Plasimo modeling of hollow-cathode geometry: laser tube configuration for sputtering metal-vapor lasers

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Abstract. We report results of the studies of a new version of a hollow-cathode discharge, namely, a multiple hollow-cathode discharge. The geometry comprises a main cylindrical cathode, which defines the active laser volume, and a number of short cylindrical side cathodes arranged radially to the main cathode along its length. PLASIMO’s Drift-Diffusion module is used to describe numerically the new laser tube configuration and to demonstrate its advantages.

1. Introduction
Hollow-cathode metal-vapor lasers are a class of gas lasers oscillating on metal ion transitions excited in the negative glow of a hollow-cathode discharge (HCD). If the metal-vapor density necessary for laser oscillation is produced by sputtering the cathode made of a refractory metal (such as copper, silver, gold), these lasers are regarded as sputtering metal-vapor lasers (SMVL). Despite the comparatively low power (up to about 1 W), the quality of the laser beam is very high and the lasers of interest for many applications, especially in biotechnology, forensics, UV Raman spectroscopy. These lasers are usually small and compact devices, with low power consumption and low cost.

The paper presents the results of a study of a new version of a multiple hollow-cathode discharge [1]. An important aspect of this design is that the discharges that occur in the cathode holes (CHs) can be used as additional sources of metal atoms obtained by sputtering. Moreover, the two discharge components can function independently. Inside the main cathode, the optimal conditions for laser oscillation are realized (pressure and current density), while in the side CHs the current density is higher, thus facilitating the production of metal vapor. Hence, the CHs can also be regarded as additional controllable reservoirs of metal atoms. Thus, by varying the potential between the cathode and the auxiliary anodes, it is possible to control independently the metal atom density and the excitation of the various species in the laser active volume.

The new design resembles the longitudinal segmented hollow cathode design and, hence, the insight obtained from previous geometrical feature studies [2-5] can be applied to the new design. For instance, by choosing a proper distance between the CHs, it is possible to achieve a nearly

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homogeneous plasma distribution and realize uniform sputtering in the main cathode. This will prolong the life time of the laser tube.

The optimal conditions (input current, pressure and He-Ar ratio, length/diameter ratio) limit the possibilities to increase the laser power by increasing the input power or by increasing the sputtering efficiency (by increasing the pressure or adding heavier atoms). The dimensions of the hollow cathode and the electrodes design affect considerably the discharge plasma parameters, the axial plasma homogeneity and, hence, the laser power. In the case of SMVLs, this influence is even stronger because due to the sputtering and the following metal deposition the cathode surface and electrode geometry change considerably during the operation process.

The PLASIMO modeling platform [6,7] has been used to construct a model that facilitates in-depth studies of the plasma behavior in this version of a multiple hollow cathode discharge.

2. Setup studied

The case study of the design is schematically presented in figure 1. The cathode cylinder has a 5-mm inner diameter, a 20-mm outer diameter and a 10-cm length. The refractory metal is Cu. Two ring anodes $A_{0i}$ are placed at both sides of the main cathode. Along the cathode length, three holes are made acting as additional side cathodes $C_i$. The distance between the holes along the cathode length is 40 mm. The inner diameter of these cathodes is 3 mm and their length is 7.5 mm. Three rod anodes $A_i$ are arranged above each of the side cathodes. All electrodes are mounted in a quartz tube with a 20-mm inner diameter; hence, the discharge can burn only inside the cathode cavities. The discharge conditions for laser oscillation used as an input for the model are: He-Ar gas mixture with a 5-% Ar concentration and a total constant gas pressure of 1.3 kPa.

3. Model description

The 2-dimensional time-dependent multi-fluid model [8] is used to study the new version of a multiple hollow-cathode discharge. One of the main assumptions in the model is that the background gas is dominant. The balance equations are solved for the previously defined active species, namely, electrons, ions and excited atoms.

The time evolution of the density for each active species $p$ is described by the particle balance:

$$\frac{\partial n_p}{\partial t} + \nabla \cdot \Gamma_p = S_p.$$  

The net source term $S_p = \sum c_{p,r} R_r$ is determined by the reactions occurring in the discharge, where $c_{p,r}$ is the net stoichiometric number of particles of species $p$ created in one reaction $r$, and $R_r$ is the corresponding reaction rate.

The flux density $\Gamma_p$ is solved in the drift-diffusion approach:

$$\Gamma_p = \mu_p E n_p - D_p \nabla n_p,$$

where $E$ is the electric field, $\mu_p$ is the mobility and $D_p$ is the diffusion coefficient.

The first term $\mu_p E n_p$ gives the flux due to the electric field (drift) and the second term $D_p \nabla n_p$ represents the flux due to density gradients (diffusion).
The time evolution of the electron density is given by the energy balance equation:

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \Gamma_e = S_e.$$  

The summation runs only over the electron impact reactions. To determine the effective source term for electron energy, the heating by the electric field and the energy loss in inelastic collisions must be taken into account. The energy flux density is:

$$\Gamma_e = \frac{5}{3} \mu_e E n_e - \frac{5}{3} D_e \nabla n_e.$$  

The model geometry is schematically presented in figure 2. The axis of symmetry $z$ in cylindrical coordinates coincides with the optical axis of the laser and, due to this symmetry, the simulation is only for a half of the outer diameter (10 mm). The distance between the centers of the holes is 40 mm, but due to discharge symmetry we simulate the half distance between the holes centers (i.e. 20 mm). A constant voltage of $-300$ V is applied. The gas mixture is He with 5% of Ar and the total gas pressure is set to 1.3 kPa. The He and Ar neutral gas atoms are assumed to be uniformly distributed throughout the discharge volume. The other species included in the model are the electrons, He*, He+, Ar*, Ar+, Cu and Cu+. For the ionic species, the mobility is a function of the reduced electric field $E/N$. The mobility coefficient for the electrons is defined as a function of the mean electron energy $\varepsilon$. In the present model, these functions are obtained from the freeware Boltzmann equation solver BOLSIG+ [9] and are included in the model in the form of lookup tables as a function of the mean electron energy. The set of included reactions contains 13 reactions. The ground state He and Ar atoms are directly ionized by electron collisions, or excited to the lumped levels Ar* and He*. These levels can be converted into ions by means of electron collisions or Penning ionization. The ground-state copper atoms can be ionized by electron impact ionization, charge transfer and Penning ionization.

4. Results and discussion

To verify the presumption of injecting additional atoms sputtered in the side cathodes to the cavity of the main cathode, a simulation is performed using the PLASIMO platform and is applied for three specific cases:

- sputtering is applied only to the main cathode $C$;
- sputtering is applied only to side cathode $C_i$;
- sputtering is applied to both $C$ and $C_i$.

In the first case, when sputtering is applied only to the main cathode $C$, the Cu atoms are concentrated near the cathode wall. The distribution of the Cu atoms sputtered from the wall of the main cathode is shown in figure 3(a). The Cu ions are located mostly at the center of the cathode cylinder in a radial direction 3(b) because of the higher electron density and intensive processes of ionization at the center of the main cathode.

In the second case, the main cathode is assumed to be with negligible sputtering and the sputtering occurs only in the side cathode $C_i$. The density distribution of Cu atoms produced by sputtering of the side cathode $C_i$ is presented in figure 4(a). The atoms are localized in the cathode holes near the walls. In this case, the Cu atoms density is higher compared to the previous case when the sputtering was applied to the main cathode only. The metal vapor production increases since the current density is
higher. After ionization, the Cu ions enter the main cathode cavity, as seen in figure 4(b), and their density is also higher.

**Figure 3.** Density distributions of the Cu atoms (a) and Cu ions (b) when the sputtering is applied to the main cathode.

In the third case when sputtering is applied to both cathodes, the on-axis distribution profile is a superposition of the profiles of the two previous cases. The density distributions of the Cu atoms and Cu ions in this case are presented in figure 5(a) and 5(b), respectively.

The sputtered Cu atoms are concentrated near the cathode walls, while the Cu ions are located mostly in the center of the main cathode, because of the intensive plasma region and higher electron density that leads to a more efficient electron-impact ionization. In the side cathode holes, the current density is higher, thus raising the production of metal vapor.

**Figure 4.** Density distributions of the Cu atoms (a) and Cu ions (b) when the sputtering is applied to the side cathode.

**Figure 5.** Density distributions of the Cu atoms (a) and Cu ions (b) when the sputtering is applied to the both cathodes.
Figure 6. Mean density of the Cu atoms (a) and Cu ions (b) when the sputtering is applied to the main cathode only, to the side cathode only and when both cathodes are sputtered.

5. Conclusions
The PLASIMO modeling platform is used to study a new version of a hollow-cathode discharge, where the sputtering is applied not only to the main cathode, but also to the side cathode. The maxima of the density of the sputtered Cu atoms and Cu ions are located at the center in radial and axial direction. The current density is higher in the side cathode holes, thus raising the production of metal vapor. The average densities calculated show that the Cu atoms and Cu ions densities increase and are almost doubled in the case when both cathodes are sputtered. Therefore, the cathode holes can be considered as additional controllable sources of metal atoms in the novel multiple hollow-cathode discharge.

Acknowledgments
This work was supported by the Bulgarian Ministry of Education and Science under the National Research Program “Young scientists and postdoctoral fellows” approved by DCM#577/17.08.2018.

The first author would like to thank Prof. Hassan Chamati for his continuous support. His advice through numerous discussions was invaluable during the preparation of this article.

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