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ASSESSMENT OF THE MAXIMUM SUPPLIED ELECTRIC POWER FOR A PURE COPPER VAPOR LASER

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ABSTRACT

Based on a previously proposed model for analytical calculation of gas temperature, an improved methodology for determining the threshold of the supplied electric power in the active laser volume is developed. A comparison is made with previous publications. It is noted that the proposed methodology is better at accounting for the processes of heating and cooling of the laser tube. It is shown that the proposed methodology can be applied to a wider range of metal vapor lasers and other high-voltage devices, operating at high temperatures.

Keywords: pure cooper bromide laser, gas temperature, electric power threshold, heat conduction equation, analytical solution.

1. Introduction

Presently, it is thought that copper and copper compound vapor lasers have been studied in good detail. This type of lasers are characterized by the highest output power in the visible spectrum (green - 510.6 *nm* and yellow - 578.2 *nm*), exceeding 120 *W* [1, 2]. Together with the higher quality of the laser beam, this makes them commercially perspective due to their wide range of applications. For this reason, the development of new laser sources with high output power continues to be the subject of active scientific research.

An important problem related to the stable operation of metal vapor lasers, as well as the development of new lasers is the sustainability of an optimal temperature mode of the neutral gas in the laser tube. It is well known that the distribution of gas temperature in the active volume is an important characteristic of the discharge. The temperature affects the general physical operating life of the laser, the decrease of laser generation over time, and the quality of the laser beam. When gas temperature exceeds certain levels, thermal ionization processes cause an increase in current density at the center of the tube. The gas discharge compresses into a thin string, leading to a decrease in laser generation and deterioration of the mode composition of the laser radiation. A black spot appears at the center of the tube and laser generation stops. It is important to note that the direct measurement of the temperature of the neutral gas inside the laser tube is impossible. Only the temperature of one of the outer walls of the laser tube is measured using the so called thermocouple or optically, which unfortunately is quite inaccurate. The currently existing mathematical models of gas temperature in metal vapor lasers are inaccurate and ineffective as they calculate the temperature of the gas under the condition that a constant temperature of the outer wall of the tube is set [3, 4]. Thus, when modeling new devices, where such a constant temperature of the wall is unknown, the temperature inside the tube cannot be determined. The variable radial distribution of volume power density in the active medium is also not accounted for and neither are the external environment conditions. It is known that the distribution of volume power density in the cross-section of the discharge is highly irregular. For example, for pure copper vapor lasers with neon as buffer gas, this irregularity has been detected experimentally through short-term interruption of the radiation and instantaneous measurements. The calculation of the temperature of the gas is also significant as it is an important element of all kinetic models, describing the physical processes over time. The preliminary calculation of the maximum possible supplied electric power is of particular interest.

Pure copper and copper compound vapor lasers with their various designs and characteristics have a wide range of practical and scientific research applications.

These types of lasers are used in medicine mainly in the fields of dermatology and photocoagulation. This laser is preferred for medical applications due to its small size, short heating time and the fact that it does not require pumping. The two lines are used separately or in combination. The yellow line of laser radiation is close to the highest point of absorption of oxy-hemoglobin at low melanin levels when treating spots and telangiectasia at a depth of 1-2 mm. The green line is used to treat pigmentations, specific photo-thermal coagulations of blood vessels, delicate operative interventions such as palatoplasties, rejuvenation of areas of skin and others.

Pure copper vapor lasers and laser systems are used for micro machining of various materials: drilling, cutting, marking, etching, etc. The ability to achieve precision of up to 10 microns with some materials cannot be rivaled by any other method. The laser allows the processing of: metals, plastics, polymers, ceramics, leather, wood, etc.

More details on the technical characteristics and application of the metal vapor lasers with metal compounds are given in [5].

Of a particular interest is the preliminary determination of the maximum supplied electrical power. As the temperature increases, the thermal advantage populates the lower laser level. At a specific critical value of the temperature, its population can reach values, which would not allow the creation of an inverse population. This is particularly important for pulse lasers with transitions from a resonance to a metastable level, such as the type of laser considered here. In order to determine the maximum population of the lower laser level N_ν we will assume that this population cannot be higher than some part of the basis level N_0 [6]:

$$\frac{g_0}{g_\nu}\frac{N_\nu}{N_0}=\exp\left(-\frac{E_\nu}{kT}\right)\le\alpha \qquad (1)$$

where E_ν is the energy of the lower laser level, g_ν and g_0 are the statistical weights of the levels, *k* is the Boltzmann constant.

In [6] the line λ=510.5 nm at levels α = 0.01, the threshold limit temperature $T_{\lim}=3500K$ is reached when the supplied power per unit length is $P_L=140W/cm$. The results have been obtained under the following assumptions:

1) uniform distribution of volume power density in the active laser medium;

2) temperature of the wall is set and fixed in subsequent calculations;

3) geometric dimensions of the laser tube, and in particular the radius of the tube, are not taken into account;

4) threshold temperature is determined according to the average temperature of the discharge in relation to the temperature of the wall;

5) processes of natural convection of the tube to the surrounding space are not taken into account.

2. Problem setup

In order to determine the distribution of the temperature of the gas in the cross-section of the tube, it is necessary to solve the stady-state heat conduction equation in the following form:

$$\operatorname{div}\left(\lambda_g \operatorname{grad} T_g\right)+q_v=0 \qquad (2)$$

where λ_g is the heat conductivity coefficient of the gas, q_v is the volume power density of the internal heat source, and T_g is the temperature in the tube.

In literature, equation (2) is usually solved using boundary conditions of the first and second kind in the following form:

$$T_g\left(R_1\right)=T_1, \quad \left.\frac{\partial T_g}{\partial r}\right|_{r=0}=0. \qquad (3)$$

$$0<r<R_1,$$

where, R_1 is the inner radius of the tube - Fig.1.

In [6] it is assumed that the temperature of the wall is known. The assumption $q_v(r)=const$ is made and two cases for the heat conductivity coefficient of the gas are considered:

a) $\lambda_g=const$;

b) $\lambda_g=\lambda_2\left(1+b(T_g-T_2)\right)$.

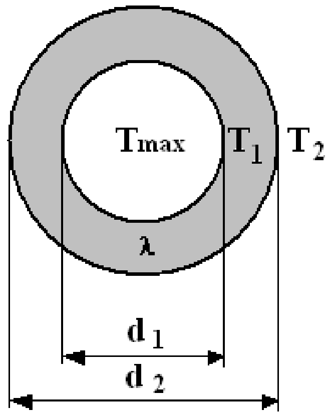

Fig. 1. Cross-section of the discharge tube of Cu laser: $d_1=8.8mm$; $d_2=10mm$.

The threshold temperature $T_{\lim}=3500K$ is determined in accordance with (1). At a set temperature of the wall $T_{wall}=1850K$, by solving equation (2) at boundary conditions (3), the linear threshold of the supplied electric power is determined in case a) $P_{\lim}=140W/cm$ and in case b) $P_{\lim}=200W/cm$.

Significant changes occurred in the field of analytical calculation of the temperature of the gas of metal and metal compound vapor lasers after the publication of this article, making it possible to determine the threshold of the supplied electric power in a new way. For this reason, it is necessary to provide a short preliminary overview of the new methodology for determining the temperature of the gas.

3. Overview of existing methods for analytical solutions of the heat conduction equation

In a later publication [7], it is noted that the more accurate approximation of the heat conductivity coefficient of the gases is in the form: $\lambda_g=\lambda_0 T_g^m$, where λ_0 and *m* are coefficients, dependent on the type of gas.

Up to now, the formula most frequently used to describe the temperature of the gas with an uniform volume power density $q_v=\text{const}$ and boundary conditions (3) has been [7]:

$$T_g(r)=\left[T_1^{m+1}+\frac{q_v(m+1)}{4\lambda_0}(R_1^2-r^2)\right]^{\frac{1}{m+1}} \qquad (4)$$

In numerous publications [8-12], methods are developed, allowing for the temperature of the gas to be determined by accounting for the radial distribution of volume power density. Also, new boundary conditions of the third and forth kind are proposed, which do not require a preset temperature of the wall. Cases of natural and induced convection are considered for different types of metal and metal compound vapor lasers. This allows for a new approach to determining the temperature of the gas, especially when developing new laser sources, for which the temperature of the wall is unknown.

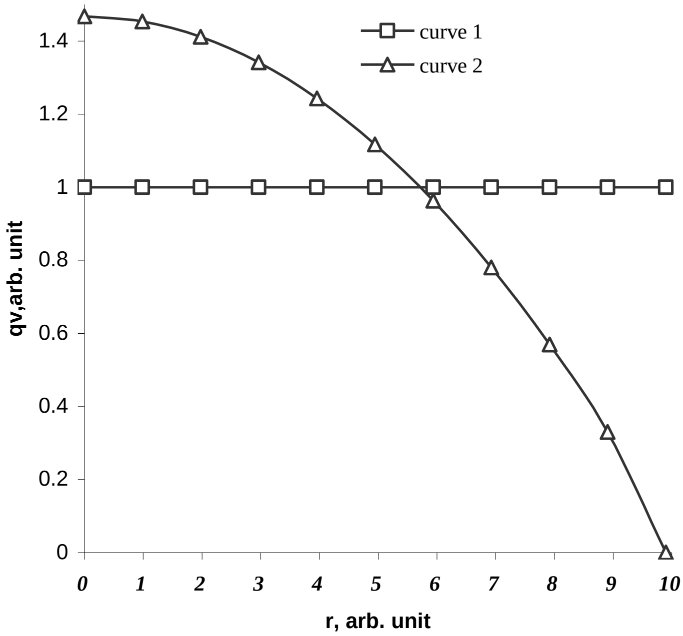

Fig. 2. Examples of qualitative radial distributions of volume power density in the cross-section of the laser tube of a pure copper vapor laser in relative units: □ - curve1 ($q_v(r) = q_0 = const$), Δ - curve 2 of the type

$$q_{v,2}(r) = K_1 q_0 (a + br^2)$$

A formula is proposed for a randomly set q_v, representing a general solution for the temperature of the gas in the cross-section of the discharge, in the following form:

$$T_g(r) = \left[T_1^{m+1} - \frac{(m+1)}{\lambda_0} \int_{\ln R_1}^{\ln r} \left(\int_{-\infty}^{y} e^{2t} q_v(e^t) dt \right) dr \right]^{\frac{1}{m+1}} \quad (5)$$

$0 < r < R_1$

In the case of a random form of the function for the volume power density (of course such that the integral exists), it may be necessary to use symbolic and numeric calculation and mathematical software such as Mathematica, Matlab, etc. A number of type distributions for $q_v(r)$, which are most often polynomial in nature, are considered. It is established that with sufficient accuracy (3% at the center of the tube), it is most appropriate to represent $q_v(r)$ as a second degree polynomial in the following form:

$$q_{v,2}(r) = K_1 q_0 (a + br^2) \quad (6)$$

where $K_1 = 1.4383$, $a = 1.0183471$, $b = -0.001077$, q_0 is the average volume power density. For comparison, in Fig.2, the two relationships are given in relative units: curve 1 - $q_v(r) = const$ and curve 2 - $q_{v,2}(r)$ from (6). The two relationships are plotted for one and the same supplied electric power (the areas, defined by each of the graphs and the *X* axis are the same).

When the volume power density is presented in the form $q_{v,2}(r)$ from (6), the distribution of the temperature is given by the following formula, resulting from the general solution of (5) with a subsequent integration:

$$T_{g,2}(r) = \left(T_1^{m+1} - \left\{ (m+1) K_1 q_0 (r^2 - R_1^2) \times (4a + br^2 + bR_1^2) \right\} / 16\lambda_0 \right)^{\frac{1}{m+1}} \quad (7)$$

In order to solve equation (2), in this paragraph we will consider mixed boundary conditions of the third and fourth kind, which for a cylindrical configuration are in the following form:

$$T_1 = T_2 + \frac{q_l \ln(d_2/d_1)}{2\pi\lambda_1} \quad (8)$$

$$Q = \alpha F_2 (T_2 - T_{air}) + F_2 \varepsilon c\left[\left(\frac{T_2}{100}\right)^4 - \left(\frac{T_{air}}{100}\right)^4\right] \quad (9)$$

Boundary conditions (8) express the equation for continuity of the heat flux at the limit of two mediums. Here, q_l is the power per unit length, $q_l = Q/l_a$, l_a - length of the active zone, λ_1 is respectively the heat conductivity coefficient of the tube, d_j, $j = 1,2$ are the diameters of the tube. Boundary condition (9) gives the heat exchange between the outer surface of the laser tube and the external environment. It contains two terms. The first term comes from the Newton-Riman law for heat exchange through convection, and the second from the Stefan-Boltzmann law for heat exchange through radiation. The quantity Q is the total heat flux, equal to the total consumed electric power, α is the heat transfer coefficient, F_2 is the area of the outer active surface of the tube, ε is the integral radiation coefficient, dependent on the material, c - radiation coefficient, $T_{air} = 300K$ - air temperature.

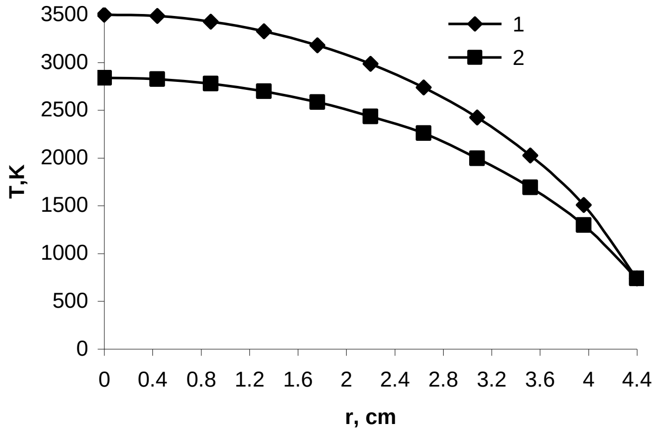

Fig. 3. Distribution of the temperature of the gas in the cross-section of a Cu laser: curve 1 – by formula (5); curve 2 – by formula (4).

First, we will determine the heat transfer coefficient α. The Nusselt criterion is used to obtain α, regardless of the type of convection:

$$Nu = \alpha H / \lambda \quad (10)$$

The Grashoff criterion is applicable for free convection:

$$Gr = g\beta H^3 (T_3 - T_{air})/\upsilon^2 \quad (11)$$

The following relationship between the two criteria is valid for horizontal tubes with natural convection:

$$Nu = 0.46 Gr^{0.25} \quad (12)$$

The latter equation is valid when $700 < Gr < 7\times10^7$. The quantities used in (10)-(12) are as follows: H is the characteristic body size, here $H = d_2$, β is the thermal coefficient of gas volume expansion, for the air $\beta_{air} = 3.41\times10^{-3}, K^{-1}$, υ is the kinematic viscosity, $\upsilon_{air} = 15.7\times10^{-6} m^2/s$, λ is the thermal conductivity coefficient, $\lambda = \lambda_{air} = 0.0251\ W/(mK)$. The data is for air temperature 300*K* [8-12].

Through (10)-(12), the formula for the calculation of α assumes the form:

$$\alpha = \frac{0.46\lambda_{air}}{d_2}\left(g\beta_{air} d_2^3 \frac{T_2 - T_{air}}{\upsilon_{air}^2}\right)^{0.25} \quad (13)$$

Boundary condition (9), expressed through the power per unit length, assumes the following final form:

$$q_l = 0.46\pi\lambda_{\text{air}}(T_2 - T_{air}) \times \left(g\beta_{\text{air}} d_2^3 \frac{T_2 - T_{air}}{\upsilon_{\text{air}}^2}\right)^{0.25} + \pi d_2 \varepsilon c\left[\left(\frac{T_2}{100}\right)^4 - \left(\frac{T_{air}}{100}\right)^4\right] \quad (14)$$

In equation (14) with a given q_l, the only unknown quantity is T_2. It can be found by solving this nonlinear equation. It is easy to show that there exist an unique real root of (14). After calculating the temperature T_2, T_1 is determined from (8) in reverse order. In order to determine the temperature of the gas inside the tube, (7) is used with the now known T_1.

4. New methodology for determining the electric power threshold

The geometric parameters of the considered laser source are given in Fig. 1. In the examined model, the temperature at the center of the tube $T_{\max} = 3500K$ is known and the unknown quantity is the linear power density. The unknown quantity is found using the "shooting" method. We set different values of the linear power density. Using formula (14) we determine the unknown temperature T_2. Using formula (8) - the temperature T_1. Using formula (7) we determine the distribution of the temperature in the cross-section of the tube. We compare $T_{\max}$ with the set temperature 3500*K*. This way, after a few attempts we find out that the maximum permissible temperature is achieved at linear power density of $q_l = 35.5W / cm$.

The distribution of the temperature of the gas in the cross-section of the laser volume is shown in Fig. 3, curve 1. The same Fig. shows as a comparison the distribution of the temperature of the gas with the simplified model, formula (5). Our results are lower when compared with the results obtained in [6] (140 *W/cm* and 200 *W/cm*). This is mainly due to the significant assumptions, presented at the beginning of this paper, which simplify the model and make it quite inaccurate. One of the reasons for this is that we examine the relationship between the volume power density and the radius of the tube. Fig. 2 shows that in our case, the power is practically concentrated in the center of the tube, which means that less total consumed electric power is required in order to achieve the same temperature in the center of tube.

5. Conclusion

Based on the previously developed temperature model, an improved methodology for determining the maximum supplied electric power of a pure copper vapor laser has been presented. The developed method is better at accounting for the specifics of and the heat processes within the laser tube. It can be used when developing new laser sources with increased output power, which also necessitates the increase of the supplied electric power. The developed method is universal to some extent and can be adapted for other laser sources or high-voltage devices, for the normal operation of which heat balance is of crucial importance.

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