Analytical calculation of the gas temperature and time-resolved measurement of the electron temperature of a gas discharge in He and Ne-He mixtures

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Abstract. The gas and electron temperatures were determined in a nanosecond pulsed longitudinal discharge in a new high-temperature discharge tube design developed for a high-power large-volume middle-infrared He-SrBr₂ laser. Assuming that the gas temperature varies only in the radial direction, analytical solution of the steady-state heat conduction equation was obtained at uniform power input and, for the first time, for each zone of the discharge tube, namely, discharge zone, ceramic tube, discharge-free zone incompletely filled with zirconia fibers insulation, and quartz tube. The line-ratio optical emission spectroscopy method was used to determine experimentally for the first time the time-resolved electron temperature in the discharge afterglow, namely, measurement of the relative intensities of some He and Ne spectral lines originating from different upper levels. The average values of the electron temperature were also found by averaging the time-resolved electron temperature over the time.

1. Introduction

One of the main fundamental and relevant problems in plasma physics is determining the main plasma parameters, such as the electron density, the gas and electron temperatures. This is particularly important for the gas-discharge laser physics, gaseous discharges, plasma technologies, gas-discharge mass spectroscopy, absorption and emission spectroscopy and plasma in general. As was demonstrated in [1], the characteristic constants for the heavy-particle interaction depend on the gas temperature. In what concerns the metal or metal-halide vapor lasers, the thermal mode, as well as the radial temperature distribution, are of great importance for the stability of the laser operation and for achieving high output characteristics, because they not only control the laser-levels kinetics, i.e. the creation of population inversion, but also the concentration of the active particles, i.e. particles on whose transition laser oscillation is obtained. The experimental technique for gas temperature measurement relying on measurements of the Doppler broadening of spectral lines and thermal lens focal distance are definitely imprecise. The electron temperature determines the characteristic constants for elastic and inelastic electron-atom and electron-ion collisions, as well as the three-body electron-ion recombination [2, 3]. For gas-discharge lasers in particular, the electron temperature influences the creation of population inversion via the abovementioned processes, which populate or

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depopulate the upper and lower laser levels. Typical methods to measure the electron temperature include the use of a Langmuir probe and laser Thomson scattering (LTS), which are inapplicable to the gas discharge used in our experiments. Several models have been described which predict, among other parameters, the electron temperature values with considerable discrepancies and, moreover, without overlap [2, 3].

Two methods have been proposed and investigated to increase the operating temperature (up to 1300 °C) of the gas-discharge tube typical for middle-infrared (MIR) He-SrBr2 laser pumped by a nanosecond pulsed longitudinal discharge [4]. This laser has enormous prospects for application in laser medicine and as an alternative laser source of free electron lasers. Briefly, the methods consist in adding Ne to the He buffer-gas without additional active-volume insulation [5] and, the one presented in this paper, development of a new discharge tube design with ZrO2 active-volume insulation. For this discharge tube, we present here calculations of the gas temperature distribution and experimental time-resolved measurements of the electron temperature applying for the first time the line-ratio method of OES to the nanosecond pulsed longitudinal discharge. The average values of the electron temperature were also found by averaging the time-resolved electron temperature over the time.

2. Experimental setup

The new high-temperature large-volume discharge tube is shown schematically in figure 1. The basic tube with a 71.5-mm inside diameter and a 76-mm outside diameter is made of fused quartz. A ceramic insert, confining the discharge zone, with a 30.5-mm inside diameter, a 38.5-mm outside diameter and a length of 98 cm is coaxially sleeved in the basic tube. The zone between the ceramic insert, basic quartz tube and the holders of the ceramic insert is incompact filled with ZrO2 fibrous insulation. The discharge operates in a self-heating regime. The gas discharge tube is not loaded with SrBr2, as is shown in figure 1. The temperature at the quartz tube surface is measured by a thermocouple. The electrodes of the discharge tube are made of porous copper with a special design. CaF2 windows are glued to the ends of the discharge tube. The nanosecond pulsed longitudinal discharges investigated are excited by an electrical scheme with interacting circuits (IC scheme). The spectral studies were performed using a Bentham M300 spectrometer equipped with one 1800 groove/mm holographic grating and a DH-2 photo-multiplier. The spontaneous emission pulses were displayed on a Tektronix 2455A oscilloscope with a 20 MHz cutoff filter.

3. Theoretical and experimental results

3.1. Analytical solution of the steady-state heat-conduction equation

Assuming that the gas temperature varies only in the radial direction, the steady-state heat conduction equation is solved at uniform power input as in [5]. For the first time, the well-known solution of this equation is obtained for the case of one discharge zone with radius \( R_1 \) and three discharge-free zones, namely, a ceramic tube within \( R_1 \leq r \leq R_2 \), a compact or incompact fill of ZrO2 insulation within \( R_2 \leq r \leq R_3 \), and a basic quartz tube within \( R_3 \leq r \leq R_4 \). The dependence of the thermal conductivity \( k \) of gases and gas mixtures has the form \( k = B T_g^a \), where \( B \) and \( a \) are constants (within a certain temperature range) specific for each gaseous or solid medium. The constants \( B \) and \( a \), which determine...
the thermal conductivity, could be obtained through fitting the existing experimental data taken from [6]. The thermal conductivities of He, the ceramic Al$_2$O$_3$ tube, the compact fill of ZrO$_2$ insulation, the incompact fill of He-ZrO$_2$, and the basic quartz tube are presented in table 1.

|         | He     | Al$_2$O$_3$ | ZrO$_2$ | He-ZrO$_2$ | quartz |
|---------|--------|-------------|---------|------------|--------|
| B       | 34.9x10$^{-4}$ | 44323.1     | 7326.2x10$^{-4}$ | 655.9x10$^{-4}$ | 705.9x10$^{-4}$ |
| a       | 0.670  | -1.227      | 0.130   | 0.366      | 0.487  |

In figure 2, a comparison is shown between the gas temperature distributions for two discharge tube designs, namely, without and with zirconia insulation in the discharge-free zone for a gas discharge in pure helium. The following cases are considered: 1 and 2 are gas temperature profiles neglecting and taking into account, respectively, the influence of the ceramic tube radiance on the gas temperature distribution, which were already presented in [5], for a gas discharge tube without zirconia insulation; 3 is the case experimentally studied with compact fill of zirconia insulation; 4 and 5 are the cases experimentally investigated with incompact fill of zirconia insulation for two different average input powers of 2.1 kW and 2.6 kW, respectively.

3.2. Experimental determination of time-resolved and average electron temperature

Under local thermodynamic equilibrium (LTE) conditions, measuring the relative intensity ratio of two lines originating from different upper levels $i$ and $j$ would be sufficient for determining the electron temperature by using the relative intensity ratio below, the Boltzmann relation for the relative equilibrium populations of the two upper levels and the expression derived from them:

$$\frac{I_i}{I_j} = \frac{\lambda_i n_i A_i}{\lambda_j n_j A_j}, \quad \frac{n_i}{n_j} = \frac{g_j}{g_i} e^{\frac{E_j - E_i}{k_b T_e}},$$

$$T_e = \frac{\ln \left( \frac{I_i \lambda_i n_i A_i}{I_j \lambda_j n_j A_j} \right)}{k_b},$$

where $\lambda_i$ and $\lambda_j$ are the wavelength of the transitions measured from levels $i$ and $j$; $A_i$ and $A_j$ are the transition probabilities, i.e. the spontaneous rate coefficients for the transitions from measured levels $i$ and $j$; $n_i$ and $n_j$ are the populations in levels $i$ and $j$; $g_i$ and $g_j$ are the statistical weights, i.e. the degeneracies of levels $i$ and $j$; $E_i$ and $E_j$ are the energies of levels $i$ and $j$; and $k_b$ is the Boltzmann constant. Using the data required for experimental determination of the electron temperature $T_e$ presented in [5] for each He and Ne transition, the time dependence of the electron temperature is...
shown in figure 3 for the afterglow of a nanosecond pulsed longitudinal discharge in pure helium (45 Torr) and with addition of a small amount of neon (5, 10 and 15 Torr, maintaining the total Ne-He mixture pressure of 45 Torr constant) to the helium buffer gas. The average input power used is also given in the figure, as well as the average values of the electron temperature found by averaging the electron temperature over the time. As one can see, the dependence of the time-resolved and average electron temperatures on the added neon pressure has a pronounced minimum at 10 Torr.

**Conclusions**

By solving analytically the steady-state heat-conduction equation for uniform power input and under the assumption that the gas temperature varies only in the radial direction, it is shown that the crucial problem impeding the further development and application of high-temperature large-volume He-SrBr₂ laser is solved through the development of a new discharge tube design with incompact ZrO₂ active-volume insulation. The line-ratio OES method of remote measurement is the only method applicable to nanosecond pulsed longitudinal discharges. This method is used for the first time to determine experimentally the time-resolved electron temperature in the nanosecond pulsed longitudinal discharge afterglow.

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