Dynamic properties of a glow discharge in long tubes

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Abstract. The impedance of a glow discharge in narrow long tubes characteristic of gas-discharge lasers is investigated. An expression for the impedance is obtained taking into account the falling character of the current-voltage characteristics, the dynamic properties of the positive table and the cathode region. Satisfactory consistent calculated and experimental results are achieved.

Glow discharge in extended tubes is widely used in gas-discharge lasers. The use of gas-discharge lasers in industry and research is a dynamic and promising direction, which makes a significant contribution to improving the efficiency of scientific research, opening new industries and technical processes.

When a gas-discharge laser is in operation, its discharge gap is a nonlinear element of the current circuit. The falling volt-ampere characteristic, characteristic of glow discharge lasers (GDL), does not carry complete information about the possible behavior of a discharge gap in a circuit with external disturbances and proper fluctuations of the discharge current. In this case, there is a need for an electrical circuit in which there is a discharge gap GDL, for example, in a current circuit, a system of passive or active stabilization of the laser radiation power. More complete information about the properties of the discharge GDL can be obtained by studying its behavior in dynamics [1, 2]. Here by means of external periodic or aperiodic perturbations of the equilibrium state of the discharge, the picture of the phenomena of processes in the discharge gap responsible for its properties in the non-stationary mode of operation can be studied. A characteristic of such studies is the characteristic of AC impedance – dynamic resistance or discharge impedance [3].

At total pressures of the order of 0.1 ... 1 kPa and current density at the mA·mm⁻², the processes in the positive column of GDL are satisfactorily described by a system of equations consisting of the balance equation of charged particles and the current continuity equation, on the basis of which the dynamic current-voltage characteristic. The energy distribution of electrons was described by the Maxwell function, and the rate of direct ionization was described by an exponential function. The discharge conditions realized in the LTE correspond to the area of a sharp drop in the I – V characteristic of the gas gap when there is a transitional stage from free diffusion of electrons to ambipolar.

From the analysis of the dynamic resistance of the positive column taking into account the current-voltage characteristics, it can be seen that the function \( Z_d (\omega) \) includes the active and reactive components and can be transformed into: \( Z_d = R + jX \). Taking into account the approximated current-
voltage characteristics, the expressions for the active and reactive components of the dynamic resistance are as follows [4]:

\[
R = \frac{(I^2_2 U^2_2)^{-1} + \omega^2 \left[ (I^2_1 U^2_1)^{-1} - \left( I_2 \left( U_k + aE_z I^b \right) \right)^{-1} \right] - (I^2_0 U^2_0)^{-1} + \omega^2 \left( I_0 \left( U_k + aE_z I^b \right) \right)^{-1}}{U^2_2 - 2\omega^2 \left[ \left( U_k + aE_z I^b \right) U_2 \right]^{-1} + \omega^2 U^2_1 + \omega^4 \left( U_k + aE_z I^b \right)^{-2}}.
\]

\[
X = \frac{\omega \left[ (I^2_1 U^2_1)^{-1} + \omega^2 \left( I_0 U_1 \right)^{-1} - (I^2_2 U^2_2)^{-1} + \omega^2 \left( I_1 \left( U_k + aE_z I^b \right) \right)^{-1} \right]}{U^2_2 - 2\omega^2 \left[ \left( U_k + aE_z I^b \right) U_2 \right]^{-1} + \omega^2 U^2_1 + \omega^4 \left( U_k + aE_z I^b \right)^{-2}}.
\]

Analysis of the expression for the impedance of a positive column allows us to obtain an equivalent replacement scheme in the form of an \(RL\)-circuit. The real discharge gap includes the cathode region of the discharge, the dynamic properties of which can affect the behavior of laser discharges using short-duration active media. The different nature of the processes in individual zones of the cathode space makes it difficult to obtain an analytical expression for the dynamic resistance of the cathode region (\(Z_k\)).

In the first approximation, an equivalent replacement circuit for the cathode discharge region can serve as a parallel \(R_kC_k\)-circuit, where \(R_k\) – active resistance of the cathode region to direct current, \(C_k\) – capacitance of gap cathode - positive column (figure 1).

**Figure 1.** Complete replacement circuit of the real discharge gap.

Here \(X = \omega \cdot L_{eq}\), where \(L_{eq}\) – this is the equivalent inductance of the positive glow discharge column, the expression for which is obtained on the basis of the initial expression for \(Z_d(\omega)\) [5].

\[
L_{eq} = \frac{\left( I^2_1 U^2_1 \right)^{-1} + \omega^2 \left( I_0 U_1 \right)^{-1} - \left( I^2_2 U^2_2 \right)^{-1} + \omega^2 \left( I_1 \left( U_k + aE_z I^b \right) \right)^{-1}}{U^2_2 - 2\omega^2 \left( U_0 U_2 \right)^{-1} + \omega^2 U^2_1 + \omega^4 U^2_0}.
\]

Expression for \(L_{eq}\) taking into account voltage characteristics:

\[
L_{eq} = \frac{j \left[ \left( I^2_1 U^2_1 \right)^{-1} + \omega^2 \left( I_0 U_1 \right)^{-1} - \left( I^2_2 U^2_2 \right)^{-1} + \omega^2 \left( I_1 \left( U_k + aE_z I^b \right) \right)^{-1} \right]}{U^2_2 - 2\omega^2 \left( \left( U_k + aE_z I^b \right) U_2 \right)^{-1} + \omega^2 U^2_1 + \omega^4 \left( U_k + aE_z I^b \right)^{-2}}.
\]

Frequency dependence \(L_{eq}(f)\) at fixed glow conditions has resonant character and tends to zero at frequencies in units of megahertz. Under these conditions, the dynamic resistance of the positive
column tends to static discharge resistance $R$, which is consistent with the ideas of the similarity of the positive column of a high-frequency discharge of a direct current discharge (figure 2).

![Figure 2](image)

**Figure 2.** Frequency dependence equivalent inductance of the discharge at $P = 100$ Pa, $d = 5$ mm, $L=0.9$ m and different discharge currents.

The calculation of the dynamic resistance was made by an expression that takes into account the falling nature of the current-voltage characteristics, using the software for calculating the dynamic resistance of GDL. It is interesting to note that the hodograph points corresponding to different currents, but calculated for the same modulation frequency, lie on the same straight line emanating from the center of the complex plane (figure 3) [6].

To compensate for the influence of parasitic circuit elements and a gas-discharge device, as well as to take into account the possible difference in the amplitude and phase-frequency characteristics of the voltage and current channel amplifiers, the measurement setup was calibrated over the entire range of modulation frequencies under study.

![Figure 3](image)

**Figure 3.** Hodograph of impedance in a mixture He:Ne = 6:1, at $L = 0.9$ m, $d = 5$ mm, $p = 100$ Pa.
The results of measuring the dynamic resistance of helium-neon and CO$_2$-lasers qualitatively and in order of magnitude coincide with the calculated dependences (figures 4, 5) [7].

![Hodograph of impedance in a mixture He:Ne = 6:1, L = 0.9 m, d = 5 mm, p = 100 Pa.](image)

**Figure 4.** Hodograph of impedance in a mixture He:Ne = 6:1, L = 0.9 m, d = 5 mm, p = 100 Pa.

![Hodograph $Z_d$ in mixture CO$_2$:N$_2$:He = 1.5:3:7.5 at L = 0.35 m, d = 8 mm, p = 1700 Pa.](image)

**Figure 5.** Hodograph $Z_d$ in mixture CO$_2$:N$_2$:He = 1.5:3:7.5 at L = 0.35 m, d = 8 mm, p = 1700 Pa.

This studies allowed us to obtain a refined expression for the total impedance of a glow discharge, taking into account the properties of an extended positive column and the cathode region, as well as using approximating expressions for the current – voltage characteristics. The resulting expression for impedance can be used in analyzing the stability of the pumping sources of gas-discharge lasers [8].

**References**

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