ULTRAVIOLET ION LASERS

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This article reviews ultraviolet laser results obtained with positive column noble gas ion lasers, hollow cathode metal vapor ion lasers, pulsed recombination lasers, and multiply ionized rare gas species emitting in the VUV region. We also discuss the recent use of direct current electron beams to pump cw ion lasers, and the possibilities of higher efficiency and shorter wavelength ultraviolet lasers using this new excitation scheme.

INTRODUCTION

At present, ion lasers are the most powerful cw sources of coherent radiation in the ultraviolet. More than 100 cw ion laser transitions have been reported in this spectral region, with the shortest wavelength being the 224.2 nm transition of Ag II. Figure 1 sur marizes the wavelength and power of the most important ultraviolet ion laser transitions. Powers obtained both in a true cw and quasi-cw or long pulse mode are shown. Multiply ior ized noble gas species provide the highest cw powers with, for example, an output power of 61 W from the combined 351.1 and 363.8 nm Ar III lines. Lower current thresholds and shor ter wavelengths have been obtained from singly ionized metal vapor transitions excited in hollow cathode discharges. Recombining plasmas have produced ion laser action in the ultraviolet, but only in the pulse mode. Vacuum ultraviolet laser radiation has been obtained from multiply ionized rare gas species, but to date only in a pulsed regime.

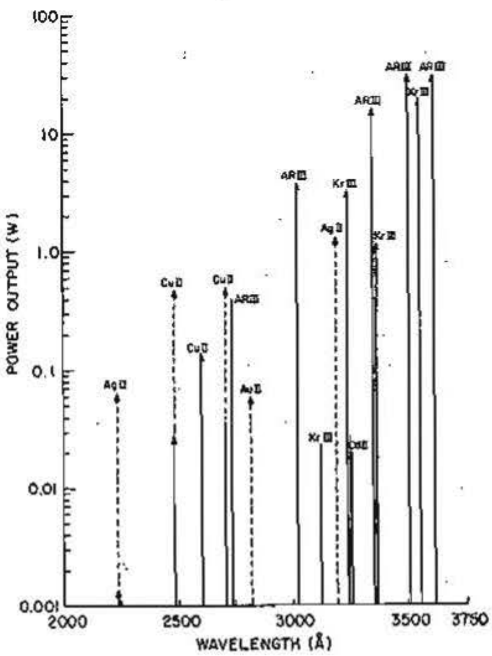

Fig. 1. Most powerful cw and quasi-cw ultraviolet ion laser lines. Cw powers in full line, quasi-cw powers in dashed line.

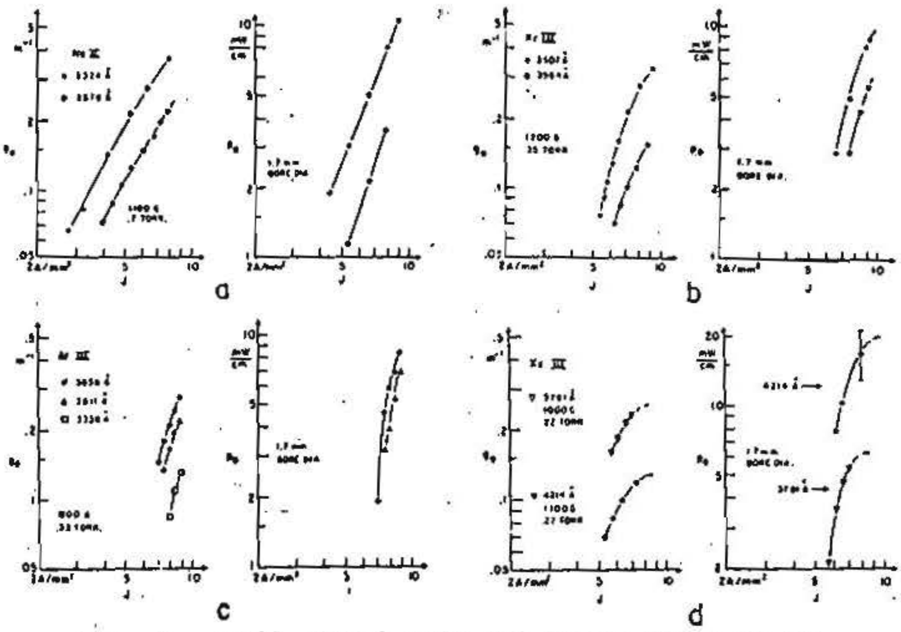

Fig. 2. Small signal gain and output power of UV ion liner as a function of discharge current: a) neon II; b) krypton III; c) argon III; d) xenon III [2].

Below we review selected ion laser results obtained with positive column noble gas lasers, hollow cathode metal ion lasers, pulsed recombination ion lasers, and with multiply ionized rare gas species emitting in the VUV region. The use of dc electron beam excitation to pump cw ion lasers was recently demonstrated. This new excitation mechanism offers the possibilities of higher efficiencies and shorter (VUV) wavelengths so this new excitation scheme for cw ion lasers is also discussed.

UV NOBLE GAS ION LASERS

Ultraviolet cw laser action from noble gas ions was obtained for the first time by Paanamen [1] in 1966. He obtained laser radiation from Ne II (332.4 and 337.8 nm), Ar III (351.1 nm) and Kr III (350.7 nm) exciting noble gases with currents between 45 and 85 amps in a 3.5 mm bore discharge tube with an effective length of 56 cm. Paanamen obtained cw laser power of 0.3 W, 30 mW, and 13 mW for Kr III, Ne II, and Ar III transitions, respectively. In 1968, J. Fedley [2] made a detailed study of the ultraviolet laser emission of ionized Ne, Ar, Kr, and Xe gases. Using a segmented graphite tube 34 cm long with a 1.7 mm bore diameter, Fedley measured the gain and power of the strongest laser lines. His results are summarized in Fig. 2.

Cw laser power over 1 W was obtained simultaneously in both Ar III (351.1 nm and 363.8 nm) and Kr III (350.7 nm) by Banse et al. [3] using a fused silica tube with a 12 mm bore. Latimer [4] and Bridges and Mercer [5] reported cw laser powers of 1.7 and 2.3 W, respectively, for the Ar III lines using narrow bore (4 and 2.3 mm) tungsten disc discharge tubes. Figure 3 summarizes the results obtained by Bridges and Mercer. They reported an efficiency of $1 \cdot 10^{-4}$. The laser output powers obtained in these experiments and the fundamental features of the discharge tubes are similar to the ones commercial cw ion laser tubes still in use today.

Significantly larger laser output powers were obtained by Tio et al. [6] in 1976 using a 12 mm bore tungsten disc discharge tube 15 cm long. They obtained 16 W of combined power from the Ar III lines using a discharge current of 485 amps; 55% of the power was obtained on the 363.8 nm line and the rest on the 351.1 nm transition. They also reported cw laser powers of 7, 1.8 W, and 0.15 W on the UV transitions of Kr III (350.7 and 350.4 nm), Xe III (378.1 and 374.6 nm), and Ne II (332.4 nm). Finally, Luthi et al. [7] in 1977, reported the largest cw ultraviolet laser power obtained to date. They used a segmented metal discharge tube of 12 mm bore to obtain 61 W on the 351.1 and 363.8 nm Ar III transitions. Table 1 and Fig. 4 summarize the results obtained by Luthi et al. for Ar III and Kr III. The output power was observed to increase without saturation up to the maximum available discharge

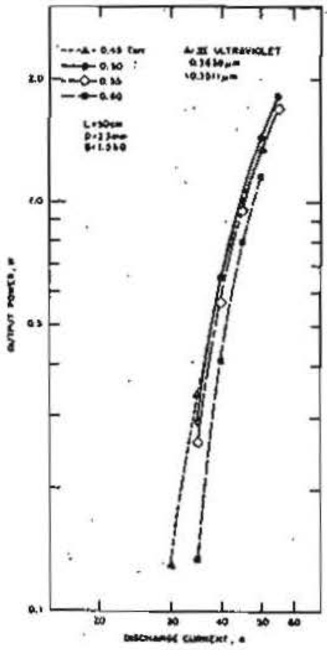

Fig. 3

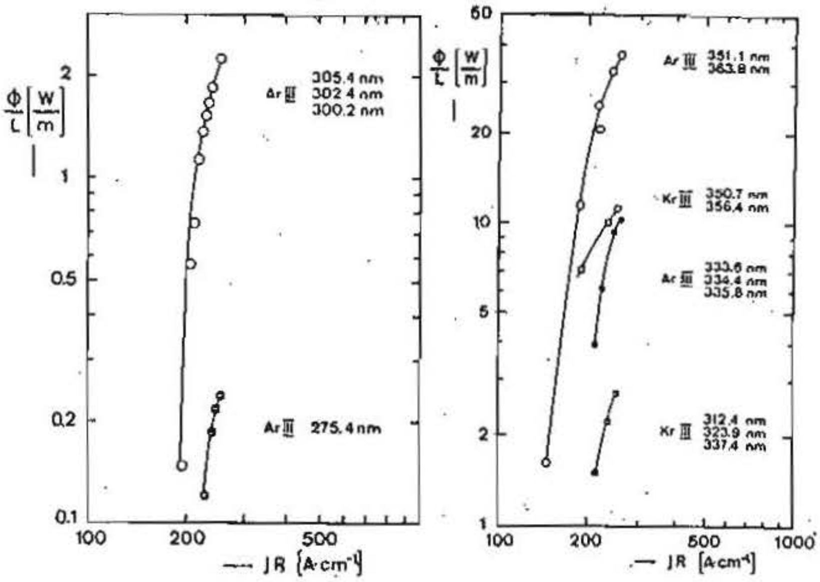

Fig. 4

Fig. 3. Output power of a disc bore Ar III ultraviolet laser. The tube parameters are given in the figure [5].

Fig. 4. a) Measured jR dependence of the UV laser output power P_0 per unit length of the discharge. (Wavelength <310 nm, discharge diameter 12 mm, fill pressure optimized for each current position.) b) Wavelength >310 nm [7].

Table 1

Cw UV Laser Transitions. Measured UV Laser Power at Maximum Available Current, i = 480 A of Power Supply. (Discharge Diameter: 12 mm, Discharge Length: 1.7 m, Fill Pressure: 1.25 Torr for Ar, 1.3 Torr for Kr [7])

Ion	Wavelengths (nm)	Power (W)	Output reflector (%)	Relative contribution (%)
ArIII	363,7 351,1	61	98	50 50
ArIII	335,8 334,4 333,6	17	97,5	25 45 30
ArIII	305,4 302,4 300,2	3,8	99	5 40 55
ArIII	275,4	0.4	98,5	100
KrIII	356,4 350,7	19	98	30 70
KrIII	337,4 323,9 312,4	4,5	97,5	25 70 5

current of 480 A, indication that higher output powers might be possible at larger discharge current densities for most of the UV lines. In studies done in pulsed discharges [8] (τ = 0.2-0.3 microsecond), the maximum power was observed to still rise with discharge current density, J, up to values more than an order of magnitude higher than the ones of the experiment of Luthi et al. In particular, for the Ar III 351.1 nm line a power of 1 kW was measured in pulse operation ($J = 7200\ A \cdot cm^{-2}$, $R = 0.35$ cm) [8].

METAL VAPOR ION LASERS

$He\text{-}Cd^+$ laser. Cw operation on Cd II at 325.0 nm was obtained independently by Silfvast [9] and Goldsborough [10]. Silfvast obtained 6 mW from He-Cd discharge in a 4 mm by 100 cm tube. Goldsborough [11] obtained 20 mW in a tube 2.4 mm diameter and 143 cm long at a current of 110 MA and 3.4 Torr helium pressure. The cadmium source temperature was 220°C, corresponding to a vapor pressure of about 2 mTorr.

Silfvast [12] proposed the Penning reaction following a suggestion by Webb:

$$He^*(2s\,{}^3S_1) + Cd \rightarrow He + Cd^+(5s^2\,{}^2D) + e + \Delta\varepsilon$$

for the excitation mechanism of the $5s^2\ {}^2D$ upper laser levels of the 325.0 and 441.6 nm transitions and fast radiative decay via the highly allowed UV transitions to the ion ground state as the depopulating process for the $5p\ {}^2P$ lower laser levels. Experiments by Collins [13], Webb [14], Schearer and Padovani [15], and Silfvast [16] support this excitation scheme. However, the fact that cw laser action was also obtained (at much lower laser powers) in Ne-Cd, Ar-Cd, and Xe-Cd mixtures [17] complicates the simple picture of the Penning process being the only population mechanism.

The observation that the laser power increased with decreasing noble gas pressure made Wang and Siegman [17] the highest direct electron impact from the Cd atom ground state as the excitation mechanism for those experimental conditions. Aleinkov and Ushakov [18] measured a large cross section, $1.5 \cdot 10^{-16}\ cm^{-2}$, for this process.

More recently, the group at Nagoya University studied the $He\text{-}Cd^+$ laser excitation mechanisms by modeling and experiments [19-20]. Their studies concentrate on the population of the Cd II $5s^2\ {}^2D_{5/2}$, upper level of the 441.6 nm transition, however, the conclusions should be expected to be valid also for the $5s^2\ {}^2D_{3/2}$, upper level of the 325.0 nm line. They found that the model can only fit the experimental data if both Penning reactions and stepwise electron excitation from the Cd (II) ground state are considered. They substain that the dominant excitation mechanism on current densities of a few mA is the Penning process of reaction 1, and that at higher current densities the stepwise electron excitation process dominates [20].

Many other singly ionized metal vapor species lase in the ultraviolet. Positive column discharges are not a good active medium for metal vapor ion lasers since the electron temperature decreases very rapidly with increasing metal vapor pressure. This was clearly shown by T. Goto et al. [21] under typical $He\text{-}Cd^+$ laser discharge conditions with the double-probe method. Their results are summarized in Fig. 5. As a result, metal vapor density and electron temperature cannot be independently optimized. The decrease of the electron temperature also causes a drop in the ionization rate, and consequently this represents a drawback for most metal vapor ion lasers. Other electric discharge excitation schemes that overcome these problems are discussed in the following sections.

Hollow cathode metal vapor ion lasers. Hollow cathode discharges have more suitable characteristics for obtaining laser action from noble gas-metal vapor systems. The discharge that fills a hollow cathode is mainly a negative glow sustained by energetic beam electrons [22]. The bombardment of the cathode surface by ions, fast neutrals, and photons produces secondary electrons that are subsequently accelerated in the cathode dark space to form a 300-400 eV electron beam. These fast electrons can efficiently ionize the atoms in the discharge creating an attractive active medium for ion lasers. The electron energy distribution as resulting from solving the Boltzmann equation for electrons in a He-Hg hollow cathode discharge is shown in Fig. 6 [23]. The general features of this electron energy distribution agrees well with the one measured by Gill and Webb using an electrostatic energy analyzer [24]. The beam electrons that enter the negative glow at an energy close to eV_c, where V_c is the discharge voltage, degrade in energy undergoing inelastic and elastic collision. Most of the secondary electrons created in the ionizing collisions are created at low energy [25], and the resulting distribution is the one shown in Fig. 6.

Since the negative glow is basically field free and sustained by beam electrons the discharge is rather insensitive to the presence of metal vapor that sputters from the cath-

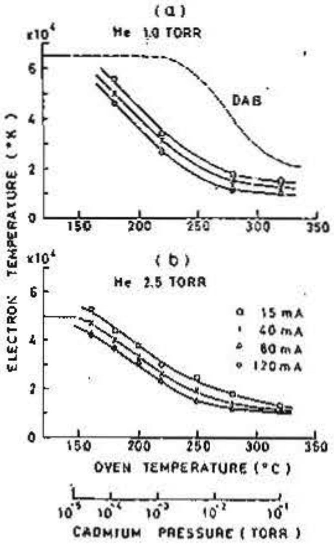

Fig. 5

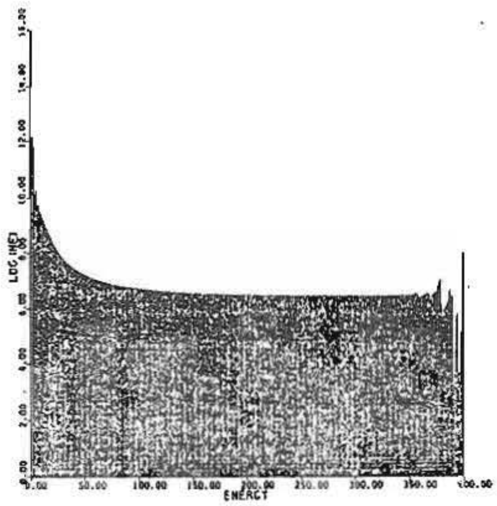

Fig. 6

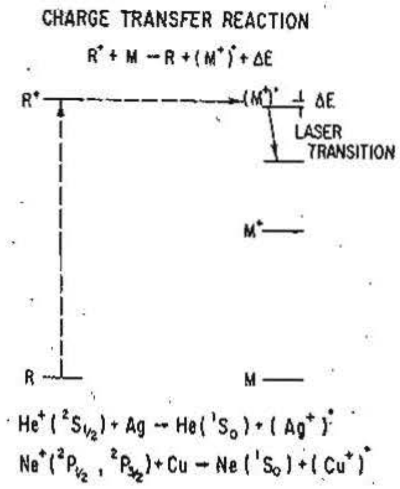

Fig. 7

Fig. 5. Electron temperature as a function of cadmium pressure (oven temperature) under typical He-Cd$^+$ discharge conditions. A dashed line shows the result calculated from the theory of Dorgela et al. [21].

Fig. 6. Electron energy distribution in a 0.3 cm diameter, 50 cm long He-Hg hollow cathode discharge calculated solving the Boltzmann equation for electrons. Discharge current: 10 A, He density: $1.2\cdot10^{17}$ cm^{-3}, He density: 310^{15} cm^{-3} [23].

Fig. 7. Diagrammatic representation of a charge transfer reaction.

ode as compared with a positive column. This is an advantage, since it allows for a better optimization of the metal vapor concentration without abruptly degrading the electron energy distribution, and diminishing the ionization rates. Moreover, as first pointed out by Willett [26] and Karabut [27], the cathode material itself may be sputtered into the discharge thereby providing the ground state metal atoms. Nonvolatile metals may thereby be vaporized without the use of ovens or self-heating discharges. This is a considerable practical advantage and was first realized in a laser by Csillag et al. [28], in a slotted hollow cathode of the Schuebel type [29].

The laser upper levels of many metal vapor transitions in hollow cathode discharges are populated by charge transfer reactions, schematically represented in Fig. 7 and summarized as:

$$B^+ + M \rightarrow B + (M^+)^* + \Delta E, \qquad (1)$$

where B, B^+, and M represent buffer gas atoms, ions, and metal atoms, respectively. $(M^+)^*$ represents metal ions in an excited energy state from which the laser action originates and ΔE is the energy difference between B^+ and $(M^+)^*$ in reaction 1. Duffendack [30-36] and his coworkers as well as Takahashi [37] investigated a variety of metal rare-gas mixtures in which charge transfer excitation of excited ionic levels was present. The use of hollow cathode discharges to create population inversions was not widespread until Fowles and his coworkers at the University of Utah first demonstrated that charge transfer [38-40] could provide selective excitation of upper laser levels in positive column devices. Several years later, using hollow cathode excitation, laser action was reported in $He-Cd^+$ and $He-Zn^+$ mixtures by Karabut [27], Sugawara [41], Schuebel [42], and Jensen [43].

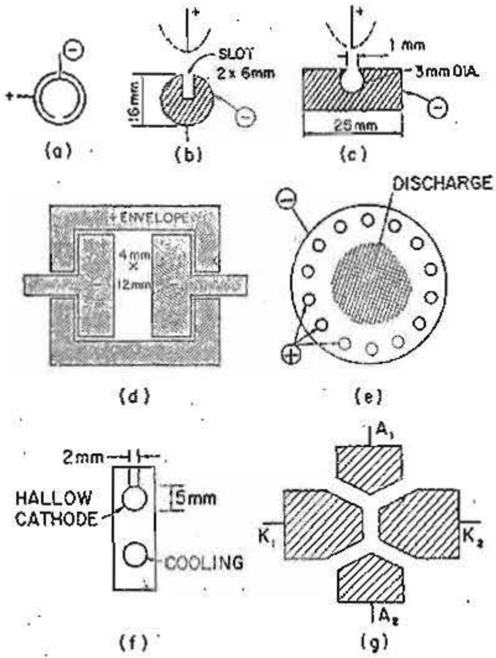

Fig. 8. Transversely excited hollow cathode laser configurations (a), Schuebel type; (b) rectangular slotted hollow cathode; (c) circular slot; (d) wave guide structure; (e) hollow anode or obstructed glow; (f) fluted hollow cathode; and (g) a rectangular hollow cathode structure. K_1 and K_2 are cathodes; A_1 and A_2 are anodes.

The first demonstration of a population inversion in a species generated solely by cathode sputtering was that reported by Csillag et al. in 1974 [28], with laser action in Cu II at 780.8 nm. The upper laser level of Cu II was populated selectively by charge transfer reactions between ground state helium ions and ground state copper atoms produced by sputtering. Subsequently, ultraviolet laser transitions were reported in Cu II, Ag II, and Au II [44-46]. The wavelength of these transitions, their level assignment, the correspondent current threshold and laser output powers are summarized in Table 2.

The above metals are particularly suited for use in hollow cathode lasers because all the metals possess high sputtering yields when bombarded with energetic (about 300 eV) ions [47]. Consequently, metal vapor densities $\geq 10^{14}$ cm^{-3} can be created by discharge sputtering [48]. In addition, metal ion levels, which lie in energy coincidence with ground state rare-gas ions, are populated by charge transfer reactions [30-36]. These factors combine to produce the required population inversions. Below we review different hollow cathode lasers and the characteristics of the most important ultraviolet hollow cathode laser systems: the $Ne-Cu^+$ and $He-Ag^+$ and $He-Au^+$.

Hollow cathode laser geometries. Laser action has been achieved in a variety of hollow cathode geometries. Figure 8 summarizes a variety of transversely excited configura-

Table 2

Small-Signal Gains and Laser Output Powers of Selected Ultraviolet Transitions of Ag^+ and Cu^+ and Au^+ [60,80]

Wavelength, nm	Measured net gain (%)*, ** $g_e - L_i$	Percent gain per meter $g_e/2l$, % m^{-1}	Laser power***
318,1 Ag^+	5,3	3,8	1,3 w
270,3 Cu^+	5,1	3,6	0,5 w
260,0 Cu^+	3,2	2,3	0,25 w
252,9 Cu^+	2,6	1,9	
248,6 Cu^+	12,2	8,3	0,5 w
224,3 Ag^+	—	—	65,0 mw
282,2 AuII	—	—	
291,8 AuII	—	—	600 mW***

*Round trip small signal gain minus intrinsic cavity loss for a l = 0.75 m cathode.
**Pulse width 120 μsec, pulse rate 40 Hz, current amplitude 100 amps.
***Obtained with a repetition rate of 40 Hz and 25 μsec duration.

tions. Historically, Chebotayev [49] and Smith [50] were the first to use a tandem-excite hollow cathode discharge (not shown in Fig. 6) as a means of exciting an He-Ne laser at 1. microns. Subsequently, Byer [51], Wieder [52], Karabut [27], Sugawara [41], Schuebel [42], Jensen [43], Piper [53], Csillag [28], and Eichler et al. [54] employed the hollow cathode discharge to excite metal ion lasers. The geometry in which the majority of laser studies were undertaken is the transversely excited slotted hollow cathode of the Schuebel [29] typ as shown in Fig. 6 (b and c).

Typical V-I curves for silver, copper, and aluminum slotted hollow cathodes are shown in Fig. 9 with various buffer gas mixtures. Note that the V-I requirements are nearly identical to those for a commercially available rare-gas ion laser. However, the dynamic impedance of the hollow cathode discharge is always positive and low (<20 Ω) which reduces discharge-power supply instabilities and allows for easy breakdown. All of the electrode configurations illustrated in Fig. 7 will operate in the hollow cathode mode only when the negative glow regions from opposing cathode surfaces merge or overlap.

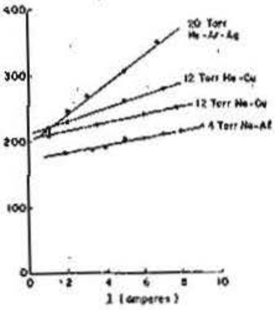

Fig. 9. V-I characteristics of selected hollow cathode discharges in Ag, Cu, and Al cathodes.

$Ne\text{-}Cu^+$ laser. In the $Ne\text{-}Cu^+$ hollow cathode discharges, the $3d^95s$ levels of Cu II are populated by charge transfer reactions between copper atoms and ground state rare-gas ions. A summary of the strongest Cu II transitions is given in Table 2. Figure 10 depicts the selectivity of the charge transfer pumping scheme for $Ne\text{-}Cu^+$ by indicating the energy coincidence between the rare-gas ions and upper laser levels of illustrative laser transitions, e.g., 248.6 nm. Seven UV laser transitions originating from the $3d^95s$ levels of Cu II were observed [44]. The wavelengths ranged from 248.6 to 270.3 nm. Multiline laser power from the 259.9, 260.0, and 270.3 nm lines was 350 mW, while single line output of 500 mW was obtained from the 248.6 nm line. In the case of the $Ne\text{-}Cu^+$ laser, only neon was used; no other buffer gases were added to increase sputtering. The optimum neon pressure was 12

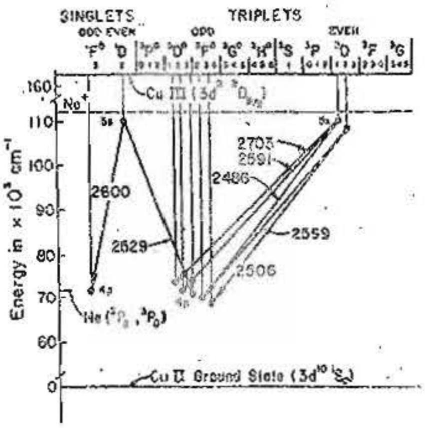

Fig. 10. Partial term diagram of Cu II displaying selected laser transitions (solid lines) and the energies available from ground-state helium and neon ions. Wavelengths are indicated in nanometers.

Torr. Auschwitz et al. [55] reported enhancement of the UV laser emission lifetime by a mixture of 0.1% argon to the neon buffer gas. For the laser lines 259.1 and 260.0 nm they achieved mean output powers up to 60 mW (total mirror transmission 2%).

More recently, K. Jain [56] reported a multiline UV power of 800 mW exciting a 25 cm long hollow cathode of the flute type (see Fig. 8f) with 40-microsecond pulses at a peak current of 40 A and a repetition rate of 250 Hz. The fractional distribution of the laser output power was 0.23:0.11:0.37:0.29 in the 248, 2529, 2591, and 2599-2600 Å lines. The highest true cw power was reported by Eichler et al. [57], who obtained 200 mW exciting a 2 × 6 mm slotted hollow cathode (see Fig. 8b) with a current of 70 A with the characteristic ripple of three-wave rectification. The gain was estimated to be 5% m^{-1} and a 3.6% optimum output coupling was employed. They also reported a quasi-cw peak output power of 0.9 W with rectified 50 Hz half-wave excitation. Figure 11 shows the variation of the cw and half-wave mean powers as a function of the discharge current.

He-Ag^+ laser. The $4d^9nx$ and $4d^85s^2$ configurations of Ag II are excited in He-Ag and Ne-Ag discharges, respectively. Figure 12 depicts selected laser transitions and indicates the near energy coincidence between the upper laser levels and the helium. This diagram also includes the visible and IR Ag II laser transitions.

The 224 nm laser transition, $5d\,^1S_0 - 5p\,^1P_1^0$ obtained the first time by McNeil et al. [45] is the shortest wavelength cw laser transitions reported in the literature to date. The threshold for this transition is only 2 A and peak output power of 50 mW with a 1 mW average has been reported in [58]. The optimum pressure is 20 Torr He with 0.2 Torr Ar. The variation of the output power on the mirror transmission for the 224 nm line in a 25 cm long rectangular slot cathode, excited by a 40 A pulse is shown in Fig. 13. The best fit to the experimental data gives a value of the unsaturated gain of 25%/m. The strongest laser transition of Ag II according to the experiments of Warner et al. [59], and Solanki et al. [60] is at 318 nm $4d^85s^2\,^1G_4 - 4d^95p\,^3F_3^0$, provides peak single-line output power of 1.3 W. This transition is excited by charge transfer collisions with Ne+. However, in the experiments carried out by K. Jain and S. Newton [56], this transition was found to be much weaker than the 224 nm line, and the gain was measured to be 5%/m.

He-Au^+ laser. Figure 14 indicates the six ultraviolet laser transitions of Au II which have been 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 in near energy coincidence with the ground state helium ion. Threshold currents for the 280 nm laser transitions are measured to be as low as 3 A or about a factor of 20 less than threshold currents for ultraviolet laser transitions in rare-gas ion lasers. Multiline output power of 125 mW [46] and 600 mW [58] has been demonstrated in the 250 to 290 nm region. For the 282 nm line, Jain and Newton [56] reported true cw laser action for a slotted cathode length as short as 5 cm. With a cathode length of 2.5 cm lasing was achieved in a quasi-cw regime with current pulses of 300-microsecond duration.

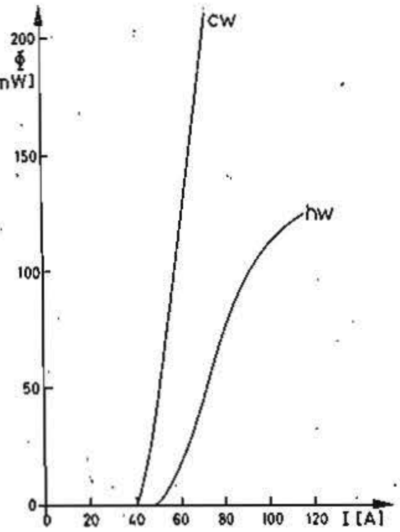

Fig. 11

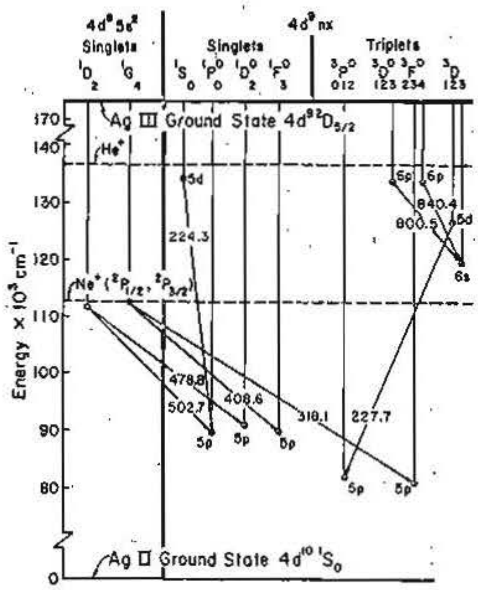

Fig. 12

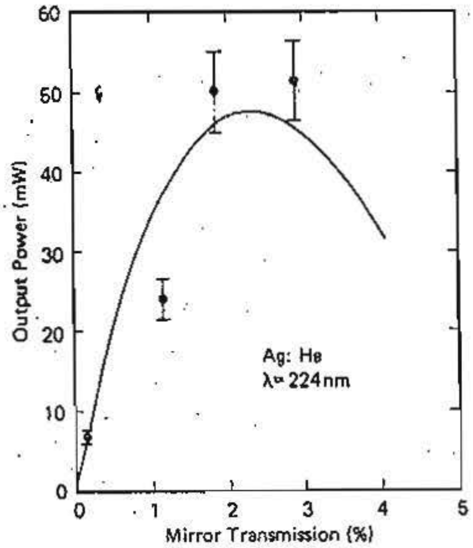

Fig. 13

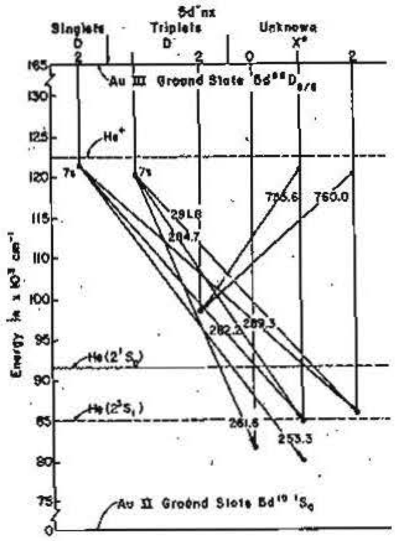

Fig. 14

Fig. 11. Cu II and half wave (hw) UV laser output (mean power) as a function of hollow cathode discharge current [57].

Fig. 12. Partial term diagram of Ag II showing selected laser transitions (solid lines) and the energies available from ground state helium and neon ions. Wavelengths are indicated in nanometers.

Fig. 13. Dependence of output power on mirror transmission for 224 nm line of Ag II in He-Ag hollow cathode laser. Solid line is a fit done with gain of 25%/m, a saturation parameter S, 1/S = 6 W and total cavity loss of 0.07 [56].

Fig. 14. Partial term diagram of Au II indicating selected laser transitions (solid lines) and energies available from ground state helium ions. Wavelengths are indicated in nanometers.

Vacuum ultraviolet radiation from highly ionized noble gases. As mentioned above the shorter cw ion laser transition is the 224.3 nm line if Ag II obtained in He-Ag hollow cathode discharges. Singly ionized noble gases are the most power source of cw visible laser radiation and as mentioned in §1, cw ultraviolet laser radiation in noble gases is obtained

Table 3

Vacuum Ultraviolet Ion Laser Emission from Noble Gases [61]

Measured wavelength (± 0.003 nm)	Spectrum	Threshold** (A/cm^2)	Relative performance***	Measured wavelength (± 0.003 nm)	Spectrum	Threshold** (A/cm^2)	Relative performance***
206,530 *	NeIV?	4 000	~50	196,808	KrIV	8000	~4
202,219 *	NeIV	4 500	~50	195,027	KrIV	7000	440
184,343	ArV?	11 000	~10	183,243	KrV?	9600	10
219,192 *	KrIV	6 200	600	175,641	KrIV	7800	1000
205,108 *	KrIV	7 500	3	231,536 *	XeIV?	3000	1400

*Wavelengths measured in air. These lines are included from [8] for comparison.

**Threshold at pressure for optimum output. Threshold can be up to half this value at lower pressure.

***Performance measured at 11,000 A/cm^2 discharge current density. Pressure was 6 μ for the krypton and 10 μ for the argon VUV transitions. The transitions from [8] are given in watts.

mainly from the double ionized species. J. Marling has demonstrated vacuum ultraviolet laser action from highly ionized noble gases, in a pulse (200 nsec) regime [61]. As we shift towards shorter wavelength and more highly changed ions, higher current densities are required. To achieve laser action below 200 nm, Marling used electrical discharge excitation pulses with 500 nsec duration and peak current density up to 14,000 A/cm^2 in a z-pinch longitudinal discharge. Table 3 summarizes the VUV laser results obtained using highly ionized noble gases. The two strongest emissions exhibited 0.1-1 kW peak power from Kr IV at 195.0 nm and 175.6 nm. Figure 15 shows the relative peak power of these laser transitions as a function of discharge current. No saturation is apparent. Using the same excitation technique he also found numerous new laser transitions from multiply charged ions in the 200-250 nm expected region [9].

Summarizing laser action in the vacuum ultraviolet has been obtained in several highly ionized species. However, this was done with short pulse excitation (500 nsec) since current densities of the order of 10^4 A are required.

Recombination ion lasers. Gudzenko and Shepelin suggested in 1963 that population inversion could be produced during plasma recombination [62]. This is a way to efficiently use the energy stored in the plasma ions to efficiently excite laser transitions. Several ultraviolet laser transitions have been obtained using this excitation principle. Zhukov et al. [63] in 1976 utilized experimental data on recombination lasers obtained in the years since Gudzenko and Shepelin's proposal, to formulate more specifically the requirements that the discharge conditions and the distributions of atomic and ionic active levels have to satisfy to achieve population inversion during the plasma recombination period. Zhukov et al. established a generalized criteria for the existence of population inversion which for the case of widely spaced levels with the assumption that each group consists of just one level is:

$$g_1(A_1 + F_1 n_e)/g_2(A_2 + F_2 n_e) > W_1/W_2, \qquad (2)$$

where g_i, A_i, F_i, W_i are the multiplicity, transition probability, electron deexcitation rate, and total pumping rate to the upper (i = 2) and lower (i = 1) levels. They analyzed both the cases of radiative and collisional regimes, as summarized below. In the case of low electron densities the $F_i n_e$ terms can be neglected and an inversion is established because of the optical transitions. It is usually then necessary to ensure that the gap between the upper and lower levels is considerably less than between the lower and zeroth levels because this distribution of levels ensures the necessary ratios between the optical probabilities of the transitions. Such level systems are shown in Fig. 16a. However, the inversion is destroyed when n_e and, consequently, the rate of pumping by recombination increase sufficiently because then terms $F_1 n_e$ and $F_2 n_e$ predominate and the values of these terms increase with decreasing distance between the levels. Thus, for this distribution of levels the recombination regime is unlikely to ensure high gains and output powers, since electron deexcitation sets a limit. However, if the level system has the structure shown in Fig. 16b, electron deexcitation can play a role in favor of population inversion. An inversion cannot be established by the optical transitions since $A_{21} > A_{10}$ (due to the fact that $\Delta E_{21} > \Delta E_{10}$) and this is why ratio of the probabilities of transitions resulting from electron deexcitation becomes acceptable because then $F_1 n_e > F_2 n_e$. A population inversion

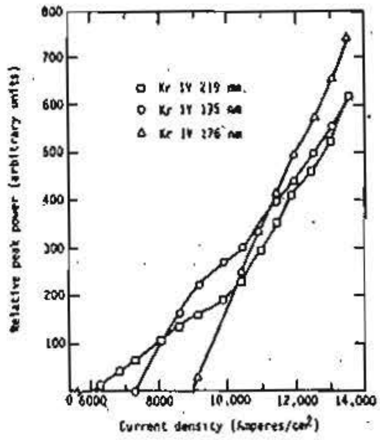

Fig. 15

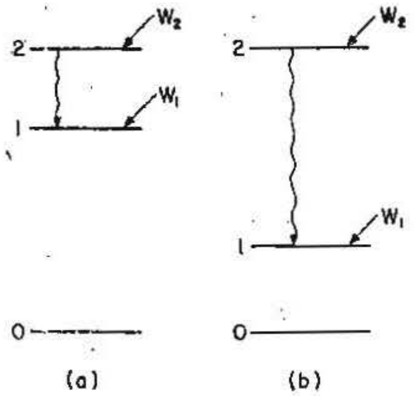

Fig. 16

Fig. 15. Relative peak power of the Kr IV laser transitions at 176, 195, and 219 nm as peak excitation current density is varied between 6000 and 14,000 A/ /cm^2. No saturation is apparent [61].

Fig. 16. Level systems. W_2 and W_1 represent the pumping terms in a recombining plasma.

can be established by such transitions at high plasma densities and for high recombination pumping rates, so that the stimulated radiation may be intense and the gain may be high.

The researchers of Rostov University summarized the general requirements which have to be satisfied if a population inversion is desirable under recombination-collisional conditions in the following way [62]:

1) the upper laser level should be one of the lowest in the higher group of closely spaced levels;

2) the lower laser level should be one of the highest in the lower group of closely spaced levels;

3) the transitions between the levels should be allowed;

4) the electron density should be sufficiently high to ensure that the probability of collisional transitions within groups exceeds the probability of optical transitions;

5) the electron temperature should be as low as possible.

Such conditions are met for the 373.7 nm transition of Ca II on the afterglow of a He-Ca discharge. Zhukov et al. [64] obtained 0.5 W of average laser output power in this line using excitation pulses of 300 A, 150 nsec at 5 kHz repetition frequency in a discharge tube 11 mm in diameter and 50 cm long. The laser pulses were several microseconds long. Ultraviolet laser action in a recombination plasma was also obtained by Silfvast et al. in In III at 298.3 nm and 300.8 nm [65]. In this experiment the laser action was obtained when a series of small vaporized plasmas, formed in the gaps between a row of electrodes of the lasing species by a high voltage pulse, is allowed to expand or recombine [66]. The laser pulse length was also in the microsecond range. Silfvast et al. observed laser action in the same transition in Ag II (IR), Cd III (visible), and In IV, demonstrating that the concept of isoelectronic scaling can be used in recombination lasers to obtain laser action at shorter wavelengths [65].

No cw ultraviolet recombination laser has been reported to date. This is due to the difficulty of obtaining a plasma that possesses both high ionization rates, and low electron temperature and in which the laser lower level is not significantly excited by electron impact from the ground state. D. Wood and Silfvast [67] have, however, recently reported quasi-cw (1 sec) laser action in the infrared on the 1.40, 1.43, 1.44, and 1.64 micron transitions of Cd I. This result was obtained in an arc created between two Cd electrodes and rapidly flowing He gas between them to create an expanding plasma.

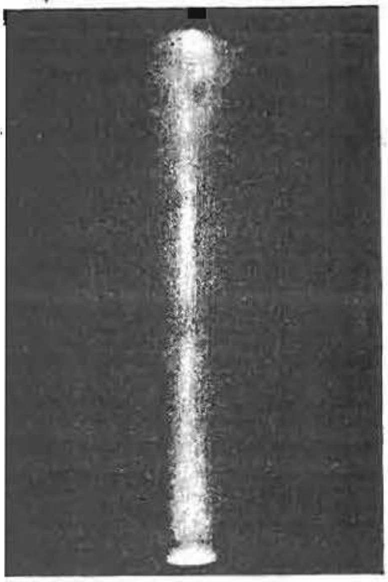

Fig. 17. Emission from a 0.5 A electron beam created by a glow discharge electron gun.

RECENT DEVELOPMENTS AND FUTURE WORK

As discussed in the preceding section, hollow cathode discharges have an electron energy distribution with a high energy (300-500 eV) component. This energetic electron can easily ionize buffer gas ions, that populate the laser upper levels by thermal charge transfer reactions. The hollow cathode-charge transfer scheme has been successful in achieving laser action with low current threshold in more than 10 transitions below 300 nm. However, the production of energetic electrons in a conventional hollow cathode discharge is inefficient. In a cold cathode HCD the electrons are generated mostly by ion bombardment of the cathode surface. These electrons are then accelerated through the cathode fall to form an electron beam. Neglecting ionization in the dark space, the electron beam current I_e is related to ion current I_+ by the relationship

$$I_e = \gamma I_+, \qquad (3)$$

where γ is the electron secondary emission coefficient. Considering that the total current $I = I_e + I_+$, we can state that

$$I_e = (\gamma/(1+\gamma))I. \qquad (4)$$

From this it follows that the electron beam generation efficiency, B_e, is:

$$R_e = I_e/I = \gamma/(1+\gamma). \qquad (5)$$

At an impinging ion energy of 200-300 eV most materials present $\gamma \approx 0.1$. Also notice that most of the ions do not impinge on the cathode with the total cathode fall energy eV_c, since they suffer charge exchange collisions. For a value of $\gamma = 0.1$, the resulting electron beam generation efficiency from (5) is $\eta = 0.09$. Recently, Rocca et al. [69] proposed and demonstrated [70-74] the use of dc electron beams as a new way of exciting cw ion lasers. For this purpose they have developed glow discharge electron guns [75-78] that produce well-collimated electron beams of energies between 1 and 10 keV and currents up to 1.2 A. The glow discharge electron guns operate in helium at pressures up to 3 Torr without differential pumping. Electron beam generation efficiencies as high as 80% have been measured. This results in an order of magnitude laser improvement with respect to a hollow cathode discharge. Figure 17 shows a 0.5 A electron beam created by a glow discharge electron gun. Using the laser setup of Fig. 18, the researchers at Colorado State University have obtained cw laser action in more than 30 infrared and visible transitions in 7 different singly ionized species: Hg, I, Cd, Se, As, Zn, and Kr. In the laser setup shown in Fig. 18 the beam electrons created by the glow discharge electron guns are guided by an axial magnetic field to assist an efficient deposition of the electron beam power into the gas. The electron

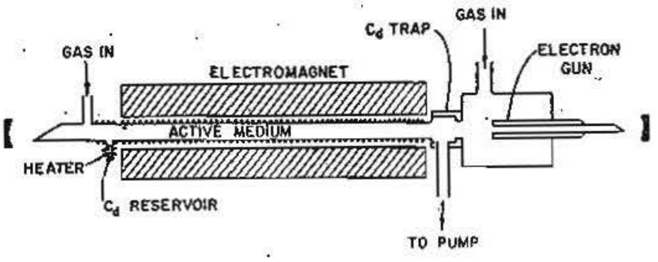

Fig. 18. Schematic diagram of an electron beam pump Cd ion laser [74].

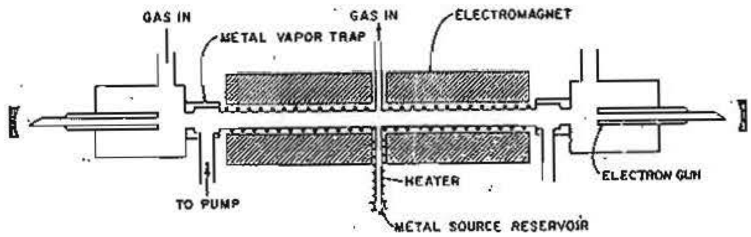

Fig. 19. Metal vapor ion laser excited with two glow discharge electron beams [79].

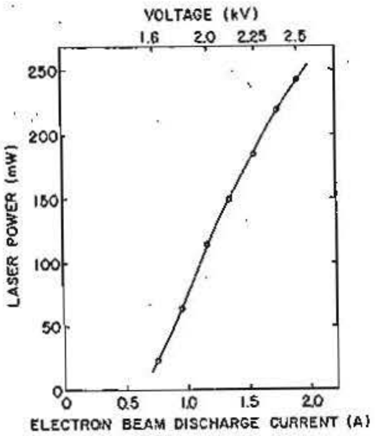

Fig. 20. Laser output of 614.9 nm Hg II transition as a function of electron beam discharge current and voltage. Average helium pressure in active medium was 1.5 Torr. Magnetic field 3.2 kG; Hg reservoir temperature 120°C [79].

guns have the unique feature of providing a clear optical path throughout the axis. This permits one to match the electron beam created plasma volume with the corresponding volume of the optical resonator. The laser configuration shown in Fig. 19 is similar to the one of Fig. 18, but in this case two opposing electron guns are used. This allows an increment on the electron beam power deposited per unit volume and also provides a more uniform plasma. Using this setup, Rocca et al. obtained 1.2 W of cw laser power from the 491.2 and 492.4 nm transitions of Zn II exciting a He-Zn mixture and 0.25 W on the 614.9 nm transition of Hg II exciting a He-Hg mixture [79]. This power is over order of magnitude higher than the ones obtained with either hollow cathode or positive column lasers. This is also the first time that metal vapor ion lasers operate cw in the visible region of the spectrum at a power of >1 W. The variation of 614.9 nm laser power with electron beam discharge parameters is shown in Fig. 20.

So far the efforts concentrated in demonstrating the advantages of this new excitation scheme in charge transfer systems operating in the visible region of the spectrum. However, similar improvements are expected to occur also for ultraviolet transition, in systems like Ne-Cu and He-Ag and this is part of future work.

The electron beam-charge transfer systems have the potential for creating high efficiency cw ultraviolet lasers if we consider that:

a) most of the discharge power (up to 80%) goes into the creation of energetic beam electrons;

b) beam electrons efficiently create noble gas ions;

c) most of the energy stored in the rare gas ions can be selectively deposited in the laser upper levels by thermal charge transfer cross sections that present very high cross sections ($>10^{-15}$ cm^2);

d) systems like $Ne\text{-}Cu^+$ and $He\text{-}Ag^+$ have a large quantum efficiency (24 and 20%, respectively) for 250.0 nm transitions.

Simplified calculations done to estimate the efficiency of electron beam pump cw charge transfer systems show that values in the vicinity of 1% could be expected.

CONCLUSIONS

Doubly charged noble gas ions are at present the most powerful source of coherent radiation in the ultraviolet region of the spectrum. A cw output power of 61 W has been obtained from the combined 351.1 and 363.8 nm Ar III lines. VUV laser action has also been obtained from multiplying changed noble gas ions, but only in a pulsed region. Cw laser action at shorter wavelengths and lower current thresholds have been obtained from metal ions selectively excited by charge transfer reactions with noble gas ions in hollow cathode discharges. The Ag II laser transition at 224.2 nm obtained in a Ne-Ag mixture in a sputtering hollow cathode discharge is the shortest cw ultraviolet laser line up to date.

Recombining plasmas have also produced ion laser action in the ultraviolet, but so far only in a pulsed regime. The use of dc electron beam excitation has recently been demonstrated to increase by more than an order of magnitude the maximum cw output power of charge transfer metal vapor lasers. This new excitation mechanism is expected to increase the power and efficiency of metal vapor ultraviolet ion lasers and offers the possibility of extending their range to the vacuum ultraviolet.

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