A High-Voltage Hollow-Cathode Au–II 282-nm Laser
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Abstract—Laser operation on the Au–II 282.3-nm line is obtained from a high-voltage, segmented hollow-cathode discharge tube with external mirrors. Measurements of the laser output power and the small-signal gain demonstrate that, for a given total discharge current, the optimum performance of the laser is obtained for a discharge length for which the linear current density is approximately 65 mA cm⁻¹. The gain is approximately 25% at this current density and increases with current density up to the highest value used (250 mA cm⁻¹), at which the gain exceeds 50%. The threshold current decreases monotonically with decreasing length, the lowest observed value being 0.28 A for a length of 5 cm. A quasi-CW output power of 20 mW is obtained for a gain length of 20 cm and a discharge current of 3.2 A in a partially optimized tube with unoptimized output coupling.

I. INTRODUCTION
LASER action has been achieved on a large number of ultraviolet metal-ion transitions in hollow-cathode lasers employing such metals as copper, silver, and gold as the cathode material [1]–[5]. An advantage of the hollow-cathode laser is that the metal vapor can be produced by sputtering rather than by thermal means, and the hollow-cathode discharge generates a high density of buffer gas ions, which is necessary for efficient pumping by thermal charge transfer. Lasers of this type operating on ultraviolet transitions typically have threshold currents of at least several amperes at a discharge voltage in the range 300–400 V and active lengths of tens of centimeters. The output power is increased by raising the current, without the advantage of a significant increase in the operating voltage. Furthermore, the low slope-resistance (~10Ω) renders these devices susceptible to localized arcing at high current densities.

We have reported elsewhere a new high-voltage, hollow-cathode laser that employs a novel segmented cathode structure and have studied its operation on the He–Cu⁺ 780.8-nm line [6]. This geometry has also been shown to be superior to both the conventional hollow cathode and hollow slotted-anode cathode devices [7]. The design allows high-voltage operation of a hollow cathode of cylindrical geometry without inserting an anode which would otherwise reduce the discharge volume which is available for laser operation and restrict the flow of the sputtered atoms into that volume. In this paper we present a study of the operation of the device on the Au–II 282-nm ultraviolet transition. The higher efficiency of the pumping discharge allows the use of a short active length and gives a lower threshold current than that reported by earlier workers [8]. The dependence of the laser output power on the active length at a fixed value of the total discharge current is measured and interpreted in terms of the dependence of the measured small-signal gain coefficient on the discharge current per unit length. To the best knowledge of the authors, this is the first published direct measurement of the small-signal gain for the Au–II 282-nm line. The gain for a given length increases with the current over the range studied. A significant consequence of the discharge regime for our device is the existence of an optimum active length for a given current, which is favorable to the operation of a compact UV metal ion laser.

II. EXPERIMENTAL
Each discharge module of the laser tube had the same geometry as described in [7], comprising four quadrant-shaped copper electrodes with the concave, active areas gold-plated to a thickness of 10 μm. These electrodes were arranged so that the concave surfaces defined a cylindrical discharge volume having a diameter of 4 mm. Two diametrically opposite electrodes were connected as cathodes, the remaining electrodes being anodes, as shown in Fig. 1. This configuration was found to produce the best laser performance when a similar device was operated on the 780.8-nm Cu–II transition [7]. Insulated circular brass plates at each end of the electrode array prevented discharges from forming on the end surfaces of the electrodes. Alumina spacers were used to maintain a 0.3-mm spacing between adjacent electrodes and between the electrodes and the brass end-plates, such a separation being sufficient to exclude the discharge from the gaps over the range of currents and pressures and applied voltages employed. The edges of the spacers were at least 5 mm from the discharge to minimize the risk of a short circuit being developed due to deposition of metal on the spacers. The spacers extended to the external surfaces of the tube where a vacuum grade epoxy (Varian 'Torr-seal') was applied to provide a vacuum seal. Four discharge modules as described above were joined

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in tandem between a pair of Brewster windows, which were seated on O-rings. The material of the Brewster windows was Suprasil quartz.

The modular construction allowed the use of 5, 10, 15, or 20 cm active lengths, as required in a scaling study, and as is desirable even if a fixed, long active length is required, since such division of the total discharge length by metal dividing plates (either floating or at anode potential) has been shown to greatly increase the arc-free current density that can be sustained [9]. A 5 scc per minute flow of He–1% Ar buffer gas was provided by a gas entry point near each Brewster window and was extracted through a line near the middle of the tube in order to retard degradation of the Brewster windows. In an experimental laser of this type, traces of organic vapor originating from such sources as the vacuum system and the discharge can form films on exposed optical surfaces such as mirror surfaces. The action of ultraviolet radiation on these films further degrades the coatings with an attendant decrease in the net gain. One advantage in using external mirrors with readily demountable Brewster windows is that damage to the laser mirrors is avoided. The surface degradation is confined to the Brewster windows, which can be easily cleaned. The most significant advantage of the use of Brewster windows is that it permits direct measurement of the gain. The discharge tube was placed in an optical cavity comprising two concave mirrors of radius of curvature 1.2 m placed approximately 0.8 m apart. The ‘rear’ mirror has a nominal reflectivity of 99.9%, and that of the output coupler was either 99.9% or 99%. The laser power supply employed a current-switching tetrode valve and could generate a square pulse of current of up to 4 A at 2 kV. A pulse duration of 0.5 ms was used at a repetition rate of 1 pulse per second. Such pulses were long enough for the laser output to approximate continuous-wave behavior towards the end of the pulse, and the low repetition rate favored conservation of the gold-plating and allowed operation without the need for forced cooling. A dc ‘simmer’ current of 1 mA was maintained between pulses to assist the breakdown during the main discharge.

The laser output power was measured using a Hamamatsu UV-enhanced photo-diode type S1226-44BQ fitted with a Microcoatings interference filter to isolate the 282-nm line. The laser power signals were stored on a Nicolet digital oscilloscope (Model 2090). Signal averaging was performed as necessary to limit the scatter to about 2%. The power measurements were based on the specification of photo-diode sensitivity provided by the manufacturer and our measurement of the transmission of the filter at the laser wavelength. The laser gain measurements were made by inserting in the optical cavity an adjustable loss element which comprised a pair of contrarotating quartz plates, each polished to λ/10 flatness and having faces parallel to within 10" of arc. The plates were adjusted so that they were always equally inclined to the optic axis of the laser and there was no skew between the plates and the Brewster windows. The contrarotation ensured that there was no net lateral displacement of a beam passing through the plates. The transmission loss for the plates at each value of the angle of incidence was calculated using the appropriate Fresnel equation. The gain measurement technique involved adjusting the current in one discharge module (with the loss plates set at the Brewster angle) to bring the laser to threshold. Thus the gain in this discharge module just compensated the total losses in the cavity, including the transmission of the output coupler. The desired current was then established in one or more of the remaining discharge modules using a second similar power supply, and the loss element was adjusted to reestablish threshold operation. The small-signal gain per pass of the additional module(s) for that current was then equal to the loss of the loss element. This method does not require knowledge of the value of the cavity losses, which are hard to define.

### III. RESULTS AND DISCUSSION

Voltage–current characteristics for a single discharge module employing a He–1% Ar buffer gas are shown in Fig. 2, indicating a discharge voltage 2–3 times that of a conventional hollow-cathode discharge. This figure shows that at constant current, a discharge voltage versus pressure graph would have a minimum similar to that obtained with a classic hollow-cathode. In the present case, the minimum is at a pressure in the range 5–15 mbar. Thus, for discharge currents of practical interest for laser operation and at the higher pressures represented in Fig. 2, the discharge voltage increases with increasing buffer-gas pressure. This contrasts with the behavior of a copper segmented hollow-cathode tube of the same bore diameter and length, which, with a He–Ar buffer gas at similar pressures, operates on the low pressure side of the minimum in a voltage versus pressure graph [7]. This difference may be attributed to a higher secondary electron emission coefficient by ion bombardment for the gold surface, see for example, [10]. After sufficient conditioning, each of the discharge modules operated at the same voltage (within ~60 V at a discharge voltage of 1000 V) for a given value of current. Hence, several modules could be connected in parallel across a single power supply without any ballast resistors, and the total discharge current was shared approximately equally between all modules.

The laser output power using a He–Ar buffer gas was found to be weakly dependent on the argon concentration up to 4%, the role of the argon atoms being to enhance the sputtering. The optimum argon concentration was approximately 1%. Similarly, with such argon concentration, the pressure dependence of the laser output power indicated a broad maximum at a total pressure of approximately 30 mbar. The remainder of the study was conducted using He–1% Ar at a pressure of...
20 mbar. The lower-than-optimum pressure was adopted in order to reduce the risk of damage to the tube due to the development of discharges in the 0.3-mm gaps between the electrodes.

The dependence of the laser threshold current on the active length is shown in Fig. 3 together with the dependence found by Jain and Newton [8] in their study of the slotted hollow-cathode He–Au+ 282-nm laser. The output mirror employed for both sets of data had a transmission of 0.1%. Our values of threshold current for the 5-, 10-, and 15-cm active lengths in Fig. 3 are significantly lower than those represented in the graphs of output power versus discharge current (Fig. 4), since the laser had been operating for an extended period prior to collecting the data of Fig. 4, and the Brewster windows had presumably degraded. The windows were carefully cleaned immediately prior to collecting the data of Fig. 3 in order to determine the threshold current under the most ideal conditions. Our findings contrast with that of Jain and Newton in two major respects. First, their threshold current shows a minimum for a cathode length of approximately 120 mm, whereas in the present work it increases monotonically with length. They explain the increase in threshold current when the length is increased beyond 120 mm as being due to the reduced current density and slightly reduced cathode fall voltage, which would result in a lower sputtering yield and therefore a lower gain. They further suggest that the increase in threshold current when the active length is decreased below 120 mm may result from a depopulation of the upper laser level by superelastic collisions with slow electrons, which become more abundant as the current density increases. Both types of behavior with similar explanations have also been reported by McNeil in a study of infrared and ultraviolet transitions in He–Cu and Ne–Cu systems [11]. However, the segmented hollow-cathode in the present work has a steeper voltage–current characteristic than does a conventional hollow cathode. Consequently, the increase in the operating voltage, which results from the increase in the current density for a reduced gain length at a fixed current, causes a significant increase in both the sputtering yield and the helium ion concentration. This effect is likely to dominate the dependence of the threshold current on active length. The second contrast with the results of Jain and Newton is that our values of threshold current are much lower. For example, for the 50-mm active length, our threshold current is approximately 10% of that obtained by Jain and Newton. In terms of threshold power, since at 0.28 A our discharge voltage (~650 V) is approximately double that of a conventional hollow-cathode discharge, the threshold power in the present study for the 50-mm active length would be only ~20% of the corresponding value obtained by Jain and Newton. For the 150-mm tube (having the minimum threshold current in the Jain and Newton study), our threshold current and power are approximately 30% and 60%, respectively, of the corresponding values reported by Jain and Newton. Thus the segmented hollow-cathode discharge is more efficient for pumping the laser transition than is the conventional hollow-cathode.

The graphs of the 282.3-nm laser output power as a function of the discharge current for active lengths of 5, 10, 15 and 20 cm (Fig. 4) show no sign of saturation over the range of currents employed. The output coupler transmission is ~0.1%. The various intersections of the lines indicate that, for a given total laser current, there is an optimum discharge active length. This is shown more clearly in Fig. 5, where the same output-power data are plotted against the discharge length with the total discharge current as a parameter. Each curve for the three lowest values of current displays a clear maximum at a discharge length approximately indicated by an arrow. The value of the linear current density corresponding to the maximum in each of these three curves is approximately 65
Fig. 4. Laser output power versus total discharge current for gain lengths of 0, 5, 10, 15, and 20 cm. Buffer gas is He–1% Ar at 20 mbar, and output coupler transmission is 0.1%.

Fig. 5. Laser output power versus gain length for total discharge currents of 0.7, 0.8, 1.0, 1.2, and 1.5 A. The optimum gain-length for each of the three lowest values of current is indicated by an arrow. Buffer gas is He–1% Ar at 20 mbar.

Fig. 6. Small-signal gain per pass versus total discharge current for the gain lengths 5, 10, and 15 cm. Buffer gas is He–1% Ar at 20 mbar.

Fig. 7. Small-signal gain per unit length versus discharge current per unit length of discharge. Gain lengths are 5, 10, and 15 cm. Buffer gas is He–1% Ar at 20 mbar.

mA cm⁻¹. Similar behavior is displayed by the curve for 1.2 A, with a peak suggested near a value of current density of 60 mA cm⁻¹.

Graphs of the small-signal gain per pass versus the total discharge current for active lengths of 5, 10 and 15 cm are shown in Fig. 6. These curves show that for low values of the total current (e.g., 400 mA), the greatest gain is obtained with a 5-cm discharge length, whereas for high values of the total current (e.g., 1200 mA), the greatest gain is obtained with a 15-cm discharge length. This indicates that for a particular value of the total discharge current, there is a corresponding active length that provides the maximum small-signal gain per pass. This conclusion is consistent with the observation (see Fig. 5) that for a particular value of laser current, the output power is maximized by the choice of an optimum active length. A quantitative analysis of this aspect is aided by consideration of Fig. 7 in which the data of Fig. 6 are replotted as a graph of small-signal gain per unit length versus the discharge current per unit length. A universal curve results for the three active lengths, having the significant feature that there is a point of inflection. Consequently, there is a point 'P' where a straight line through the origin is tangential to the curve, and the gradient of this line is the maximum possible for a chord connecting the origin to any point on the curve. The physical significance of the point 'P' is that it represents the maximum value of the ratio of the gain per unit length to the current per unit length. This means that the gain per pass will be maximized for a particular value of the discharge current, provided that the active length is adjusted so that the current density equals the value represented by the point 'P.' The optimum current density obtained from Fig. 7 is approximately 70 mA cm⁻¹, which corresponds closely with the optimum value of the current density for output power as obtained from Fig. 5.
A similar analysis may be performed on the graph of relative gain per unit length versus current density for the He–Au+ 282-nm transition reported by [8]. They infer the gain per unit length values (in arbitrary units) by using the inverse proportionality between gain per unit length and total discharge length at laser threshold. The lowest current density that they employ is about 90 mA cm⁻¹, and in extrapolating their graph of gain per unit length versus current density to the origin, the curve is drawn concave down. However, the lower points are consistent with the existence of a point of inflection near a current density of 120 mA cm⁻¹, and an optimum current density of approximately 160 mA cm⁻¹. The only output power data presented by Jain and Newton are for a fixed current of 10 A and active lengths in the range 2.5–25 cm. Consequently, their current density always exceeded the optimum value estimated above, consistent with their reported monotonic increase in output power with increasing active length.

We propose the following physical basis for the shape of our graph of gain per unit length versus current density. It has been shown that the helium ion concentration [He⁺] in a conventional hollow-cathode discharge initially increases linearly with increasing current density and saturates at a low value of that quantity [11], [12]. For a He–Au+ laser, this represents a balance between the rate of production of the He⁺ and their rate of loss by charge-transfer pumping of the ground state Au atoms. For the segmented hollow cathode of the present work, the discharge voltage increases markedly with the current. The higher-energy oscillating beam electrons give a higher rate of production of the He⁺ so that the [He⁺] will saturate at a higher level than for a conventional hollow cathode. At low values of the current density, the sputtering is dominated by the rare-gas ions. As the current is increased, there is a marked transition to sputtering dominated by metal ions. Warner et al. [12] have demonstrated a linear relationship between the metal atom concentration [M] and the current density in both the low- and high-current regimes for a conventional hollow-cathode discharge. In a separate study of a He–Cu discharge employing the high-voltage segmented hollow-cathode geometry of the present work, we have demonstrated a linear relationship between [M] and the current at high current densities with a steep transition into this regime at a current density of about 130 mA cm⁻² [6]. The charge-transfer pumping rate to the upper laser level is proportional to the product of the [He⁺] with the concentration of the Au atoms. Therefore the laser pumping rate (and hence the small-signal gain) will initially increase superlinearly with current density and, in the absence of other factors, would be expected to increase linearly with current at high current densities. The decrease in the slope of the gain characteristic (Fig. 7) is attributed to the depopulation of the upper laser level by superelastic collision with slow electrons, which are more abundant at higher current densities [8].

For a total discharge current of 3.2 A distributed uniformly over the 20-cm gain length, a 12-mW output power was obtained from each end of the laser, with mirrors of nominal transmission 0.1% at each end of the discharge tube. The maximum output power observed from one end of the laser was 20 mW, with the same discharge conditions and a 1% output coupler. The length of the laser was only 40% of the optimum length for this value of the total current (assuming that the optimization condition described above can be extrapolated to lengths beyond 20 cm), and neither the output coupling nor geometrical factors such as the diameter of the discharge have yet been optimized. A vacuum-bakeable version of this device, currently under development, will use internal mirrors and will allow a test of the true CW capability.

IV. Conclusions

Laser operation on the Au–II 282.3-nm line, with a higher efficiency than that for a conventional hollow cathode, has been demonstrated using a high-voltage, segmented, hollow-cathode discharge tube with external laser mirrors. The threshold current was shown to decrease monotonically with decreasing discharge length, and was only 0.28 A for the shortest discharge length tested. To the knowledge of the authors, this is the lowest reported threshold current for a Au–He+ 282-nm laser. The laser output power was shown to be optimized for a given total discharge current if the discharge length of the laser is adjusted to produce a linear current density of 65 mA cm⁻¹. Direct measurements of the small-signal gain as a function of the discharge length and current have been made and quantitatively support the above conclusion regarding the existence of an optimum linear current density. The gain has a value of approximately 25% m⁻¹ at the optimum current density and rises to a value in excess of 50% m⁻¹ for the highest current density used (250 mA cm⁻¹).

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References


K. A. Peard, photograph and biography not available at the time of publication.

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Z. Donkó photograph and biography not available at the time of publication.