1 W Operation of Singly Ionized Silver and Copper Lasers

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***Abstract*—We report a multiline output power of 1 W from the 800.4, 825.5, and 840.4 nm Ag II transitions and 350 mW from the 408.6 nm Ag II transition resulting from pulsed operation of a silver hollow cathode laser. Continuous output of 1 W was obtained in a copper hollow cathode from the 780.8 nm Cu II transition. Design considerations for continuous high-power operation of the hollow cathode discharge are also discussed.**

CONTINUOUS wave laser oscillation has been obtained in several nonvolatile metal vapors at numerous wavelengths between 224.3 and 840.4 nm, utilizing the hollow cathode discharge as the laser medium [1]-[8]. The laser tube employed in most of these investigations has been a Schuebel type slotted hollow cathode [9]. This design is simple to construct and reliable in pulsed operation. A cross section of the slotted hollow cathode laser employed in the metal vapor studies is seen in Fig. 1(a). The cathode consists of a 50 cm, 99.99 per-

Manuscript received May 1978. This work was supported in part by the Office of Naval Research and in part by ERDA.
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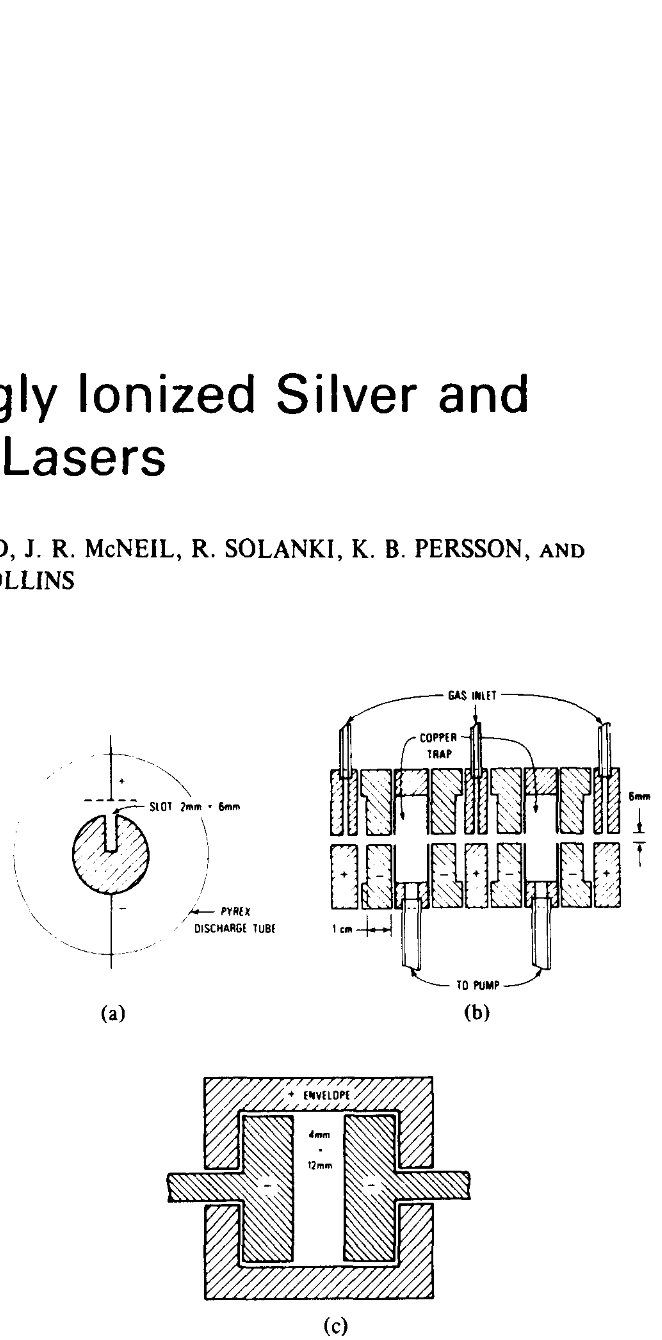

Fig. 1. High power hollow cathode laser designs. (a) Slotted hollow cathode, cross-sectional view; (b) coaxial hollow cathode, longitudinal section view; (c) rectangular hollow cathode, cross-sectional view.

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TABLE I
PEAK[a] OUTPUT OF SELECTED METAL ION LASER TRANSITIONS

λ (nm)	Metal	Buffer Gas	Power (mW)
259.9, 260.0	Cu	Ne	350
282.0 - 292.0	Au	He	125
318.1	Ag	Ne	350
408.6	Ag	Ne	350
478.8	Ag	Ne	100
780.8[+]	Cu	He	1000
800.4 - 840.4	Ag	He	1000

+ CW operation, obtained in the hollow cathode configuration, Fig. 1(c).
[a]Since the typical duty cycle of these pulsed lasers is 0.01, average powers are a factor of 100 lower (except as noted).

cent pure metal (Ag, Cu) rod with a 2 mm wide by 6 mm deep slot. The anode is a 50 cm long stainless steel mesh. These electrodes are surrounded by a Pyrex discharge tube which is pumped down to 7.5×10^{-10} N/m^2 (10^{-7} torr) and filled with the appropriate rare gas mixtures. Because there are no provisions for cathode or envelope cooling, this laser tube is limited to low dc currents (<5 A), or pulsed operation (50 A) with low duty cycle. Nonetheless, in a quasi-CW mode of operation, described below, the slotted hollow cathode laser has produced multiwatt output power as summarized in Table I.

We obtained 1 W output from the 800.4, 825.5, and 840.4 nm transitions of Ag II in a silver slotted hollow cathode, using a 1600 N/m^2 (12 torr) He-Xe gas fill, with a pressure ratio of 100:1. The Xe was added in order to increase cathode sputtering, thereby increasing the silver density in the discharge. Optimum output coupling was achieved by using an 8 percent transmitting mirror and a 99 percent reflecting mirror. Both mirrors were mounted internally to minimize cavity losses. At 8 A dc, multiline CW output power of 100 mW was obtained. The 840.4, 825.5, and 800.4 nm lines had threshold currents of 1.2, 3.0, and 3.0 A, respectively. In order to go to higher powers, the laser was subsequently excited by a 1 A dc sustainer current together with 60 A, 200 μs duration current pulses, at a repetition rate of 25 Hz. Average power of 5 mW was measured in this mode of operation, distributed among the 840.4, 825.5, and 800.4 nm lines in an approximate ratio of 3:1:1. The pulsed laser output consisted of 1 W peak, 200 μs duration pulses. When the silver slotted hollow cathode was filled with 2700 N/m^2 (20 torr) of Ne, 350 mW of the 408.6 nm transition in Ag II was observed under the same quasi-CW operation as above. A 99 percent reflector and a 1 percent transmitter were used, mounted internally. Since the typical duty cycle of these pulsed lasers is 0.01, average powers are two orders of magnitude less than peak powers. To achieve higher average power, dc excitation of hollow cathode lasers is required.

High continuous power (20 kW electrical dissipation) operation of a hollow cathode discharge places severe demands on the design of a hollow cathode laser tube. Arc formation and discharge power dissipation are the major technical problems. Two important causes of discharge arcs are nonuniform current distribution in the device and a buildup of sputtered cathode material on anode-cathode insulation. To minimize arc problems, the discharge configurations employed in this investigation have incorporated segmented, individually ballasted cathodes; confinement of the discharge within the hollow cathode proper; and anode-cathode insulation which is isolated from the discharge. Since most of the electrical power fed into the hollow cathode discharge ends up heating the cathode by ion bombardment, the cathode design in a high power hollow cathode laser tube must be able to dissipate kilowatts of power. We have two approaches. The first is to water cool the cathodes, producing a room temperature nonvolatile metal vapor laser. The second approach involves running the cathodes hot, letting radiation and gas conduction to a water cooled discharge envelope dissipate the power. A complete description follows.

Three new copper hollow designs were developed and their performance evaluated using the 780.8 nm transition of Cu II. The first design, a coaxial hollow cathode laser utilizing sputtering, is shown in Fig. 1(b). The 1 cm long, 6 mm bore cathodes were water cooled and individually ballasted, which enabled laser operation on various lengths of active medium. The tube was designed for flowing rare gas (10 torr-l/s) and included a copper trap for deposition of sputtered copper vapor away from critical anode-cathode insulation. Laser oscillation at 780.8 nm was observed with a total active length as short as 1 cm at a threshold of 0.2 A with a gas fill 600 N/m^2 (4.5 torr) He, 26 N/m^2 (0.2 torr) Ar, and two high reflecting mirrors. We estimate gain of 1 percent per centimeter by considering mirror and Brewster window losses.

The second sputtering laser design, shown in Fig. 1(c), consisted of twelve individually ballasted cathode segments. Each segment consisted of a pair of opposing, water cooled cathodes, 10 cm in length. These cathode segments were surrounded by a water cooled, vacuum tight anode envelope. The cathode separation and the anode-cathode distances were chosen so that the discharge was entirely contained between the cathode surfaces. This provided a discharge of cross-sectional area 4 mm by 12 mm. Not only did the small anode-cathode gap (0.5 mm) prevent a discharge in that region, but it discouraged metal vapor from diffusing behind the cathodes, thereby eliminating arcing problems due to metal vapor deposits on insulation. A CW output power of 1 W at 780.8 nm was obtained with this design. The optical cavity consisted of a 2 percent transmitting mirror and a 99 percent reflector mounted internally to minimize losses. No attempt was made to optimize output coupling. The discharge parameters included a laser current of 40 A dc, an input voltage of 400 V, and a He-Ar gas fill of 1100 N/m^2 (8 torr), with relative pressures of 20:1. The laser output power did not vary by more than 10 percent over 50 h of continuous operation.

A self-heated hollow cathode design is now in the developmental stage. This approach is being explored in order to utilize discharge heating to generate the metal vapor. The anode-cathode geometry is similar to that of the slotted hollow cathode [see Fig. 1(a)]. The cathode consists of a 2.54 cm diameter, 13 cm long molybdenum rod with a 9.5 mm cylindrical slot machined the length to give a cylindrical discharge volume. A stainless steel anode mesh is introduced directly above the slotted cathode. Copper wire, placed in the bottom of the cathode slot, melts with discharge heating and completely wets the walls of the slot. A quartz jacket is placed around the cathode in order to electrically and thermally insulate it from the water cooled anode envelope. Preliminary results from this self-heated hollow cathode tube are quite promising. At a current of 3.8 A dc, input voltage of 440 V, and 3300 N/m^2 25 torr) of He, 500 mW of the 780.8 nm Cu II transition is observed, using a 99 percent reflector and a 2 percent transmitting mirror.

There are two important features of this self-heated hollow cathode laser which distinguish it from the sputtering hollow cathode lasers. First, the 0.5 W output power was obtained in a total discharge length of 13 cm, one tenth the length necessary for a similar output in the sputtered tubes. Secondly, the wallplug efficiency of this device is 0.03 percent, five times higher than that of the sputtering hollow cathode lasers. The increase in efficiency is attributed to an increase in the copper density in the discharge due to vaporization of copper from the hot cathode. Under the discharge conditions described above, the cathode temperature was estimated to be between 1350 and 1500°C, giving a partial pressure of copper vapor in the 13 N/m^2 (0.1 torr) range. This high rate of vaporization leads to a problem, however. The reservoir of copper in the molybdenum cathode body is exhausted within a few hours. We are presently working on cathode structures that will extend the lifetime of this laser tube.

There are several properties of these hollow cathode metal vapor lasers which make them particularly attractive. First, no external oven is needed to generate the metal vapor. Either sputtering due to ion bombardment of the cathode or vaporization from a self-heated cathode is sufficient to produce high metal vapor density in the discharge. Secondly, since the pumping mechanism for most of the observed transitions is charge transfer [10] from rare gas ions into the excited metal ions, a simple change of rare gas fill or cathode metal provides a host of new high-power CW laser lines. A summary of selected laser lines and output powers obtained to date is given in Table I. The present powers from the infrared transitions of Ag II and Cu II make them good candidates as pump sources for CW dye lasers and for alkali-halide color center lasers in the 1 μm region [11], [12]. For example, the 800.4-840.4 nm transitions in Ag II closely match the absorption peak of Kodak IR 132[1] and IR 140 dyes at 830 nm.

In summary, new tube designs permit continuous high average power operation of the hollow cathode discharge. 1 W of output power was obtained from the 800.4-840.4 nm transitions in Ag II and the 780.8 nm transition of Cu II. As a consequence of this work, it is reasonable to envision 1 W CW lasers in the ultraviolet spectra of Ag II, Cu II, and Au II in the near future.

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[1] The use of trade names is necessary to specify the material; it does not imply endorsement by the National Bureau of Standards.