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Dependence of laser power and gain on the cathode length of a sputtering copper ion laser

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Abstract. The dependence of the laser output power and the small signal gain for the 780.8 nm copper ion transition as a function of the cathode segments length in a sputtering longitudinal hollow cathode discharge are measured. The optimal cathode length in regard of maximum laser power is determined. From one and the same active volume at equal input power a considerable increase of laser output power is observed using the optimal length cathode segments. The results are in good agreement with the previously performed calculations and measurements of axial current and plasma characteristics, showing that the plasma is most intense near the anode ends of the cathodes. The measurements confirm that the highest laser power and excitation efficiency is achieved when the laser active volume comprises a series of anodes and cathodes, each cathode 2 cm long. This report is a part of a series of investigations aimed at optimization of the longitudinal hollow cathode discharge used as excitation medium of cathode sputtered metal ion lasers.

1. Introduction

Hollow cathode discharges (HCD) have been studied extensively for many years due to their wide range of applicability in different fields: atomic spectroscopy, gas lasers, vacuum microelectronic devices, material processing, etc. Due to the high density of fast electrons in the HCD and the efficient cathode sputtering it is often used as an active medium for excitation of laser oscillation on ion transitions of non-volatile metals (Cu, Au, Ag etc.) through charge exchange collisions with He, Ne, or other rare-gas ions.

The laser excitation efficiency and discharge stability of the HCD depend strongly on the geometry of the electrodes. In spite of the decades of research and use of HCD, still there are not enough empirical data and definitive models, describing the influence of different hollow cathode configurations and discharge conditions upon the discharge and laser performance. A better understanding of the effect of the hollow cathode geometry and dimensions on the excitation processes in the HCD plasma will contribute to increasing the discharge excitation efficiency and laser power by choosing the proper electrode configuration.

The stability of the longitudinal HCD – a set-up, consisting of successive hollow cathodes and anodes, is much better compared to the transverse HCD, but a considerable axial inhomogeneity exists, which affects strongly the excitation efficiency of the discharge [1, 2]. This axial non-uniformity is more clearly pronounced in the case of sputtering metal vapour lasers [3–5] where the
current plays a dual role, both for sputtering of the cathode to produce the necessary metal atom density, and for excitation of the laser transitions.

To determine the optimal discharge conditions and the optimal cathode length in order to and sustain uniform current and plasma distribution and to achieve maximum laser power and gain, we have studied a copper ion laser excited in He-Cu longitudinal HCD with variable length of the cathodes. The influence of cathode geometry is demonstrated by the behaviour of the 780.8 nm copper ion line, which has the highest gain and oscillation can be observed at comparatively low discharge current. The estimated excitation rate of the upper laser level of the 780.8 nm transition is compared to the measured laser power in all studied laser configurations. Because of the similar mechanism of laser lines excitation (charge exchange collisions of Cu atoms with He$^+$ or Ne$^+$, respectively), the oscillation in the infrared Cu ion lines may be regarded as a pattern for lasing in the UV spectral range in Cu-Ne discharge, as well as for potential lasing in the vacuum UV in He-Cu discharge.

2. Experimental

The dependence of the laser output power and the small signal gain for the 780.8 nm copper ion transition as a function of the cathode segments length in a sputtering longitudinal hollow cathode discharge (HCD) are measured. The studied laser transition ($6s^3D_3 - 5p^3F_4$) is of special interest because the upper laser level $6s^3D$ is also the upper level for a number of potential laser transitions in the 150 nm ÷170 nm (VUV) spectral range (figure 1) [6].

![Energy level diagram of Cu ion](image)

**Figure 1.** Partial energy level diagram of Cu ion with energies of He$^+$, He$^m$, Ne$^+$ and Ne$^m$ superimposed. The IR laser lines are shown, wavelengths are in nanometres. To the right groups of IR and UV laser lines, as well as potential VUV laser lines are indicated by arrows.
2.1. Discharge tube design
All experiments are performed using a specially designed discharge tube (figure 2), comprising a series of 31 cylindrical electrodes (16 electrodes with 1 cm length and 15 electrodes with 2 cm length), isolated from each other by 0.5 mm gap. All electrode segments, 4 mm inner diameter and 15 mm outer diameter, are made of high quality oxygen-free copper. They are mounted in a quartz tube with 15 mm inner diameter; hence the discharge can burn only inside the copper rings.

![Figure 2. Laser tube and resonator.](image)

Each electrode can be connected independently to the electric power supply, allowing individual ballasting of the electrodes for better discharge stability. By connecting together several electrode segments it is possible to configure a longitudinal HCD with a changeable length of the cathodes. In table 1 the investigated electrode configurations are shown.

| Laser tube configuration       | LT1 | LT2 | LT3 | LT4 | LT5 |
|-------------------------------|-----|-----|-----|-----|-----|
| Single cathode length $l$, cm | 1   | 2   | 3   | 5   | 8   |
| Number of cathodes $n$        | 14  | 15  | 10  | 7   | 5   |
| Full active length $L=l*n$, cm| 14  | 30  | 30  | 35  | 40  |
| Reduced active length $L_r=2*n$, cm | 14  | 30  | 20  | 14  | 10  |

The two ends of the quartz tube are cut at Brewster angles for 780.8 nm. The optical resonator, 1 m long, is formed by two highly reflecting mirrors for the 740-800 nm spectral range.

The measurements of small-signal gain coefficient are made by introducing into the laser resonator an adjustable loss element (RC in figure 2). The loss-element comprises two contra-rotating high optical quality quartz plates, ensuring a lack of displacement of the laser beam passing through the plates. The method for measuring the gain is described in details in [7].

The discharge is excited by 3 ms sinusoidal current pulses with 3 Hz pulse repetition rate. The peak values of the laser output power, the discharge voltage and the total cathode current are measured simultaneously. All pulses are recorded by a digital 200 MHz Tektronix oscilloscope (TDS 420A) with a 20-MHz cutoff filter and are stored in a computer. A Digikrom spectrograph equipped with a 1200 g/mm grating (blaze wavelength 500 nm) and a CCD camera has been employed for recording the laser spectrum in the IR spectral range.

2.2. Laser
Laser oscillation on seven copper ion lines is observed in a buffer gas He with Ar admixture to promote sputtering. Lasing is obtained at total (i.e., He & Ar) gas pressure 0.3 – 3.0 kPa with 4 – 7% Ar concentration in all five discharge tube configurations (table 1). The behavior of all seven laser
lines with current and gas pressure is the same, so all further measurements are made for the strongest 780.8 nm laser line. Due to the high threshold current of the remaining lines simultaneous oscillation of all lines is obtained only in the tree tubes with shorter cathodes. In figure 3 the laser emission spectra from the tube with 2 cm long cathode segments is shown.

\[ \begin{array}{ccc}
\lambda_{\text{nm}} & \text{Transition upper - lower} & \text{Threshold current}, \text{A} \\
760.4 & 6s^2_1d_{2} - 6p^0_2 & 5.4 \\
760.5 & 6s^2_1d_{2} - 6p^0_3 & 5.8 \\
770.0 & 6s^2_1d_{2} - 6p^0_3 & 5.6 \\
780.8 & 6s^2_1d_{2} - 5p^0_3 & 1.3 \\
782.6 & 5p^0_3f_{5} - 5p^0_2 & 1.5 \\
784.5 & 6s^2_1d_{2} - 6p^0_3 & 4.0 \\
788.8 & 6s^2_1d_{2} - 6p^0_3 & 6.9 \\
\end{array} \]

**Figure 3.** Recorded laser emission spectra from LT2 at 1.6 kPa He with 5% Ar and 20 A excitation current. In the table the corresponding threshold current for each line is shown.

The laser power increases with current and we have not observed saturation up to 30 A discharge current, the limit of the power supply. Because of the shorter active length at \( l = 1 \) cm, the current density reached in this configuration is almost twice higher than that, reached in the other variants. The discharge stability is also influenced by the length of the cathodes and is better for the shorter cathodes, while at \( l = 8 \) cm, in spite of the lower discharge voltage, the input power is limited by arcing.

**Figure 4.** Full laser output power (a), laser power from 1 cm active length (b), and reduced laser power (c) dependence on current density at optimal for laser oscillation conditions.
In figure 4a the laser output power dependence on current density is presented. As it is seen in the figure, the highest laser power is obtained when the cathodes are 2 cm long. As the total discharge tube active length is different for different cathodes length, we consider the laser power obtained from 1 cm cathode length (specific laser power) as more reliable measure of the corresponding discharge configuration efficiency (figure 4b). Due to the twice shorter active length at l = 1 cm, the specific laser power obtained from LT1 and LT2 is almost the same. The specific laser power obtained from the longer cathode configurations (l = 3, 5 and 8 cm) is lower, which is indication that the excitation efficiency is lower probably because a part of the cathode volume does not participate in the laser excitation process. The considerably lower laser power obtained from the discharge tube with l = 8 cm cathodes is presumably due also to additional losses as a result of optical absorption in the longer inactive volume of the cathode. Assuming that only 2 cm length of each of the cathodes contributes to the process of lasing, we can define a reduced active length \( L_r \) (the last row in table 1). According to this assumption, the cathode active length, contributing to the lasing process remains the same for LT1 and LT2, while it is shorter for LT3 (20 cm, instead of 30 cm), LT4 (14 cm, instead of 35 cm) and LT5 (10 cm, instead of 40 cm). In figure 4c the laser power divided on the reduced active length as a function of current density is shown. As it is seen, the obtained results are very similar for all five investigated configurations, confirming the assumption that only about 1 cm of the cathode near each anode end is participating in the process of laser excitation.

It is known that the laser power depends on the efficiency of excitation of the upper laser level, i.e. on the efficiency of the charge transfer process between Cu atoms and ground state He\(^+\) ions. To study the influence of cathode length on the process of charge exchange excitation, we have calculated the spatially averaged Cu atom, Cu\(^+\) ion and He\(^+\) ion densities, and estimated the excitation rate of the upper laser level \( \sim k_{ct}N_{Cu}N_{He}^{+} \). To evaluate the average active particle densities responsible for the formation of population inversion and lasing, we have used the simple analytical discharge model of Warner et al. [8], which explains many of the operating characteristics of sputtered metal-ion charge-transfer excited hollow cathode lasers [9].

![Figure 5. The estimated excitation rate of the upper laser level of the 780.8 nm transition, compared to the measured laser power \( P_L \) and gain \( G \) at this line in the studied laser configurations.](image-url)
As it is seen in figure 5, the production rate of Cu$^{+}$ ions in the upper laser level is almost the same for all cathode lengths, while the measured laser power and small signal gain decrease almost twice when changing the cathode segment length from 2 cm to 3 cm. Obviously, the measured different laser power and gain is not due to different excitation efficiency at different length of the cathode segments, but rather to the fact that due to the axial non-uniformity only a short part of the cathode (~ 1 cm) near the anode ends participate in the process of laser oscillation. Further decrease of cathode segment length (LT1) does not contribute to increasing the laser power.

3. Conclusion
The demonstrated dependence of laser power and efficiency upon the length of the cathode segments in a longitudinal HCD is in good agreement with the previously performed calculations [2, 3] and measurements [3–5] of axial current and plasma characteristics, showing that the plasma is most intense near the anode ends of the cathodes. The measurements confirm that the highest laser power and excitation efficiency is achieved when the laser active volume comprises a series of anodes and cathodes, each cathode 2 cm long. When longer cathode segments are used, due to the non-uniform discharge in the cathode the efficiency of part of the cathode volume is lower and it does not contribute to the process of lasing. Moreover, using longer cathodes may introduce additional optical losses in the resonator, which will worsen the excitation conditions.

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