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**EXPLORATORY STUDY OF METAL VAPOR LASERS
OPERATING IN THE ULTRA-VIOLET AT KILONATT POWER LEVELS**

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Abstract

CW laser action has been extended down to 220 nm. Moreover, cw oscillation has been obtained on twenty additional transitions in the spectral range between 220 and 320 nm. Ultra-violet laser thresholds as low as 2 A have been observed. In comparison, rare gas ion lasers require 20 to 50 A to reach threshold. Metals of interest are sputtered into the discharge giving metal densities of 10^{14} atoms cm^{-3} without using external ovens or discharge heating. Recent attempts to scale the output power levels to 1 W cw are presented with particular emphasis on the 780 nm transitions of Cu II and the 840 nm transitions of Ag II.

I. Introduction

We have extended the range of cw laser oscillation down to 220 nm in the work described here, as well as demonstrating that 350 mW of output power can be obtained at 260 and 318 nm. Prior to this work, the main sources of cw ultra-violet laser action are the Kr^{++} , Ar^{++} , and Cd^+ lasers which operate continuously at 364, 351 and 325 nm respectively. Attempts to obtain a 1 W ultra-violet laser operating below 320 nm are described.

Charge transfer reactions of the form:

have been investigated for a possible ultra-violet laser, where R^+ is a ground state helium or neon ion, M^+ is an excited metal (Cu, Ag or Au) ion and ΔE is the energy differences between R^+ and M^+ . We have already shown that charge transfer is a favourable pumping scheme for pumping ultra-violet laser transitions because of the following reasons.

First, the cross-sections for charge-transfer reactions^{1,2} are in excess of 10^{-15} cm^2 ; second, there is sharp selectivity of charge-transfer reactions for forming upper laser levels but not lower levels;³ finally, laser oscillation occurs in the singly ionized spectrum rather than in multiply ionized species, resulting in higher quantum efficiency.

The discharge arrangement employed for this work is the hollow cathode. Below we give a summary of the laser results observed and then describe a qualitative model for the laser discharge.

II. Summary of Ultraviolet Laser Results

Ne-Cu laser

We have obtained cw laser oscillation on the seven Cu II transitions shown in Fig. 1. The laser transitions were excited in a copper hollow cathode described below. Note in Fig. 1 that the 1D and 3D terms of the $3d^9 5s$ electronic configurations of Cu II give rise to all seven transitions.

Fig. 1 A partial term diagram of Cu II indicating the seven ultraviolet laser wavelengths and transition assignments. The energy available from Ne^+ and Ne^M ($1^3P_2, 3P_0$) in a collision of the second kind is also shown.

Both the 1D and the 3D terms lie in near energy coincidence to the ground-state neon ion and a charge-transfer reaction:

Reaction (B)

is thought to provide the dominant excitation mechanism. We have obtained 350 mW of output power from the 260 and 259 nm transitions in our preliminary work and will be attempting to obtain a 1 W output.

Ne-Ag Laser

Table 1 lists the ten transitions of Ag II which we have obtained when a silver hollow cathode is excited with a helium or neon buffer gas. Note that previously reported unidentified laser transitions^{5,6} are now known to arise from grating ghosts.⁷ Details of the laser tube construction are given later. The 227 and 224 nm transitions, $5d^3D_2 - 5p^3P_1^0$ and $5d^1S_0 - 5p^1P_1^0$ respectively, are the shortest wavelength cw laser transitions

Table 1. New metal ion laser transitions

Air (nm)	Ion	Power output (mW)
224.3	Ag	< 0.1
227.8	Ag	< 0.1
248.5	Cu	2
250.6	Cu	2
252.9	Cu	1
259.0	Cu	100
259.9	Cu	100
260.0	Cu	150
270.3	Cu	200
282.2	Au	30
284.7	Au	50
289.4	Au	50
291.8	Au	50
318.1	Ag	350
408.6	Ag	250
478.8	Ag	100
740.4	Cu	50
755.6	Au	50
760.0	Au	50
773.9	Cu	30
780.8	Cu	1000
782.6	Cu	20
789.6	Cu	50
794.4	Cu	50
798.8	Cu	50
800.4	Ag	100
840.4	Ag	1000

reported in the literature to date. The strongest laser transition of Ag II is at 318 nm, $4d^8 5s^2 \ ^1G_4 - 4d^9 5p \ ^3F_3^o$, provides peak single-line output power of 350 mW. We are presently designing silver hollow cathodes with the goal of achieving 1 W output at 318 nm.

He-Au Laser

Figure 2 indicates the six ultra-violet laser transitions of Au II observed when a helium discharge is excited in a gold hollow cathode. Note that all of the Au II laser transitions arise from energy levels near energy coincidence with the ground state helium ion. Threshold

Fig. 2 Partial term diagram of Au II with representative infra-red and ultra-violet laser transitions (solid lines). Selected energy levels from the $4d^8 5s^2$ electronic configuration are shown and the energy available from the ground-state helium ion, He⁺, in a thermal energy charge-transfer collision. Reaction (A) is also shown. All wavelengths are given in nanometres.

currents for the 280 nm laser transitions are measured to be as low as 2 A or about a factor of ten less than threshold currents for ultra-violet laser transitions in rare-gas-ion lasers. Multi-line output power of 125 mW has been demonstrated in the 280 to 290 nm region.

III. Hollow Cathode Laser Discharge

The hollow cathode configuration used in the Cu II, Ag II and Au II studies are shown in Fig. 3. In all systems the hollow cathodes were 50 cm long. It is noteworthy that the metal vapour of interest was created

via discharge sputtering rather than via an external oven or discharge heating. Measurements of the ground state copper density are summarized in Fig. 4. Under optimum conditions a copper density of 10^{14} atoms cm^{-3} was created with the cathode at 20°C . Hence, our vacuum envelope was made of pyrex and high temperature materials were not required. We have experimented with a variety of anode and cathode geometries and have achieved laser action from circular as well as rectangular cross-section slots. It is noteworthy that TEM_{00} output is best achieved in the cylindrical configuration, although ease of construction favours a rectangular slot if transverse mode quality is not important. Also shown in Fig. 3

Fig. 4 Copper density versus discharge current

is the anode geometry used. The anode consisted of a stainless steel mesh placed 5 mm above the cathode slot, extending the entire length of the cathode. We found that the mesh anode allows higher discharge currents to be used without arc formation as compared to other anode configurations. The curve-shaped anode illustrated in Fig. 3 gives the best performance, to date, of all anode geometries we have attempted.

We believe that ultra-violet lasers using charge-transfer collisions as a pumping scheme have the potential for total system efficiencies approaching 0.2%. In total system efficiency, we include the following: the discharge efficiency for creating ground-state rare-gas ions; the

efficiency with which this energy is transferred to the excited metal ion via a collision such as (A); and the quantum efficiency of the laser transition itself. The quantum efficiency for a He^+ , Ne^+ , Ar^+ or Xe^+ pumped ion laser operating at 250 nm is 20, 24, 36, and 41% respectively. Only rare-gas-halogen lasers have larger quantum efficiencies and larger demonstrated operating efficiencies in the ultra-violet.

The hollow cathode discharge is particularly simple to model for the charge-transfer mechanism. To a first approximation, the efficiency of creating rare-gas ions in a hollow cathode discharge is given by $\gamma/(1+\gamma)\beta$, where γ is the second Townsend coefficient of the cathode material and βV_i is the average energy lost by a beam electron emerging from the cathode dark space.⁴ The ultimate efficiency for the charge transfer laser, η , can then be expressed as:

$$[\gamma/(1+\gamma)\beta](V^*/V_i) = \eta_i$$

where V^*/V_i is the quantum efficiency, V^* is the photon energy, and V_i is the ionization potential of the rare gas. For the Ne-Cu laser system the calculated total system efficiency is 0.2%.

IV. Research Publications Under ERDA Support

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4. McNeil, J.R., Johnson, W.L., Collins, G.J., and Persson, K.B., Ultra violet Laser Action in He-Ag and Ne-Ag Mixtures, Applied Physics Letters, Vol. 29, No. 3, 1 August 1976.

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6. de Hoog, F.J., McNeil, J.R., and Collins, G. J., Discharge Studies of the Ne-Cu Laser, Journal of Applied Physics, Vol. 48, No. 9; September 1977.
7. Warner, B.E., Gerstenberger, D.C., Reid, R.D., McNeil, J.R., Solanki, R., Persson, K.B., and Collins, G.J., [i] W Operation of Singly Ionized Silver and Copper Lasers, IEEE Journal of Quantum Electronics, Vol. QE-14, No. 8, August 1978.