Study on threshold capabilities of a copper bromide vapor laser

D V Fidanov

1 Faculty of Mathematics and Informatics, University of Plovdiv Paisii Hilendarski 24 Tzar Assen Street, 4000 Plovdiv, Bulgaria
E-mail: dimitarf@gmail.com

Abstract. This paper presents theoretical and simulation results for the operating parameters of a copper bromide (CBr) laser. The CuBr active medium finds applications as both as a laser source and a vapor amplifier. A methodology is developed to serve as the basis for the solution of a two-dimensional quasi-stationary heat conductivity equation on the cross-section of the gas tube for modeling the temperature of the neutral gas and the electron temperature of the discharge. This methodology makes it possible to determine the maximum electrical power supplied and the maximum electron temperature in terms of thermal ionization and electric ionization resistance of the gas discharge. Analytical results are applied in computer simulations and for the assessment of parameters of an actual CuBr laser.

1. Introduction

Copper and copper compound vapor lasers continue to be the subject of experimental and theoretical research. This type of lasers have numerous unique properties – they are the most powerful sources in the visible spectrum (516.6 nm and 578.2 nm) and have high laser beam coherence and convergence. The development of lasers with high laser output generation (over 100 W) are of particular interest. This extends significantly their range of applications. This type of lasers are also a source of ultraviolet radiation (248.6 nm, 259.2 nm, 260.0 nm, and 270.3 nm) [1].

Copper vapor lasers, and particularly CuBr vapor lasers, have a wide range of practical applications: in medicine and medical research, dermatology and photocoagulation (Tanzi et al., 2003); in industry for microprocessing of various materials - drilling, cutting, marking, etching, etc. [2]; in scientific research for isotope separation of various chemical elements, in studies of magnetic properties of materials, etc.; for pumping titanium-sapphire lasers, dye lasers, etc.; in high-speed photography, show business and advertising, laser microscopy, laser displays and nanotechnology, the defense industry, brightness amplifiers, for air and underwater navigation, and studies of air and ocean pollution, etc. [3, 4, 5].

In recent years, due to the development of high-speed video recorders (CCD and CMOS cameras) for up to 100 fps, there has been renewed interest in metal vapor systems as brightness amplifiers. To this end, CuBr lasers are being used increasingly frequently in some modern laser active optical systems for visual monitoring in real time of various objects and processes protected against intensive wide band background light. Such processes are the interactions of intense energy flows with surfaces, plasma welding, extraction of new materials and nanostructures, processes of thermonuclear synthesis, plasma-induced processes, etc. The experimental results of visualizations of objects and processes using high-speed laser-based monitors with CuBr vapor lasers are presented in [6]. In [7] CuBr brightness amplifiers with 100 kHz pulse repetition frequency are developed and studied. Results
obtained by a bistatic laser monitor with two CuBr laser sources at high pulse repetition frequencies are described in [8].

Further development of CuBr vapor lasers poses numerous topical problems both in terms of experiments and research into their physical operating parameters – output power, laser efficiency, laser beam quality, gain and more.

One possible option for the increase of laser output power is to increase the electric power supplied into the gas discharge. This leads to higher electron energy and respectively increased laser generation. The increased electric power supplied to the gas discharge has its natural limits. Thermal overheating occurs in the gas as well as thermo-ionizing instability. This leads to a reduction of laser generation at the center of the tube or its complete termination. In [9] it is determined that the maximum permissible temperature of the gas in copper vapor lasers is $T_g = 3500 \text{K}$.

Up until now, no methodology has been developed which allows for preliminary assessment the values that can be reached when increasing electron energy from the positions of gas thermal resistance. Such methodology would enable the performance of preliminary planning of the experiment for existing laser sources and its use as the basis for development of new ones.

The objective of this paper is the creation of a new methodology to assess both the increase of gas temperature and electron temperature.

2. Methodology development

2.1. Determination of the gas temperature in the discharge

In order to determine the temperature of the gas in the cross-section of the tube (see Figure 1), it is necessary to solve the two-dimensional quasi-stationary heat conductivity equation:

$$\text{div} \left( \lambda_g \text{grad} T_g \right) + q_v = 0$$  \hspace{1cm} (1)

where $\lambda_g$ 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. For gases $\lambda_g$ usually is approximated by the expression $\lambda_g = \lambda_0 T_g^m$, $m$ and $\lambda_0$ are constants.

In order to solve equation (1), we use boundary conditions of the first and second kind

$$T_g (R) = T_w, \quad \frac{\partial T_g}{\partial r} \bigg|_{r=0} = 0$$  \hspace{1cm} (2)

where $0 < r < R$, $R$ is the tube radius, $T_w$ is the tube wall temperature.

The more general case of a radial distribution of the volume power density is considered. There is insufficient reliable data about the nature of the radial distribution of power along the laser tube cross-section. Research in [10] shows that the most suitable representation of $q_v$ is through a polynomial and in particular the use of a second order polynomial in the form:

$$q_v (r) = K q_0 \left( a + b r^2 \right)$$  \hspace{1cm} (3)

where $K = 1.4383$, $a = 1.0183471$, $b = -0.001077$, $q_0$ is the average volume power density ($q_0 = \frac{Q}{V}$, $W/m^3$), $Q$ is the electric power supplied to the gas discharge, $V$ is the tube volume.

When the volume power density is given by (3), the distribution $T_g (r)$ of the gas temperature is presented by the following formula [10]:
\[ T_g (r) = \left( T'_w \right)^{m+1} - \frac{(m + 1)K \cdot q_0 (r^2 - R^2) (4a + br^2 + bR^2)}{16 \lambda_0} \]  

(4)

2.2. Determination of the electron temperature

In order to determine the temperature of the electron gas \( T_e (r) \), we need to solve a two-dimensional quasi-stationary equation

\[ \nabla \lambda_e \nabla T_e = - \xi \cdot q_v \]  

(5)

where \( \lambda_e \) is the coefficient of electron heat conductivity of the electron gas, and \( \xi \) indicates the portion of the total supplied power that goes to heating the electrons. Under the boundary conditions similar to (2) with \( T_e (R) = 0 \) (the energy of the electrons is zero), the solution to equation (5) takes the form [11]:

\[ T_e (r) = \left( T_e (R) \right)^{m+1} - \frac{(m + 1)K \cdot \xi \cdot q_0 (r^2 - R^2) (4a + br^2 + bR^2)}{C_e \bar{\sigma} \cdot 16 \lambda_0} \]  

(6)

Here quantities \( C_e \), \( \bar{\sigma} \) and \( \xi \) depend on the specific laser source, its geometric and energy characteristics and these are determined using the method detailed in [11].

3. Subject of investigation

The subject of investigation is a real operational CuBr laser, described in [12]. The principle scheme and the geometric characteristics are given in Fig. 1 and Table 1.

![Figure 1. Gas discharge tube (GDT): (1) working channel, (2) electrodes, (3) CuBr containers, (4) traps, (5) exit windows, (6) HBr generator, (7) CuBr container heaters; L is the active zone length.](image)

| Parameter                     | Value | Measure |
|-------------------------------|-------|---------|
| GDT diameter \( (d = 2R) \)   | 0.7   | cm      |
| Active zone length \( (L) \)  | 14    | cm      |
| Maximum pump PRF             | 630   | kHz     |
| Buffer gas (Ne) pressure     | 25    | Torr    |
4. Results and discussion
Using the developed methodology, simulations were carried out to estimate the threshold values of CuBr laser parameters. Figure 2 shows the cross-sectional distribution of gas temperature for two values of the supplied electric power in the gas discharge $Q = 600$ and $800$ W, with $50\%$ losses. According to [12], the temperature of the wall is between $500$ and $700\, ^\circ C$. We select a value in the specified interval - $T_w = 950\, K$.

![Figure 2. Distribution of gas temperature in the tube’s cross-section for two values of the supplied electric power $Q = 600$ W and 800 W.](image)

Figure 3 shows the value of the gas temperature $T_0$ at the center of the tube when the electric power supplied to the gas discharge is altered. The temperature of the wall is $T_w = 950\, K$. From this figure it could be estimated that the maximum permissible electric power supplied to the gas discharge, at which the temperature at the center of the tube reaches its maximum of $3500\, K$ is approximately $Q = 850$ W.

![Figure 3. Change in the gas temperature $T_0$ at the center of the tube when the electric power supplied to the gas discharge is altered. The temperature of the wall is $T_w = 950\, K$.](image)
In order to determine the distribution of the electron temperature in the cross-section of the tube, in equation (6), it is necessary to pre-determine the constants $C_c$, $\sigma$ and $\xi$. Following [11], for $Q=600\,\text{W}$, $R=3.5\,\text{mm}$, $T_{e,\text{exp}}=1.5\,\text{eV}$, $\sigma=4.10^{-5}\,\Omega^{-1}$, $C_c=2.47\times10^{-8}$, for $\xi$ we obtain $\xi=4.85.10^{-5}$.

The Wolfram Mathematica software system is used to solve (6) and to run the computer simulations. The distribution of the electron temperature in the tube’s cross-section for three values of the supplied electric power ($Q_1=600\,\text{W}$, $Q_2=800\,\text{W}$ and $Q_3=1000\,\text{W}$) is shown in Figure 4.

![Figure 4](image)

**Figure 4.** Distribution of the electron temperature in the tube’s cross-section for three values of the supplied electric power.

Figure 5 shows in a single graphic the value of the gas temperature, series 1, K and the electron temperature, series 2, eV at the center of the tube as a function of the electric power $Q$ supplied to the gas discharge.

![Figure 5](image)

**Figure 5.** Dependence of gas temperature and the electron temperature at the center of the tube as a function of the electric power supplied to the gas discharge.

The graphic in Figure 5 can be used as a help diagram. For instance, by setting the maximum permissible gas temperature at the center of the tube at 3500 K (left coordinate axis), we calculate that the maximum permissible input power for the gas discharge is $Q=850\,\text{W}$, which corresponds to the maximum value of the electron temperature at the center of the tube $T_e\approx2.28\,\text{eV}$ (right coordinate axis).
the maximum energy of the electrons by the positions of the thermal ionization and electric ionization resistance of the gas discharge. This methodology can be used for a wide range of gas lasers and metal vapor and metal compound vapor lasers to plan experiments for existing lasers and to develop new ones, including for monostatic and bistatic laser optical systems.

Acknowledgement

This work is supported by grant MU19-FMI-010 of NPD at University of Plovdiv Paisii Hilendarski, financed by the Bulgarian Ministry of Education and Science.

References

[1] Webb C and Jones J eds 2004 Handbook of Laser Technology and Applications vol 2 (New York: Institute of Physics Publishing)
[2] Steen W M and Mazumder J 2010 Laser Material Processing (London: Springer-Verlag)
[3] Zureng X, Guiyan Z and Fucheng L 1992 Applications of the CuBr vapor laser as an image-brightness amplifier in high-speed photography and photomicrography Applied Optics 31 3395–3397
[4] Gocheva-Ilieva S G and Iliev I P 2011 Statistical Models of Characteristics of Metal Vapor Lasers (New York: Nova Science Pub Inc)
[5] Kazaryan M A, Batenin V M, Buchanov V V, Boichenko A M, Klimovskii I I and Molodykh E I 2017 High Brightness Metal Vapor Lasers: Physics and Applications (Boca Raton: CRC Press)
[6] Evtushenko G S, Trigub M V, Gubarev F A, Evtushenko T G, Torgaev S N and Shiyanyov D V 2014 Laser monitor for non-destructive testing of materials and processes shielded by intensive background lighting Rev Sci Instrum 85(3) art no 033111
[7] Trigub M V, Evtushenko G S, Torgaev S N, Shiyanyov D V and Evtushenko T G 2016 Copper bromide vapor brightness amplifiers with 100 kHz pulse repetition frequency Optics Communications 376 81–85
[8] Evtushenko G S, Trigub M V, Evtushenko G S, Troitskii V O, Shiyanyov D V 2016 B bistatic laser monitor Technical Physics Letters 42(6) 632–634
[9] Isayev A A, Kazarian M A and Petrash G G 1974 Possibility of generation of high average laser powers in the visible part of the spectrum Soviet Journal of Quantum Electronics 3 521–523
[10] Iliev I P and Gocheva-Ilieva S G 2010 Model of the radial gas temperature distribution in a copper bromide vapour laser Quantum Electronics 40(6) 479–483
[11] Gocheva-Ilieva S, Iliev I and Fidanov D 2019 Primary analytical model for determining the electron temperature of a CuBr laser IOP Conference Series: Materials Science and Engineering 618 012018
[12] Boichenko A M, Evtushenko G S, Nekhoroshev V O, Shiyanyov D V and Torgaev S N 2015 CuBr-Ne-HBr laser with a high repetition frequency of the lasing pulses at a reduced energy deposition in the discharge Physics of Wave Phenomena 23(1) 1–13