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IMPROVED COMPREHENSIVE METHOD OF CALCULATING OUTPUT POWER OF HE-NE LASERS

Abstract: *In this paper, an improved method for estimating the He-Ne laser radiation power is compared with experimental data, which takes into consider the dependence of the population inversion on the laser axis on the transverse dimensions of the active element. The numerical calculations results correspond to the experimental data.*

Key words: *effective mode volume, population inversion, He-Ne laser power, tube geometry.*
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Introduction

This paper continues the cycle of papers devoted to the dependence of the energy characteristics of the He-Ne laser on the geometry of its active element [1-14]. In these articles, a method was proposed for estimating the radiation power of a He-Ne laser with an arbitrary geometric shape of the active element. Namely, it is proposed to be considered by the formula

$$P = \int_{NMV} \varepsilon E^2 \delta N dV \qquad (1)$$

where E is the modulus of electric field strength in the resonator, δN is the population inversion and the integration occurs in the effective mode volume *NMV*. *NMV* is defined as a body bounded by the surface, where the $E^2\delta N$ value falls in e^2 times compared to $E_0^2\delta N_0$ (where δN_0 is the δN value at the axis, and e is the natural logarithm base). The emission power of a laser with circle, rectangular and elliptical cross sections of the active element with different transverse dimensions has been calculated, assuming the same δN_0. However, with the further development of the model, assumptions were made about the influence of the transverse dimensions of the tube on the value δN_0. In [14], this problem was investigated, and it was shown that indeed, δN_0 should decrease with an increase in the transverse size of the active element. In this paper, we compare the results of calculations of the power of a He-Ne laser with active elements in the form of cylindrical tubes of different radii with experimental data from classical works.

Population inversion and He-Ne laser output power

First, let us recall the main results obtained earlier. In [12], the processes in the discharge positive column (PC) in laser tubes of smoothly varying diameter were investigated, and a system of equations was obtained that solves the problem of coupling external, controlled parameters of the PC (radius of the discharge channel $R(z)$, gas inlet pressure p_H, and discharge current I_p) with its main internal characteristics: the electron temperature T_e, the concentration of charged particles n, longitudinal electric field strength $\mathbf{E}_z$. There was also obtained such an expression for the electron concentration as a function of the radial r and longitudinal z coordinates: $n_e = n_e\,(r, z)$:

$$n_e\left(r,z\right)=\frac{J_0(r\mu_1^{(0)}/R_z)\cdot 0,737I_p}{R_0^2 f_R^2\left(z\right)eb_eE_{0z}f_{E_z}\left(z\right)} \qquad (2)$$

where J_0 – zero-order Bessel function, $\mu_1^{(0)} \approx 2.4048$ – its first root, $R(z) \equiv R_z = R_0 f_R(z)$ - is the discharge channel radius as a function of the longitudinal coordinate z ($0 < z < l$), directed along the discharge tube axis ($R_0 = R(0)$ - is the channel radius value at $z=0$ => $f_R(0)=1$), I_p - is the discharge current, e – elementary charge, b_e electron mobility. In equation (2) $\mathbf{E}_z$ - the longitudinal electric field has the form $\mathbf{E}_z = \mathbf{E}_{0z} f_{Ez}(z)$ (where $\mathbf{E}_{0z} = \mathbf{E}_z(0)$, $f_{Ez}(0)=1$) and it is from the equation:

$$\left(eE_z\right)^2\left(z\right)=3kT_e\left(z\right)\frac{m_e\nu_{ea}\left(z\right)}{m_a}\{m_e\nu_{ea}\left(z\right)+$$

$$+\frac{4}{R(z)^2\nu_{ia}}\left[eU_i+kT_e\left(z\right)\left(1,7+\ln 0,4\sqrt{\frac{m_i}{m_e}}\right)\right]\} \qquad (3)$$

where m_a, m_i, m_e – are the masses of atoms, ions, and electrons respectively, ν_{ea} and ν_{ia} - are the frequencies of electron-atomic and ion-atomic collisions, U_i - atom ionization potential. In turn, the electron temperature T_e in (3), which is a function of the longitudinal coordinate ($T_e = T_e(z)$), can be found from the equation:

$$\sqrt{\frac{\varepsilon_i}{kT_e\left(z\right)}}\cdot\exp\left(\frac{\varepsilon_i}{kT_e\left(z\right)}\right)/\left(1+\frac{\varepsilon_i}{2kT_e\left(z\right)}\right)=$$

$$=0,552\frac{e}{\sqrt{m_e}}\left(\frac{C_i\sqrt{\varepsilon_i}}{b_in_a}\right)n_a^2\,R_0^2\,f_R^2\left(z\right) \qquad (4)$$

where ε_i - is the ionization energy, k – is Boltzmann's constant, b_i - i is the ions mobility, n_a - is a concentration of atoms, C_i - is a constant of approximation of the direct ionization cross section $\sigma_{0i}(\varepsilon_e)$ dependence on the electron's energy ε by the linear dependence: $\sigma_{0i} = C_i(\varepsilon_e - \varepsilon_i)$ at $\varepsilon_e \geq \varepsilon_i$.

Knowing the electron concentration, it is possible to estimate the metastable helium atoms concentration and excited neon atoms, and then population inversion δN. Using the values of the PC parameters in the work [14] it was shown that the population inversion δN_0 on the axis of the cylindrical tube decreases with increasing tube radius a.

In this regard, the method of calculating the He-Ne laser power is refined considering the dependence $\delta N_0(a)$. For a laser with a cylindrical active element, the radiation power will be according to the formula:

$$P=\int_0^{2\pi}\int_{z_1}^{z_2}\int_0^{\rho(z)}\varepsilon E^2\delta Nd\varphi dzrdr=$$

$$=\frac{4\pi E_0^2\varepsilon R_e}{k}\int_{z_1}^{z_2}dz\delta N_0(a)\Bigg(\frac{1-\exp(-2\rho^2(z)/w^2(z))}{4}-$$

$$\frac{\mu_1^{(0)2}}{32a^2}(w^2(z)-(w^2(z)+2\rho^2(z))\cdot$$

$$\cdot\exp(-2\rho^2(z)/w^2(z)))+$$

$$+\frac{\mu_1^{(0)4}}{512a^4}(w^4(z)-(w^4(z)+2w^2(z)\rho^2(z)+2\rho^4(z))\cdot$$

$$\cdot\exp(-2\rho^2(z)/w^2(z)))\Bigg) \qquad (5)$$

where R_e is the radius of curvature of the corresponding equivalent confocal resonator: $R_e = \{4S(R_1 - S)\}^{1/2}$, $S = d(R_2 - d)/(R_1 + R_2 - 2d)$, R_1 and R_2 – radii of mirrors, d – distance between mirrors, z_1 and z_2 – coordinates specifying the position of the tube inside the optical resonator ($z_2 - z_1 = l$ – tube length), z it is counted from the Gaussian beam waist, E_0 – the value of the field on the axis at $z=0$, $k=2\pi/\lambda$ – wavenumber, $w(z)=\sqrt{(R_e+4z^2/R_e)/k}$, $\mu_1^{(0)}$ $=2.4048$ – is the first solution of the zero-order Bessel function J_0, a – is the radius of the tube, $\rho(z)$ – solution equation

$$\{2+\ln 2-\ln(w^2(z)k/R_e)-2r^2/w^2(z)+$$

$$+\ln(J_0(\mu_1^{(0)}r/a))\}\,|_{r=\rho}=0$$

and the dependence $\delta N_0(a)$ is taken from the paper [14].

The purpose of this paper was to compare the calculations of the He-Ne laser radiation power according to the refined formula (5) with experimental data for cylindrical tubes of different radius a.

Calculation and comparison with experiment

We have taken experimental data from well-known classical fundamental works on He-Ne laser [15-19]. The calculation results according to formula (5) and experimental data are shown in Figure 1. Here, the radiation power (calculated P_{teor} and experimental P_{exp}) is deposited along the ordinate axis, and the laser number from the experiments is deposited along the abscissa axis. The laser parameters are given in Table 1.

The parameters of the corresponding lasers are given in Table 1.

Table 1. Laser parameters

Laser number	1	2	3	4	5
Work	[15]	[15]	[16]	[17]	[18]
l, m	0.125	0.55	0.11	0.22	0.45
a, mm	0.75	1.5	1.5	0.75	0.775
d, m	0.22	0.7	0.25	0.34	1.3

***R*₁, m**	**0.5**	**2**	**3**	**2**	**1.5**
***R*₂, m**	**∞**	**∞**	**10**	**2**	**1.5**
Laser number	**6**	**7**	**8**	**9**	**10**
Work	**[19]**	**[19]**	**[19]**	**[19]**	**[19]**
***l*, m**	**0.11**	**0.11**	**0.11**	**0.11**	**0.11**
***a*, mm**	**0.3**	**0.4**	**0.5**	**0.3**	**0.4**
***d*, m**	**0.135**	**0.135**	**0.135**	**0.135**	**0.135**
***R*₁, m**	**0.4**	**0.4**	**0.4**	**0.8**	**0.8**
***R*₂, m**	**0.4**	**0.4**	**0.4**	**0.8**	**0.8**
Laser number	**11**	**12**	**13**	**14**	**15**
Work	**[19]**	**[19]**	**[19]**	**[19]**	**[19]**
***l*, m**	**0.11**	**0.38**	**0.38**	**0.38**	**0.38**
***a*, mm**	**0.5**	**0.75**	**1.0**	**1.25**	**1.5**
***d*, m**	**0.135**	**0.45**	**0.45**	**0.45**	**0.45**
***R*₁, m**	**0.8**	**1.265**	**1.265**	**1.265**	**1.265**
***R*₂, m**	**0.8**	**1.265**	**1.265**	**1.265**	**1.265**
Laser number	**16**	**17**			
Work	**[19]**	**[19]**			
***l*, m**	**0.38**	**1.195**			
***a*, mm**	**1.75**	**1.75**			
***d*, m**	**0.45**	**1.265**			
***R*₁, m**	**1.265**	**3.572**			
***R*₂, m**	**1.265**	**3.572**			

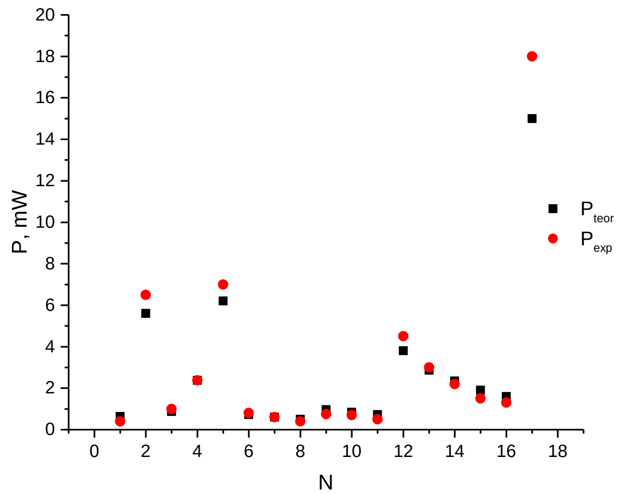

Fig 1. Comparison of calculated P_{teor} power values with experimental P_{exp} values for 17 lasers

Conclusion

The results of the evaluation of the He-Ne laser output power for the case of an active element in the form of a cylindrical tube according to уточненному методу are in good agreement with experimental data. This once again proves the correctness of this method. Currently, the positive discharge column model is becoming more complicated for the case of a polyatomic gas, which will further refine our model.

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