Thermal Deformation of a Rectangle Nd-ion Doped Laser Crystal by High Power Diode Laser End-pumped

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Abstract In order to solve thermal effect of laser crystal induced by high power diode laser end-pumped, the thermal deformation on pump face of laser crystal was exactly calculated. Through work characteristic analysis of laser crystal in diode laser end-pumped all-solid-state lasers, a thermal model of rectangle laser crystal was built. Based on the heat conductive equation, a new solution of Poisson equation was introduced and the general analytical expression of thermal deformation of rectangle laser crystal was obtained. And thermal deformation influenced by diode laser eccentric-end-pumped was investigated. Compared to the finite-element analysis or other numerical solutions, the analytical solution will not produce any calculation error. The analytical solution of thermal deformation will supply a theoretical instruct for solving thermal effect of laser crystal and improving the performance of lasers.

Keywords Lasers; Laser crystal; End-pumped; Analytical solution; Thermal deformation.

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0 Introduction

Diode laser pumped all-solid-state lasers (DPSSL) operating in infrared and visible spectral regions have wide applications in the fields of industry, military, medical treatment and scientific research[1]. DPSSL can easily operate with TEM_{00} mode output and have high pump conversion efficiency by diode laser end-pumped[2]. With high power diode laser end-pumped, inhomogeneous local heating and large thermal gradient distribution in lasing gain medium will inevitably induce thermal effects[3,4]. Thermal effects include photoelasticity effect, thermal stress fracture, thermal deformation and so on, which influence performance of lasers, such as the stability of resonator, width of lasing mode, mode coupling efficiency and beam quality[5~7].

Many methods had been adopted to study thermal effects of laser crystal[8,9]. In this paper, through work feature analysis of laser crystal, a thermal model of rectangle laser crystal was built. In the thermal model some characteristics, such as an axially heated cuboid with a thermal conductive boundary at the periphery, and the coupled pump light having Gaussian distribution, were considered. And the unreasonable assumptions, such as the rectangle crystals approximated as the cylindrical crystals and the heat flux along radial[10,11], were abandoned. Based on heat conductive equation (The Poisson equation) and its boundary condition, a new analytical solution was deduced and the temperature field and thermal deformation of rectangle laser crystal end-pumped by diode laser were obtained. Particularly the thermal deformation influenced by diode laser eccentric-end-pumped was investigated.

1 Thermal deformation analytical analysis of rectangle laser crystal

To counteract the thermal effects generated by pump radiation, laser media must be kept in active cooled during the operation. It was demonstrated that cooling laser crystal to cryogenic temperatures resulted in a significant improvement in average power and beam quality. Fig. 1 shows the cooling schematic diagram of laser crystal by diode laser end-pumped and its thermal sink. Here b and c are the side lengthes of rectangle laser crystal, the pump spot of diode laser was controlled by a

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coupler formed by a self-focus lens or a battery of lens.

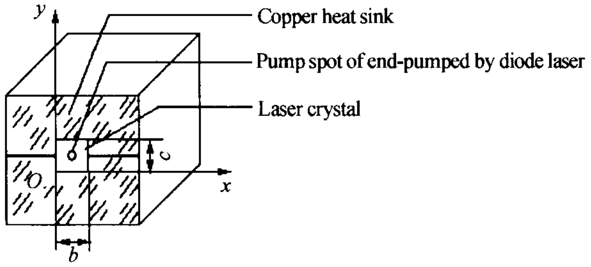


Fig. 1 Schematic diagram of laser crystal by diode laser end-pumped

The intensity distribution of a fiber-coupled diode laser was expressed as the Gaussian distribution. Though reshaped and refocused by a coupler, the performance was not changed. The intensity distribution on pump-face of rectangle laser crystal was given by

$$I(x,y,0)=I_0\mathrm{e}^{-2\frac{(x-\frac{b}{2})^2+(y-\frac{c}{2})^2}{\omega_p^2}} \tag{1}$$

where I_0 was the center intensity of pump light; ω_p was the waist spot radius of pump light.

Only a part of the applied pump power was converted into laser radiation; the remaining power was transferred to the heat, which results from competing mechanisms as radiationless transition and absorption of the host lattice. The intensity distribution of the pump light in laser crystal was given by

$$I(x,y,z)=I(x,y,0)\mathrm{e}^{-\beta z} \tag{2}$$

Here β was the absorption coefficient of laser crystal.

Since laser crystal was kept in good theremo - contact with the heat sink, the four side-faces have a fixed temperature (In mathematic method temperature was assumed as 0). Two pump-faces were connected with air, heat dissipated by convection was less than the heat conduction through the four-sides, which was no more than 1%. An approximate solution was introduced that the pump-faces of rectangle laser crystal were the adiabatic condition. So the boundary conditions of rectangle laser crystal end-pumped by diode laser were obtained.

$$\begin{aligned}&u(0,y,z)=0;u(b,y,z)=0\\&u(x,0,z)=0;u(x,c,z)=0\\&\frac{\partial u(x,y,z)}{\partial z}\Big|_{z=0}=0;\frac{\partial u(x,y,z)}{\partial z}\Big|_{z=a}=0\end{aligned} \tag{3}$$

The heat conductive equation of laser crystal was the Poisson equation

$$\frac{\partial^2 u(x,y,z)}{\partial x^2}+\frac{\partial^2 u(x,y,z)}{\partial y^2}+\frac{\partial^2 u(x,y,z)}{\partial z^2}=-\frac{q_v}{\lambda} \tag{4}$$

Where λ was the thermal conductivity coefficient of laser crystal. $q_v(x, y, z)$ was the heat power density in laser crystal, which was described as

$$q_v(x,y,z)=\eta I_0\mathrm{e}^{-2\frac{(x-\frac{b}{2})^2+(y-\frac{c}{2})^2}{\omega_p^2}}\mathrm{e}^{-\beta z} \tag{5}$$

where η was the thermal conversion coefficient, which decided by the fluorescent quantum effect and internally loss of laser crystal. And $\eta=1-\lambda_p/\lambda_l$, here λ_p was the wavelength of diode laser; λ_l was the lasing wavelength in cavity.

According to the boundary condition Eq. (3), a general analytical expression of Eq. (4) was given by

$$u(x,y,z)=\sum_{n=1}^{\infty}\sum_{m=1}^{\infty}\sum_{l=0}^{\infty}A_{nml}\sin\frac{n\pi}{a}x\sin\frac{m\pi}{b}y\cos\frac{l\pi}{c}z \tag{6}$$

Where the coefficient A_{nml} was

$$A_{nml}=\frac{8I_0\beta c\eta(1-\mathrm{e}^{-\beta c}\cos l\pi)}{\lambda ab\pi^2(\beta^2c^2+l^2\pi^2)(\frac{n^2}{a^2}+\frac{m^2}{b^2}+\frac{l^2}{c^2})}\cdot\int_0^b\int_0^a\mathrm{e}^{-2\frac{(x-\frac{a}{2})^2+(y-\frac{b}{2})^2}{\omega_p^2}}\sin\frac{n\pi}{a}x\sin\frac{m\pi}{b}y\,\mathrm{d}x\mathrm{d}y \tag{7}$$

When laser in operation, laser crystal will have a stable temperature gradient distribution, which thermal equilibrium temperature was $u(x, y, z)$. The thermal expansion of dz slice in laser crystal was given by

$$\mathrm{d}\rho(x,y,z)=\alpha_a u(x,y,z)\mathrm{d}z \tag{8}$$

Here α_a was the thermal expansion coefficient of laser crystal.

Since the heat source located pump-end of laser crystal, it can be assumed that the other end had not any thermal deformation. So the thermal deformation $\rho(x,y,z)$ of rectangle laser crystal was expressed as

$$\rho(x,y,z)=\alpha_a\int_0^c\sum_{n=1}^{\infty}\sum_{m=1}^{\infty}\sum_{l=0}^{\infty}A_{nml}\sin\frac{n\pi}{a}x\sin\frac{m\pi}{b}y\cdot\cos\frac{l\pi}{c}z\mathrm{d}z \tag{9}$$

2 Temperature field and thermal deformation of Nd-doped laser crystal

2.1 Temperature field and thermal deformation of Nd : YVO_4 crystal by center-end-pumped

Nd : YVO_4 crystal has been often used in diode laser end-pumped lasers because of its large stimulated emission cross section at lasing wavelength and high absorption over a wide pumping wavelength bandwidth. Ignored the influence of temperature to the other physical characteristic of laser crystal, the thermal conductivity coefficient of Nd : YVO_4 crystal is 5.10 W/m/K, the thermal expansion coefficient at z direction 4.43×10^{-6}/K. Depended on Ref. [12], the absorption coefficient of 0.5% Nd-doped Nd : YVO_4 crystal is 14.8 cm^{-1}. Fig. 2 and Fig. 3 show the temperature field distribution and thermal deformation of a-cut Nd : YVO_4 crystal ($6\times3\times3$ mm^3) when the pump power was 10W and the spot diameter of pump light was 0.4 mm.

Fig. 2 shows when the pump power was 10 W, the maximal relative temperature rise of Nd : YVO_4 crystal was 231.2℃.

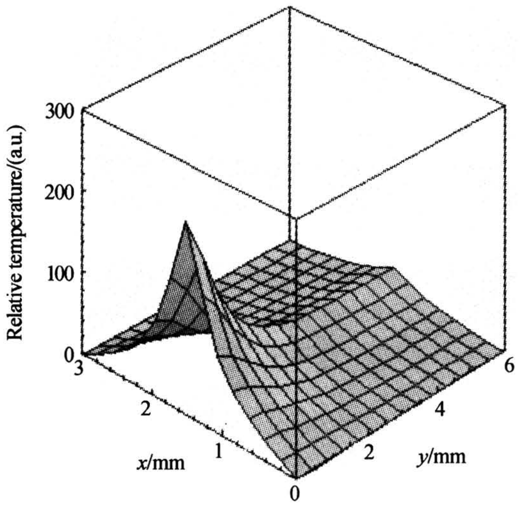


Fig. 2 Three-dimensional temperature field of Nd : YVO_4 crystal center-end-pumped by diode laser

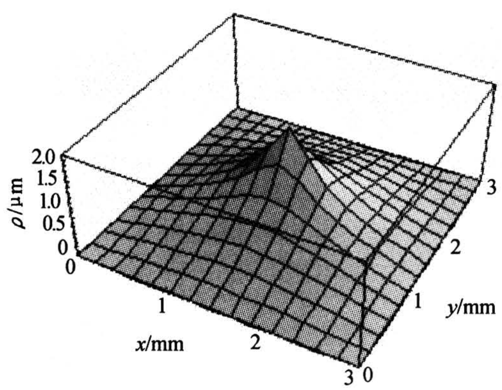


Fig. 3 Three-dimensional thermal deformation of Nd : YVO_4 crystal center-end-pumped by diode laser

In Fig. 3, it is shown that when the pump power was 10 W, the maximal thermal deformation of pump-face center was 1.81 μm. Compared with Ref. [9], temperature field distribution and thermal deformation of Nd : YVO_4 crystal by the analytical method was agreed with the finite-element analysis. It was known that in the numerical solution different calculation results will be got if selected different step index. The analytical solution will not produce any calculation error.

2.2 Temperature field and thermal deformation of Nd : YVO_4 crystal by eccentric-end-pumped

As there was no standard criterion to indicate the pump spot lying on the center of end-face, the coating-face unavoidable thermal damaged, it was necessary to investigate the temperature field and thermal deformation of laser crystal eccentric-end-pumped. At the same pump condition with Fig. 2 and 3, Fig. 4 and 5 show the temperature field distribution and thermal deformation of a-cut Nd : YVO_4 crystal eccentric-end-pumped by diode laser, which the coordinate of pump point was ($b/3$, $c/2$).

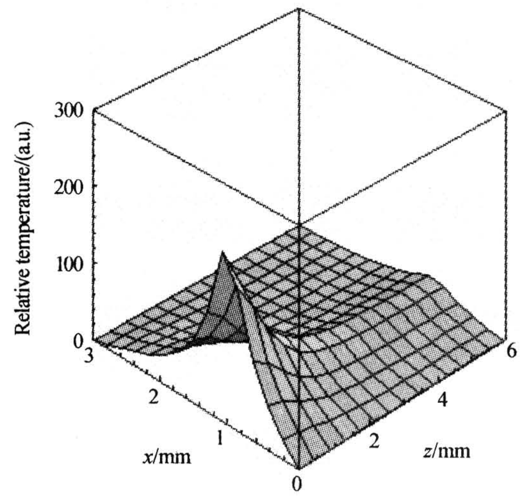


Fig. 4 Three-dimensional temperature field of Nd : YVO_4 crystal eccentric-end-pumped by diode laser

Fig. 4 shows when the pump power was 10W, the maximal relative temperature rise of Nd : YVO_4 crystal was 225.7℃, which the maximal relative temperature rise decreased by 2.4%.

Fig. 5 shows when the pump power was 10W, the maximal thermal deformation of Nd : YVO_4 crystal was 1.74 μm, which the maximal thermal deformation decreased by 4%.

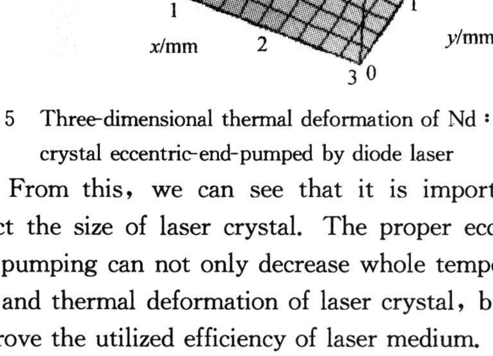


Fig. 5 Three-dimensional thermal deformation of Nd : YVO_4 crystal eccentric-end-pumped by diode laser

From this, we can see that it is important to select the size of laser crystal. The proper eccentric-end-pumping can not only decrease whole temperature rise and thermal deformation of laser crystal, but also improve the utilized efficiency of laser medium.

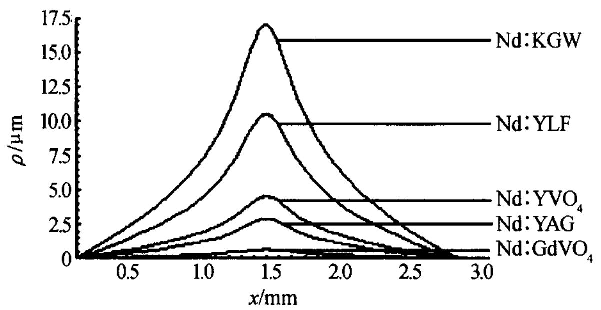
2.3 Thermal deformation of several kind of Nd-doped laser crystals

At present most DPSSL were invented by Nd-doped laser crystals, such as Nd : YAG, Nd : $GdVO_4$[13], Nd : KGW[1], Nd : YLF[14]. An attractive feature of these crystals was higher laser radiation, which was an advantage when a nonlinear crystal for second-harmonic generation was used. Table 1 shows some specialty parameters of Nd-doped laser crystals.

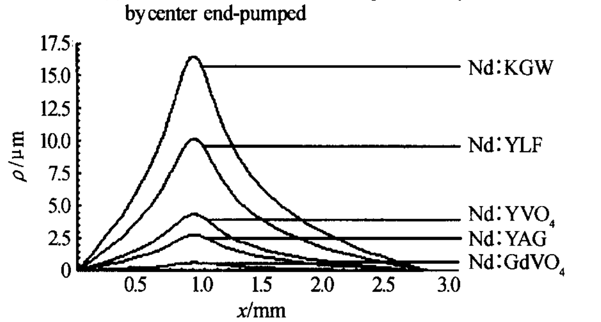
Table. 1 Specialty parameters of Nd-doped laser crystals in all-solid-state lasers

No.	Crystal's mane	Nd-iondoped concentration/%	Absorption coefficient /cm^{-1}	Thermal conductivity/ W $cm^{-1}K^{-1}$	Thermal Expansion coefficient/$10^{-6}K^{-1}$
1	Nd : YAG	1.1	9.10	0.140	7.80
2	Nd : YVO_4	0.5	14.8	0.051	4.43
3	Nd : $GdVO_4$	1.0	74.0	0.117	1.50
4	Nd : KGW	8.0	36.0	0.026	8.50
5	Nd : YLF	1.0	4.50	0.06	13.0

In Fig. 6(a), it is showm that when the pump power was 25W, the spot diameter of pump light was 0.4 mm, the thermal deformation of Nd : KGW was 17.0 μm, the Nd : YLF crystal was 10.51 μm, the Nd : YAG crystal was 2.88 μm and the Nd : $GdVO_4$ crystal was 0.67 μm. Fig. 6(b) shows that when the pumped point was ($b/3$, $c/2$), the thermal deformation of Nd : KGW crystal had 16.34 μm, the Nd : YLF crystal was 10.10 μm, the Nd : YAG crystal was 2.77 μm and the Nd : $GdVO_4$ crystal was 0.64 μm.



(a) Thermal deformation of Nd-doped laser crystals by center end-pumped



(b) Thermal deformation of Nd-doped laser crystals by eccentric end-pumped

Fig. 6 Thermal deformation of Nd-doped laser crystals by diode laser

From Fig. 6, it is known that the thermal deformations of Nd-doped laser crystals were all decreased by the eccentric-end-pumped.

3 Conclusions

The thermal deformation of laser crystal was an important subject in the design of DPSSL system. For laser crystal has anisotropy in the thermal conductivity, this would induce different thermal deformation. Since the anisotropic 3-D thermal conduction equations were difficult to solve, the finite-element analysis (FE) was obtained. In this paper, based on the Poisson equation, the analytical solution of thermal deformation of rectangle laser crystal was obtained. And thermal deformation influenced by diode laser eccentric-end-pumped was investigated. The thermal deformation of laser crystal by eccentric-pumped will supply an experimental instruct for solving thermal effect of laser crystal and improving the performance of all-solid-state lasers.

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高功率半导体激光端面泵浦方形掺 Nd^{3+} 离子激光晶体热形变研究

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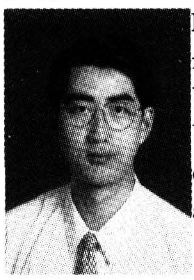
摘 要 为了解决高功率半导体激光器端面泵浦激光晶体引起的热效应问题，激光晶体泵浦端面的热形变必须进行准确的计算．通过对于全固态激光器中激光晶体的工作特点分析，建立了矩形截面激光晶体热分析模型．基于热传导方程，提出了泊松方程的一种新解，并获得了矩形截面激光晶体端面热形变分布的一般解析表达式．同时讨论了半导体激光器偏心泵浦激光晶体给端面热形变带来的影响．与有限元分析方法以及其他数值分析方法相比，解析分析方法不会给计算引入任何的误差．热形变的解析分析为解决激光晶体的热效应问题以及提高激光器的性能提供了理论的依据．

关键词 激光器；激光晶体；端面泵浦；解析分析；热形变



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