feature, peaking at 520 Å, due to interband transitions in the tin substrate.

Lifetime measurements made at 780 Å by deflecting the electron beam away from the specimen using a rapidly rising voltage pulse applied to the electron gun's deflection plates gave an upper limit to the fluorescence lifetime at this wavelength of 10 ns.

Finally, estimates of the fluorescence efficiency of the process, obtained by comparing the He/Sn fluorescence with synchrotron radiation through the same monochromator and using the same detector yield a value between 0.01 and 1.0 fluorescent photons into 4π steradians per incident 2.5-keV electron.

With sufficiently high electron beam intensities ($\geqslant 1$ mA) this process appears to offer the possibility of a new solid state VUV photon source.[24]

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1-W cw Zn ion laser

J. J. Rocca, J. D. Meyer, and G. J. Collins
Department of Electrical Engineering, Colorado State University, Fort Collins, Colorado 80523

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We have obtained 1.2 W of cw laser power on the 4911.6- and 4924.0-Å transitions of Zn II by exciting a He-Zn gas mixture with a dc glow discharge electron beam. In addition, 0.25-W output power has been obtained on the 6149.9-Å line of Hg$^+$ using the same excitation scheme. The combination of electron beam ionization of rare gas atoms and subsequent charge transfer excitation to metal ion levels is shown to have the potential of significantly increasing the efficiency of ion lasers. cw multiwatt visible and ultraviolet ion lasers operating at efficiencies $> 10^{-3}$ appear feasible using this excitation scheme.

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We have obtained 1.2 W of cw laser power on the 4911.6- and 4924.0-Å transitions of Zn II by exciting a He-Zn gas mixture with a dc glow discharge electron beam. With the same excitation scheme 0.25 W of cw laser radiation on the 6149.9-Å line of Hg$^+$ has also been obtained. This represents an order of magnitude increase in the output power previously obtained from these metal vapor laser transitions[1,2] and is the first time that metal vapor ion lasers have operated cw in the visible region at a power of 1 W.

The laser designs used to obtain these results were similar to those employed previously,[1–6] the main difference being the use of two glow discharge electron guns, one at each end of the plasma tube, as shown in Fig. 1. These glow discharge electron guns produce well collimated dc electron beams at energies between 1 and 6 keV and at currents up to 1 A. They have been described in a previous publication.[3] The use of two electron guns doubles the available electron beam power and also increases the uniformity of the electron beam created plasma.

In the laser setup of Fig. 1(a), the two 50-cm-long elec-

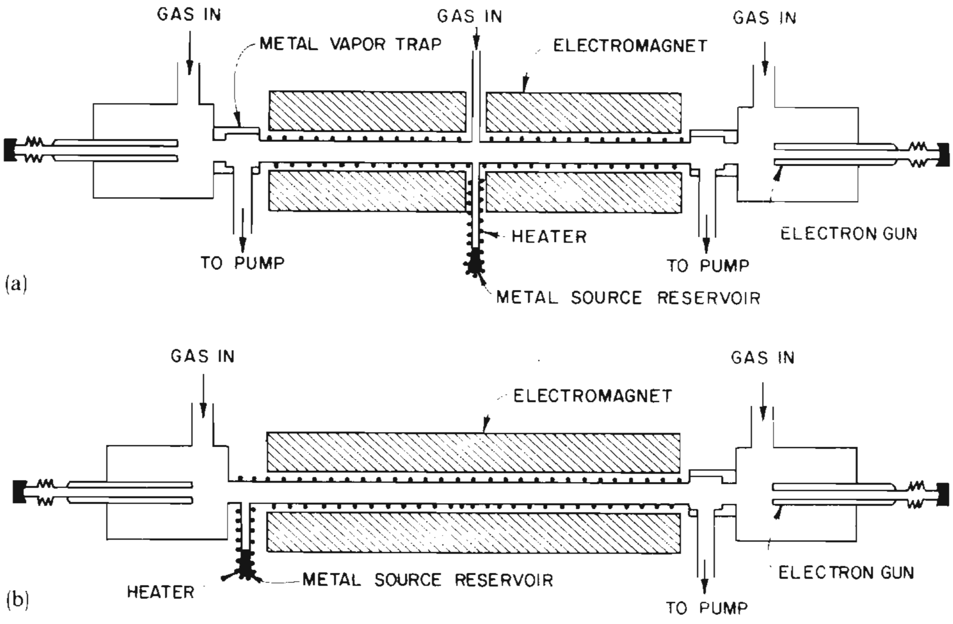

FIG. 1. Schematic diagram of the dual electron gun laser setup used in the (a) He-Hg$^+$ and (b) He-Zn$^+$ experiments, respectively.

tromagnets that help to confine the electron beams are separated from each other by approximately 2 cm to allow the introduction of both metal vapor and helium into the middle of the plasma tube. Both ends of the plasma tube are connected to a vacuum pump, allowing for continuous gas flow.

Using this experimental setup and internally mounted 2-m radius of curvature mirrors, we obtained 0.25 W of cw laser power on the 6149.9-Å transition of Hg II. The variation of laser output with electron beam discharge current and voltage is shown in Fig. 2. The laser output power increases linearly with current and no saturation was observed up to the maximum current investigated. The output coupler in this case had 94% reflectivity at 6150 Å. The optimum operating conditions were 1.5 Torr of He, a Hg source reservoir temperature of 130 °C, and a magnetic field of 3.2 kG.

Placing the metal vapor source reservoir in the middle of the plasma tube helped to provide a more uniform metal vapor distribution; however, the reduction of the magnetic field in this region, owing to the separation of the electromagnets, caused part of the electron beam to collide with the plasma tube walls. To reduce electron beam power loss in the Zn II laser experiment we used the setup shown in Fig. 1(b). In this scheme the metal vapor source reservoir was at one end of the plasma tube and the vacuum pump connection at the other end. High purity helium was introduced into the electron gun chamber at the reservoir side to assist in the distribution of Zn vapor. Helium was also introduced into the opposite gun chamber to permit the control of the pressure for optimum operation of the electron guns. The glow discharge electron guns used in this experiment had aluminum cathodes, just as the ones described in Ref. 3, but had an 8.5-mm-diam optical path through the axis to allow better use of the active volume and to diminish diffraction losses. The optical cavity consisted of two 4-m radius of curvature internally mounted mirrors. Reflectivities were $R_1 > 99.8\%$ and $R_2 = 93.5\%$ at 4920 Å. Using this laser setup we obtained 1.2 W of cw laser power on the 4911.6- and 4924.0-Å transitions of Zn II. This output power was obtained at a discharge current of 1.7 A and a total discharge input power of 3.5 kW. The optimum helium pressure in the plasma tube was 3 Torr and the magnetic field for maximum output was 2.9 kG. This output power is 30 times larger than the highest cw power obtained with hollow cathode devices[7] and also represents a 18 fold improvement over our previously reported value obtained with electron beam excitation.[2] The efficiency is 0.034% and is over eight times greater than that obtained in hollow cathode lasers.[7]

We consider that even larger improvements in the output power and operating efficiency of electron beam pumped ion lasers is possible by optimizing the optical cavity to make

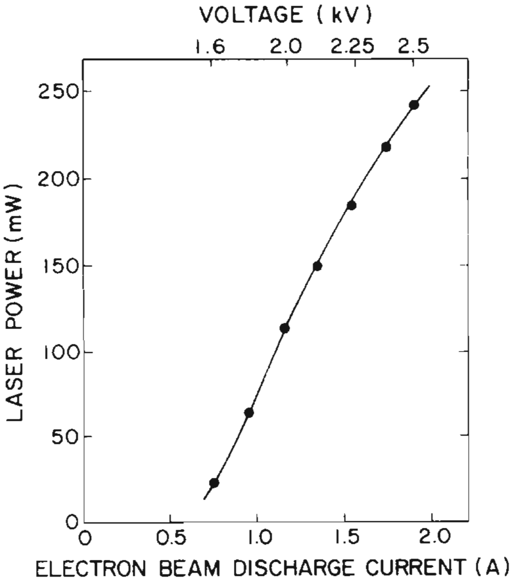

FIG. 2. Laser output power of the 6149.9-Å Hg II transition as a function of electron beam discharge current and voltage. Average helium pressure in the active medium was 1.5 Torr. Magnetic field 3.2 kG. Hg reservoir temperature was 130 °C.

better use of the active volume, by improving the efficiency with which the electron beam power is deposited into the gas, and by using monoisotopic metal vapor. The simple calculations presented below give an estimate of the maximum possible efficiency of a cw electron beam pumped charge transfer laser. To a first approximation, we can estimate the laser efficiency E_F as shown in Eq. (1):

$$E_F = D_e \; q_e \; Br \; E_e, \tag{1}$$

where D_e is the efficiency with which we deposit the discharge power into the upper laser level, q_e the quantum efficiency, Br the branching ratio, and E_e the optical extraction efficiency.

In an electron beam excited noble gas-metal vapor mixture, the laser upper level is mainly populated by thermal charge transfer collisions of noble gas ions with ground state metal vapor atoms. The noble gas ions are created dominantly by direct electron beam ionization of noble gas atoms. We can generate electron beams with an efficiency g_e between 50% and 80% using glow discharge electron guns.[3] An electron beam of energy > 0.5 keV impinging on a He gas target deposits 60% of its power into the creation of ions.[8] However, only a portion of that power I_e will be deposited into the production of helium ions when an electron beam impinges on a helium-metal vapor mixture. In the case of a 10 to 1 partial pressure ratio of helium to metal vapor, we would expect roughly half of the power to be deposited into helium ions if the ionization cross-section ratio of metal atoms to helium atoms was 10 to 1.[9] Consequently, we expect that the fraction I_e of the electron beam power to be used in the creation of helium ions will equal 30%. Only a fraction of these ions will pump upper laser levels via charge transfer. The noble gas ions are lost by diffusion to the walls, electron recombination, and charge transfer collisions with ground state metal vapor atoms. Thermal charge transfer collisions have a large cross section (130 Å^2 in the case of He$^+$-Hg collisions).[10] Therefore, at metal vapor concentrations $> 10^{15}$ cm^{-3} and electron densities below 10^{14} cm^{-3} the charge transfer loss channel dominates, and the fraction F of noble gas ions lost by pumping upper laser levels can be $F > 0.8$. In summary, the overall efficiency D_e with which the discharge power is deposited in the laser upper level is then

$$D_e = g_e \; I_e \; F \simeq 0.15. \tag{2}$$

The quantum efficiencies for visible metal vapor laser transitions ($h\nu = 2.4$ eV) excited by He$^+$ ions are roughly 10%. Then, considering $q_e = 0.1$ and assuming $Br \; E_e = 0.2$ we estimate from Eq. (1) the maximum laser efficiency is 3×10^{-3}, which is still considerably higher than the efficiencies we have obtained up to date. For ultraviolet transitions ($h\nu = 5$ eV) in helium-metal vapor systems the quantum efficiency q_e is 0.2 and in principle, according to Eq. (1), efficiencies in the vicinity of 0.6% could be obtained in an electron beam excited charge transfer system. Although the above calculations are only a crude estimate, it is clear that the possibility of high efficiency is based on three important points summarized below. The first point is that the majority of the discharge power (50%–80%) goes into the creation of beam electrons; secondly, helium ions are efficiently created by these energetic beam electrons; finally, charge transfer reactions can selectively and efficiently deposit the energy stored in the rare gas ions into the laser upper level. For a more accurate estimate of the maximum possible efficiency of electron beam pumped charge transfer ion lasers, an elaborate model of the electron beam created plasma is required. We are presently working on a computer model in which the electron energy distribution is calculated by numerically solving the Boltzmann equation for electrons. The distribution is then used to calculate the excitation and ionization rates necessary to determine the population in the laser levels and subsequently laser output power and operating efficiency.

In summary, we have obtained 1.2 W of cw laser power on the blue lines of Zn II exciting a He-Zn mixture with an electron beam. cw multiwatt visible and ultraviolet ion lasers operating at efficiencies $> 10^{-3}$ seem feasible using this new excitation scheme.

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