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The Thermal Effect Characteristics of Side-Pumped Slab Medium Operating in Heat Capacity Mode①

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Abstract: The analytic expression of temperature profile of side-pumped slab medium operating in heat capacity mode is derived and its temperature and corresponding stress distribution are simulated. Comparing with temperature and stress distributions of conventional mode, the advantages of heat capacity operation are demonstrated in quantity. The results show that, in general, stress fracture limit is the main mechanism to limit power scaling for medium operating in conventional mode while upper temperature limitation is the main for heat capacity mode. The simulations also show that the thermal focal length of heat capacity laser is much longer than that of conventional laser under the same pump conditions and for heat capacity operation the temperature of gain medium increases linearly and the temperature difference between the surface and the center almost keeps constant with the pumping time.

Key words: solid-state laser; thermal effect; heat capacity

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Solid state laser technology is a well developed field and numerous embodiments and modes of operation have been demonstrated. In the past years, researchers mainly focus on strengthening pump power and enlarging gain medium volume and improving cooling effect[1]. However, thermo-mechanics stresses from the waste heat removing, which is inevitable, limits the average power available to a level where a variety of industrial and scientific research fields are out of reach if approached this conventional steady state technology[2]. Coherent combination of multiple laser beams is one of promising ways to obtain high power laser, but it is difficult to keep the multiple beams coherent especially to keep all the phases' equal[3]. Recently a novel laser operation mode called heat capacity operation was presented by Lawrence Livermore National Lab[4]. In this mode, the laser operation is broken into two discrete processes. During lasing, the active medium is thermally well insulated and cooling does not present, and cooling takes place while the laser is not operating. So as lasing proceeding, wasted heat deposited within the medium will heats up until it reaches the some maximum acceptable temperature within tens of seconds. During operation, the amount of energy of the laser is proportional to its mass, the heat capacity and the temperature difference. As the medium is not cooled when lasing, the slab on the surface is hotter than that in the center, which leads to the inversion of the temperature and stress profile compared to steady state operation, thereby the compressive stress appears on the surface for heat capacity operation case. Since dielectric materials is inher-

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ently five times stronger in compression than in tension, this temperature inversion increases the inherent fracture limit of the system and allows a heat capacity operated laser to pump much harder than a conventionally operating slab laser, which is key feature of laser operating in heat capacity mode[5]. Some experiments have test the novel mode. In 1997, a 10 Kw output of heat capacity laser at a repetition rate of 20 Hz for 10 seconds was designed and operated with a flashlamp-pumped Nd: glass medium[6] and the wavefront correction technique and unstable resonator, two times diffraction limited beam quality was obtained[7] and the system has been delivered to the Army's High Energy Laser Systems Test Facility at the White Sands Missile Range[8]. If Nd: glass gain medium is replaced by Nd: GGG, the repetition rate can increase from 20 to 200 Hz, so 100 Kw output is promising to get from the system[9]. Now, this new mode has been paid attention to by many countries including China[10]. Heat capacity laser is one novel mode to get high power, and its thermal effect characteristics have been investigated qualitatively[5]. In this paper, analytic expression of side pumped slab gain medium operating in heat capacity mode is derived, and based on the expression the temperature and stress profiles are simulated and analyzed in comparison with conventional state operation in quantity and the temperature changes with time and thickness also are discussed.

1 The Derivation of Analytic Expression of Temperature Profile

A slab medium is side pumped uniformly as Fig. 1 shown. If the edge effect is neglected, the temperature and stress appear in yz plane is uniform and change only along x axis.

The periodic time of single pulse pump is much less than the thermal relaxation time constant are set, the temperature distribution is governed by the equation

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

where T is dependent of axisand time t, α is the diffusivity coefficient.

Supposing the ambient conditions is ideal adiabatic, the boundaries satisfy

$$\frac{\partial T}{\partial x}\Big|_{x=\pm L/2} = 0 \tag{2}$$

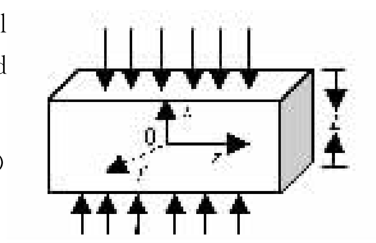

Fig. 1 The Coordination in the Slab and the Pumping Mode

After the single pulse pump, the initial temperature is given by

$$T(x, 0) = F(x) + T_0 = Q(x)/Vc\rho + T_0 \tag{3}$$

where T_0 denotes the temperature before pulse pumps, $F(x)$ is the temperature increase as the result of the single pulse, c is the specific heat, $Q(x)$ is thermal power loading per unit volume when slab is pumped by energy W per pulse with heat transformation ratio η, heat energy is average of pump power. Based on the nonuniformal absorption mode, if beam is absorbed one time only, $Q(x)$ reads as[11]

$$Q(x) = \frac{\eta W}{2}(e^{-\mu(L/2-x)} + e^{-\mu(L/2+x)}) \tag{4}$$

with L, thickness along x axis, μ, the absorption coefficient.

According to the separation of variables method, the solution of equation (1), which presents the temperature distribution of slab pumped by only a pulse with the boundary conditions and initial condition, can be expressed as[12]

$$T(x, t) = T_0 + \sum_{m=0}^{\infty} C_m \cos(x\beta_m) e^{-\alpha\beta_m^2 t} \tag{5}$$

where coefficients C_m obeys orthogonal eigenfuction equations

$$C_m = \frac{2}{L}\int_{-L/2}^{L/2} \cos(\beta_m x) F(x) dx, \text{ when } m \neq 0 \tag{6}$$

and

$$C_0 = \frac{1}{L}\int_{-L/2}^{L/2} F(x)\mathrm{d}x, \text{ when } m = 0 \tag{7}$$

β_m are the roots of the eigenfunction equation

$$\sin(\beta_m L) = 0 \text{ when } m \neq 0; \text{ and } \beta_m = 0 \text{ when } m = 0 \tag{8}$$

If the slab laser is pumped repetitively, the thermal increase in the medium 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 heat capacity slab under repetitive pumping is given as[13]

$$T(x, t) = T_0 + C_0 t/t_p + \sum_{m=1}^{\infty} C_m \cos(x\beta_m) e^{-\alpha\beta_m^2 t} \frac{1 - e^{-m\beta_m^2 t_p}}{1 - e^{-\beta_m^2 t_p}} \tag{9}$$

On substituting the coefficients into equation (9), the result of the transient temperature distribution of slab pumped symmetrically and uniformly on two sides without cooling can be expressed as

$$T(x, t) = T_0 + \frac{1}{L}\left[\int_{-L/2}^{L/2} F(x)\mathrm{d}x\right]\frac{t}{t_p} + \frac{2}{L}\sum_{m=1}^{\infty}\left\{\left[\int_{-L/2}^{L/2}\cos(\beta_m x)F(x)\mathrm{d}x\right]\cos(\beta_m x)e^{-\alpha\beta_m^2 t}\frac{1 - e^{-m\beta_m^2 t_p}}{1 - e^{-\beta_m^2 t_p}}\right\} \tag{10}$$

The temperature gradients generate mechanical stresses in the laser slab medium. For one dimension temperature distribution, the stress of the slab is described by[14]

$$\delta_{yy} = \delta_{zz} = \frac{1}{1-v}\left(\frac{N_T}{l} + \frac{12M_T}{l^3}y - \beta E T\right) \tag{11}$$

$$\delta_{yx} = 0 \tag{12}$$

N_T, M_T are defined as $N_T = \beta E\int_{-L/2}^{L/2} T(y)\mathrm{d}y$ and $M_T = \beta E\int_{-L/2}^{L/2} T(y)\mathrm{d}y$, Where β is thermal expansion coefficient, E is Young's modulus, and v is Poisson ratio. The stress can be solved according to the corresponding temperature profile.

2 Numerical Simulation

Nd: GGG slab gain medium with $10\times30\times10$ mm^3 is assumed. The pumping wavelength λ is 809 nm, and the pumping peak power is 30 kW with duty cycle 15%, and the average energy output is 6 J per pulse. The η, including transportion loss, unabsorbed pumped loss, energy defect loss, unextracted upper state power and diffractive loss, is set 0.25. The other calculation parameters are given in table 1. For the conventional state operation, the transient temperature of slab two sides pumped is given by [18].

Table 1 The Parameters Values of Nd: GGG Crystal[15~17]

μ /(cm^{-1})	β /($\times10^{-6}K^{-1}$)	v	k /(ms^{-1})	ρ /($g\cdot cm^{-3}$)	k /($Wm^{-1}K^{-1}$)	c /($J\cdot g^{0+1}c$)	E /($\times10^7 kg\cdot cm^{-2}$)	σ_{max} /($kg\cdot cm^{-2}$)
4	8	0.28	3.4	7.1	10	0.4	0.22	3 000

Firstly, the material chosen is discussed. According to equation (10), the temperature profiles of Nd: GGG and Nd:YAG medium which operate within 5 seconds at the repetition rate of 400 Hz are plotted in Fig. 2. The temperature distributions of the two crystals are very similar as the figure shown. For the symmetry, all the figures in the paper only give the half for saving space. The temperature on the surface of Nd:GGG is little higher than that of Nd:YAG while the center is reverse, because the absorption coefficient of Nd:GGG crystal is little larger than that of Nd:YAG while the conductivity relation is just opposite. But Nd:GGG is an optimal crystal for solid-state heat-capacity laser because of its good optical and spectral properties and attainable large diameter resulting from its easiness of growth with flat interface[19].

According to equation (10) in this paper and equation (11) in. refence[18], the temperature distribution as the function of thickness is given by Fig. 3. The figure shows that when the slab medium operates in heat capacity the temperature is higher on the surface than in the center because more energy is absorbed on the surface while steady state operating medium is reverse as the result of cooling structure. Besides the inverse character of temperature, from Fig. 3 it can be found that the increase of temperature of heat capacity state is more than that of conventional state. When the slab operates without cooling over duration of 3.54 seconds at 1 000 Hz, the maximum temperature reaches 400 K, which is the upper temperature limit given by level population redistribution effects for Nd^{3+} in a typical garnet[5], and the maximum value is about 386 K. For the steady state operation, the maximum value is only 365 K and minimum temperature is around 301 K under the same pump conditions as above, which is only higher 6 K than the temperature of cooling water, 295 K. In the same figure, the temperature difference between from center to surface for heat capacity state (about 14.4 K) is much lower than that of steady state (about 60 K). For the steady state operation, the temperature difference almost does not vary after the steady state occurs which often needs several seconds[20]. In fact, the same phenomena takes place for the heat capacity operation though there does not exist the steady state. Assuming symmetric steady pumping for the laser slab and adiabatic boundary conditions the temperature difference ΔT between the surface and the centerline for heat capacity case can be written as approximately[4]

$$\Delta T = T_{\text{surface}} - T_{\text{center}} = \frac{2}{\pi}\left[\frac{pxl(1-e^{-\mu l})}{(1+x)k}\right]\left[\frac{(\mu l)^2}{(\mu x)^2+4\pi^2}(1-e^{-(4\pi^2\alpha t)/l^2})\right] \quad (13)$$

where p is the irradiance in each pump beam, x is the ratio of thermal energy to stored gain energy in the laser medium, l is the thickness of slab. Set the same pump conditions as Fig. 3. ΔT varying with l and t is depicted in Fig. 4. When $l=1$ cm, ΔT is around 15 K, which is in agreement with the former value 14.4 K. Fig. 4 shows the ΔT almost does not change with pump time. In equation (13), only if $t > l^2/31$, $e^{-(4\pi^2\alpha t)/l^2}$ is almost a constant with the time elapsing, which explains ΔT change characteristic with time. As the thickness l affects the absorption of pump beam, ΔT increase with the increase of thickness monotonously is plotted in Fig. 4., which is due to the fact that larger the thickness is, less heat is absorbed in the center. The temperature difference will leads to the thermal focal length difference. Though the thermal focal length is composed of the effects of temperature a gradient and stress from the variation of the refractive index and the distortion of the end-face curvature of the slab, the temperature dependent variation of the refractive index constitute the major contribution of the thermal lensing[21]. If we only consider the main part, under the pump conditions in Fig. 3 the focal length of heat capacity slab is about 4 times that of steady state.

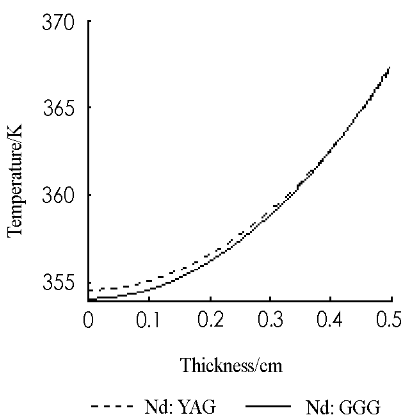

Fig. 2 The Temperature Distributions of Nd:GGG and Nd:YAG Crystal within 5 s under 400 Pluses per Second

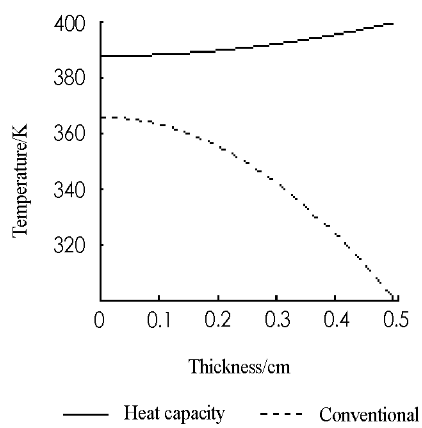

Fig. 3 The Temperature Profile of Nd:GGG Gain Medium Operating in Different States Within 3.54 s at 1 000 Hz

Fig 5. gives the temperature rise with time on the surface of the slab. It can be seen that for the conventional operation mode the temperature increases very slowly after several seconds because the balance of cooling and absorption. For the heat capacity medium, the temperature increases almost linearly with time, which seems unreasonable according to equation (10) because there exists the exponent term of time. But the nonlinear part with time $e^{-\alpha\beta_m^2 t}$ on the side of equation (10) varies very slowly with time, so the equation is approximately a linear equation with time. Additionally, here c and k are assumed to constants with T, which is not in agreement with the practice exactly. In fact, specific heat and conductivity monotonously increase with the temperature in the neighbor of room temperature[12]. If considering relations, the temperature gradient depend of time for heat capacity mode will rise slowly.

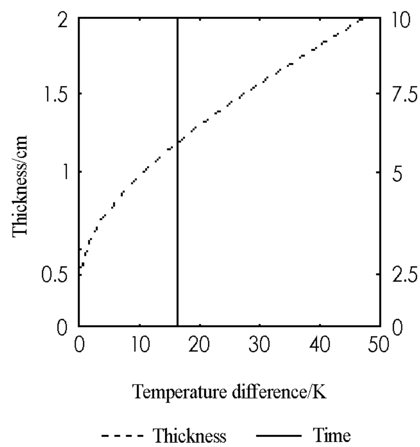

Fig. 4 The Temperature Difference of Heat Capacity Medium vs. Thickness at 4 s and vs. Operating Time with Repetition Rate 1 000 Hz

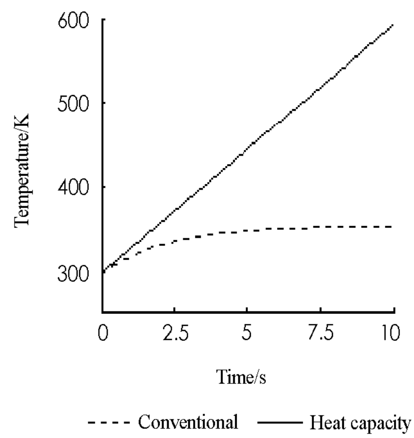

Fig. 5 The Temperature Against Pumping Time in Different States on the Surface at 1 000 Hz

Substituting the temperature expressions into equation (11), the stresses distribution can be simulated as shown in Fig. 6. The figure shows that for the conventional state, tensile stress appears on the surface while the compressive in the center of slab medium. The stresses inversion of slab gain medium operating in heat capacity is obvious from the plot. The pump conditions is the same as Fig. 3, the heat capacity slab medium is up to the upper temperature limitation ,400 K, while maximum temperature of the medium operating in steady state is much below the value. But Fig. 6 shows the tensile stress, 2 400 kg/cm^2, on the surface for the conventional state operating arrives at the acceptable maximum value, 3 000 kg/cm^2, if considering the safe operation value is best to below 0. 7 factor of theoretical value while the stress of slab operating in heat capacity, −1 300 kg/cm^2, is far lower the maximum value since the compressive appears on the surface and allowable compressive stress is five times of tensile stress. Since the surface damage threshold is lower than that of bulk-damage which stems from the fact that even after the polishing process used in the finishing of optical elements, there are residual scratches, defects, and imperfections on the surface[21], so we may only consider the stress on the surface as the stress fracture limit standard. In fact, the tensile stress that appears in the heat capacity laser is only a small faction of that appearing in steady state laser. For the heat capacity operation, the peak tensile stress σ_k at the midthickness region of the slab is approximated as[4]

$$\sigma_h = \left[\frac{\alpha EPxl(1-e^{\alpha l})}{\pi^2(x+1)k}\right]\left[\frac{(\alpha l)^2}{(\alpha l)^2+4\pi^2}(1-e^{-(4\pi^2\gamma)/l^2})\right] \tag{14}$$

The tensile stress σ_s that occurs on the surface during the steady state operation is approximated as[4]

$$\sigma_s = \frac{\alpha EPxll(1-e^{\alpha l})}{6k(1-v)}\left(\frac{x}{1+x}\right)\frac{6[e^{\alpha l}(\alpha l-2)+\alpha\alpha l+2]}{\alpha^2 l(e^{\alpha l}-1)} \tag{15}$$

According to the above two approximation expressions, the tensile stress profile is shown in Fig. 7. From the figure we can see, only if the thickness is not beyond 3.5 cm the tensile stress of heat capacity laser medium is smaller than that of steady state operation. In this simulation, the thickness is set to 1cm, from Fig. 7 σ_s/σ_h is about 6.5, which in agreement with the ratio 2 350/400 shown in Fig. 6. From the above analyses on temperature and stress we can make a conclusion that for the conventional state the tensile stress on the surface is often the limitation to power scaling while for the heat capacity state the maximum upper allowable temperature is often the limitation.

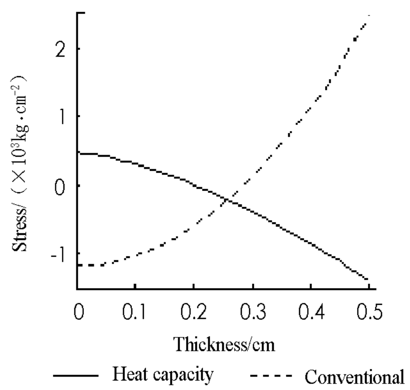

Fig. 6　The Stress Profile of Nd:GGG Gain Medium Operating in Different States Within 3.54, 1 000 Hz

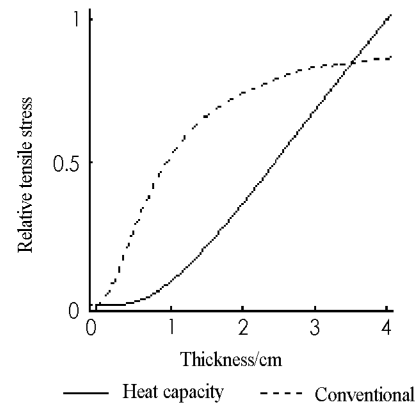

Fig. 7　Relative Tensile Stress of Slab Operating in Two Modes as a Function of Thickness at 1 000 Hz.

3　Conculusion

In summary, the analytical expression of temperature profile of slab medium operating in heat capacity state is presented based on the nonuniformal absorption mode. The inversion characteristics of temperature and stress distribution is proved in quantity and the simulations shows that the upper temperature limitation limits the power scaling for heat capacity laser medium instead of stress fracture limitation, which is opposite to the steady state operating medium. The temperature of heat capacity slab almost increases linearly with time if the heat specific and thermal conductivity are treated as constants. The simple thermal focal lengths are compared, that of heat capacity medium is several factors longer than that of steady state for heat capacity operating medium. For the heat capacity laser, the temperature difference between the surface and center is almost a constant and its increases monotonously with thickness of the slab.

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热容激光器侧泵介质的热效应特征

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摘要：推导了热容工作模式下侧面抽运板条激光介质温度分布的解析表达式，并模拟了其温度和相应的应力分布. 与常规运转的介质的温度和应力分布进行了比较，定量分析了热容运转模式的优越性. 结果表明，一般而言，常规运转情况下，应力断裂极限是限制功率进一步增大的主要原因，而在热容运转模式下，限制因素是上能级温度. 模拟表明，相同抽运情况下，热容运转模式下的热透镜长度远比常规运转模式下长. 在热容运转模式下，介质温度随时间线性增加，中心与表面的温度差几乎不随时间改变.

关键词：固体激光器；热效应；热容

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