cw recombination laser in a flowing negative glow plasma

Jorge J. Rocca
Electrical Engineering Department, Colorado State University, Fort Collins, Colorado 80523

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cw laser oscillation has been obtained in the 1.43-μm line of Cd I populated by electron-ion recombination in the flowing afterglow of a negative glow plasma. The metal vapor in the recombining plasma is produced at room temperature by cathode sputtering. Negative glow plasmas having an electron energy distribution in which energetic beam electrons and supercooled secondary electrons coexist under steady-state conditions are shown to be an attractive medium for the excitation of cw recombination lasers.

cw laser oscillation has been obtained in the 1.43-μm $(6p\,^3P_1^0\text{–}6s\,^3S_1)$ transition of Cd I following electron-ion recombination in the flowing afterglow of a negative glow plasma. We also observed cw laser radiation in the 5337-Å $(4f\,^2F^0_{5/2}\text{–}5d\,^2D_{3/2})$ and 5378-Å $(4f\,^2F^0_{7/2}\text{–}5d\,^2D_{5/2})$ lines of Cd II due to change transfer excitation from helium ions. Negative glow plasmas have an electron energy distribution that simultaneously has energetic beam electrons that can efficiently ionize and a large density of cool electrons that can readily recombine.[1] These characteristics combined provide high recombination rates under stationary conditions.

Quasi-cw recombination laser action (1 ms pulse) was previously reported using kiloamp magnetoplasma-dynamics arcs expanding into vacuum.[2,3] Recently, using a low voltage arc jet, it was demonstrated that recombination lasers can operate in a cw mode by obtaining laser action during 1 s in Cd I infrared transitions.[4] The plasma of an arc, however, has a relatively low electron temperature ($KT_e = 1\text{–}2$ eV),[3] and this constitutes an important disadvantage for its use as an excitation source for shorter wavelength recombination lasers where the production of multiple ionized species is required.

The ideal plasma for a recombination laser should have both a large density of energetic electrons for efficient ionization and a large concentration of cool electrons for rapid recombination. These are contradictory requirements for stationary arc plasmas, and a fast expansion is needed to cool the electrons to a temperature where they can readily recombine by a three-body process. By using electron beams, it is possible to establish stationary plasmas that are simultaneously dense and cold.[1] In negative glow plasmas, the ionization is due to energetic beam electrons. Secondary electrons, which result from ionization processes mostly with zero energy, can only gain energy from elastic collision with beam electrons and from recombination and superelastic deexcitation processes. These electrons are thermalized at a low energy by frequent collisions with gas atoms. In stationary negative glow plasmas, the electron energy of the thermalized secondary electrons is typically 0.1 eV.[1,5] Electron cooling is achieved under stationary conditions, and a fast gas flow is in principle not needed for this purpose. Nevertheless, a fast gas flow that further cooled the plasma was used in the experiment described here to create a region without energetic electrons with the purpose of avoiding electron impact excitation of the laser lower level of the 1.43-μm line. As shown below, the presence of energetic electrons that can excite the lower level of this transition upsets the population inversion.

The experiment reported here demonstrates that negative glow plasmas can be advantageously used to excite cw recombination lasers. In contrast with the laser output of the arc-jet laser previously reported,[4] the output of the cw negative glow recombination laser is stable and free of spikes, and it does not present the electrode cooling problem that limited the operation of the arc recombination lasers to periods of the order of 1 s. Also, the energetic beam electrons that sustain negative glow plasmas provide efficient ionization and might allow the operation of cw recombination lasers at shorter wavelengths.

The experimental setup employed is schematically represented in Fig. 1. A discharge is established between a hollow cathode and a mesh anode. The cathode has a slot 4 cm long, 1.2 cm deep, and 0.2 cm wide. The device was also successfully operated with cathodes having slot widths up to 0.5 cm. Helium flows through the anode mesh and the cathode slot at 6 ℓ per minute at 760 Torr. A small amount of argon (10%) was added to enhance cathode sputtering. A 1000 ℓ per minute rotary pump was used to initially evacuate the vacuum envelope to a pressure of 10^{-3} Torr and to establish the gas flow. Metal vapor is produced by sputtering of the hollow cathode material. A dense negative glow develops within the cathode slot, and a short positive column links

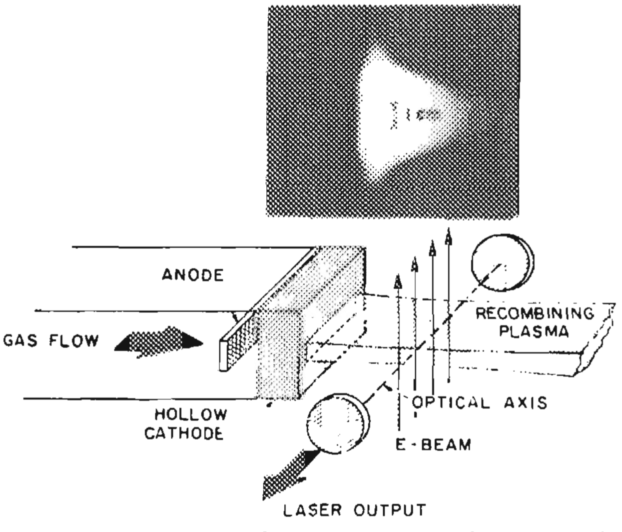

FIG. 1. Schematic diagram of the cw recombination laser and top view of the afterglow of the hollow cathode discharge.

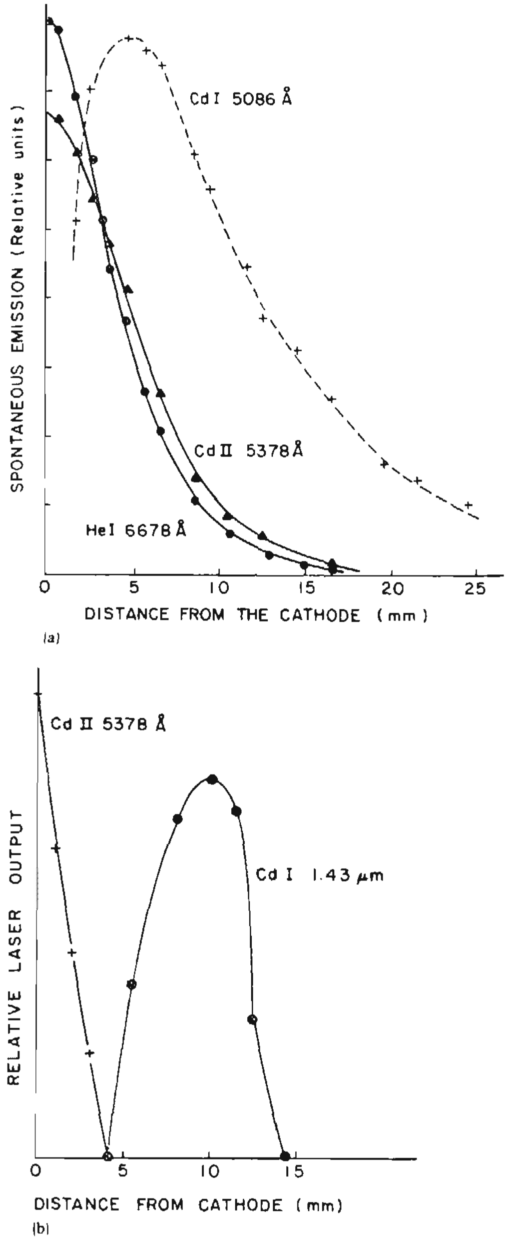

FIG. 2. (a) Spontaneous emission intensity of the Cd II 5378 Å, Cd I 5080 Å, and He I 6678 Å lines as a function of distance from the cathode; (b) laser intensity of the Cd II 5378 Å and Cd I 1.43-μm lines as a function of distance from the cathode.

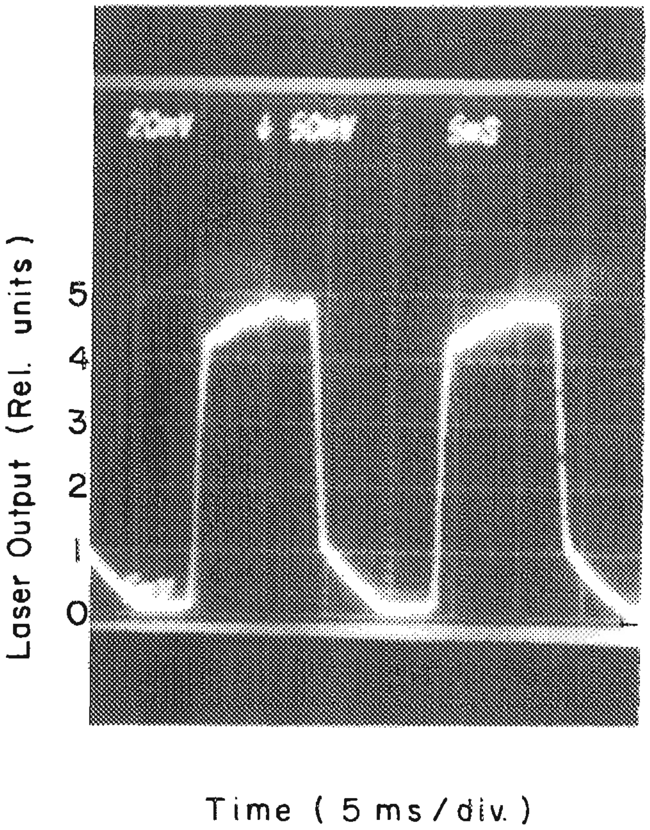

FIG. 3. cw laser output signal as observed in an oscilloscope using a chopper wheel and a Ge detector. Discharge current 1 A.

it to the anode. The gas flow expands the plasma from inside the slot downstream to form the stationary recombining plasma plume shown on the top of Fig. 1. An optical cavity was constructed using two 2 m radius of curvature highly reflecting mirrors in the 1.0–1.5-μm spectral region. The entire discharge structure was mounted in a glass tube that can be moved with respect to the axis of the optical resonator using a dynamic vacuum seal. The optical cavity was set having its axis in the same plane of the cathode slot. In this manner, different regions of the recombining plasma jet could be tested for laser action.

The spatial variation of spontaneous emission of this flowing afterglow was analyzed using a monochromator and a set of lenses and collimating slits providing a 2-mm spatial resolution. Figure 2(a) shows the intensity of the spontaneous emission of the He I 6678 Å, Cd I 5086 Å, and Cd II 5378 Å lines as a function of distance from the cathode face for a discharge current of 800 mA and a gas flow of 6.5 ℓ per minute. In the flowing afterglow, the He I lines get excited by recombination of He ions and are most intense near the cathode slot where the density of helium ions and the electron density is maximum. The Cd II 5337 Å and 5378 Å lines are excited mainly by charge transfer collisions between helium ground state ions and Cd atoms; consequently, they also show maximum intensity near the cathode.

The charge transfer reaction that depletes the He ions constitutes a source of Cd ions. Due to this source of Cd ions and the decreasing electron temperature in the afterglow, the intensity of the Cd I lines peaks at several millimeters from the cathode as shown in Fig. 2(a).

The spatial variation of the stimulated emission was measured by introducing collimators inside the optical cavity and changing the distance between the cathode front face ($d = 0$) and the axis of the optical resonator. The results are shown in Fig. 2(b) for both the Cd I 1.43-μm line and the Cd II 5378-Å laser line. Laser emission from the Cd II green lines peaks near the hollow cathode where the charge transfer rate between He ions and Cd atoms is maximum. The cw laser emission at 1.43 μm peaks at 10 mm from the cathode and occurs in a region approximately 1 cm wide.

Figure 3 shows the cw laser output at 1.43 μm as displayed on an oscilloscope using a chopper wheel and a Ge photodetector. The laser signal is observed to be slightly modulated by the output of the three-phase unfiltered power supply used for excitation, but it is free of the spikes observed in the arc recombination laser.

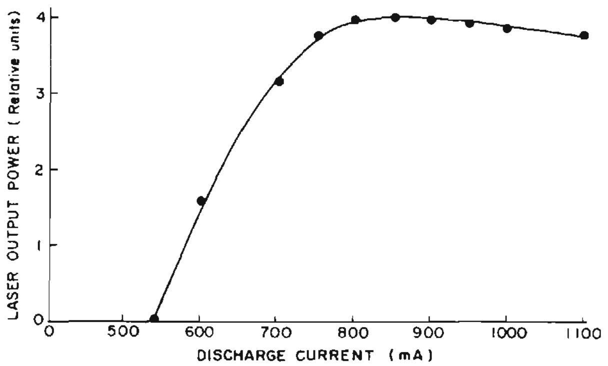

FIG. 4. cw laser output power of the 1.43-μm line as a function of discharge current. The gas flow was set at 6.5 ℓ per minute. The discharge chamber pressure was 7 Torr.

The relative variation of the cw laser intensity of the 1.43-μm Cd I line as a function of discharge current is shown in Fig. 4. The measurements were taken having the cathode front face at 10 mm from the axis of the optical resonator. The current threshold for cw oscillation was 540 mA. The laser output saturates at a current of 800 mA due to electron impart de-excitation of the laser upper level. In the case of 1.43-μm Cd I line, electron de-excitation limits the small-signal gain and laser power to small values.[6] By introducing a variable loss inside the cavity, we measured a small-signal gain of 0.35% cm^{-1} at 10 mm from the cathode.

The consequences of the presence of energetic electrons in the gain region were studied by introducing in this space a second slotted hollow cathode discharge, or alternatively as shown in Fig. 1, a beam of electrons produced with a glow discharge electron gun.[7] The laser output of the 1.43-μm line was observed to decrease in the presence of either of these discharges. The effect is noticeable at hollow cathode discharge currents as low as 2 mA. The experiments were done at plasma densities well below the critical density for significant electron de-excitation of the laser upper level. This result indicates that the presence of energetic electrons in the gain region results in electron impact excitation of the laser lower level, adversely affecting the 1.43-μm Cd I recombination laser. As a consequence, the rapid gas flow is needed to separate the excitation and gain regions if cw laser action is to be obtained in this transition. In other systems in which the laser lower level is not significantly populated by electron impact, it might be possible to obtain cw recombination laser action in a stationary negative glow plasma.

In summary, we have shown that a negative glow plasma can be advantageously used for the excitation of cw recombination lasers. In the device reported here the metal vapor in the recombining plasma is produced at room temperature by sputtering of the cathode material. By replacing the cathode material it is possible to explore recombination laser action in other elements. Also the large density of energetic electrons that exists in these plasmas causes efficient ionization and might allow excitation of cw recombination lasers at shorter wavelengths.

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[1] Z. Yu, J. J. Rocca, G. J. Collins, and C. Y. She, Phys. Lett. A **96**, 125 (1983).
[2] T. Hara, K. Kodera, M. Hamagaki, K. Matsunaga, M. Inutake, and T. Dote, Jpn. J. Appl. Phys. **19**, 4606 (1980).
[3] E. M. Campbell, R. G. Jahn, W. F. von Jaskowsky, and K. E. Clark, Appl. Phys. Lett. **30**, 575 (1977); J. Appl. Phys. **51**, 109 (1980).
[4] W. Silfvast, O. Wood, II, and J. Macklin, Appl. Phys. Lett. **42**, 347 (1983).
[5] B. Warner, Ph.D. thesis, University of Colorado, Boulder, Colorado, 1979.
[6] O. Wood and W. Silfvast, Appl. Phys. Lett. **41**, 121 (1982).
[7] J. J. Rocca, J. Meyer, M. Farrell, and G. J. Collins, J. Appl. Phys. **56**, 790 (1984).