# HOLLOW-CATHODE METAL ION LASERS

PhD thesis

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## 1. Historical review

The first **metal ion lasers** were constructed in 1965 at the University of Utah, where zinc and cadmium atoms were evaporated into positive column helium and neon discharges. Pulsed laser action was achieved on four different transitions in the infrared and visible regions. Later on lasing was reported on ultraviolet transitions of cadmium. Metal ion lasers are excited by Penning ionization and charge-transfer collisions of metal atoms with noble gas metastables and noble gas ions, respectively. In both cases metal atoms are ionized and excited in one step.

**Hollow-cathode** metal ion lasers appeared in the seventies. In hollow-cathode discharges (due to the presence of fast electrons) the density of noble gas atoms can be kept high, as compared to positive columns, even for relatively high concentration of metal atoms. This is advantageous especially when the upper laser level is excited by the charge-transfer reaction. In 1974 the first **sputtered** copper hollow-cathode laser was constructed in the Central Research Institute for Physics in Budapest. In the active region the metal vapor was produced by the ions bombarding the cathode surface. During the following years laser action has been achieved in many different metal/noble gas mixtures.

Besides the requirement of higher power, better stability and longer lifetime, there was always a challenging task to obtain laser action on shorter and shorter wavelength in the ultraviolet region. As a result **high-voltage** hollow-cathode discharges has been developed. At the beginning of the nineties very efficient laser excitation was achieved by the use of the **segmented hollow-cathode** arrangement. The laser threshold was lowered and the gain was increased significantly for many ultraviolet transitions.

Unfortunately the lifetime of the sputtered laser systems is usually very short. In spite of the long development period, the first commercial lasers appeared only few years ago. The final success can be attributed to the application of advanced technologies during the production process that helped to increase the purity of the laser tubes. These lasers are used for Raman spectroscopy. One of the other disadvantages of the sputtered lasers is that the discharge current and the metal density cannot be optimized at the same time. In principle this problem can be solved by a high-voltage discharge laser in which the metal vapor is produced by thermal evaporation.

## 2. Aims

The present thesis contains the results of experimental and modeling investigation of a segmented hollow-cathode gold ion laser and a novel heated hollow-anode-cathode laser.

It is the 282 nm laser transition that makes the gold ion laser interesting. There are many questions open connected to the operation of this laser discharge. The spectral and beam properties of the laser are not known either.

Since up to now the hollow-anode-cathode discharge was only used for the excitation of sputtered lasers, the heated zinc ion laser represents a new step in the development of metal ion lasers. Moreover, if laser action was obtained on the potential 210 nm transition that would be the shortest-wavelength continuous laser.

My aims can be summarized as follows:

a. to determine the operation characteristics of the sputtered segmented hollow-cathode gold ion laser:
   - to optimize the laser operation by means of parametric studies, to investigate the characteristics of the laser beam,
   - to make a computer simulation in order to obtain a better insight into the processes that play an important

role in the segmented hollow-cathode discharge,

b. to determine the characteristics of a novel hollow-anode-cathode zinc ion laser in which the metal vapor is produced by thermal evaporation.

## 3. Investigation methods

*Segmented hollow-cathode gold ion laser*

The 690 nm transition of the gold ion laser made it possible to investigate the mode structure of the beam. The laser tube consisted of six discharge modules, each 5.6 cm long with inner diameter of 3.1 mm. The inner surfaces of the cathodes were gold-plated to a thickness of $\sim$30 $\mu$m.

The output power was measured by a Hamamatsu PIN diode, the transversal modes were analyzed by a CCD camera. The structure of the longitudinal modes was determined by means of a Tec-Optics SA2 scanning Fabry-Perot interferometer. A He-Ne laser was applied to calibrate the dispersion of the interferometer. The spectrum of the discharge was detected by a Zeiss PGS-2 monochromator that was equipped by a photomultiplier tube.

To improve the sputtering efficiency a small amount of argon was added to the helium buffer gas. The laser was excited by $\sim$1 ms long current pulses with repetition rate of 1 Hz in order to avoid overheating of cathodes. The pulses were synchronized to the driving frequency of the Fabry-Perot interferometer.

*Simulation model of the segmented discharge*

The computer simulation code consists of five interconnected modules. The Monte-Carlo simulation of fast electrons and the module of the thermalization of sputtered metal atoms calculate the source functions of ions and thermalized metal atoms in the negative glow. These source functions are used as an input for the negative glow part of the model, where the rate equations of different species are solved. The motion of fast ions (and atoms) in the cathode sheath is followed by Monte-Carlo simulation. This way the spatial distribution of the electric charge is obtained in the sheath. Using the Poisson equation the distribution of the electric field is calculated. The last module determines the temperature distribution in the discharge. Different parts of the model are run iteratively until convergence is reached.

*Heated hollow-anode-cathode zinc ion laser*

The active region of the laser consisted of six hollow-anode-cathode modules, each 6 cm long with inner diameter of 8 mm. The electrodes were placed in a stainless steel housing that was heated by an oven. Zinc was evaporated into the laser from a side-arm placed at the tube center. At the ends of the active region additional dc positive column discharges were applied as confinement sections of the metal vapor. Due to the cathaphoretic effect zinc atoms were selectively driven towards the cathodes, not leaving them to escape from the heated region. Prior to the construction of the laser the characteristics of the cathaphoresis were investigated in details on a separate discharge tube.

## 4. New scientific results

*1. The mode structure of the 690 nm segmented hollow-cathode Au-II laser has been determined.*

The distribution of the light intensity in the cross-section of the laser beam was investigated by means of a CCD camera. It has been found, that under the conditions of the present measurements (the resonator length = 1.4 m, the mirrors' curvature = 3 m, the inner diameter of the laser tube = 3.1 mm) the laser operates only in the $TEM_{00}$ transversal mode. A scanning Fabry-Perot interferometer was used to measure the longitudinal mode structure. In the 10-20 mbar pressure range single mode operation was obtained, showing that there is a significant homogeneous broadening of the laser transition [f1].

*2. The time dependence of the laser power during the 1-ms-long current pulses has been explained by a simple model that describes the temperature and pressure changes in the tube.*

Due to the increased temperature in the active region the buffer gas density gradually decreases during the current pulses. This can explain the time dependence of the laser power [f1].

*3. Parametric studies has been carried out on the 282 nm segmented hollow-cathode Au-II laser and the optimal operating condition has been found.*

The output power and small-signal gain of the 282 nm Au-II laser has been measured as a function of the buffer gas pressure, discharge current and the concentration of the argon admixture. The laser power and the gain increases with pressure in the 10-20 mbar range. It has been found that the highest small-signal gain (52 $\%m^{-1}$) and the highest power (100 mW) can be obtained at argon concentrations of 0.75 and 0.25%, respectively [f3].

*4. A computer model of the segmented hollow-cathode discharge has been developed. The model provides us information about many discharge properties that are difficult to measure. Based on the modeling results the characteristics of the Au-II laser can be predicted.*

The model of the segmented hollow-cathode discharge consists of five interconnected blocks: electron Monte-Carlo simulation, thermalization of sputtered atoms, model of the negative glow, model of the cathode sheath and calculation of the temperature distribution. The structure of the discharge, the density distribution of ions and metal atoms and the flux energy distribution of particles hitting the cathode is obtained. It has been shown that the electron temperature can be used as a fitting parameter in the models of high current density laser discharges [f3].

*5. The characteristics of the cathaphoresis of zinc in positive column helium and neon discharges have been determined experimentally and a theoretical explanation of the results has been given.*

In positive column discharges of noble gas - metal vapor mixtures the metal atoms are driven towards the cathode (cathaphoresis). The spatial distribution of the zinc atom density along the positive column has been measured in helium and neon discharges. The metal source was placed at the cathode side of the positive column. It has been shown that the zinc density decreases towards the anode first linearly and further away exponentially. The theory of Gaur and Chanin has been modified for the conditions of the recent measurements giving an explanation of the experimental results [f2].

*6. A novel heated inner-anode zinc laser has been designed. The small-signal gain and the output power of the laser have been measured as a function of the buffer gas pressure, zinc density and discharge current.*

It has been shown that both the discharge current and the metal density has to be optimized in hollow-cathode metal ion lasers in order to reach the highest gain and output power. The maximal small-signal gain of $\sim$50 $\%\text{m}^{-1}$ has been obtained at the 492.4 nm transition. No gain has been found at the potential 210 nm laser transition. It is assumed that better laser parameters can be obtained by lowering the inner diameter of the cathode.

## 5. Publications

Scientific journals:

[f1] G. Bánó, L. Szalai, K. Kutasi, P. Hartmann, Z. Donkó, K. Rózsa, Á. Kiss, T. M. Adamowicz: Operation characteristics of the Au-II 690-nm laser transition in a segmented hollow-cathode discharge, *Applied Physics B: Lasers and Optics* **70**, 521-525 (2000)

[f2] G. Bánó, P. Horváth, K. Rózsa: Cathaphoretic confinement of Zinc evaporated into helium and neon discharges, *Journal of Physics D: Applied Physics* **33**, 2611-2617 (2000)

[f3] G. Bánó, L. Szalai, K. Kutasi, Z. Donkó, K. Rózsa, T. M. Adamowicz: Au-II 282 nm segmented hollow cathode laser - parametric studies and self-consistent modeling, accepted for publication: *Journal of Applied Physics*

Conferences:

[k1] L. Szalai, T. M. Adamowicz, A. Tokarz, G. Bánó, K. Kutasi, Z. Donkó, and K. Rózsa: Optimum Operating Conditions of a Hollow - Cathode Au-II Laser, Optika'98 : 5th Congress on Modern Optics, Budapest, Hungary, 14-17 September 1998 *Proc. of SPIE* **3573**, 28-31 (1998)

[k2] L. Szalai, T. M. Adamowicz, A. M. Tokarz, G. Bánó, K. Kutasi, Z. Donkó and K. Rózsa: Operation characteristics of a segmented hollow-cathode Au ion laser, 11th Symposium on elementary processes and chemical reactions in low temperature plasma, Low Tatras, Slovakia, 22-26 June 1998, Book of contributed papers, p. 157.

[k3] L. Szalai, G. Bánó, K. Kutasi, Z. Donkó and K. Rózsa: Optimization of hollow cathode discharges for pumping metal ion lasers, Tenth International School on Quantum Electronics: Laser Physics and Applications, Varna, Bulgaria, 21-25 September 1998, *Proc. of SPIE* **3571**, 140-144 (1999)

[k4] M. Jánossy, G. Bánó, Z. Donkó, K. Rózsa, L. Szalai: Charge transfer excitation cross-sections in the He-$Au^+$ laser, XV. ESCAMPIG, Lillafüred, Hungary, Aug. 26-30, 2000. *Europhysics Conference Abstracts* **24F**, p. 86

[k5] G. Bánó, L. Szalai, K. Kutasi, P. Horváth, P. Hartmann, Z. Donkó, K. Rózsa: High-voltage hollow-cathode metal ion lasers for the UV, Week of Doctoral Studies °00, Prague, June 13 to 16, 2000, Proceedings of contribution papers, edt. J. Safránková, p. 290