continuously operating nuclear reactor. The ability of a xenon laser to operate at high (up to 650 °C) temperatures was demonstrated experimentally for the first time.

This non-self-sustaining-discharge laser utilizing an Ar–Xe mixture had a number of advantages compared with electron-beam-controlled CO and CO_2 lasers[8,13] and electric-discharge excimer lasers[14] investigated by us earlier: First, the active medium of the new laser was a mixture of rare gases so there was no problem of degradation of the active mixture because of undesirable chemical reactions; second, lasing involved high electronic transitions, so that it was possible to operate at higher temperatures of the active medium.

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