Ultraviolet laser action in He-Ag and Ne-Ag mixtures*

J. R. McNeil,† W. L. Johnson,‡ and G. J. Collins§

Department of Electrical Engineering, Colorado State University, Fort Collins, Colorado 80523

K. B. Persson

National Bureau of Standards, Boulder, Colorado 80302

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We report eight new laser transitions which span the wavelength region from 220 to 400 nm. Six of the ultraviolet transitions are observed in Ne-Ag mixtures and two are observed in He-Ag mixtures. The 227.8- and 224.3-nm laser transitions of Ag II, $5d\,^3D_2$-$5p\,^3P_1^o$ and $5d\,^1S_0$-$5p\,^1P_1^o$ respectively, are the shortest-wavelength cw laser transitions reported in the literature to date. Output characteristics of the ultraviolet laser transitions as a function of buffer gas pressure and discharge current are presented. The strongest laser transition $4d^85s^2\,^1G_4 \rightarrow 4d^95p\,^3F_3^o$, at 318.1 nm, provides single-line peak output power of 350 mW. The output power does not appear to saturate at the limit of our input current, 50 A.

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We have previously reported 18 cw laser transitions in the blue-green spectral region when a neon discharge was excited in a silver hollow cathode.[1] We have extended the Ne-Ag studies from the visible into the ultraviolet and have discovered six new laser transitions between 285.0 and 385.0 nm. Moreover, we have observed two additional Ag II laser transitions in the 220-nm region when exciting a helium discharge in the silver hollow cathode described previously.[1]

Table I lists the eight ultraviolet 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 monochromator equipped with a 1200 line/mm grating. The distance from the monochromator 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 able to unambiguously assign only three of the eight laser transitions to the Ag II spectrum. The silver hollow cathode employed was >99.99% pure silver with the major impurity given by the manufacturer as bismuth. Hence, it is unlikely that any elements except neon, silver, and bismuth would be present in the discharge with any significant density. We have made a search of the bismuth spectrum and are unable to associate any of the observed laser transitions with the bismuth spectrum. It is also noteworthy that the identification of the Ag II spectrum as summarized by Moore[2] is likely to be incomplete.[3] In an attempt to classify the unassigned laser transitions, we have taken the Ag II energy levels listed by Moore and have calculated *all* allowed optical transi-

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

λ_{air} (nm) (± 0.02 nm)	λ_{actual} (nm)	Transition assignment Upper	Lower	Threshold Current[a] (A)
224.34	224.34[b]	$5d\,^1S_0$	$5p\,^1P_1^o$	7
227.76	227.74[c]	$5d\,^3D_2$	$5p\,^3P_1^o$	7
286.21		unidentified		14[d]
299.26		unidentified		15[d]
308.80		unidentified		14[d]
318.06	318.07[e]	$5s^2\,^1G_4$	$5p\,^3F_3^o$	9.5
382.62		unidentified		8
383.05		unidentified		7

[a]Threshold currents measured at a rare-gas pressure of 14 Torr.

[b]Identification taken from H.A. Blair, Phys. Rev. 36, 173 (1930).

[c]Identification taken from A.G. Shenstone, Phys. Rev. 31, 317 (1928).

[d]Only quasi-cw oscillation (200-μs duration) was observed.

[e]Identification taken from C.E. Moore, *Atomic Energy Levels* (U.S. GPO, Washington, D.C., 1971), NSRDS-NBS, Vol. 3.

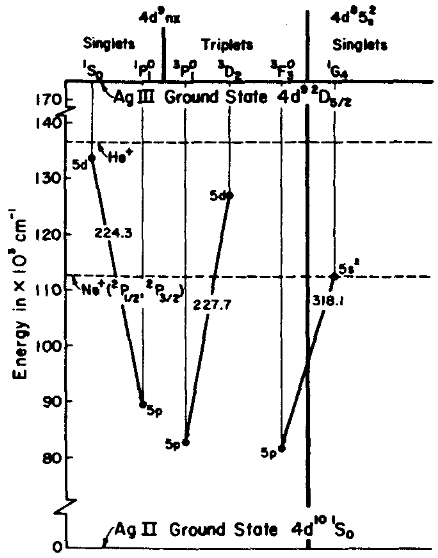

FIG. 1. Partial term diagram of Ag II with illustrative ultraviolet laser transitions (solid lines). Selected terms arising from the $4d^9nx$ and $4d^85s^2$ electronic configurations are shown. The energy available from ground-state neon and helium ions in a thermal energy charge-transfer collision, Reactions (1) and (2), respectively, are also shown. Note that the ground-state neon ion is split into two levels ($^2P_{1/2}$ and $^2P_{3/2}$) separated by 782 cm^{-1}. All indicated wavelengths are in nm.

tions in Ag II using only parity and Δj selection rules. This procedure resulted in the positive identification of only three of the observed laser lines; the other five laser transitions of Table I remain unidentified.

The three identified laser transitions of Ag II are at 318.1, 227.8, and 224.3 nm and are shown in Fig. 1 and Table I. The 318.1-nm transition did not oscillate in a pure helium or a He-Ar discharge. Oscillation was obtained *only* in pure neon. The 318.1-nm transition arises from the $4d^85s^2\ ^1G_4$ term of Ag II. The $^1G_4$ term lies 8 cm^{-1} below the energy of the ground-state neon ion in the $^2P^0_{1/2}$ level. Hence, it is judged that a charge-transfer reaction of the type

$$Ne^+ + Ag \rightarrow Ag^+(^1G_4) + Ne + \Delta E \quad \text{(Reaction 1)}$$

is responsible for selectively populating the $^1G_4$ level. Note that the neon ion ground state is split into two levels ($^2P^0_{1/2}$ and $^2P^0_{3/2}$).

It is noteworthy that the 227.8- and 224.3-nm transitions, $5d^3D_2$-$5d^3P^0_1$ and $5d^1S_0$-$5p^1P^0_1$, respectively, both arise from energy levels which lie slightly below the energy of the ground-state helium ion. See Fig. 1. The 227.8- and 224.3-nm transitions would not oscillate in pure neon or pure argon discharges. Oscillation was only obtained in a helium discharge with a *small* argon or neon impurity. Hence, we claim that the $^3D_2$ and $^1S_0$ levels of Ag II are excited by a charge-transfer reaction of the type

$$He^+ + Ag \rightarrow Ag^+(^3D, ^1S) + He + \Delta E \quad \text{(Reaction 2).}$$

Our judgment of the importance of Reactions (1) and (2) in the excitation of the Ag II laser is based on the preliminary measurements described above as well as on past experience with other charge-transfer excited laser systems.[4-5] Although we anticipated in a previous publication[1] that Reaction (2) would strongly populate the $4d^96s^1D$ and $4d^96s^3D$ levels of Ag II, we have *not* observed any Ag II laser transitions originating from these levels.

The silver hollow was similar to that employed in our previous studies.[1] The active medium was 50 cm long and 2×6 mm in cross section. The required silver density was obtained by discharge sputtering rather than by an external oven. The bulk temperature of the silver cathode never exceeds 400 °C; as a result the partial pressure of silver due to discharge heating is less than 10^5 atoms/cm^3 (10^{-11} Torr) which is not judged to be sufficient for laser threshold. Based on previous studies of other metal vapor lasers, a vapor density on the order of 10^{13} atoms/cm^3 (0.001 Torr) is generally required for laser action to occur.[6] It is noteworthy that a temperature in excess of 1000 °C is required to achieve a vapor density of 10^{13} atoms/cm^3 (0.001 Torr). Hence, discharge sputtering is a considerable practical advantage. The major disadvantage of discharge sputtering is that the silver vapor density is a function of the discharge current, and we are *not* able to optimize the silver density independently of discharge current. We are presently measuring the ground-state silver density as a function of discharge current and neon pressure, using the method of fractional absorption.

Both the Ne-Ag and He-Ag laser systems displayed a similar behavior of output power versus rare-gas pressure. The onset of laser action occurred at 6–8 Torr. The output power rose gradually with increasing pressure displaying a broad maximum around 26 Torr. Laser output power then dropped sharply at pressures above 26 Torr and ceased entirely with a buffer gas pressure of 34 Torr. Threshold currents are listed in Table I, and the lowest values were obtained at pressures of 14 Torr. True cw oscillation was obtained only on five of the eight transitions because the threshold currents on three of the transitions exceeded the capability of our dc power supply, 10 A. To study these three transitions, a pulse generator capable of delivering 50-A current pulses of 200-μs duration was employed. Laser action occurred throughout the 200-μs pulse, indicating that cw laser action is possible on these three transitions as well. In the case of the He-Ag laser, a small amount of neon or argon was mixed with the helium (1 part in 200), and the threshold currents were observed to decrease by a factor of 3. We believe this threshold reduction is due to the greater sputtering yield of neon or argon as compared to helium.[7]

Our preliminary experiments employed high-reflectivity mirrors (< 0.1% transmittance) to cover the wavelength region from 220.0 to 400 nm. Of the eight ultraviolet laser transitions, relative intensity measurements indicated that 318.1 nm was by far the strongest, with nearly 90% of the output power in this single transition. Subsequently, a narrow band mirror (± 25 Å centered at 318.1 nm) with 0.75% transmittance was used, and 350 mW of single-line output power was obtained from the 318.1-nm transition. We have not optimized the coupling mirror transmittance for the 318.1-nm transition; nor have we observed any saturation of the output power with increasing discharge current.

In summary, we have obtained eight new laser transitions in Ne-Ag and He-Ag mixtures extending cw laser action down to 224.3 nm, the shortest-wavelength cw laser transition reported to date. Our strongest transition, at 318.1 nm, provides > 350 mW of output power. No attempt has been made to optimize the coupling mirror transmittance.

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§Consultant, National Bureau of Standards (Boulder).

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