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Analysis of thermal conditions of high-power semiconductor lasers and their arrays

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Abstract. **The results of thermophysical investigations of semiconductor lasers are reported, which underlie the formulation of the optimal requirements on the materials, design parameters, and technological assembling conditions for high-power semiconductor lasers and their one- and two-dimensional arrays with the goal of most efficient heat removal. The methods are outlined for calculating the residual post-assembling mechanical stress and determining the assemblage conditions under which the attendant stress is insignificant and its effect on the laser quality is minimal. Also the methods are given for calculating the thermal resistance for different heat sinks, including heat sinks with forced cooling, and of determining the design requirements on the heat sink arising from specific service conditions.**

Keywords: *laser diode, mechanical stress, tensile strength, solder alloy, heat sink, heat removal.*

1. Introduction

Despite the rather high electric-to-light energy conversion factor (above 50 %), providing a means for efficient heat removal from the active region of a laser crystal still remains a serious problem in the fabrication of semiconductor lasers. The thermal energy is released in the crystal due to the nonradiative recombination of the carriers injected into the active region, their thermalisation, and radiation absorption in the passive regions of the crystal as well as due to the Joule losses in the flow of the pump current through the semiconductor volume and the current-carrying contacts [1, 2].

The efficiency of real semiconductor lasers is equal to about 50 % – 60 %, and, therefore, about 40 % – 50 % of the electric energy delivered to a semiconductor crystal is converted to thermal energy in one way or another, with the effect that the active region of the laser crystal is heated. The rise in the temperature of the active layer in its turn reduces the internal quantum efficiency, decreases the gain, increases the threshold current, reduces the output power, and shifts the output wavelength. Furthermore, the rise in the working temperature of the active region of the laser crystal has an adverse effect on the reliability and service life of the laser.

A characteristic parameter for the heat sink of specific design with a laser crystal mounted on it is the thermal resistance R_T. The reciprocal of the thermal resistance R_T characterises the thermal conduction of the laser diode structure, i.e., the passage of thermal energy from the active region of the laser crystal to the ambient medium.

In the consideration of heat removal from a laser crystal to the ambient medium, account is taken of the specific features of the problem, which consist in that the region of release of a relatively large amount of thermal energy is small in comparison with the heat-removing elements. When developing the semiconductor laser fabrication technology it is therefore necessary to take into account the requirements imposed on the materials, shape, dimensions, and surface condition of the heat sinks.

It is also necessary to afford the selection of reliable and long-lived solder alloy materials suitable for attaching a laser crystal to the heat sink, of materials for the ohmic contacts of the crystal, of the techniques, regimes, and conditions of assembling, etc. The technological conditions of attaching the crystal to the heat sink should correspond to the conditions whereby the mechanical stress is either non-existent or minimised. The solution of the above problems invites theoretical calculations as well as thorough experimental technology research with the inclusion of the wealth of presently available data accumulated in the industrial fabrication of semiconductor lasers by different manufacturers.

Nakwaski [3, 4] considered the temperature effects in semiconductor laser crystals for different heterostructure materials. In these papers, the calculated temperature distribution in each layer of the heterostructure was presented. The temperature distributions in the transverse section of the crystal were calculated both in the plane of the p – n junction and in the perpendicular direction. Given in Refs [5, 6] is a complicated analytical expression for the temperature distribution in the heat sink. However, in the above papers no account was taken of the effect of the interlayers between the crystal and the heat sink – solder alloys and coatings – on the thermal properties of the laser. They are very hard to include in the analytical expression for a three-dimensional heat spreading. Furthermore, by resorting to the technique outlined in the above-specified papers it is impossible to accurately calculate complex heat sinks like, for instance, heat sinks with forced cooling, heat sinks of the C-mount type, etc.

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The present paper gives a method of calculation based on exact numerical techniques for the solution of the problems of thermal conduction, laminar fluid flow, and mechanical materials matching without limitations that arise from the structural features of heat sinks and conjunctive materials. Conductive and convective (with forced circulation) cooling methods are considered.

2. Method of designing heat sinks with the inclusion of requirements imposed on laser diodes

The best-known and commonly used design of a semiconductor laser diode is a metal (quite frequently copper) heat sink, with a laser crystal soldered to one of its surfaces. Apart from the function of heat transfer from the laser crystal to the surrounding medium, the heat sink also fulfils the function of a current-carrying contact. The second current-carrying lead of the laser crystal is a wire lead also soldered or welded onto a metallised crystal surface which affords the ohmic contact. The specific feature of this design consists in that the heat release is characterised by a high density in a small volume.

Because the dimensions of the laser crystal itself and, quite frequently, of the area of heat release region in the crystal are rather small [(10 – 100) μm × 1000 μm] and do not afford efficient heat transfer to the ambient medium, the metallic heat sink should fulfil the function of the 'expander' of the thermal surface which is in contact with the ambient medium.

In this case, the thermophysical problem solution for each specific semiconductor laser design imposes specific structural and technological requirements on the materials, shape, dimensions, and surface conditions of the heat sinks. Furthermore, the method of heat removal – convective (using a heat-transfer agent), conductive, or mixed – is defined depending on the specific problem and the amount of heat released. Also determined are the requisite properties of the heat-transfer agents where active convective cooling is involved.

The solution of this problem for heat sinks of various design is based on the numerical solution of the heat conduction equation

$$\rho C \frac{\partial T}{\partial t} - \nabla(k \nabla T) = Q, \tag{1}$$

where ρ is the density, C is the heat capacity, and k is the thermal conductivity coefficient of the materials; Q is the thermal energy release density.

For every specific application and heat sink design, the boundary conditions are selected in compliance with the requirements that follow from the means of heat transfer to the surrounding medium.

Considered in the case of conductive heat exchange with the surrounding medium are the boundary conditions of the first and second kinds. The boundary condition of the first kind, $T_b = \mathrm{const}$, is considered when it is required to maintain a constant temperature (T_b) at one of the faces of the heat sink. The boundary condition of the second kind may be considered for a known thermal flux distribution at the boundary. In other cases, when the cooling is effected due to convection, use is made of the boundary condition of the third kind:

$$-k \nabla T = g,$$

where $g = \alpha_t(T_w - T_{liq})$ is the thermal flux at the boundary and α_t is the heat-transfer coefficient [7].

For heat sinks with a forced cooling by a liquid heat-transfer agent, the flow velocity u in a microchannel is defined by the solution of the Navier – Stokes equation for an incompressible fluid [7, 8]:

$$\tilde{\rho} \frac{du}{dt} = \eta \nabla^2 u - \nabla P, \tag{2}$$

where η is the dynamic viscosity of the liquid; P is the microchannel inlet – outlet pressure difference; and $\tilde{\rho}$ is the density of the heat-transfer agent.

The heat transfer by a liquid in the convective – conductive way is taken into account through the combined solution of Eqn (2) and the thermal energy balance equation [7, 8]

$$k \nabla^2 T = \tilde{\rho} \tilde{C} (\boldsymbol{u} \nabla) T, \tag{3}$$

where $\tilde{C}$ is the heat capacity of the liquid.

The boundary conditions for these equations are selected in the following way. The microchannel of heat-transfer agent motion is assumed to be symmetric about the central axis (or plane), while the dependence of the fluid velocity at the microchannel inlet on the transverse coordinate y is assumed to be parabolic:

$$u = u_0 \frac{y}{d_m}\left(1 - \frac{y}{d_m}\right),$$

where d_m is the microchannel width and $u_0 = \mathrm{const}$.

Also prescribed at the microchannel inlet is a constant temperature value of the heat-transfer agent: $T = T_{in}$. The wetting (adherence) condition at the channel walls is written as $\boldsymbol{u} = 0$. Through these walls there occurs thermal energy transfer from the heat-sink material by way of thermal conduction. At the channel outlet, use is made of the boundary conditions of unimpeded fluid motion and the convective heat exchange is assumed to be far stronger than the conductive one:

$$P = 0, \quad \boldsymbol{ut} = 0, \quad \boldsymbol{n} \nabla T = 0,$$

where $\boldsymbol{n}$ and $\boldsymbol{t}$ are the normal and tangential unit vectors relative to the microchannel outlet section plane.

Solving Eqns (2) and (3) subject to the above boundary conditions permits determining the coefficient of heat removal at the microchannel boundaries for given parameters of a heat-transfer agent. Next, on substituting the resultant values of the heat removal coefficient into the boundary conditions, in the solution of the thermal conduction problem (1) it is possible to determine the thermal characteristics of the heat sinks of specific design in every specific case of laser application.

Copper is one of the commonly employed materials for the heat sinks of semiconductor lasers. This material is primarily selected due to its availability and high (in comparison with other materials) thermal conductivity coefficient $\alpha \sim 400$ W m^{-1} K^{-1} [9, 10]. However, copper exhibits a higher coefficient of thermal expansion (CTE) $\alpha \sim 16 \times 10^{-6}$ K^{-1} than semiconductors {for semiconductors, α is equal to $(5-7)\times10^{-6}$ K^{-1} [9]}. The difference in CTE values is significant from the standpoint of the emergence of mechanical stress in a laser crystal and the conjunctive solder alloys upon assembling.

The solution of the problem of mechanical matching of semiconductor laser crystals with metallic heat sinks permits defining the requirements on the manufacturing methods and materials as well as on the specific design of the laser diode.

The relationship between the stress and strain tensors with the inclusion of the thermal effects is of the following form [11, 12]:

$$\sigma_{ij}=\frac{E}{1+\nu}\left(\varepsilon_{ij}+\frac{\nu}{1-2\nu}\,\delta_{ij}\,\delta_{ik}\right)-\frac{E\alpha\Delta T}{3(1-\nu)}\,\delta_{ij}, \qquad (4)$$

where

$$\sigma_{ij}=\begin{pmatrix}\sigma_{xx} & \sigma_{xy}\\ \sigma_{yx} & \sigma_{yy}\end{pmatrix}$$

are the components of the in-plane stress tensor;

$$\varepsilon_{ij}=\begin{pmatrix}\varepsilon_{xx} & \varepsilon_{xy}\\ \varepsilon_{yx} & \varepsilon_{yy}\end{pmatrix}$$

are the strain tensor components, which are related to the displacement vector components u_x, u_y in the two-dimensional case by the expressions

$$\varepsilon_{xx}=\frac{\partial u_x}{\partial x},\ \varepsilon_{yy}=\frac{\partial u_y}{\partial y},\ \varepsilon_{xy}=\varepsilon_{yx}=\frac{1}{2}\left(\frac{\partial u_x}{\partial y}+\frac{\partial u_y}{\partial x}\right)$$

$$(\varepsilon_{ll}=\varepsilon_{xx}\ \text{for}\ i=j=1;\ \varepsilon_{ll}=\varepsilon_{yy}\ \text{for}\ i=j=2);$$

E is the Young modulus; ν is the Poisson coefficient; $\Delta T=T_{\text{melt}}-T$; and δ_{ij} is the Kronecker symbol.

The equilibrium equation with the inclusion of stress induced by thermal effects is of the form [11, 12]

$$\frac{\partial\sigma_{ij}}{\partial x_i}-\frac{E}{3(1-2\nu)}\frac{\partial(\alpha\Delta T)}{\partial x_i}=0. \qquad (5)$$

The solutions of Eqns (4) and (5) in combination with the deformation compatibility condition (the Sen-Venan condition) [12]

$$\frac{\partial^2\varepsilon_{ij}}{\partial x_i^2}+\frac{\partial^2\varepsilon_{ji}}{\partial x_j^2}=\frac{\partial^2\varepsilon_{ij}}{\partial x_i\,\partial x_j}$$

and the condition for the absence of external load completely define the values of stress and strain in the vicinity of every point in the transverse section of the laser structure (crystal, solder alloy, heat sink).

Therefore, for known parameters of the materials and a given laser design it is possible to calculate the stress and deformation emerging during its cooling (upon bonding the crystal to the heat sink). This allows selecting optimal solder alloys for attaching the laser crystal to the heat sink that would minimise the residual mechanical stress both in the crystal and at the point of bonding the crystal to the heat sink. The performance of semiconductor lasers as well as their reliability and service life depend on this interconnection and on the variation of its properties during operation and storage.

Investigations of the mechanical and thermophysical properties of the laser crystal structure, its ohmic constants, conjunctive solder alloys, and heat sink permit defining the requirements on the fabrication technology of laser diodes of specific design in relation to their use environment.

3. Requirements on heat sink and solder alloys

Despite the significant difference between the CTEs of copper and a semiconductor laser crystal, most frequently used at present are copper heat sinks. In this case, for a solder alloy use is made of the so-called low-temperature solders (In, PbSn, SnAg, etc.), which allow minimising the after-soldering crystal compression, when the temperature lowers to room temperature or lower, if required by the operating conditions. We consider the most common version of a laser diode: a laser crystal soldered to a copper heat sink with the aid of indium. To elaborate the requirements on the heat sink dimensions, the coating materials, and the solder thickness, it is necessary to solve the three-dimensional thermal conduction problem with the inclusion of specific requirements on the laser diode (including requirements on the laser crystal design) that follow from the operating conditions. To begin with, for a heat sink we consider a copper parallelepiped measuring $s\times d\times h=3\times3\times2$ mm, onto which a single laser crystal ($500\times600\times100$ μm) is soldered. The active region faces the heat sink and measures $W\times L=10\times600$ μm. Figures 1 – 3 show the structures of the heat sinks for single laser crystals, high-power semiconductor lasers, linear and 2D laser diode arrays, including the case of forced cooling.

The results of numerical solution of the heat conduction equation (1) subject to the corresponding boundary conditions are plotted in Fig. 4 for different dimensions of a right-angled copper heat sink.

For a strip laser with a contact width $W\approx10$ μm, the temperature drop takes place in a small volume of the heat sink located close to the crystal. The requirement that the

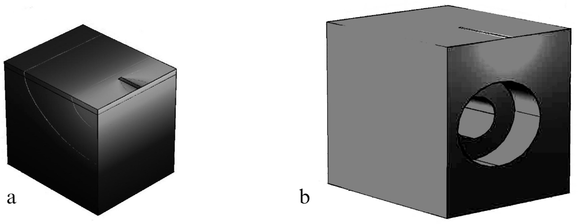

Figure 1. Examples of the heat sinks for single laser crystals with a strip contact width of less than 50 μm (a) and an active region width of 100 μm and more (b).

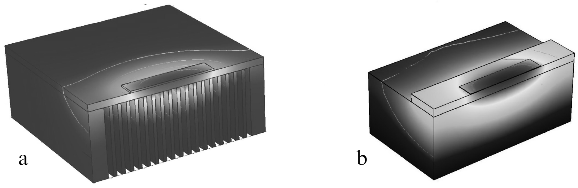

Figure 2. Heat sink designs for mounting cw linear laser arrays: ribbed heat sink for convective cooling (a) and heat sink for conductive heat transfer to a more massive heat sink (b). Qualitatively shown are the thermal flux distribution regions.

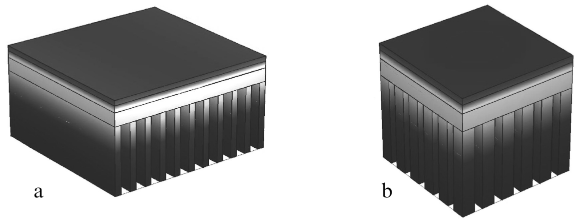

Figure 3. Ribbed (a) and needle-shaped (b) heat sinks for 2D laser arrays with forced cooling. Qualitatively shown is the heat distribution over the ribs.

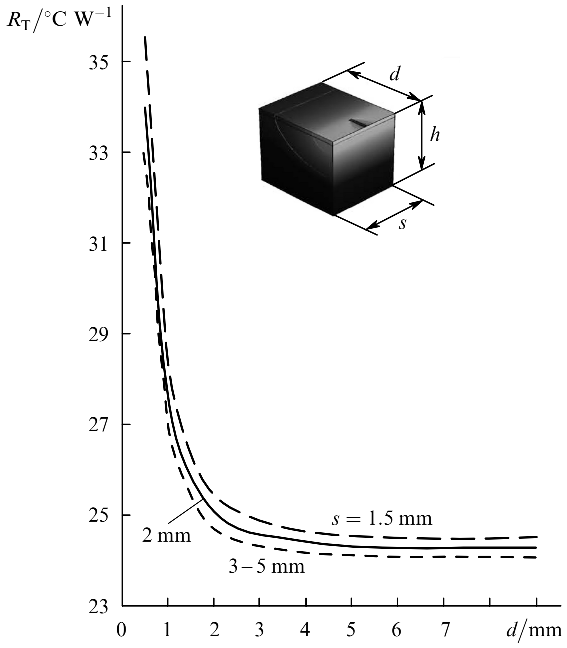

Figure 4. Thermal resistance of a contact plate with a 3-μm thick In solder alloy as a function of contact plate thickness d for $h = 3$ mm and different s values. The strip contact width is $W = 10$ μm, the heat removal is effected across the lower heat sink surface, the laser crystal length is $l_0 = 600$ μm.

temperature field should be expanded in the volume of the heat sink increases its dimensions and therefore rises its thermal resistance.

One or several faces of the contact plate may serve as a heat-removing surface, depending on the specific application. This function is quite often fulfilled by the face opposite to the face attached to the laser crystal or the heat sink surface perpendicular to this face.

Figure 4 shows the values of the thermal resistance of the rectangular heat sink of a strip ($W = 10$ μm) laser in the case when the heat is removed into the ambient medium with a given temperature through the heat sink surface opposite to the mounting face. Figure 5 gives the results of calculations of the thermal resistance, which is determined by the heat sink and the solder alloy, for high-power single-crystal semiconductor lasers with wide strip contacts ($W = 100$ μm) mounted on a conventional heat sink of the C-mount type (see Fig. 1b). Plotted are the dependences of the thermal resistance on the solder alloy thickness when using In and PbSn. For single-crystal lasers, the problem under consideration is three-dimensional.

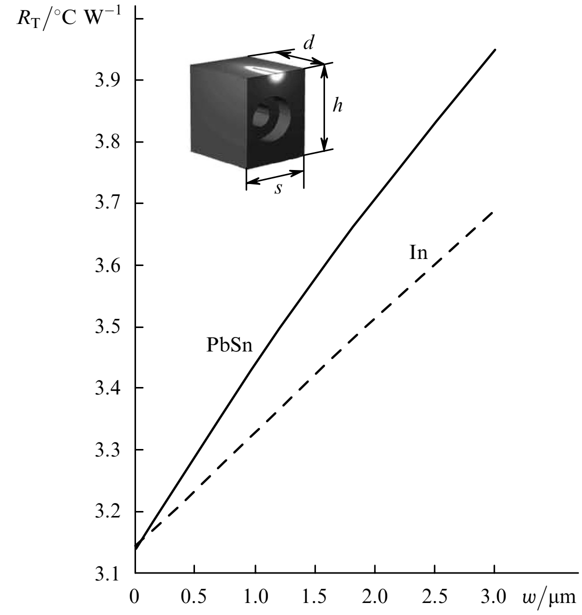

Figure 5. Thermal resistance of a conventional contact plate of the C-mount type with a solder alloy as a function of solder thickness w for $l_0 = 1$ mm, $W = 100$ μm. The heat removal is effected across the rear surface of the contact plate.

The problem becomes two-dimensional for 5- or 10-mm long linear laser arrays (see Fig. 2). When the heat sink width exceeds the length of a linear laser array, the condition for edge crystals becomes more favourable due to the three-dimensional heat distribution in the heat sink. As regards the crystals located in the middle of the linear array, the heat is removed from them in two directions (downwards and backwards).

Figure 6 shows the temperature distributions with height H in heat sinks of various design for linear and 2D laser arrays. Curve (*1*) relates to a cw linear laser array mounted on a diamond heat sink in the case of conductive (see Fig. 2a) heat exchange with the surrounding medium. The face opposite to the linear array has a temperature of 300 K. Curve (*2*) shows the rib temperature distribution with height for a water-cooled copper heat sink with a micro-channel ribbed cooler and curve (*3*) the heat sink

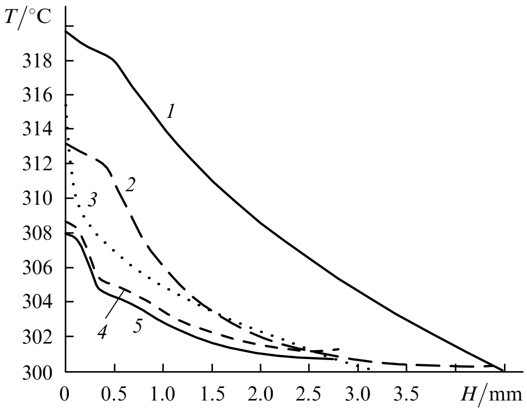

Figure 6. Vertical temperature distributions over variously designed heat sinks for linear and 2D laser arrays (see text).

temperature distribution with height for a linear laser diode array with a strip 10-μm wide contact and a 250-μm pitch.

From curves (*4*) and (*5*) it is possible to trace the rib temperature distribution with height in a copper ribbed heat sink for two-dimensional laser arrays, where a rectangular dielectric plate with a thermal conductivity coefficient of 250 W m^{-1} K^{-1} is the base on which laser linear arrays are mounted.

By taking advantage of the data given in Fig. 6 or similar calculations for other heat sink designs, in every specific case it is possible to determine the optimal height of the heat sink or of the rib in convective heat exchange to ensure the minimal or acceptable thermal resistance.

4. Calculation of the parameters of technological heat-removal conditions in the assemblage of laser crystals

The employment of low-temperature solders (In, PbSn, SnAg, etc.) imposes certain requirements on the technological conditions of assemblage. The determination of temperature-time assemblage conditions for each specific laser design is the crucial technological factor, which affects both the performance and reliability of the laser. The stress emerging during assemblage because of the unmatched CTEs of the heat sink and the laser crystal is the determining fact that affects the reliability and service life of the semiconductor laser. The assemblage regimes that minimise the residual stress can be selected by calculating the stress and its relaxation times for the solder alloys involved. To this end we take advantage of the solutions of Eqns (4) and (5) for given dimensions and materials of the heat sink, crystal, and solder alloy.

By considering the cooling of a heat sink with a mounted crystal upon solder solidification, it is possible to determine the requisite rate of temperature lowering from the melting temperature to room temperature. The selection criterion is the absence of stress exceeding the tensile strength in the solder material.

The magnitudes of strain σ applied to one of the surfaces of the solder, which is located between the crystal and the heat sink, and of the difference between the shear velocities of two opposite surfaces of this material are related as [11, 13]

$$\sigma = \eta \frac{v_2 - v_1}{w}, \tag{6}$$

where η is the material viscosity; w is the solder thickness; v_1 and v_2 are the shear velocities of the solder surfaces attached to the crystal and the heat sink, respectively.

To simplify the calculations, one of these interfaces (solder–crystal) is assumed to be immobile ($v_1 = 0$). Then, $\Delta v = v_2 \equiv v$. In this case, the surface shear velocity relative to the heat sink is $v = \Delta l / \Delta t$, where

$$\Delta l = \Delta\alpha \Delta T l_0 \tag{7}$$

is the difference between the lengths of the heat sink and the crystal, which shortened when the temperature lowered from the solder melting temperature to room temperature (ΔT); l_0 is the linear crystal dimension; Δt is the time during which this shortening takes place; and $\Delta\alpha$ is the difference between the CTEs of the heat sink and crystal materials.

Expression (6) now takes on the following form:

$$\sigma = \eta \frac{\Delta l}{w \Delta t}. \tag{8}$$

By using expressions (7) and (8) it is possible to determine the relaxation time during which there occurs the relative displacement of the opposite solder surfaces (plastic deformation) under the action of the stress $\sigma(\Delta T)$:

$$\Delta t_{\text{rel}} = \frac{\eta l_0 \Delta\alpha \Delta T}{w \sigma(\Delta T)}. \tag{9}$$

From expressions (7) and (8) for the temperature variation rate we obtain

$$\frac{\Delta T}{\Delta t} = \frac{w\sigma}{\eta l_0 \Delta\alpha}. \tag{10}$$

With the exception of σ, all quantities in this expression are known for a given laser design. The unknown stress σ, which emerges in the solder material on lowering the temperature by a certain value, are calculated with the aid of Eqns (4) and (5) for given dimensions and materials of the laser crystal, heat sink, and solder alloy.

In the course of laser crystal mounting, the emergence of stress in the solder exceeding the tensile strength σ_{ts} cannot be tolerated, i.e. $\sigma_{\max}$ should be less than σ_{ts}. With this in mind, with the aid of formula (10) we obtain the condition for the temperature decrease rate

$$\frac{\Delta T}{\Delta t} < \frac{w\sigma_{\text{ts}}}{\eta l_0 \Delta\alpha}. \tag{11}$$

In other words, the time Δt_{tech} during which the temperature lowers by a given value $\Delta\tilde{T}$ should be longer than the relaxation time Δt_{rel} of the stress which emerges when the temperature lowers by $\Delta\tilde{T}$: $\Delta t_{\text{tech}} > \Delta t_{\text{rel}}$.

Figures 7 and 8 give the results of calculations of the stress in the In solder performed using Eqns (4) and (5) for a laser crystal of length $l_0 = 1$ mm soldered to a copper heat sink. For a cooling by 130°, which corresponds to a

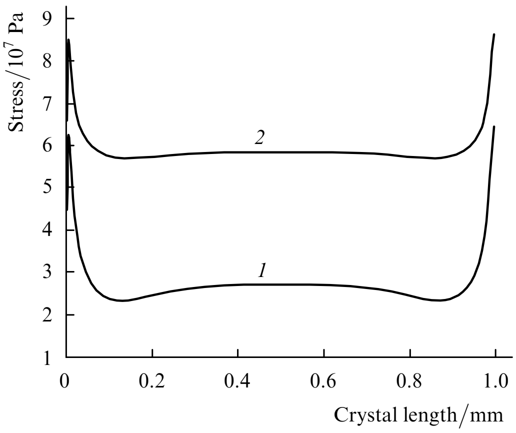

Figure 7. Distribution of the stress in the central plane inside a 3-μm thick solder along the length of a laser crystal ($l_0 = 1$ mm) soldered onto a copper heat sink with indium (*1*) and PbSn (*2*) in the case when the temperature lowers by 130 °C – from the melting temperature of the solder alloy to room temperature.

temperature lowering from the melting temperature of In (156 °C) to room temperature, the resultant stress is equal to $(2.5 - 5) \times 10^7$ Pa (Fig. 7). The tensile strength for this solder is equal to 6×10^6 Pa [14]. If the stress emerging during cooling that follows the crystal soldering is not allowed to relax, discontinuous regions, hollows, and microcracks will appear in the solder. This will impair both the thermal characteristics of the interconnection and its mechanical properties. One can see from Fig. 7 that the stress at the crystal edges is 1.5 – 2 times higher than the stress at its centre. That is why use should be made of the stress at the crystal edges when comparing the stress with the tensile strength σ_{ts}.

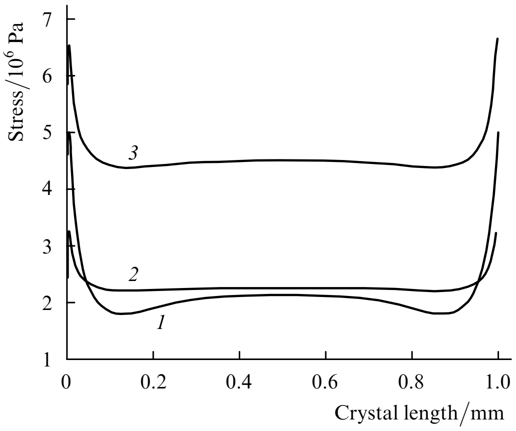

Figure 8. Distribution of the stress in the central plane inside a 3-μm thick solder along the length of a laser crystal ($l_0 = 1$ mm) soldered onto a copper heat sink with indium [on temperature lowering by $\Delta T = 10$ °C (*1*)] and PbSn [for $\Delta T = 5$ °C (*2*) and 10 °C (*3*)].

When developing the manufacturing method, it is required to set the temperature lowering rates such that the relaxation processes in the solder material manage to take place. For a 3-μm thick In solder, for instance, when the temperature lowers by 10 °C (from the solidification temperature) the resultant stress is equal to $(2 - 4) \times 10^6$ Pa [curve (*1*) in Fig. 8]; these values are lower than σ_{ts} for indium. If this lowering is effected in a time exceeding the relaxation time of this stress, it is possible to avoid the emergence of microcracks, discontinuous regions, and voids in the solder materials. For instance, the In solder relaxation time calculated by the above method is, for a temperature variation by 10 °C, equal to about 10 s. In this particular case, the manufacturing assemblage facility should be programmed in such a way that the temperature lowering by each degree takes place in more than one second.

Similar calculations for a PbSn solder with $w = 3$ μm yield the requisite temperature lowering rate of less than 0.8 °C s^{-1}. The stress distribution with laser crystal length in the central plane inside this solder, which connects the laser crystal with a copper heat sink, is plotted in Fig. 7 [curve (*2*)] and Fig. 8 [curves (*2*) and (*3*)].

5. Conclusions

The numerical solution of heat conduction equation subject to boundary conditions has allowed us to calculate in each specific case the thermal resistance for different heat sink designs – high-power diode lasers, linear and 2D laser diode arrays, including the case of forced cooling. This technique permits determining the optimal heat sink dimensions corresponding to prescribed operating conditions, both in the conductive and convective heat transfer.

The results of our work, which rely on the numerical solution of the system of constitutive equations of structure mechanics with the inclusion of thermal effects, permit finding the technological assemblage conditions for every specific design of a laser crystal and heat sink as well as for different solder alloys. This technique also enables determining the conditions whereby the stress emerging in the assemblage is minimised. For instance, when employing an In solder to mount a GaAs crystal onto a copper heat sink, the temperature lowering rate should be lower than 1 °C s^{-1}. When use is made of a PbSn alloy, temperature lowering rate should not exceed 0.8 °C s^{-1}.

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