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cw laser action in the blue-green spectral region from Ag II*

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We have observed 18 cw laser transitions in Ne-Ag mixtures spanning the wavelength region from 408.6 to 585.2 nm. The upper laser levels of Ag II are judged to be pumped by a charge-transfer reaction between a ground-state neon ion and a ground-state Ag I atom resulting in simultaneous ionization and excitation of the silver atom. Output characteristics of the Ag II laser transitions as a function of neon pressure and discharge current are presented. The two strongest transitions are 478.8 and 502.7 nm in the blue and green, respectively.

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Karabut *et al.*[1] have previously reported two infrared laser transitions from Ag II in an oven-heated He-Ag discharge. We have observed 18 cw laser transitions when a neon discharge is excited in a silver hollow cathode. The new laser transitions cover the blue-green wavelength region from 408.6 to 585.2 nm. Laser action occurs *only* in neon discharges; we have *not* observed any visible Ag II laser transitions using helium or argon discharges excited in the silver hollow cathode.

Figure 1 is a partial term diagram of Ag II in which three laser transitions, positively assigned to the Ag II spectrum, are shown. Note that the upper laser levels of the identified transitions lie close to energy coincidence with Ne^+ in its ground state. Based on previous studies[2,3] we believe that the dominant excitation mechanism of the observed laser transitions is a thermal-energy charge-transfer reaction of the type,

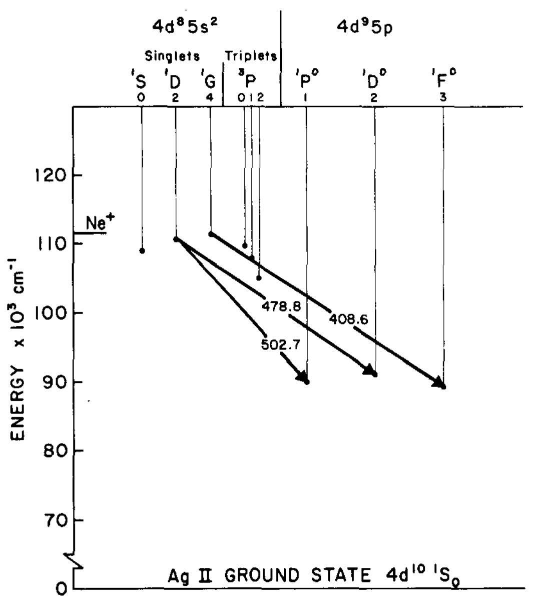

FIG. 1. Partial term diagram of Ag II with illustrative blue-green laser transitions (solid lines). Selected terms arising from the $4d^95p$ and $4d^85s^2$ electronic configurations are shown. The energy available from the ground-state neon ion Ne^+ in a thermal-energy charge-transfer collision, reaction (1), is also shown. All wavelengths are in nm.

$$Ne^+ + Ag \rightarrow (Ag^+)^* + Ne + \Delta E, \qquad (1)$$

where ΔE represents the energy difference between the ground-state neon ion and the excited silver ion $(Ag^+)^*$.

Table I lists all observed laser transitions, the measured threshold currents, and tentative transition assignments. The wavelengths of the observed laser transitions were measured to an accuracy of 0.02 nm using a $\frac{1}{2}$-m monochrometer equipped with a 1200-line/mm grating. The distance from the monochrometer entrance slit to the laser output mirror was 1.5 m to ensure that the detected signal arises only from laser radiation. As discussed below, we were not able to *unambiguously* assign 15 of the observed laser transitions to the Ag II spectrum. The silver hollow cathode employed as >99.99% pure silver with the major impurity given by the manufacturer as bismuth. Hence, it is unlikely that any elements besides neon, silver, or bismuth would be present in the discharge with any significant density. We have made a search of the bis-

TABLE I. cw laser transitions observed in Ne-Ag mixtures.

λ_{air} (nm) Measured (± 0.02 nm)	λ Actual	Transition assignment Upper	Lower	Threshold current (A)[a]
408.62	408.59[b]	$5s^2\,^1G_4$	$5p\,^1F_3^0$	35[c]
430.96		Unidentified		7.5
449.79		Unidentified		9
450.55		Unidentified		8
464.92		Unidentified		8
472.50		Unidentified		8
473.39		Unidentified		28[c]
478.84	478.84[d]	$5s^2\,^1D_2$	$5p\,^1P_1^0$	5.5
482.32		Unidentified		5.5
482.96		Unidentified		30[c]
492.83		Unidentified		20[c]
496.57		Unidentified		20[c]
507.72	502.73[d]	$5s^2\,^1D_2$	$5p\,^1D_2^0$	14[c]
505.94		Unidentified		18[c]
526.72		Unidentified		7
574.65		Unidentified		5.5
575.03		Unidentified		17[c]
585.28		Unidentified		16[c]

[a]Threshold currents measured at a neon pressure of 12 Torr.
[b]Identification taken from C.E. Moore, Ref. 4.
[c]Only quasi-cw oscillation (200 μs duration) was observed.
[d]Identification taken from E. Rasmussen, Phys. Rev. 57, 840 (1940).

muth spectrum and are unable to associate any of the observed laser transitions with bismuth. It is noteworthy that the identification of the Ag II spectrum as summarized by Moore[4] is likely to be incomplete,[5] and we have 15 unidentified laser transitions listed in Table I. In an attempt to classify the unassigned laser transitions, we have taken the energy levels given by Moore and have calculated *all* allowed optical transitions in Ag II, using only parity and Δj selection rules. This resulted in the positive identification of only three of the observed laser lines with the Ag II spectrum as shown in Fig. 1 and Table I. It is noteworthy that the unidentified 585.28-nm transition of Table I is *not* the transient Ne I transition at 585.25 nm, $3p^1[\frac{1}{2}]_0$ to $3s^1[\frac{1}{2}]_1^0$ in Racah notation.

Note that all three identified laser transitions require a double electron jump. In a single configuration approximation two-electron transitions are *strictly* forbidden, hence, admixtures of other configurations play an important role in describing the $4d^85s^2$ terms of Ag II. We suspect that the majority of the unidentified laser transitions have upper levels which originate from terms belonging to the $4d^85s^2$ configuration of Ag II. The reasons for this judgment are twofold. First, the majority of the Ag II terms which originate from the $4d^85s^2$ configuration lie slightly below but in near energy coincidence with the neon ground-state ion (see Fig. 1); hence reaction (1) is likely to occur. Second, because two-electron transitions are forbidden in the single-configuration (central-field) approximation the spontaneous-emission lifetimes of the $4d^85s^2$ levels will be large, thereby favoring the creation of a population inversion between upper levels of the $4d^85s^2$ configuration and lower levels of the $4d^9nx$ configurations.

Figure 2 illustrates the hollow cathode geometry employed. A slot 2×6 mm in cross section and 50 cm long was cut into a rectangular bar of silver (> 99.99% purity). A stainless-steel anode was placed 4 mm above the cathode as shown in Fig. 2. This design is similar to one we have described previously in the literature.[6] The silver density required for laser action is obtained by discharge sputtering rather than via an external oven. The temperature of the bulk of the silver cathode never exceeds 400 °C; hence the partial vapor density of silver due to discharge heating of the cathode is less than 3×10^5 cm^{-3}. However, based on previous studies of other metal vapor lasers, a vapor density of sputtered material on the order of 3×10^{14} cm^{-3} (0.01 Torr) is generally required for laser action to occur.[7] It is noteworthy that a temperature in excess of 1000 °C is required to achieve such a vapor density of silver. We are presently measuring the ground-state silver density as a function of discharge current and neon pressure using the method of fractional absorption.

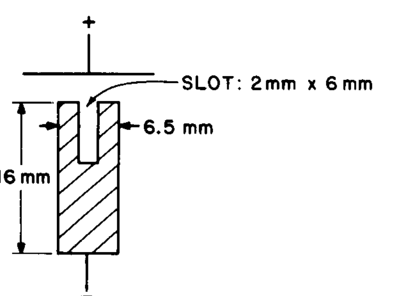

FIG. 2. Cross section of the hollow cathode geometry employed. The cathode is a rectangular bar of > 99.99% pure silver.

True cw oscillation was obtained on only 9 of the 18 transitions because the required threshold currents exceed 10 A, the limit of our dc power supply. As a consequence, those transitions with threshold currents above 10 A were inverted using a pulse generator capable of 50-A current pulses 200 μs in duration. Laser action on all transitions occurred throughout the duration of the current pulse, demonstrating that cw oscillation was achieved. The output power of the laser transitions increased with increasing neon density from a threshold value of 1.8×10^{17} cm^{-3} (6 Torr), reaching a broad maximum around 3.6×10^{17} cm^{-3} (12 Torr) of neon. Laser action ceased when the neon density exceeded 6×10^{17} cm^{-3} (20 Torr). Observed threshold currents are given in Table I. We have not observed any saturation of the output power with increasing discharge current up to the limit of our pulse generator, 50 A. Using broadband mirrors (> 99.8% reflectivity) which span the region from 400.0 to 490.0 nm we have measured a peak multiline output power at 42 mW at 50 A input current. The peak power was calculated by measuring the average power (0.34 mW) and dividing by the duty cycle (0.008).

In summary, we have observed 18 blue-green laser transitions when we excite a neon discharge in silver hollow cathode. The list of observed laser transitions and tentative level assignments are summarized in Table I. Multiline peak output power in the blue-green spectral region of 42 mW has been obtained.

We are presently attempting to obtain ultraviolet laser action below 260.0 nm using He-Ag mixtures as suggested by Collins.[7] Here, a selective charge-transfer reaction with He^+ ions populating the $4d^96s\ ^3D$ and $4d^96s\ ^1D$ terms of Ag II will be employed.

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