Determination of the plasma impedance of a glow discharge in carbon dioxide

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Abstract. In this work an expression for the dynamic resistance of a glow discharge flowing in long tubes is obtained and analyzed. The expression describes the physical processes occurring in the positive column of a glow discharge. The frequency dependences of the active and reactive components as well as the dynamic resistance module for the discharge conditions corresponding to CO₂–lasers have been calculated. Based on the simulation results developed a computer program in the C# programming language for modeling the dynamic resistance discharge of glow discharge lasers.

Gas-discharge devices are used widely in various fields of science and technology [1]. The high prevalence of such devices is due to the wide variety of design solutions associated with the type of discharge flowing in the device. Among of such devices a special place is occupied by instruments with an extended positive column of a glow discharge [2, 3]. Glow discharge lasers belong to such devices. Glow discharge lasers are used actively for technological and metrological purposes. Due to physical and constructive features, the laser radiation has a temporary instability due to the influence of various factors. Therefore glow discharge lasers are used in along with radiation power stabilization systems [4].

Methods for stabilizing the power of laser radiation are classified on passive and active. In practice are used often active methods. Passive methods stabilizing do not take into account all the factors affecting the instability of the laser radiation power. Active stabilization methods assume negative feedback. One of the options for stabilizing the power of laser radiation is adjustment the pump level. In glow discharge lasers this process reduces to modulating the discharge current. Let us assume that at the time \( t \) the laser had a power level \( P_0 \) at a current \( I_0 \), which corresponds to the point \( A \) (figure 1). Due to external influences, the energy characteristic of the laser can shift and this current will correspond to the power \( P_0 + \delta P \) (point \( B \)). The principle of current stabilization of power consists in forced changing the discharge current by such a value \( \delta I \) so that the radiation power level again is equal to \( P_0 \) (point \( C \)).

The discharge conditions realized in glow discharge lasers correspond to the region of sharp drop in the CVC of the discharge gap. In such a case there is a transition stage from the electrons free diffusion to the ambipolar. To obtain expressions for the total dynamic resistance, one can use the method of small perturbations. In accordance with this method, the current and voltage of the discharge will, respectively, 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 at the discharge \( i, u \) are the variable components of the discharge current and voltage, where \( u \ll U_0, i \ll I_0 \).
Figure 1. Explanation of the operation principle of the radiation power stabilization system.

Then the dynamic resistance will be determined by solving:

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

Solution (1) was sought in the form:

\[ Z_d = \frac{U_0^{-1} (j\omega)^2 + I_1^{-1} j\omega + I_2^{-1}}{U_0^{-1} (j\omega)^2 + U_1^{-1} j\omega + U_2^{-1}}. \] (2)

After transformation (2), an expression for the dynamic resistance of the glow discharge lasers is obtained, as the total positive column resistance

\[ Z_d = R + j\omega = \left( \frac{I_1 U_2}{U_0} \right)^{-1} + \left( \frac{I_1 U_1}{U_0} \right)^{-1} - \left( \frac{I_1 U_0}{U_0} \right)^{-1} + \omega^2 \left( \frac{I_1 U_0}{U_0} \right)^{-1} \]

\[ + j \left( \frac{1}{U_2^2 - 2\omega^2 \left( U_0 U_2 \right)^{-1} + \omega^2 U_1^2 + \omega^2 U_0^2} \right) \] (3)

where \( R \) and \( X \) – active and reactive components of the impedance of the positive column; \( \omega \) – angular frequency. The remaining parameters in (3) depend on the discharge conditions [5].

An important role in the analysis of the dynamic discharge resistance is played by a static current-voltage characteristic. For the glow discharge lasers conditions the CVC has a falling character [6]. An experimental study of the CVC was conducted out on the basis of the serial laser LGN-705. The laser was connected to a vacuum system, allowing pumping out and filling the working volume. The length of the positive column was \( L = 400 \) mm, the diameter of the discharge gap was \( d = 9 \) mm. Figure 2 shows the current-voltage characteristics for the filling of \( \text{CO}_2:\text{N}_2:\text{He} = 1:1:6 \), depending on the pressure of the gas mixture. In this case the CVC can be approximated by an expression that includes the length of the discharge gap \( L \) and the longitudinal potential gradient \( E_z \):

\[ U_0 = U_k + aE_z L^b, \]

where \( U_k \) – the cathode voltage drop, which is determined by a pair of gas-cathode material; \( a, b \) – constants depending on the nature of the gas and the discharge conditions. In this case can introduce a static slope of the current-voltage characteristic [7]:

\[ \rho = \frac{dU}{dl} = abLE_z l^{-1}. \]
The anode voltage drop was then assumed to be zero. The longitudinal gradient of the potential $E_z$ in the positive column of envy from the genus of gas, working pressure, and also the diameter of the discharge gap. It can be determined taking into account the electron accommodation coefficient $\chi$ [8]:

$$E_z = \frac{3kT_e \sqrt{\chi}}{2e\varepsilon_e}.$$  

Rigorous calculation of $\chi$ for the conditions of discharges in long narrow tubes, realized in the gas discharge lasers, is difficult because of the diversity and complexity of the processes occurring in the plasma. In the literature there are experimental data about $\chi$ relating to a number of pure gases. They reflect the dependence $\chi = f(T_e)$ for a narrow range of the discharge conditions, so the use of the reference values in the calculation is difficult [9–11].

To automate the analysis of the discharge impedance behavior, a program was developed in the programming environment of MS Visual C# (figure 3). The program allows calculating the active, reactive components of impedance, the impedance module, and also building an impedance hodograph. Before calculating the user, it is possible to select the type of gas mixture, set 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.

The dynamic properties of the discharge in the range of measurement parameters corresponding to the working conditions of glow discharge lasers are described quite adequately by a model that takes into account, as the main factors, the inertia of the direct ionization process, the finite time for establishing the space charge, and the falling character of the CVC. 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 the nonstationary regime is required.
Figure 3. Example of calculating the plasma impedance for a mixture CO\textsubscript{2}:N\textsubscript{2}:He.

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