ANALYSIS OF THERMAL PARAMETERS OF CO_2-TRANSMITTER FOR LIDAR SYSTEMS

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Thermal parameters of different discharge chambers of air-cooled CO_2*-lasers are analyzed. Expression is obtained for specific power output per unit length of a laser. Phenomenon of thermodiffusion is considered for the case of H-waveguide laser. Thermal parameters of* CO_2*-laser are experimentally studied.*

The main requirement imposed upon qn$_2$-transmitters of lidar systems is stability of transmitting laser parameters. One of destabilizing factors is the unstable thermal parameters. To stabilize temperature and ensure the required thermal mode, liquid cooling of discharge chamber walls is usually used. New constructive approaches (coaxial lasers,[1,2] slit lasers[3,4]) although allow increase in power output per laser unit length, do not lift the restriction on liquid cooling. At the same time, small-size transmitters for lidar systems requiring no liquid cooling are much-needed.

In this paper, we study the possibility to ensure the required temperature mode, as well as specific characteristics for three types of discharge chambers of qn$_2$-lasers with diffuse cooling. Such chambers are shown in Fig.1. The well-studied tube construction was used as a reference one.[5]

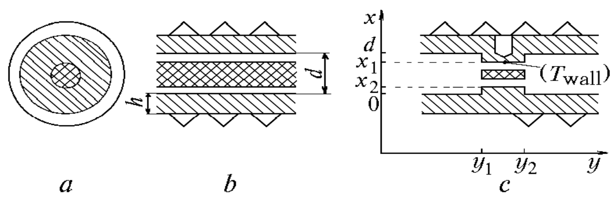

FIG. 1. Discharge chambers: discharge area ; cooled fin surface ; the wall with high thermal conductivity ; T is the temperature measurement point in the experimental chamber.

By analyzing the thermal parameters of these discharge chambers, temperature distribution in the discharge chambers was estimated from the main equation of thermodynamics[7]

$$\frac{\mathrm{d}}{\mathrm{d}x}\left[K(T)\,\frac{\mathrm{d}T}{\mathrm{d}x}\right] + F(x) = \frac{K_0}{(a+1)\,T_0^a}\,\frac{\mathrm{d}^2\theta}{\mathrm{d}x^2} + F(x) = 0\ , \tag{1}$$

where T is gas temperature; T_0 is temperature of discharge chamber walls; $K(T)$ is the coefficient of thermal conductivity: $K(T) = K_0\,(T/T_0)^a$; K_0 is the coefficient of gas thermal conductivity under normal conditions; the value of a depends on gas parameters ($a = 0.7$ for helium-rich mixtures[1]); $\theta(T) = [T(x)]^{a+1}$; $F(x)$ is the function describing the volume distribution of heat sources. We considered the models of heat sources distribution close to the real situation in the discharge zone

$$F(x) = \begin{cases} W_{\rm sp}(1-\eta) = \mathrm{const} & \text{(a)} \\ W_{\rm sp}(1-\eta)\ 6\,\dfrac{d-x}{d^2}\,x & \text{(b)} \end{cases}\ , \tag{2}$$

where $W_{\rm sp}$ is the average specific power output, W/cm^3; η is laser efficiency; d is the distance between electrodes. Boundary conditions imposed upon the Eq. (1) have the form

$$\theta(0) = \theta(d) = T_0^{a+1}. \tag{3}$$

With the help of Eq.(1), the equation for temperature at the discharge chamber axis was determined

$$T_{\rm ax} = T_0 \times \left[1 + 0.25\,G_i\,\frac{W_{\rm sp}\,(1-\eta)\,(1+a)}{K_0\,T_0}\,d^2\right]^{1/(a+1)},$$

$$i = 1, 2, 3, 4. \tag{4}$$

For the laser of tube construction $G_1 = 0.4$; for the slit laser $G_2 = 1$ (2a); $G_3 = 30/48$ (2b); for H-waveguide laser

$$G_4 = 6\left[-\frac{7d^2}{48} + \frac{(x_1+x_2)d}{4} - \frac{x_1\,x_2}{2}\right] / (x_2 - x_1)^2.$$

Equivalent tube diameter for H-waveguide and slab laser, at which temperature distribution coincides with the temperature distribution in the tube of diameter d, equals to

$$D_{\rm eq} = \sqrt{2.5\ G_i}\ d\ . \tag{5}$$

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Assuming that the parameters T_{ax}, η, and T_0 are close for lasers of all the three constructions, we can obtain the equation for power output per laser unit length P_l

$$P_l = \frac{1}{2G_i}\left(\frac{S}{d^2}\right) P_l^T \, . \tag{6}$$

Here P_l^T is the power output per laser unit length; S is cross-section area of the active substance taking part in generation.

These lasers can be pumped in continuous and pulse-periodic mode. Most interesting for the considered application is the pulse-periodic (quasi-continuous) mode of operation. It should be noted that at such a mode of operation in H-waveguide laser, in contrast to slab structure, gas motion is observed. It is caused by temperature gradient between electrodes and ballast space (Fig. 1*c*). Total heat flow Q in this case can be estimated as follows:

$$Q = [(\lambda_1 + \lambda_2) + \alpha^2 \, k_B \, \gamma_i(1 - \gamma_i) n_0 \, D] \times$$

$$\times \, \nabla_y \, T + \lambda_2 \nabla_x \, T \, . \tag{7}$$

Here $\lambda_{1(2)}$ is the coefficient of gas (metal) heat conductivity; α is the thermodiffusion coefficient; k_B is the Boltzmann's constant; D is the diffusion coefficient; γ_i is the molar fraction of ith gas; $n_0 = p/k_B T$; p is gas pressure.

In estimation of the thermodiffusion coefficient, the following assumptions were made:

1. Gas ratio in q n $_2$-laser is q n $_2$:N_2:He = 1:1:8.

2. Let us assume for thermodynamic calculations that m(q n $_2$) = $m(N_2) \gg m$(He), i.e. the mixture is binary: $m_1 \gg m_2$. Then[6]

$$\alpha = (6C^* - 5) \, \frac{S_1 \, \gamma_1 - S_2 \, \gamma_2}{Q_1\gamma_1^2 + Q_2\gamma_2^2 + Q_{12}\gamma_1\gamma_2} \, .$$

Coefficients C^*, S_1, S_2, Q_1, Q_2, and Q_{12} are presented in Ref. 6. In this case, power output per unit length of laser is

$$P_l \geq \eta Q S / L \, , \tag{8}$$

where L is resonator length.

One of the causes of discharge instability is excess of temperature in the laser discharge chamber over some its critical value. It is especially important in air cooling of discharge chamber walls. To determine temperature at the chamber axis, it is necessary to estimate the efficiency of heat abstraction from the discharge zone.

In a discharge chamber wall, heat is abstracted from the discharge zone via heat transfer. In calculations, we assumed that walls are made of homogeneous material. The equation of heat conductivity in this case has the following form:

$$\partial^2 T / (\partial x^2) = 0 \, . \tag{9}$$

Considered were the boundary conditions of the third type. Then the temperature of inner surface of discharge chamber wall can be determined from the following equation:

$$T_0 = T_{\text{wall}} + Q_s \delta / \lambda_2 \, , \tag{10}$$

where T_{wall} is the measured temperature; Q_s is the scattered heat power; δ is wall thickness.

For more efficient heat abstraction from discharge chamber walls, we used the heat sink. From the heat balance, the following equation for heat distribution in fin can be obtained[7]:

$$\mathrm{d}^2\vartheta / (\mathrm{d}\xi^2) - (Bi)\vartheta = 0 \, , \tag{11}$$

where Bi is the Biot number; $\vartheta(x) = [T(x) - T_{\text{air}}]/[T_{\text{wall}} - T_{\text{air}}]$; $\xi = x/l$, l is the fin height; T_{air} is the temperature of air above the chamber surface. For the fin with convective heat transfer, boundary conditions have the following form:

$$T(0) = T_{\text{wall}} \, ;$$

$$- \lambda_2 \left. \frac{\mathrm{d}T}{\mathrm{d}x} \right|_{x = l} = h_{\text{av}} \, [T(l) - T_{\text{wall}}] \, , \tag{12}$$

where h_{av} is the average coefficient of heat transfer.

Thus, at the face surface the temperature can be determined as

$$\vartheta(\xi) =$$

$$= \frac{\mathrm{ch}[\sqrt{(Bi)}(1 - \xi)] + \sqrt{(Bi)}(B/\Pi l) \, \mathrm{sh}[\sqrt{(Bi)}(1 - \xi)]}{\mathrm{ch}[\sqrt{(Bi)} + \sqrt{(Bi)}(B/\Pi l) \, \mathrm{sh}\sqrt{(Bi)}]} .$$

Here b is fin cross section area; o is fin perimeter. Heat sink calculation performed by the technique proposed in Ref. 8 shows that provided the heat sink is force cooled, abstracted specific heat power is 3 W/(degree·dm^2); the coefficient of increase in cooling fin area is 6 (dm^2/dm^2). The heat sink of q n $_2$-laser of 100 W power was cooled by fans fixed at the face of discharge chamber. The calculated data were supported by experiments (Fig. 2).

To determine the temperature at the discharge chamber axis T_{axis} (4), the temperature of inner wall of the discharge chamber T_{wall} was experimentally determined (see Fig. 1*c*). The boundary conditions for Eq. (4) were found from Eq. (10). The temperature at the discharge chamber axis was calculated at the computer. With forced air cooling of the heat sink of the discharge chamber of H-waveguide laser, the temperature at its axis proved to be less than the critical temperature, that meets the condition of stable discharge.

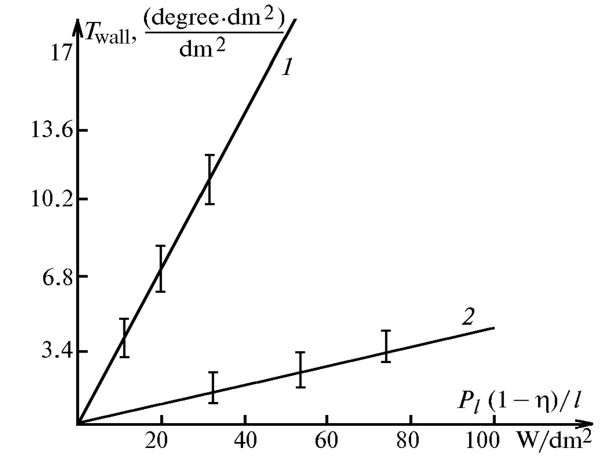

FIG. 2. Experimental curve. Bars are for experimental spread in values: curve 1 is temperature change normalized to coefficient of increase in cooling fin area vs. scattered heat power of the heat sink without forced air cooling. In this case, ratio between temperature change and power scattered by the heat sink was 24 degree/(kW·dm). *Curve 2 is temperature change normalized to coefficient of increase in cooling fin area vs. scattered heat power of the heat sink with forced air cooling. Here the ratio between temperature change and power scattered by the heat sink was* 7 degree/(kW·dm).

Thus, 1. Temperature modes of discharge chambers of three construction types were comparatively analyzed, and Eq. (6) for power output per unit laser length was obtained. 2. Theoretical calculations are supported by experiments. 3. It is seen from obtained calculation and experimental results that forced air cooling is capable to ensure the necessary temperature mode for q n $_2$-lasers with output power up to 100 W.

Analysis and optimization of pumping systems and resonators for such lasers will be considered later.

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