A simple method for experimental determination of electron temperature and electron density in a nanosecond pulsed longitudinal discharge used for excitation of high-power atomic and ionic metal and metal halide vapour lasers

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Abstract. A simple method based on the time-resolved measurement of electrical discharge parameters, such as tube voltage and discharge current, is developed and applied for determination of electron temperature and electron density in the discharge period of a nanosecond pulsed longitudinal discharge, exciting high-power DUV Cu$^+$ Ne-CuBr, He-Hg$^+$ and He-Sr$^+$ lasers.

1. Introduction

Electron temperature and electron density together with gas temperature are the most fundamental plasma parameters in gas discharges and their experimental or theoretical determination is important and relevant problem for understanding and prediction of numerous phenomena in gaseous discharges, laser physics, plasma technologies, gas-discharge mass spectroscopy, absorption and emission spectroscopy, and plasma in general. Electron temperature and electron density determine thoroughly the characteristics constants for elastic and inelastic electron-atom and electron-ion collisions, as well as three-body electron-ion recombination [1-3]. For gas discharge lasers in particular, they directly or indirectly influence on the creation of the inverse population and hence the output laser characteristics.

The strontium ion (Sr$^+$) recombination laser is a source of violet radiation (430.5 nm and 416.2 nm) with average output power exceeding 1 W [4, 5], and as such, it has potential for application in various areas of lithography, photochemistry and photobiology. The Sr$^+$ laser is valuable as a pump source for narrow-linewidth blue-green dye lasers. This laser is an ideal violet companion to copper vapour (510.6 nm green and 578.2 nm yellow) and gold vapour (628.3 nm red) lasers for a number of applications. Water-cooled Sr$^+$ recombination laser, stable-operating at average output power of 1.1 W with independent production of Sr vapour, was developed and studied [4, 5]. The highest average laser power of 1.5 W was achieved under transient conditions. The obtained results were the highest ones for cylindrical geometry of the discharge tube.

A Hg ion (Hg$^+$) laser, excited in He-Hg nanosecond pulsed longitudinal discharge (NPLD) and stable operating on the 614.9-nm laser transition at average output power of 240 mW, which was the highest one for the gas discharge Hg$^+$ lasers, was reported in [6, 7]. This laser has potential for application in various areas of photobiology, photochemistry, and spectroscopy. In addition, laser radiation at 614.9 nm could be a valuable instrument at the treatment of the cancer by using...
photodynamic therapeutics. Until now in this area gold vapour lasers has been successfully used, but their laser tube design and therefore their production are much more complicated.

Laser oscillation was obtained on four deep ultraviolet Cu ion (DUV Cu⁺) transitions - 248.6 nm, 252.9 nm, 260.0 nm, and 270.3 nm, in Ne-CuBr NPLD [7, 8]. The small-signal gain of 19 %/m and 16 %/m measured on 248.6 nm and 270.3 nm laser transitions, respectively, was the highest for DUV Cu⁺ lasers. An active zone diameter scanning of a DUV Cu⁺ Ne-CuBr laser was made [9]. The discharge conditions for achieving of a maximal average output power at the DUV lines were found for each active zone diameter. An average output power of 1.3 W and a specific average laser power of 56.6 mW/cm³ (at an active volume of 23 cm³), were obtained at multiline output. The average output power of about 0.85 W and the peak pulse power of about 3.25 W on the 248.6 nm laser line were also the highest for the DUV Cu⁺ lasers.

In view of the enormous prospect for application of these lasers, a detailed study on basic plasma parameters, namely gas and electron temperatures and electron concentration is undertaken.

Typical methods to measure the electron temperature include the use of a Langmuir probe and laser Thomson scattering, which are inapplicable to a NPLD. In the literature there are several models, which predict, among the other parameters, values of electron temperature with considerable variation, and furthermore there is no overlap.

Average and time-resolved electron temperatures, which were experimentally determined by the line-ratio method of optical emission spectroscopy, were reported in [10-12] for several metal halide vapour lasers excited by NPLDs. Average values of the electron temperature were also found by averaging the time-resolved electron temperature over the time. Unfortunately, spectral investigation through devices equipped with photomultiplier are prohibited for the discharge period of NPLDs, because of the noise from high-power electrical pulses and the steep rise of voltage and current pulses of TV.s⁻¹ and GA.s⁻¹.

2. Experimental setup

Discharge zone diameter, which is optimal for laser oscillation on the corresponding transition, and discharge zone length are shown in table 1. Optimal buffer-gas pressure is also presented in table 1.

| Laser   | \(d_a\) (cm) | \(l_a\) (cm) | \(p\) (Torr) |
|---------|--------------|--------------|--------------|
| He-Hg⁺  | 1.5          | 70           | 7            |
| Ne-Cu⁺  | 0.71         | 100          | 16.7         |
| He-Sr⁺  | 1.6          | 50           | 230 / 300    |

The investigated NPLDs discharges are excited by an electrical scheme with interacting circuits (IC scheme), shown in figure 1 and described in details in [3]. The switch T is a hydrogen thyratron TGI 1000/25. The capacitors \(C_1, \ldots, C_4\), forming a capacitor bank (CB) are of the low-inductance KVI-3 type. Their capacitance is experimentally optimized for achieving of maximal output laser parameters. The capacitor bank is charged from a high voltage (HV) rectifier. The inductor \(L_1\) is used to level the potential of the electrodes during the period of charging of the CB. The metal plates, \(P_1\) and \(P_2\), with semi cylindrical shape are made of duralumin sheet and are located close to the laser tubes. The pulsed excitation scheme could deliver voltage and current pulses with an amplitude up to 25 kV and 500 A, respectively, an excitation pulse duration of 50–300 ns, and a pulse repetition frequency of 5–30 kHz.

Varying the four capacitors, as well as the matching inductor \(L\), the amplitude, waveform and duration of the pulses of the discharge current and the tube voltage, as well as the phase shift between
them, could be manageably changed and controlled. In this way, appropriate discharge conditions for different excitation processes, such as electron impact excitation, charge transfer, Penning ionization, and etc., were found and hence output parameters of various metal atom and ion lasers were increased from 35% up to two times in comparison with the frequently used electrical pulsed excitation schemes [3, 13].

The waveforms of the discharge current and the tube voltage are detected by a Rogowski-coil probe and a low-inductance Tektronix P6015 HV probe, respectively. All pulses are displayed on a Tektronix 2455A oscilloscope with a 20 MHz cutoff filter.

![Figure 1. Schematic diagram of the excitation circuit: C1, C2, C3 and C4 - capacitors; L and L1 - inductors; P1 and P2 - metal plates; LT - laser tube; T - thyratron.](image)

3. Experimental results and discussion
As has been done in [3, 14], experimentally determined pulses of the tube voltage $U$, the discharge current $I_R$, and the current $I_{C3}$ of the capacitor C3 are mathematically processed, using the well-known equation (1), in order to eliminate the inductive component of the voltage and to calculate the active voltage $U_R$, the pulse power $W = U_R I_R$, and the plasma resistance $R = U_R / I_R$:

$$U_R = U - L_R \frac{dI_{C3}}{dt} - (L_P + L_R) \frac{dI_R}{dt}$$

where $L_R$ and $L_P$ are the stray inductances of the discharge tube and the interacting circuit, which includes capacitor C3, respectively, and are calculated from the oscillograms.

The NPLD electric field is uniform, and is determined by the external applied voltage [15]. The use of an electron energy distribution function (EEDF) of Maxwellian form instead of the true EEDF allows good agreement with experiment [15]. It is well known that the electron temperature $T_e$ is a function of the reduced longitudinal electric field $E_z / p$, which is not a strictly linear function. Experimental data for the function $T_e = f(E_z / p)$ given in [16] for self-sustained PC gas discharge in He, Ne, and Ar allow us to obtain $T_e$. From the plasma resistance $R$ and the geometrical sizes of the NPLDs (see table 1) together with data presented in table 2 [17] electron density $n_e$ can be estimated.

| Table 2. Estimated values of electron mobility $\mu_e$, effective collisions frequency for momentum length $v_m$, conductivity $\sigma$, and mean free path $l_p$. |
|-----------------|-------|-----------------|-----------------|-----------------|-----------------|
| Gas     | $\mu_e$, Torr.cm$^2$/Vs | $v_m$, Torr$^{-1}$s$^{-1}$ | $\sigma$, Torr.cm$^{-2}$/Ω | range of $E/p$, cm.Torr$^{-1}$ | $l_p$, 10$^{-2}$ cm.Torr |
| He     | 0.86  | 2.0             | 1.4             | 0.6-10          | 6               |
| Ne     | 1.50  | 1.2             | 2.4             | 0.2-2           | 12              |
For He electron density $n_e$ can be also evaluated as in [15]:

$$n_{e2} = 4.65 \times 10^{13} \frac{j \cdot p_{He}}{E_z}$$

(2)

where $n_{e2}$ is in cm$^{-3}$, $j$ is in A.cm$^{-2}$, $p_{He}$ is in kPa and $E_z$ is in V.cm$^{-1}$.

Pulses of the tube voltage $U$, the discharge current $I_R$, and the current $I_{C3}$ of the capacitor $C_3$ are shown in figure 2 (a) for a nanosecond pulsed longitudinal discharge in He used for excitation of HeHg$^+$ laser. Waveforms of the active voltage, the discharge current, the plasma resistance, and the electric power are also presented in figure 2 (b). Time dependence of the electron temperature $T_e$, the longitudinal electric field $E_z$, and the electron density $n_e$ is plotted for this gas discharge in figure 3. The electron density is calculated by the two approaches mentioned above. The discrepancy is insignificant.

Waveforms of the active voltage $U_R$, the discharge current $I_R$, the plasma resistance $R$, and the electric power $W$ are given in figure 4 for a nanosecond pulsed longitudinal discharge in He, used for excitation of He-Sr$^+$ recombination laser.

(a)                                                                               (b)

Figure 2 (a) and (b). Pulses of $U$, $I_R$, and $I_{C3}$, as well as waveforms of $U_R$, $I_R$, $R$, and $W$ for gas discharge in He, exciting He-Hg$^+$ laser

(a)                                                                               (b)

Figure 3. $T_e$, $E_z$ and $n_e$ for gas discharge in He, exciting He-Hg$^+$ laser

(a)                                                                               (b)

Figure 4. Waveforms of $U_R$, $I_R$, $R$ and $W$ for gas discharge in He, exciting He-Sr$^+$ laser
Pulses of the active voltage $U_A$ and the discharge current $I_R$ (a), as well as waveforms of the plasma resistance $R$ and the electric power $W$ (b), are presented in figure 5 for gas discharge in Ne used for excitation of DUV Cu$^+$ Ne-CuBr laser.

![Figure 5(a) and (b). Waveforms of active voltage $U_A$ and $I_R$, as well as of $R$ and $W$ for gas discharge in Ne, exciting DUV Cu$^+$ Ne-CuBr laser.](image)

Time dependence of the electron temperature $T_e$, the longitudinal electric field $E_z$, and the electron density $n_e$ is shown in figure 6 for nanosecond pulsed longitudinal discharge in He (a) and Ne (b) used for excitation of Sr$^+$ recombination and DUV Cu$^+$ Ne-CuBr lasers, respectively.

![Figure 6 (a) and (b). $T_e$, $E_z$, and $n_e$ for gas discharge in He and Ne, respectively.](image)

4. Conclusions
The electrical properties of NPLDs, exciting the high-power DUV Cu$^+$ Ne-CuBr, He-Hg$^+$, and He-Sr$^+$ lasers, are investigated. The time-resolved measurement of electrical discharge characteristics, such as tube voltage and discharge current, permits determination of electron temperature and electron density in the discharge period of these gas discharges. The obtained results are in fairly good agreement with the existing self-consistent models for the DUV Cu$^+$ Ne-CuBr and He-Sr$^+$ lasers [1-3, 18] or with the theoretical estimations, which are made following [17].
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