Liet. matem. rink., T. 42, spec. nr., 306–311

The optimization of temperature regime in diode-pumped solid-state laser when applying cooling by water

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Introduction

Due to the specific nature of the some laser materials, e.g., ytterbium doped YAG crystal, high intensity pump beams are required to achieve sufficient inversion in the laser material. However, part of the pump power is transformed into heat in a small volume of the active media. Thermal effects caused by the heat are limiting the efficiency of the laser. Recently, optimal design of a diode pumped laser was theoretically [1] and experimentally [2] investigated, and the pump and laser mode sizes relation and the deformation of the laser was considered [2].

In recent years, many scientists were interested in different kind of diode-pumped solid-state lasers geometries [4]. In this paper, we investigate slab with elliptical-mode geometry. The mathematical model of the diode-pumped solid-state laser with elliptical mode geometry is designed. We employ adaptive cooling system for the minimization of the thermal gradients in the laser material. The schematic view of the laser is presented in Fig.1.

The temperature gradient generates mechanical stresses in the laser material, since the hotter inside area is constrained from expansion by the cooler outer zone. Both the temperature dependence of the refractive index and the mechanical stresses via the photo elastic effect causes optical distortions, which limit the efficiency of the high power lasers.

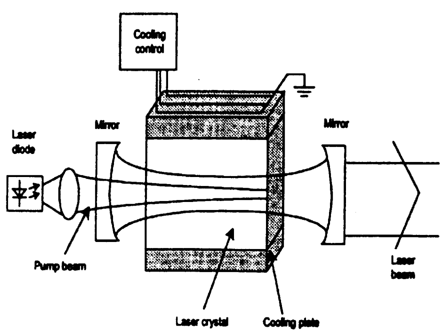

Fig. 1. Schematic view of the end-pumped laser with cooling system.

The main goal of this work is to modify the cooler of the laser material in such a way that thermal gradients caused by the pump radiation would be compensated by the gradients created by the cooler. In mathematical terms, we search for boundary conditions, which compensate thermal gradients inside the laser material. The mathematical model represented here was solved numerically. The finite – difference technique was used for the discretization of the model. Calculations indicate that the heat equation quite satisfactory describe the temperature regimes in laser crystal. The suggested solution method allows us to design a cooling system which guarantee that laser will not be deformed or decomposed.

Mathematical model

Fig. 2 illustrates the elliptical-mode geometry. The laser medium is a slab of width a (in x direction), thickness b (in y direction) and length c (in z direction).

We use Yb:KGW laser crystal to get lower intensity pump beams when compared with Yb:YAG crystals. The pump beam is generated with a high-power diode bar and injected into the $z = 0$ face. The laser is cooled from the top and bottom sides. The mathematical model of temperature regime in the laser is based on the heating equation of parabolic type

$$\frac{\partial u}{\partial t} = D_1 \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) + \frac{f(x,y,z)}{Q_1 \rho_1},$$
$$0 < x < a,\ 0 < y < b_1,\ 0 < z < c,\ 0 < t \leqslant T,$$

where u – temperature; t – time; Q_1 – crystal specific heat; ρ_1 – crystal density; $f(x,y,z)$ – the light source; $D_1 = k_1/Q_1 \cdot \rho_1$ – diffusion coefficient; k_1 – the thermal conductivity coefficient.

The initial condition ($t = 0$) is described by

$$u|_{\Omega} = u(0,x,y,z) = u_0, \quad \text{in } \Omega = \{0 \leqslant x \leqslant a,\ 0 \leqslant y \leqslant b_3,\ 0 \leqslant z \leqslant c\},$$

where u_0 is the chosen or room temperature; Ω is the whole investigated area.

The boundary conditions are organized as follows. We superimpose over and under the Yb:KGW crystal sapphire slabs and this construction is brazed by the copper. We use

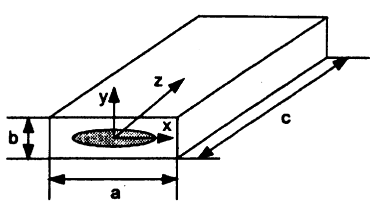

Fig. 2. Slab for a laser with elliptical mode geometry.

sapphire because of its high thermal conductivity. Sapphire is also quite easily processed and do not absorb used wave length beam. That is very important because the steam should not appear if our shot had missed the crystal, during the laser regularizing. If steam appears it can damage the optical surfaces of active element. Thereby sapphire warrants cleanliness of the optical surfaces. The temperature regime in the sapphire and in the copper is described by the differential equations

$$\frac{\partial u}{\partial t}=D_2\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right),\quad \Omega'=\{0<x<a,\ b_1<y<b_2,\ 0<z<c\},$$

$$\frac{\partial u}{\partial t}=D_3\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right),\quad \Omega''=\{0<x<a,\ b_2<y<b_3,\ 0<z<c\},$$

$$\left.\frac{\partial u}{\partial x}\right|_{x=0;x=a}=0,\ \left.\frac{\partial u}{\partial y}\right|_{y=b_3}=0,\ \left.\frac{\partial u}{\partial z}\right|_{z=0;z=c}=0,\ u|_{\Psi}=\text{const},$$

$$D_1\left.\frac{\partial u}{\partial y}\right|_{y=b_1}=D_2\left.\frac{\partial u}{\partial y}\right|_{y=b_1}\quad D_2\left.\frac{\partial u}{\partial y}\right|_{y=b_2}=D_3\left.\frac{\partial u}{\partial y}\right|_{y=b_2},$$

respectively here Ψ is the water pipe in copper.

We took pump profile to be Gaussian in x and y directions and also centered in these directions. So the light source is described by a product of super-Gaussian functions:

$$f(x,y,z)=A\cdot\exp\left(-2\left((x-a/2)/\alpha\right)^{10}\right)\cdot\exp\left(-2\left((y-b/2)/\beta\right)^{2}\right)\cdot\exp(-\gamma z),$$

here A is the integral power coefficient. This coefficient is obtained from the equality

$$A=\frac{P^*\cdot(1-\exp(-\gamma z))}{\int_0^{b_1}\int_0^{a}\exp\left(-2\left((x-a/2)/\alpha\right)^{10}\right)\cdot\exp\left(-2\left((y-b/2)/\beta\right)^{2}\right)\mathrm{d}x\mathrm{d}y},$$

where $P^*=P\cdot K$, P is the power, W; K the quantum defect, i.e., the coefficient which shows how much of the power transfers into heat.

Optimization problem

The temperature in the crystal increases when the laser beam shoots to the crystal. Because of the increasing temperature, the crystal can be deformed or simply decomposed. In order to avoid this, we have to place over and under the laser crystal refrigeration slabs. Since the biggest temperature is in the middle of the crystal, i.e., at $x=a/2$, the cooling functions will also attain minimum values there. The water pipes in copper has to minimize temperature gradients.

For simplicity, we investigate the two dimensional optimization problem. When the crystal is lightened by the lighting source, it is important that the temperature gradient $\max\limits_{[0,a]}\left|\frac{\partial u}{\partial x}\right|$ would not be too big. So the minimization problem is to find $\min\max\limits_{[0,a]}\left|\frac{\partial u}{\partial x}\right|$.

Numerical solution

Analytical solutions of the problems exist only in the simplest cases. Most science and engineering problems are comprised of complex geometries and loading configurations making an analytical solution impossible. In order to achieve a solution, a numerical solution technique must be employed. Therefore, we solve our mathematical model numerically. The finite – difference technique [3] is used for the discretization of the model.

For simplicity, we investigate a two dimensional model. We introduce the following uniform grid:

$$x = x_0 + ih_1,\ i = 0, 1, ..., N_1,\ x_0 = 0,\ x_{N_1} = a,\ h_1 = a/N_1,$$
$$y = y_0 + jh_2,\ j = 0, 1, ..., N_{23},\ y_0 = 0,\ y_{N_{23}} = b_3,\ h_2 = b_3/N_{23},$$
$$t = n\tau,\ n = 0, 1, ..., M,\ \tau = T/M,$$

where τ is the grid step with respect to time t, $h_1 - x$, $h_2 - y$. We use explicit scheme, where the initial differential equations were replaced by the difference equations

$$u_{ij}^{n+1} = g_1\left(u_{i+1,j}^n + u_{i-1,j}^n\right) + g_2\left(u_{i,j+1}^n + u_{i,j-1}^n\right) + (1 - 2g_1 - 2g_2)\, u_{ij}^n + \frac{\tau f_{ij}}{Q_1\rho_1},$$

when $1 \leqslant i \leqslant N_1 - 1,\ 1 \leqslant j \leqslant N_{21} - 1,$

$$u_{ij}^{n+1} = g_1^*\left(u_{i+1,j}^n + u_{i-1,j}^n\right) + g_2^*\left(u_{i,j+1}^n + u_{i,j-1}^n\right) + (1 - 2g_1^* - 2g_2^*)\, u_{ij}^n$$

when $1 \leqslant i \leqslant N_1 - 1,\ N_{21} + 1 \leqslant j \leqslant N_{22} - 1,$

$$u_{ij}^{n+1} = g_1^{**}\left(u_{i+1,j}^n + u_{i-1,j}^n\right) + g_2^{**}\left(u_{i,j+1}^n + u_{i,j-1}^n\right) + (1 - 2g_1^{**} - 2g_2^{**})\, u_{ij}^n,$$

when $1 \leqslant i \leqslant N_1 - 1,\ N_{22} + 1 \leqslant j \leqslant N_{23} - 1,$

$$g_k = g_k^* = g_k^{**} = \frac{\tau D_k}{h_k^2},\ k = 1, 2.$$

The initial condition was approximated by

$$u_{ij}^0 = u_0,\ 0 \leqslant i \leqslant N_1,\ 0 \leqslant j \leqslant N_{23}.$$

The boundary conditions were approximated by

$$u_{0,j}^n = u_{1,j}^n,\ u_{N_1,j}^n = u_{N_1-1,j}^n,$$
$$u_{i,n_{21}}^n = (D_1 u_{i,N_{21}-1}^n + D_2 u_{i,N_{21}+1}^n)/(D_1 + D_2),$$
$$u_{i,n_{22}}^n = (D_2 u_{i,N_{22}-1}^n + D_3 u_{i,N_{22}+1}^n)/(D_2 + D_3),$$
$$u_{i,N_{23}}^n = u_{i,N_{23}-1}^n,\quad 0 \leqslant i \leqslant N_1,\ 0 \leqslant j \leqslant N_{23},\ u_{ij} = \text{const},\ (i, j) \in \Psi.$$

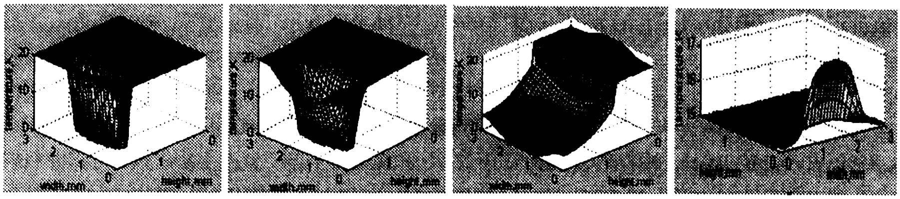

Fig. 3. Temperature regime in different times.

Solution of the optimization problem and results of calculations

The numerical analysis was made with the following values: crystal width $a = 3$ mm, crystal thickness $b = 0.5$ mm, initial temperature $u_0 = 20K$, power $P = 2.4W$, quantum defect $K = 7\%$, water temperature in pipe $u_1 = 15K$.

The entire optimization process was performed as follows. The copper slab contain water pipes. Copper slab height 1 mm, sapphire – 0.45 mm.

The water pipe was chosen to minimize temperature gradient in x direction if $y = b/2$(i.e., either the equality $\left(\frac{\partial u}{\partial x} = 0\right)$ or the inequality $\max\limits_{[0,a]} \left|\frac{\partial u}{\partial x}\right| \leqslant 5K/\mathrm{mm}$ must be satisfied).

First, we prove that one but large water pipe gives less temperature gradient than 3 or more but smaller pipes. Therefore, our calculations were made with one water pipe. We analyzed different forms of the water pipes (elliptic, trapezoidal and rectangular) and analyzed the temperature gradients. Calculations showed that we did not get the expected result. The water pipe form does not influence the temperature gradient (but shapes temperature in the crystal). It appeared that the gradient depends on the sapphire or copper slab height. If we increase copper slab thickness 5 times, we decrease temperature almost 10 times. With the copper slab thickness of 1 mm temperature gradient was 6.607 K/mm. When we changed slab thickness to 5 mm, and the temperature gradient decreased to 0.539 K/mm. Fig. 3 shows temperature regime in diode-pumped solid-state laser with elliptic water pipe in the copper.

Conclusions

Calculations indicate that the heat transfer model can be successfully used to investigate temperature regimes in diode-pumped solid-state lasers.

The results of calculations provide some recommendations for a design of the cooling system. There was suggested the method for a design of the cooling system of laser material.

The suggested solution method allows us to design the cooling system which guarantees the condition $\max\limits_{[0,a]} \left|\frac{\partial u}{\partial x}\right| \leqslant 5K/\mathrm{mm}$.

To decrease temperature gradient we have to increase copper or sapphire slab height. If sapphire slab height is more than 2 mm the cooling is not necessary, our optimization condition is satisfied.

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Kietakūnio lazerio temperatūrinio režimo optimizavimas, naudojant aušinimą vandeniu

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Straipsnyje yra sprendžiamas kietakūnio lazerio temperatūrinio režimo optimizavimo uždavinys. Uždavinio sprendimui panaudotas šilumos laidumo matematinis modelis. Skaičiavimo rezultatai parodė, kad aušinimo įrenginio forma mažai įtakoja temperatūrinį režimą.