Investigation electrical characteristic of plasma of helium-neon lasers

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Abstract. The current-voltage characteristics of a glow discharge flowing in narrow long tubes corresponding to helium-new lasers are investigated. Studies were conducted on a specially designed layout, which includes discharge tubes of different diameters. The model was connected to the pumping and filling system, which allows varying the gas content and the working pressure. The discharge was excited in mixtures based on helium and neon. A technique has been obtained for the analytical calculation of current-voltage characteristics, based on taking into account the gas heating during discharge.

Gas-discharge devices are widely used in various fields of science and technology. The high prevalence of such devices is due to the large variety of design features associated, inter alia, with the discharge type flowing in the instrument. Among the widest list of such devices, a special place is occupied by devices with an extended positive column of a glow discharge [1, 2], which include, in particular, glow discharge lasers (GDL). GDL are actively used for technological and metrological purposes. Knowledge of the behavior of the current-voltage characteristics (CVC) of the discharge tubes of the GDL provides the ability to control the deviation of the parameters of the active elements of lasers from nominal values and the implementation of the necessary correction. However, the individuality of the technical solutions implemented in the GDL makes it difficult to assess and predict the effect of changes in discharge conditions on the current-voltage characteristics of lasers [3]. To eliminate the need for additional experiments for specific discharge conditions of a laser, it is proposed to use approximating expressions for the CVC of the GDL, taking into account the variety of discharge conditions for different types of lasers [4].

In general, it can be said that for working types of gas-discharge glow discharge lasers, the voltage drop \( U \) on the tube is the sum of the cathode potential drop \( U_k \) and the voltage drop in the positive column \( U_{pc} \):

\[
U = U_k + U_{pc}.
\]

Consider this expression in more detail. Cathode potential drop depends on the type of cathode material and type of discharge. The cold cathode used in most modern GDL, \( U_k \) equals 100 – 250 V. Since the cathode usually has a current margin for emission, for working currents of gas-discharge lasers \( U_k \) is constant.

Taking into account the fact that in the narrow extended discharge capillaries used in the LTE, \( E_{pc} \) is high and is a few of kV·m⁻², the main share of the total voltage drop falls on the positive pole: \( U_{pc} \gg U_k \). Thus, it is possible to accept for conditional GDL \( U_k \) is constant.
Experimental current-voltage characteristics were obtained using the setup, which consists of a multi-model laser layout with a power supply unit, in which discharge current adjustment is provided (figure 1), and vacuum system for pumping and filling laser (figure 2). During operation, it was possible to change the length $L$ of the active medium using the switch $S$. Possible lengths of the active medium are 1.3; 1.12; 0.98; 0.78; 0.61; 0.47 and 0.35 m. The discharge current and the voltage drop $U$ at the discharge gap of the laser are measured using a built-in milliamperemeter and a digital kilovoltmeter [5].

Figure 1. Electrical installation scheme on the base of helium-neon laser.

Figure 2. Scheme of a vacuum unit for pumping a laser.

Vacuum installation includes foreline and oil fractional high-vacuum pumps, cylinders with helium, neon and a mixture of helium and neon, as well as a pressure recording system. The vacuum unit was controlled by five cranes. Crane 1 is three-way: the handle down - foreline pump is connected to the atmosphere, the handle aside – pumping the internal volume of the foreline pump; handle up –
pumping the working volume of the laser. Cranes 2 and 3 are two-way: handle down – the valve is open; handle up – the valve is closed. Cranes 4, 5 and 6 are portion: the handle down – the volume of the crane is connected to the cylinder, the handle up - the volume of the crane is connected to the working volume. Pressures greater than 0.5 mm Hg are monitored by a U-form manometer. The limit of its measurements is from 0.1 mm Hg. up to 15 mm Hg.

Before the start of the experiment, the working volume of the laser and the vacuum system were carefully pumped out to pressure $10^{-3}$ mm Hg (0.1 Pa). The sequence of actions when working with a vacuum unit was as follows. Using a crane 5 was fed a portion of the mixture into the working volume of the laser. Next, the pressure of the mixture was determined by the oil U-form manometer, equipped with a mirror scale. The readout was based on the difference in oil levels in the left and right arms of the gauge (One large scale division corresponds to 1 mm Hg). Then set the specified length of the active medium L. Smoothly increasing the laser output power, excited the laser discharge and using the built-in milliamperemeter and kilovoltmeter measured discharge current $I$ and voltage drop $U$ in the discharge gap for three values of $L$. The vacuum system of the breadboard model made it possible to carry out step-by-step pumping out, which ensured that the pressure $p$ of the working gas mixture required for the experiments was established. For this, the Crane 3 valve was closed and, by opening the Crane 2 and Crane 3 crane for 5–10 s, the intermediate volume between the Crane 2 and Crane 3 valves was pumped out, after which the Crane 2 valve was closed. With the help of the Crane 3 crane, the pressure in the intermediate and working volumes was equalized, and a new, reduced pressure was recorded. The experiment was carried out for different pressures. Experimental data were obtained for the CVC for the length of the discharge gap $L = 1.3$ m, the filling with a helium-neon mixture in the proportions 5:1, 10:1 and 15:1, the diameter of the discharge gap 6.5 mm [6].

![Figure 3. CVC of discharge at $L = 1.3$ m, $d = 6.5$ mm and ratio He:Ne =15:1.](image)

The study of the current – voltage characteristics in the field of small currents was limited by the discharge break. Of particular interest is the analytical description of the current-voltage characteristics of a glow discharge in a mixture of helium and neon. It follows from the experiment that the current-voltage characteristic of such a discharge is of a falling character, that is, the voltage drop decreases with increasing discharge current [7]. The nonlinear and non-constant character of the I–V characteristic of the positive column can be associated with plasma heating processes. To evaluate the I–V characteristic can use the following expression:

$$\frac{j}{j_0} = \left(\frac{E_0}{E}\right)^{3/2} \left(\frac{E_0}{E} - 1\right).$$
Figure 4. CVC of discharge at $L = 0.47$ m, $d = 6.5$ mm and ratio He:Ne = 5:1.

Here $j_0 = \frac{n_0 c_r T_0 v_0^0}{E_0}$, $E_0$ – field strength required to maintain a very low current at which the plasma temperature does not differ from room temperature, i.e. at which the plasma does not heat up. In the last expression $v_0^0 = \frac{\lambda}{n e_r p l} \left( \frac{2.8}{R} \right)^2$ – the frequency of the heat sink from the plasma gap.

Substituting these expressions into the formula above, we obtain the final formula for calculating and building the CVC of a positive column:

$$j = n_0 c_r T_0 v_0^0 E_0^{1/2} \left( \frac{E_0}{E} \right)^{3/2} \left( \frac{E_0}{E} - 1 \right).$$

With a certain degree of accuracy, the distribution of the field strength in the region of the positive column can be considered constant. This means that in the PC region the voltage does not depend on the coordinate.

Figure 5. Comparison of experimental and theoretical CVC at different pressures.

According to the theory of Engel and Steenbek, the cathode voltage drop does not depend on the current density, therefore the IVC of the cathode potential drop region will be parallel to the axis of the current density. The general view of the CVC is determined by the sum of the CVC of the positive
column and the CVC of the cathode region [8]. Experimental characteristics, and obtained using the above calculation method are presented in figure 5.

Comparison of experimental and theoretical CVC gives a good match. Thus, the proposed method will automate the process of calculating the values of the discharge current and voltage of the laser. It can also be expanded to other types of gas-discharge lasers.

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