The analysis of the transient temperature distribution of double-slab Nd:YAG laser medium

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A novel double-slab Nd:YAG laser, which uses face-pumped slab medium cooled by liquid with different temperatures on both sides, is proposed. The thermal distortion of wavefront caused by the non-uniform temperature distribution in the laser gain media can be self-compensated. According to the method of operation, the models of the temperature distribution and stress are presented, and the analytic solutions for the model are derived. Furthermore, the numerical simulations with pulse pumping energy of 10 J and repetition frequencies of 500 and 1000 Hz are calculated respectively for Nd:YAG laser medium. The simulation results show that the temperature gradient remains the approximative linearity, and the heat stress is within the extreme range. Then the absorption coefficient is also discussed. The result indicates that the doping concentration cannot be too large for the high repetition frequency laser. It has been proved that the high repetition frequency, high laser beam quality, and high average output power of the order of kilowatt of Nd: YAG slab laser can be achieved in this structure.

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The traditional solid-state laser medium is designed in the shape of a long thin rod. Under operating conditions the thermally loaded laser medium exhibits optical distortions which include thermal lens effects, stress-induced biaxial focusing, and stress-induced birefringence. These thermally induced effects severely degrade the beam quality and eventually limit the laser output power[1]. The limitations imposed by the rod geometry have been recognized long time ago. In 1969 Martin and Chernoch proposed to use rectangular and the proposed face-pumping. The temperature distribution of slab geometry was converted from cubical hyperbolic parabola into linear. The zig-zag optical path eliminated first-order thermal effect and reduced stress-induced birefringence, which can lead to high average power laser operation limited only by stress-included fracture of the laser medium[2]. Theories of the rectangular geometry laser had been discussed previously[3,4], however, in which the face-pumped rectangular medium was cooled by uniform temperature. Under this condition, stress calculations showed that the thermally induced stress was proportional to the temperature difference between the center of the slab and the cooled surface, in which the temperature in center was higher than that in the cooled surface. Stress based on these facts was also different between the center of the slab and the cooled surface. While the center of the slab was affected by compressive stress, the surface of the slab was affected by expansive force. Peak surface stress was of great importance, as the slab was often designed to operate near the fracture limit and the microcracks on the surface would result in fracture.

A novel scheme of double-slab Nd:YAG laser is proposed, which utilizes the face-pumped slab medium cooled by liquid with different temperatures in the both sides. According to this method, the models of the slab medium's temperature distribution and stress are put forward, and then the analytic solutions are derived. The result indicates that the doping concentration cannot be too high for the designed high repetition frequency slab laser.

Figure 1 shows the double-slab configuration layout for both face-pumped sources. The resonant cavity is composed of reflecting mirrors M_1—M_5. M_1 is high reflector and M2 is output one. A set of reflectors M_3—M_5 can reverse the laser beams, which symmetrically propagate along the higher temperature side of the former mediate slab through the lower temperature side of the later one. The distortion of wavefront caused by the non-uniform temperature distribution of the laser gain media slab is self-corrected in this structure. The optical path eliminated first-order thermal effect and stress-induced focus. The temperature distribution in the medium reduces to a one-dimensional (1D) problem governed by the time dependent equation,

$$\frac{\partial^2 T}{\partial X^2} + \frac{Q(x)}{k} = \frac{1}{a}\frac{\partial T}{\partial t}. \tag{1}$$

The pump time is much less than the thermal relaxation time for pulse pump with a periodic time, so the effects of the cooling are neglected during the pumping, and then the temperature distribution amount to transient thermal load of each pulse pumping[5]. On the other hand,

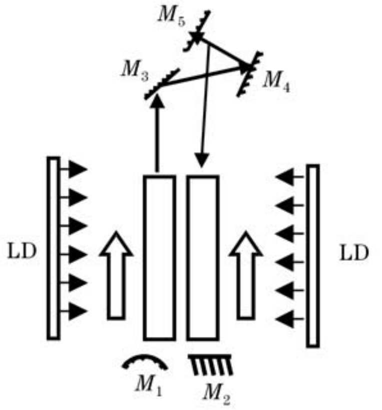

Fig. 1. The scheme of the wavefront thermal distortion self-corrected laser.

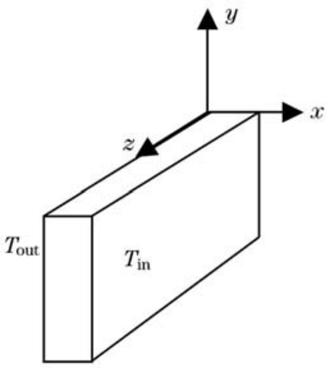

Fig. 2. The coordination in the slab.

the temperature distribution shows the same result for the different pulse shapes after pumping. The pulse shape influences the temperature distribution during the pumping. So Eq. (1) can be simplified as

$$\frac{1}{a}\frac{\partial T}{\partial t}=\frac{\partial^2 T}{\partial x^2}. \tag{2}$$

The time-dependent heat-conduction equation is solved numerically by separation of variables. Because of the symmetry of the double-slab and the uniformity of the heating-power density, it is calculated the temperature gradient in the one slab. The initial heat-conduction equation in slab medium is

$$\phi(x,0)=Q(x)+T_{\text{steady}}, \tag{3}$$

$$T_{\text{steady}}=\frac{(T_{\text{in}}-T_{\text{out}})x}{d}+T_{\text{out}}. \tag{4}$$

The heating-power density can be described as[6]

$$\begin{aligned}Q(x)&=\frac{\mathrm{d}I(x)}{\mathrm{d}x}=\frac{I_0\alpha}{2}(\mathrm{e}^{\alpha x}-\mathrm{e}^{\alpha(x-2d)})\\&=\frac{P_0\eta_1\eta_2}{2LW}(\mathrm{e}^{\alpha x}-\mathrm{e}^{\alpha(x-2d)}),\end{aligned} \tag{5}$$

where P_0 is the pumping power irradiated into the double slab, η_1 is the fraction of the absorbed pumping power converted to optical power, η_2 is the couple efficiency of the groups of the reflecting mirror, α is the absorption coefficient given by material, and L and W are the length and width of the slab, respectively. So the optical power is $\frac{1}{2}P_0\eta_1\eta_2$ for one slab, and optical power density I_0 is $P_0\eta_1\eta_2/(LW)$. In our model, the boundary conditions are defined as

$$\frac{\partial T}{\partial x}\mid_{x=0}=h_1(T-T_{\text{out}})\mid_{x=0}, \tag{6}$$

$$\frac{\partial T}{\partial x}\mid_{x=d}=-h_2(T-T_{\text{in}})\mid_{x=d}, \tag{7}$$

where T is the temperature on the surface of the slab, h_1 and h_2 are the heat transfer coefficients, which related to the temperature of the cooling fluid and velocity of flow. The heat transfer coefficient is higher as the temperature of the cooling fluid is higher. In the model, the style of the fluid is turbulent current. This time-dependent heat-conduction equation is solved numerically by the method of separation of variables. The solution of Eqs. (2)—(7) for the models are given by separation of variables. The transient temperature distribution of the double slab for the single pulse is[7]

$$\begin{aligned}T(x,t)&=T_{\text{steady}}\\&+\sum_{m=1}^{\infty}C_m[\beta_m\cos(x\beta_m)+h_1\sin(\beta_m x)]\cdot\mathrm{e}^{-a\beta_m^2 t}.\end{aligned} \tag{8}$$

β_m is the root of the proper equation

$$\tan(\beta_m d)=\frac{\beta_m(h_1+h_2)}{\beta_m^2-h_1h_2}. \tag{9}$$

C_m is given by orthogonality of eigenfuction equation,

$$\begin{aligned}C_m&=\frac{2}{[(\beta_m^2+h_1^2)(d+\frac{h_2}{\beta_m^2+h_2^2})+h_1]}\\&\cdot\int_0^d[\beta_m\cos(\beta_m x)+h_1\sin(\beta_m x)][\varphi(x,0)-T_{\text{steady}}]\mathrm{d}x.\end{aligned} \tag{10}$$

If the double-slab laser is repetitively pumped, the thermal buildup in the cylinder depends on the ratio of the pulse interval time to the thermal time constant. The expression is derived for the transient thermal profile in the double-slab under repetitive pumping. The result is given as[8]

$$\begin{aligned}T(x,t)&=T_{\text{steady}}+\sum_{m=1}^{\infty}C_m[\beta_m\cos(x\beta_m)+h_1\sin(\beta_m x)]\\&\cdot\mathrm{e}^{-a\beta_m^2 t}\frac{1-\mathrm{e}^{-n\beta_m^2 t_p}}{1-\mathrm{e}^{-\beta_m^2 t_p}}\quad(0<t<t_p).\end{aligned} \tag{11}$$

Thus avoid yielding a temperature gradient in y direction. According to the Hooke's law, the stress of the slab is described by[9]

$$\delta_{yy}=\delta_{zz}=\frac{\varsigma E}{1-\gamma}(\frac{N_T}{d}+\frac{12(y-d/2)M_T}{d^3}-T), \tag{12}$$

$$\delta_{yx}=0, \tag{13}$$

where $N_T=\int_0^d T(x)\mathrm{d}x$, $M_{T=}\int_0^d T(x)(y-d/2)\mathrm{d}x$, ς is thermal expansion, E is Young's modulus, and γ is Poisson ratio. The stress can be solved according to the resolution of the temperature. The laser medium of slab is Nd:YAG, inner of the double slab is cooled to 279 K, and the pump side of the double slab is cooled to 299 K. The temperature reaches a stationary distribution before pumping, which is used as initial condition. The heat transfer coefficient is assumed to be a forced-convection cooling, which is given as[10]

$$\frac{h_i L}{k}=\sqrt[3]{P_r}\times(0.037\times\sqrt[5]{R_e^4}-850), \tag{14}$$

where Reynolds number $R_e=u\rho x/\gamma_i$, and Planck efficient is $P_r=C_p u/k_i$. The result leading to the heat transfer coefficient will be increased, which can take out amount of heat.

The Nd:YAG slab ($60 \times 40 \times 5$ mm^3) was cooled with a chromium plated copper heat sink side faces through a thin layer of silicon vacuum grease. The pump light was coupled into the slab through the remaining small side faces. Under the condition of diode pumping the radiation of 8 diode-laser arrays, the pumping wavelength λ is 809 nm, and the peak pumping power is 30 kW, and the average output energy is 10 J per pulse. Figure 3 shows the transient temperature distribution of the slab within 10 s. The repetition frequency is 500 Hz, and the absorption coefficient is 3 cm^{-1}. Figure 4 is the corresponding stress distribution. For the YAG medium, the maximum stress is about 1800—2600 kg/cm^2[1,7]. The cooling method indicates that the stress distribution is much fewer than the maximum stress. Figure 5 shows the transient temperature distribution of the slab versus time within two slabs. The temperature reaches a stationary distribution within 10 s after the optical power is turn on. Figure 6 shows the temperature distributed at 10 s. The temperature distribution course is almost parabolic curve, but the temperature gradient remains the approximate linearity in the lasing area of slab, which caused the thermal distortion of wavefront self-compensating in this structure. We also discuss the repetition frequency of 1000 Hz with 10 s. The temperature still reaches a stationary distribution within 10 s after the pump power is turn on. Figure 7 shows the transient temperature distribution of the slab with an absorption coefficient of 3 cm^{-1}. The graphics of temperature is also parabolic curve, and the temperature gradient is large between the slab surface and center. The corresponding stress distribution is shown in Fig. 8. The stress is still within the stress extreme. We also calculate the stress with the same pump power, but the absorption coefficient is increased from 3 to 9 cm^{-1}. Under the cooling conditions, the temperature distribution with absorption coefficient of 9 cm^{-1} is shown in the Fig. 9. Figure 10 shows that the heat distribution with absorption coefficient of 9 cm^{-1} is significantly larger than that with absorption coefficient of 3 cm^{-1}. Because the pump power decreases quickly with increasing the slab thickness, it is obviously

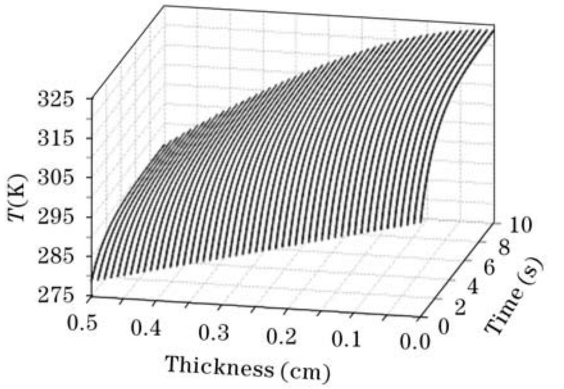

Fig. 3. The transient temperature distribution within 10 s under 500 pulses per second and 3-cm^{-1} absorption coefficient.

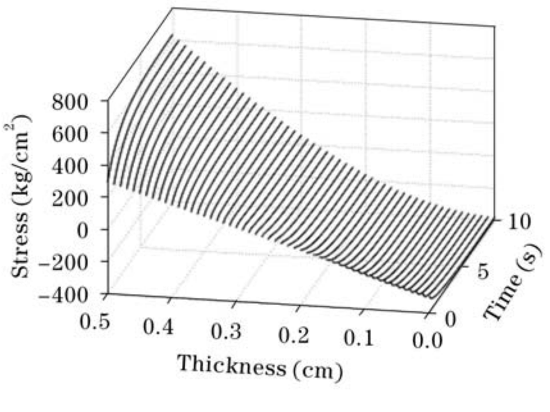

Fig. 4. The stress distribution within 10 s under 500 pulses per second, 3-cm^{-1} absorption coefficient.

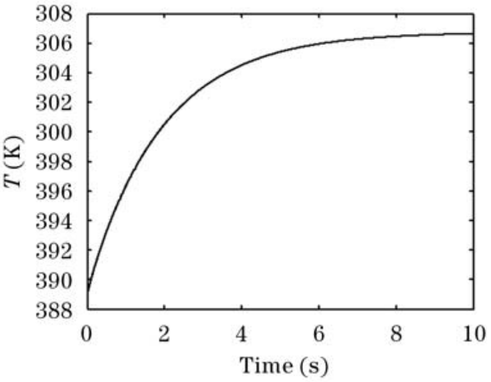

Fig. 5. The transient temperature distribution versus time within two slabs.

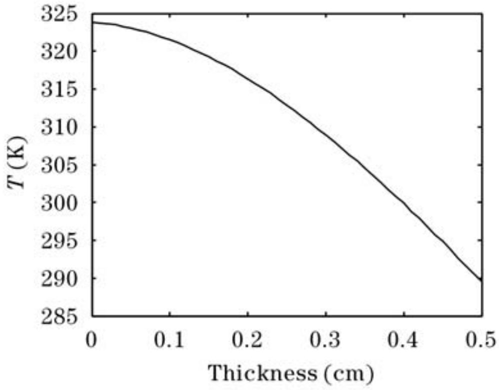

Fig. 6. The transient temperature distribution at 10 s under 500 pulses per second.

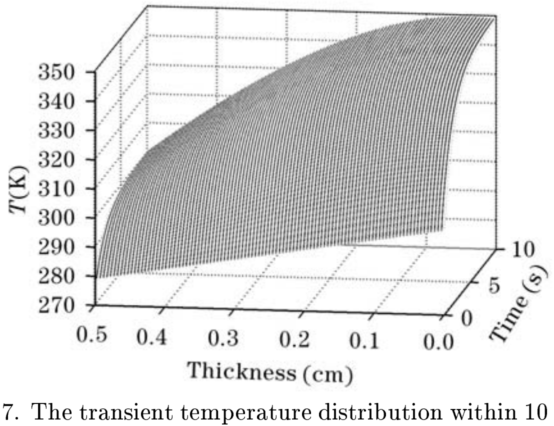

Fig. 7. The transient temperature distribution within 10 s under 1000 pulses per second and 3-cm^{-1} absorption coefficient.

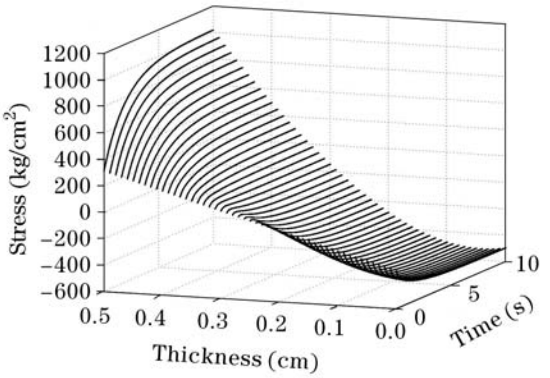

Fig. 8. The stress distribution within 10 s under the 1000 pulses per second, 3-cm^{-1} absorption coefficient.

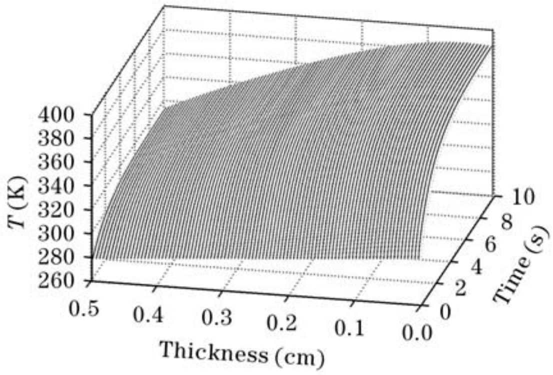

Fig. 9. The transient temperature distribution within 10 s under 1000 pulses per second, 9-cm^{-1} absorption coefficient.

that both temperature gradient and the corresponding stress have larger values in the operation model. Hence the medium with highly doping Nd should not be used in high average power laser systems.

Slab geometry solid-state lasers offer significant performance improvements over conventional rod geometry. A novel scheme of double-slab Nd:YAG laser is proposed. The thermal distortion of wavefront caused by the non-uniform temperature distribution in the laser gain medium is self-compensated in this structure. In the method of operation, the models of the thermal distribution and stress state are obtained, and the analytic solutions are derived. The results show that the slab laser employing this pumping structure can be developed with high average power output and good beam quality.

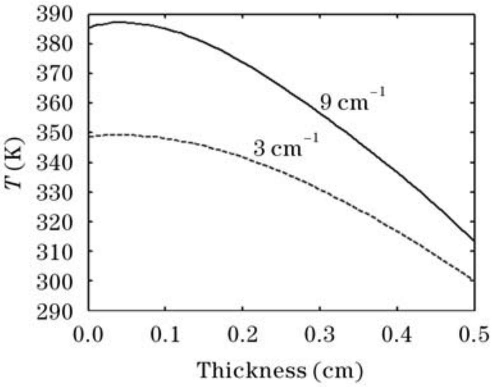

Fig. 10. The transient temperature distribution at 10 s under 1000 pulses per second and absorption coefficients of 3 and 9 cm^{-1}.

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