COMPUTATIONAL METHOD OF THERMAL DESIGN OF SOLID-STATE LASER QUANTRONS WITH NATURAL COOLING. 1. DESIGN SCHEME

G. N. Dul'nev, A. E. Mikhailov, and V. G. Parfenov

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A method is described for the rational selection of quantron construction and the optimization of its parameters.

The growing demands on the characteristics of radiation being generated by solid-state lasers, and the reduction of the scientific-research and testing-construction work time result in the necessity for utilizing computational methods in the selection of the optimal quantron construction. This especially concerns the design of quantrons with natural cooling that function in a stressed thermal mode. Their construction should be optimized with thermooptical effects taken into account. The necessity here arises for an analysis of the influence of a large number of factors on the characteristics of the radiation being generated: the kind of active medium and the construction of the illuminator, the geometric parameters of the illuminator, the kind of reflecting coating, etc. A large number of variable factors make the determination of the optimal construction by purely experimental means considerably more difficult. The situation is complicated also by the circumstance that any of the factors listed influences both the characteristics of the laser radiation being generated in the thermally unperturbed state (during operation in the single pulse mode) and the changes of these characteristics subjected to the thermal mode that appears during operation in the frequency mode. Consequently, the approach in which the device is designed without taking account of thermal effects from the beginning, then the demands on its normal thermal mode are determined, and measures to assure this mode are developed in the last stage has become obsolete. Different modifications of the structural solutions of a quantron must be examined during design by estimating the joint influence of the optical, thermophysical, thermomechanical, and thermooptical processes proceeding therein on the characteristics of the radiation being generated.

FUNDAMENTAL DESIGN PRINCIPLES AND STAGES

Because of the presence of significant errors in the initial information and the approximate nature of the models being used at this time there are no computational methods that permit reliable estimation of the absolute values of the characteristics of the radiation being generated. Consequently, it is expedient to combine mathematical modelling with a small number of experiments. To do this, the characteristics of the radiation being generated (output energy, stability of the radiation axis, divergence, intensity distribution in the beam cross section, etc.) that can be obtained for any modification being proposed for the quantron construction, is compared in the computational design with the analogous radiation characteristics achieved on the experimental unoptimized model. The experimental model should reflect a number of the construction features and the operating mode of the laser that have not already been changed in the computational design: the kind of active medium, the type of pumping tube, the duration and shape of the pumping pulse. Such an approach to the design permits experimental determination or refinement of the values of a number of quantities in the model that are needed to obtain comparative numerical estimates, diminution of the influence of model errors and uncertainty of the initial data on the analysis results, and raising the confidence in the deductions in the long run.

The design is carried out in two stages. The selection of the quantron base construction which includes determination of the quantity of pumping tubes, the reflector kind and

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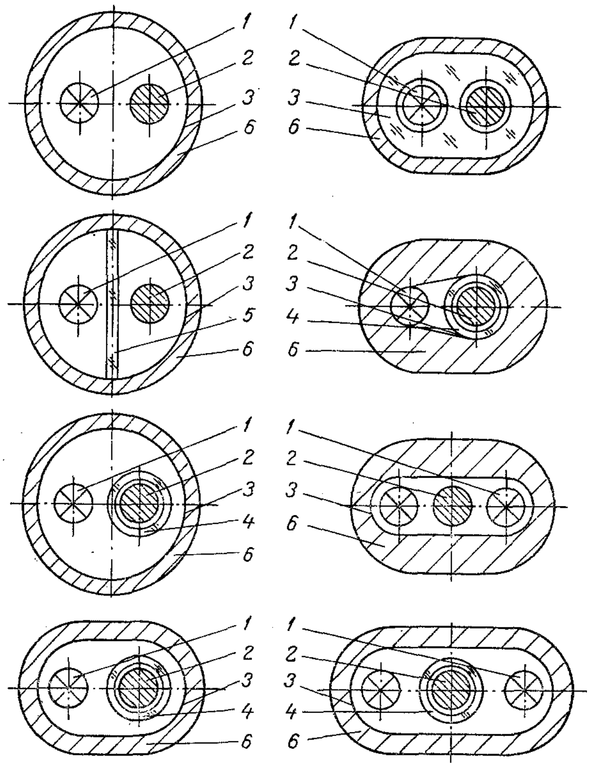

Fig. 1. Quantron base constructions: 1) pumping tube; 2) active element; 3) reflector; 4) leucosapphire tube; 5) filter; 6) housing.

shape (monoblock, hollow, etc), the kind of reflecting coating (diffuse or specular), the shape of the active element, the kind of elements and media utilized to filter the pumping radiation, improvement of the heat elimination and other purposes is realized in the first stage. Among these latter are, for instance, leucosapphire tubes in which the active elements are installed, plate filters, immersion fillers inserted in the channel between the active element and the monoblock. Some base constructions of single-tube and two-tube quantrons are presented in the figure.

Parametric optimization of the selected base construction is performed in the second design stage whereupon the activator concentration, the geometric size of the quantron elements and the parameters of their mutual arrangement, and the parameters of thermal contact between elements are determined.

Changes in the pumping system efficiency as well as the influence of the thermal mode on the characteristics of the radiation being generated must be taken into account in selecting the base construction and parametric optimization. This latter is manifest in the diminution of the gain coefficient caused by temperature changes of the spectroscopic parameters of the active medium, thermal aberrations and thermal depolarization occurring in the active elements [1-4].

The following sufficiently general tendency must be taken into account in design: structural changes diminishing the influence of the quantron thermal mode on the characteristics of the radiation being generated (for instance, an increase in the quantity of pumping tubes, utilization of a leucosapphire tube around the active element, etc.) result, as a rule, in reduction of the pumping system efficiency. Therefore, the purpose of design is the search for a construction in which a reasonable compromise is achieved between the pumping system efficiency and the thermostability of the quantron. The main problem occurring in the realization of the design procedure is associated with determining the criterion by which the quality of the quantrum construction modifications under consideration is compared. The selection of these criteria depends on both the kind of initial requirements on the characteristics of the device radiation being generated and on the test results of the model. On the basis of these results, the "critical" characteristics of the radiation being generated that must be improved in the computational design can be isolated.

ANALYSIS OF THE QUANTRON CONSTRUCTION

Analysis of the quality of quantron construction is performed on the basis of the results of computations of distributions of the sources of heat and pumping lamp radiation energy absorbed in the active element and the quantron thermal mode. These distributions are determined by using programs realizing the Monte Carlo method [5, 6]. The temperature fields of the quantron elements are determined by using a special set of programs based on the numerical solution of a system of nonstationary multidimensional heat conduction equations describing the quantron thermal mode [7].

Since the main characteristic of the radiation being generated is its output energy then the quantity

$$\eta = \frac{E(\tau)}{E_0} \tag{1}$$

ordinarily always is among the criteria by which the quality of the quantron construction modifications under consideration is compared, where $E(\tau)$ is a function describing the change in generation pulse energy from the time of laser operation obtained by computational means for the construction modification under investigation, and E_0 is the experimental value of the output energy obtained in the model during operation in the single pulse mode.

An estimate can be obtained for the relative output energy η on the basis of known approximate relationships for laser output energy [8, 9] and temperature dependences of the spectroscopic characteristics of active media investigated in [10, 11]. The simplest expression for η in the free generation mode has the form

$$\eta = \frac{D^2 l}{D_0^2 l_0 (n_\text{п} - 1)} \left[\frac{\alpha + \alpha_R}{\alpha + \alpha_\text{в} + \alpha_R} \frac{U}{U_0} \frac{D_0^2 l_0}{D^2 l} \exp(-\alpha_3 (T_v(\tau) - T_0))\, n_\text{п} - \right.$$
$$\left. - \frac{N_0 \sigma_{23} \exp(-\alpha_2 (T_v(\tau) - T_0))}{\alpha + \alpha_\text{в} + \alpha_R} \frac{z_2}{z_1} \exp\left(-\frac{\Delta E}{k T_v(\tau)}\right) - 1 \right] \times$$
$$\times \exp(\alpha_3 (T_v(\tau) - T_0)),$$
$$\alpha_R = \frac{1}{2l} \ln \frac{1}{R},$$
$$z_1 = 1 + \sum_{i=2}^{N_1} \exp\left(-\frac{\Delta E_i}{k T_v(\tau)}\right), \quad z_2 = 1 + \sum_{j=2}^{N_2} \exp\left(-\frac{\Delta E_j}{k T_v(\tau)}\right), \tag{2}$$

while for the active quality modulation mode it is

$$\eta = \frac{D^2 l}{D_0^2 l_0} \frac{n'_\text{п} - n'_k}{n_\text{п} - n_k} \exp(\alpha_3 (T_v(\tau) - T_0)),$$
$$n'_\text{п} = \frac{\alpha + \alpha_R}{\alpha + \alpha_\text{в} + \alpha_R} n_\text{п} \exp(-\alpha_3 (T_v(\tau) - T_0)) -$$
$$- \frac{N_0 \sigma_{23} \exp(-\alpha_2 (T_v(\tau) - T_0))}{\alpha + \alpha_\text{в} + \alpha_R} \frac{z_2}{z_1} \exp\left(-\frac{\Delta E}{k T_v(\tau)}\right),$$
$$n_k = n_\text{п} + \ln \frac{n_k}{n_\text{п}}, \quad n'_k = n'_\text{п} + \ln \frac{n'_k}{n'_\text{п}}. \tag{3}$$

Values of the constant coefficients α_2, α_3 for YAG and GSGG are presented in [10, 11]. The relative excess over the threshold n_Π, obtained on a model in a thermally unperturbed state, enters into (2) and (3). Let us emphasize that determination of a reliable absolute estimate of the value of the output energy $E(\tau)$ is difficult; however, its relative estimate η is sufficiently reliable, as practice shows.

The influence of thermal aberrations and thermal depolarization by an appropriate increase in the passive loss coefficient on the laser output energy is taken into account by using the term $\alpha_B(T(\bar{x}, \tau))$ dependent on the spatial distribution of the active element temperature. This term is usually approximated by a functional dependence of the additional loss coefficient on the integral thermal aberration characteristics (the magnitude of the thermal wedge deformation, the focal length of the thermal lens, etc.) and the magnitude of the thermal depolarization. To find the integral thermal aberration characteristics and the magnitude of the thermal depolarization on the basis of the active element temperature field, its thermoelastic state as well as distortions of the optical indicatrix that occur because of the photoelectric effect and temperature changes of the principal refractive indices are determined. Computation of the thermoelastic state is usually performed by using specialized programs realizing the finite element method [12].

As a rule, in the single-tube and two-tube quantrons with natural cooling that are most widespread in practice, the thermal aberrations have a sufficiently complex form because there is no angular symmetry in the active element temperature field. However, some meridian plane passing through the active element axis in which thermal aberration of the thermal lens or thermal wedge type occur that exerts the main influence on the laser output energy can often be separated out. Then by experimental or computational means the dependence of the additional passive loss coefficient α_B on the magnitude of the thermal wedge deformation or thermal lens focal length acting in the appropriate meridian plane can be determined for the resonator type selected. The contribution of thermal depolarization to the increase in the passive loss coefficient can be reflected in an analogous manner.

The simultaneous influence of the pumping system efficiency, the temperature changes of the spectroscopic characteristics, the thermal aberrations, and thermal depolarization on the relative output energy η is successfully taken into account by such means in a number of cases.

Using the relationship for the relative value of the output energy (2) and (3), the design problem can be solved in different formulations. For instance, it is possible to search for a construction assuring maximum η, i.e., yielding the highest "energetic gain" as compared with the model. It is sometimes expedient to optimize the duration (at a fixed frequency) or frequency (at a fixed duration) of laser operation instead of the quantity η, for which the diminution in output energy would not exceed a given quantity, i.e., for a fixed lower bound for η. The values of the allowable frequency or duration of operation are here found during the design process on the basis of analysis of the relationships (2) and (3). Certain examples of the comparative analysis of different base constructions according to the quantity η, the duration of operation, and the pulse repetition rate are presented in [13, 14].

A situation is often encountered when a sufficiently large output energy E_0 is obtained in the model but the main requirements on the characteristics of the radiation being generated are associated with its divergence, stability of the radiation axis location, intensity distribution in the beam cross section, etc. It is here expedient to select a construction assuring minimal thermal aberration of any kind under constraints on the minimal value of the magnitude of the relative output energy η.

In many cases more complex methods must indeed be applied. For instance, the influence of thermal aberrations and thermal depolarization on the relative output energy η is not always taken into account successfully by computational means. Then only changes in the pumping system efficiency and the temperature dependences of the spectroscopic characteristics are taken into account in computing the quantity η and a quantron construction assuring a compromise balance between the relative output energy and the magnitudes of the thermal aberrations and the thermal depolarization is determined that satisfies the designer.

The thermal design method considered was used in development of solid state laser quantrons of different construction and purpose.

NOTATION

D, ℓ, active element diameter and length for the quantron construction modification being analyzed; D_0, ℓ_0, model active element diameter and length; α, passive loss coefficient in the resonator; U, U_0, pumping system efficiencies of the quantron construction modification being analyzed and of the model; T_0, initial active element temperature; σ_{23}, effective transverse section for the passage from multiplet 2 to multiplet 3 in the generation wavelength at the initial temperature; α_2, α_3, constant coefficients governing the temperature dependences of the effective transverse section for the transition from multiplet 2 to multiplet 3 and from multiplet 3 to multiplet 2 at the generation wavelength; N_0, activator concentration; z_1, z_2, statistical sums in the ground state (multiplet 1) and multiplet 2 Stark levels; ΔE, energetic gap between multiplets 1 and 2; k, Boltzmann constant; R, reflection coefficient of the resonator output mirror; N_1, N_2, numbers of the Stark levels of multiplets 1 and 2; ΔE_i, ΔE_j, energetic gaps between the Stark levels with numbers i and 1 for multiplet 1 and j and 1 for multiplet 2; and T_V, active element mean bulk temperature.

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