SOI: 1.1/TAS DOI: 10.15863/TAS
International Scientific Journal
Theoretical & Applied Science

p-ISSN: 2308-4944 (print) **e-ISSN:** 2409-0085 (online)

Year: 2022 **Issue:** 01 **Volume:** 105

Published: 26.01.2022 **http://T-Science.org**

QR – Issue **QR – Article**

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CONFIRMATION OF A COMPREHENSIVE METHOD OF CALCULATING OUTPUT POWER OF HE-NE LASERS

***Abstract**: In this paper, the method of estimating the He-Ne laser output power was tested by matching with experimental data for such case as an active element in the form of a cylindrical tube. The result of this comparison showed a great deal of the results obtained by the previously proposed method with the experience.*

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

***Language**: English*

***Citation**: Kozhevnikov, V. A., & Ammosov, A. P. (2022). Confirmation of a comprehensive method of calculating output power of He-Ne lasers. *ISJ Theoretical & Applied Science, 01 (105),* 471-474.

***Soi**: http://s-o-i.org/1.1/TAS-01-105-35 ***Doi**: crossref https://dx.doi.org/10.15863/TAS.2022.01.105.35

***Scopus ASCC**: 2200.*

Introduction

This paper continues a variety of articles devoted to methods of calculating the energy parameters of a gas-discharge (e.g., He-Ne) laser. In the article [1], a new method was proposed for finding an approximate solution of the homogeneous Helmholtz equation with homogeneous boundary conditions. This method was applied to find the gain of a gas-discharge laser with an arbitrary cross-section of the active element. Various cross–sections were considered - circle, rectangle, ellipse [1], regular polygons [2], hyperbolic polygons and various unconventional and exotic sections [3-6]. In future, this method of finding an approximate solution of the homogeneous Helmholtz equation was generalized to an inhomogeneous boundary condition [7]. A new method was proposed for estimating the output power of a He-Ne laser with an arbitrary cross-section of the active element, using the concept of effective mode volume, and it was applied to find the power of a He-Ne laser with sections of the active element in the form of a circle, rectangle and ellipse [8-11]. In future, a positive DC discharge tube was considered under discharge conditions typical for a He-Ne laser and expressions were obtained linking the external parameters of the tube (changing the radius of the discharge channel, gas inlet pressure and discharge current) with "internal" characteristics (concentration of charged particles, electron temperature, intensity of the "longitudinal" electric field) [12-13]. Further studies made it possible to clarify the effect of the transverse dimensions of the tube on the electronic temperature of the discharge and on the value of the inverse population, which led to more accurate calculations of the output power of the He-Ne laser [14].

In this article, we return to the output power of a He-Ne laser with an active element in the form of a cylindrical tube. Although in [8-10] the results of calculations using the proposed method were verified with experimental data, but an additional check is never superfluous. We compare the results of our calculations with classical fundamental experimental work on the He-Ne laser.

He-Ne laser output power

First, let us recall the essence of the proposed method for estimating the output power of a He-Ne laser. Let the active element of the He-Ne laser be of length l placed in an optical resonator with the radius of curvature of mirrors R_1 and R_2 and distance between mirrors d (then the radius of curvature of the corresponding equivalent confocal resonator R_e is found by the formula: $R_e=\{4S(R_1-S)\}^{1/2}$, where $S=d(R_2-d)/(R_1+R_2-2d))$. The electric field in the resonator for the main Gaussian mode TEM$_{00}$ in cylindrical coordinates (r,φ,z) has the form:

$$|E| = E_0\sqrt{\frac{2}{1+\xi^2}}\exp\left[-\frac{kr^2}{R_e(1+\xi^2)}\right] \qquad (1)$$

where $\xi=2z/R_e$, E_0 – modulus of electric field when $\xi=1$ and $r=0$, $k=2\pi/\lambda$ – wavenumber, z it is counted from the Gaussian beam jumper. Beam radius (defined as the distance at which the mode field TEM$_{00}$ will decrease by e times compared to the value on the axis) at the mirrors and on the jumper, respectively, will be equal to:

$$w(z) = \sqrt{\frac{\lambda}{2\pi}R_e(1+\xi^2)} = \sqrt{\frac{1}{k}\left(R_e+\frac{4}{R_e}z^2\right)} \qquad (2)$$

Let a He-Ne laser have an active element having a cross-section of arbitrary shape Ω. In the first approximation, the distribution of the population inversion of the active medium δN in this laser satisfies the homogeneous Helmholtz equation with a homogeneous boundary condition:

$$\Delta(\delta N)+\gamma^2(\delta N)=0 \qquad (3)$$

$$\delta N|_\Gamma = 0 \qquad (4)$$

where Γ – is the boundary of the region Ω in which the solution (3) is sought. The concept of effective modal volume is introduced NMV - which is bounded by a surface where the value of $|E|^2\delta N$ decreases by e^2 times compared to $E_0^2\delta N_0$ (where δN_0 – is the value of the inverse population of δN on the axis of the active element). Then, to estimate the output power of a laser with an arbitrary cross-section of the active element, it is proposed to use the following formula:

$$P = \int_{NMV} \varepsilon E^2\delta N dV \qquad (5)$$

where ε – is the corresponding proportionality coefficient.

For the simplest case of an active element in the form of a cylindrical tube, it can be obtained that NMV – is a rotation figure with a z-dependent cross section in the form of a circle of radius ρ, such that:

$$\{2+\ln 2-\ln(w^2(z)k/R_e)-2r^2/w^2(z)+$$
$$+\ln(J_0(\mu_1^{(0)}r/a))\}|_{r=\rho}=0 \qquad (6)$$

where a – is the radius of the tube, r – is the distance to the axis, J_0 – is the zero-order Bessel function, $\mu_1^{(0)}=2.4048$ – is the first solution of the function J_0. Replacing the Bessel function with an approximate decomposition $J_0(x)\approx 1-x^2/4+x^4/64$, formula (5) for a cylindrical tube can be simplified to a one-dimensional integral:

$$P = \int_0^{2\pi}\int_{z_1}^{z_2}\int_0^{\rho(z)} \varepsilon E^2\delta N d\varphi dz r dr =$$
$$= \frac{4\pi E_0^2\delta N_0\varepsilon R_e}{k}\int_{z_1}^{z_2} dz\left(\frac{1-\exp(-2\rho^2(z)/w^2(z))}{4}-\right.$$
$$\frac{\mu_1^{(0)2}}{32a^2}(w^2(z)-(w^2(z)+2\rho^2(z))\cdot$$
$$\cdot\exp(-2\rho^2(z)/w^2(z)))+$$
$$+\frac{\mu_1^{(0)4}}{512a^4}(w^4(z)-(w^4(z)+2w^2(z)\rho^2(z)+2\rho^4(z))\cdot$$
$$\left.\cdot\exp(-2\rho^2(z)/w^2(z)))\right) \qquad (7)$$

where ρ(z) – solution (6), z_1 and z_2 – coordinates specifying the position of the tube inside the optical resonator ($z_2 - z_1 = l$).

On the other hand, the output power of a He-Ne laser with a cylindrical tube can be estimated using a well-known formula that gives excellent agreement with the experiment:

$$P = Aw_0G_m\left[1-\left(a_c/G_m\right)^{1/2}\right]^2\pi w_1^2\cdot$$
$$\cdot\left[1-\exp(-2r_0^2/w_1^2)\right] \qquad (8)$$

where $Aw_0=30$ W/cm^2 – saturation coefficient, $G_m=3\cdot 10^{-4}l/(2r_0)$ – the total unsaturated gain in the center of the Doppler-widened gain loop of Ne atoms, l – the length of the active part of the capillary, a_c – total loss ratio, r_0 – capillary radius, $w_1=\{\lambda R_e/(2\pi)\}^{1/2}$ – the radius of the beam on the output mirror. In [8-10], the results of calculations according to formula (7) were compared with both experimental data and calculations according to formula (8). In this paper, we added experimental data for comparison.

Calculation and comparison with experiment

We have taken experimental data from well-known classical fundamental works on He-Ne laser [15-16]. The parameters of the corresponding lasers are given in Table 1.

Table 1. Laser parameters and calculation results

Laser number	1	2	3	4	5
Work	[15]	[15]	[15]	[15]	[16]
l, m	0.125	0.55	0.65	2	0.11
a, mm	0.75	1.5	2.5	4	1.5

d, m	0.22	0.7	0.8	2.15	0.25
R_1, m	0.5	2	2	10	3
R_2, m	∞	∞	∞	∞	10
P (from work), mW	0.4	6.5	8.2	105	1
P (from (7)), mW	0.38	6.45	8.15	104	1.02

The calculation for these laser parameters was carried out according to formulas (1)-(7). In comparison with the works [8-10], the calculation program was rewritten from Java to C++. The last two rows of Table 1 show the power values from the corresponding articles and calculated by us using the formula (7).

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 the proposed method are in good agreement with experimental data. This once again proves the correctness of this method. Currently, new experimental data on the He-Ne laser output power are being searched for in the case of an active element with sections in the form of a rectangle and an ellipse for further verification of the method, as well as the search for the optimal cross-section shape of the active element in terms of output power.

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