Methodic of the computer calculation of the plasma impedance of the glow discharge lasers

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Abstract. In this work an expression for the dynamic resistance of a glow discharge in long tubes was obtained and analyzed. The expression describes the physical processes taking place in the positive column of a glow discharge. The analysis of the frequency dependences of the active and reactive constituents, as well as the dynamic resistance module for discharge conditions corresponding to glow discharge lasers, was performed. On the basis of the expressions obtained a computer program for modeling the dynamic resistance of discharge was developed. The program allows you to calculate and display the plots of the frequency dependences of the active and reactive constituents, as well as the module of the dynamic resistance of the discharge gaps of lasers. Also, the program provides a function for constructing hodographs of dynamic resistance.

Among the widest range of devices for plasma electronics, devices with a longitudinal positive column (PC) of discharge occupy a special place, in particular, glow discharge lasers (GDL). GDL is actively used for technological and metrological purposes. However, due to physical and structural features, the laser radiation has a temporary instability caused by the influence of various factors. This implies the use of GDL in conjunction with systems of stabilization power of radiation [1].

One of the options for stabilizing the power of laser radiation is to adjust the pump level of an active medium. In glow discharge lasers, this process reduces to a forced antiphase change in the discharge current. An important factor is the knowledge of the discharge behavior in dynamics. The discharge gap of lasers as an element of an electrical circuit has an AC resistance, which is determined by the capacitance and inductance of the plasma.

The discharge conditions realized in LTE correspond to the region of sharp drop in the current-voltage characteristic (CVC) of the discharge gap, when there is a transition stage from free electron diffusion to ambipolar one. Since GDL operate on direct current, one can use the method of small perturbations to obtain expressions for the total dynamic resistance. In accordance with it, the current and voltage of the discharge, accordingly, have the form: $U = U_0 + u$, $I = I_0 + i$. In these expressions $I_0$, $U_0$ are stationary values of the current and voltage on the discharge, corresponding to the decreasing current-voltage characteristic; $i$, $u$ are the variable components of the discharge current and voltage, with $u << U_0$, $i << I_0$. Then the dynamic resistance will be determined by solving the equation:

$$\frac{1}{I_0} \frac{\partial^2 i}{\partial t^2} + \frac{1}{I_1} \frac{di}{dt} + \frac{i}{I_2} = \frac{1}{U_0} \frac{\partial^2 u}{\partial t^2} + \frac{1}{U_1} \frac{du}{dt} + \frac{u}{U_2}. \quad (1)$$

Solution of equation (1) was sought in the form
After the transformation of equation (2), an expression is obtained for the dynamic resistance of the GDL discharge, as the total resistance to AC

\[
Z_d = \frac{U_0}{I_0} e^{ho \varphi} = \frac{I_0^{-1} (j \omega)^2 + I_1^{-1} j \omega + I_2^{-1}}{U_0^{-1} (j \omega)^2 + U_1^{-1} j \omega + U_2^{-1}},
\]

(2)

where \( R \) and \( X \) are the active and reactive components of the PS impedance; \( \omega \) is the circular frequency. The remaining parameters in (3) depend on the discharge conditions [2].

An important role in the analysis of the dynamic discharge resistance is played by the static CVC. As was said above, for the GDL conditions the CVC has a decreasing character [3]. In this case, the CVC can be approximated by an expression that includes the length of the discharge gap \( L \) and the longitudinal gradient of the potential \( E_z \):

\[
U_0 = U_k + aE_z L \rho,
\]

where \( U_k \) is the cathode voltage drop, which is determined by the pair of gas-cathode material; \( a, b \) - constants, depending on the kind of gas and discharge conditions. In this case, it is possible to introduce a static slope of the current-voltage characteristic [4]:

\[
\rho = \frac{dU}{dl} = abLE_z \rho^{b-1}.
\]

In this case, the anode voltage drop was assumed to be zero. The longitudinal gradient \( E_z \) of the potential in the positive column depends on the nature of the gas, the working pressure, and also the diameter of the discharge gap, and is related to the electron temperature \( T_e \) through the electron accommodation coefficient \( \chi \) [5]. The electron temperature is a complicated function of the discharge conditions and can be solved by solving the ionization balance equation [6] - [8].

To automate the process of analyzing the discharge impedance behavior, a program was developed in the MS Visual C# programming environment.

![Figure 1](image-url)  
**Figure 1.** Program for modeling the dynamic resistance of glow discharge lasers

Program makes it possible to calculate the active, reactive constituent, the impedance module, and also construct a hodograph of impedance. Before calculating the user, it is possible to select the type
of gas mixture, specify the discharge conditions, the range of the discharge current and the frequency of the signal. The result of the calculation is the family of dependences of the impedance components on the frequency for different discharge currents. Each dependency family is located on a separate tab. The technique based on the use of expression (3) is the basis of the technique for modeling the impedance of plasma of glow discharge lasers.

The results of calculating the dynamic resistance of the plasma obtained by using the developed program was analyze. At low modulation frequencies, the discharge plasma exhibits weakly inductive properties, and the impedance has a purely active value. Since under these conditions the VAC is of a falling nature, the active component of the discharge resistance \(R(f, I)\) will have a negative value, and be determined by the operating point on the characteristic (figure 1). With increasing frequency, the active resistance of the discharge reaches a constant value equal to the static discharge resistance. The dependence of the reactive component of the resistance \(X(f, I)\) has a resonance character (figure 2). At high modulation frequencies, the plasma does not have time to respond to external influences, so the reactive component of the impedance tends to zero. Figures 3 and 4 show respectively the families of dependences of the impedance module of the discharge \(Z_d(f, I)\), and its travel time curves. They reflect the general trends in the dependencies \(R(f, I)\) and \(X(f, I)\). The advantage of the proposed method for calculating the impedance of the discharge of laser tubes is that it allows one to correctly assess the nature of the reactivity of the discharge, the presence of active resistance of both signs [9].

The results of the simulation were compared with the experimental data of the dynamic resistance of the most widely distributed types of glow discharge lasers: a He-Ne-laser and a carbon dioxide laser (figure 2). Good agreement between theory and experiment is obtained.

![Figure 2](image)

**Figure 2.** Comparison of experimental data and simulation results: (a) – He-Ne-laser; (b) – carbon dioxide laser.

The dynamic properties of the discharge in the range of measurement parameters corresponding to the working conditions of glow discharge lasers [10] are described quite adequately by a model that
takes into account the inertia of the direct ionization process, the finite time of space charge establishment, and the falling character of the current-voltage characteristics as the main factors. The resulting expressions for impedance can be used in analyzing the stability of power supplies of gas-discharge lasers based on the principles of current, passive or active power stabilization, when knowledge of discharge behavior in non-stationary mode is required.

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