

Simulation of Thermal Effects in Totally and Partially Pumped Solid-State Laser Rod with Side-Pumping Structure

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ABSTRACT

In this work, a steady-state heat transfer equation in a side-pumped Nd:YAG laser rod was solved numerically using finite element method (FEA). The resulting temperature and stress distributions were calculated under the condition of totally and partially direct side pumping structures with LASCAD software. From the result of simulation, we compare between the different pumping lengths, and mainly indicate the effect of pumping lengths on the temperature distribution, stress, displacement and the optical path difference (OPD).

Keyword: Thermal Effects, Side-Pumping Structure, pump Uniformity.

محاكاة التأثيرات الحرارية لقلم ليزر الحالة الصلبة المضخ كلياً وجزئياً من الجانب

الخلاصة

في هذا العمل تم استخدام طريقة العناصر المحدودة لحل معادلة انتقال الحرارة عددياً لقلم ليزر النديميوم- ياك والمضخ من الجانب باستخدام ليزر الدايدود. لقد تم حساب توزيعات درجات الحرارة والاجهادات المتولدة على قلم الليزر والمضخ بصورة مباشرة كلياً وجزئياً باستخدام برنامج تصميم وتحليل تجايف الليزر (LASCAD). من خلال النتائج التي تم الحصول عليها، تمت المقارنة بين اطوال الضخ المستخدمة وتم الاشارة الى تأثير توزيع درجات الحرارة، الاجهادات، الازاحة المتولدة وكذلك تأثير طول الضخ على فرق المسار البصري.

INTRODUCTION

Diode pumped solid-state lasers have many obvious advantages over the traditional lamp-pumped solid-state lasers, especially in the aspect of overcoming the thermally induced problems. Thermal effect is still one of the major problems for the application and commercialization of high-power DPSS lasers. Strong thermal effects caused by the deposited heat in laser crystals introduce complications, that is, the laser crystal is greatly influenced by the heat induced; it limits the maximum pump power and makes its resonator unstable [1]. Subsequent

cooling of the crystal medium with the associated thermal gradient would lead to a thermally-induced change of refractive index.

Many noticeable efforts for managing and reducing thermal effects under various types of pumping geometries are found in [2-6]. In this work, thermal problems in a totally and partially side-pumped Nd: YAG laser rod under super-Gaussian pumping profile was modeled using finite element method with the LASCAD software package.

PUMP LIGHT DISTRIBUTION IN LASER ROD

Diode laser arrays with a maximum CW output power of 90W at the center wavelength of 808nm were selected to side pump an Nd: YAG rod of 3mm in diameter, and 33mm in length. In the simulation process, 9 diode arrays, which are arranged in 3 groups around the rod was used. Each group contains 3 diodes that illuminate the rod symmetrically from 3 sides. The length of the diodes are (11mm) for totally pumping structure and (10 mm) and (9mm) for partially side pumping structure as shown in Figure (1).

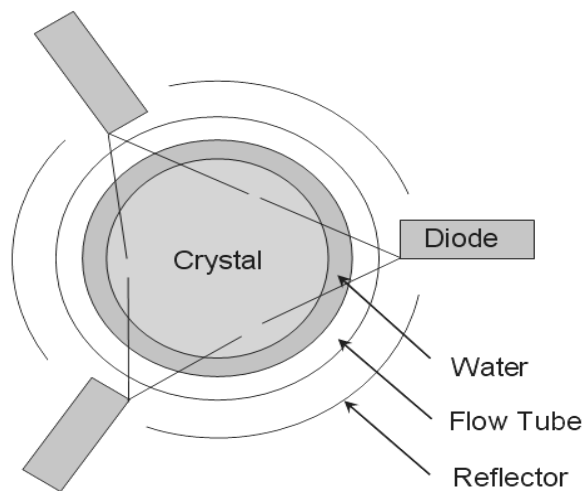


Figure (1) Cross section of laser crystal with side-pumping geometry.

For totally side pumping structure, the first group extends from $z=0$ mm to $z=11$ mm, the second from $z=11$ mm to $z=22$ mm, and the third from $z=22$ mm to $z=33$ mm, while for partially pumping structure, two pumped length has been used (30mm) and (27mm) respectively. For (30mm) the first group extends from $z=1.5$ mm to $z=11.5$ mm, the second from $z=11.5$ mm to $z=21.5$ mm, and the third from $z=21.5$ mm to $z=31.5$ mm. while for (27mm) the first group extends from $z=3$ mm to $z=12$ mm, the second from $z=12$ mm to $z=21$ mm, and the third from $z=21$ mm to $z=30$ mm. The origin $z=0$ is located at the center of the left end face of the rod. The groups are offset with respect to each other by an angle of $360^\circ/2m$, where m is the number of bars around the rod. The laser beam emitted from a linear diode array can be described with a Gaussian beam [7]. The main characteristics are that it is generally with a slow axis

divergence ($\theta_{//}$) full angle of $10^\circ - 12^\circ$ and a fast axis divergence (θ_{\perp}) full angle of $35^\circ - 40^\circ$. Since, the pumping energy distribution in the cross-section of the rod is more important for side pumping; so we can neglect the divergence in the direction of the slow axis and assumes that the fast axis pump profile of the diodes is super-Gaussian with exponent 4. The diodes illuminate the rod through a flow tube with inner diameter of 5 mm and outer diameter 7 mm. The pump light is reflected by a reflector concentric with the rod whose distance from the rod is 4 mm.

Numerical Model to Calculate Temperature Distribution

The following equation governs the temperature distribution in steady-state heat problems [8]:

$$\nabla^2 T(X) = -\frac{Q(X)}{K} \quad \dots (1)$$

Where:

$Q(X)$ is the distribution of heat power density in (W/m^2), K is the thermal conductivity in ($W/m.K$), and $T(X)$ is the temperature distribution of the laser rod in (K) with a water cooling procedure. The boundary conditions at the end and side surfaces of the rod are given by [9,10]

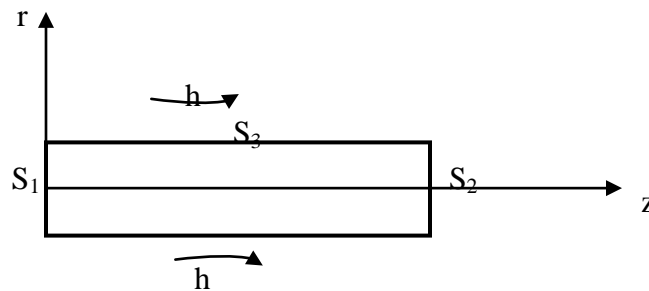
$$\left. \frac{\partial T(X)}{\partial n} \right|_{S_{1,2}} \approx 0 \quad \dots (2-a)$$

$$\left. \frac{\partial T(X)}{\partial n} \right|_{S_3} = \frac{h}{K} (T_c - T(X)) \Big|_{S_3} \quad \dots (2-b)$$

Where:

$S_{1,2}$ and S_3 represent the end and side surfaces, respectively, h is the heat transfer coefficient, and T_c is the temperature of the cooling water.

Finite elements model was used to calculate the temperature distribution of the laser rod cross section in side pumped side cooled designs. The used model is a stationary axisymmetric model. It assumes that there is a circular symmetric pump distribution that stays constant along the laser rod axis. The rod is assumed to be homogeneously cooled on its outer surface as shown in Figure (2).



**Figure (2) the boundary conditions at the end and side surfaces of the rod.
Thermal Stresses**

When the laser operates, the hotter inside area is constrained from the expansion of the cooler outer zone, and the temperature gradients generate mechanical stresses in the laser rod. The radial, tangential, and axial thermal stresses inside the laser rod can be obtained from thermal elastic theory as follows [11]:

$$\sigma_r = \frac{\alpha_T E}{1-\nu} \left(\frac{1}{r_o^2} \int_0^{r_o} \Delta T r dr - \frac{1}{r^2} \int_0^r \Delta T r dr \right) \quad \dots (3)$$

$$\sigma_\theta = \frac{\alpha_T E}{1-\nu} \left(\frac{1}{r_o^2} \int_0^{r_o} \Delta T r dr + \frac{1}{r^2} \int_0^r \Delta T r dr - \Delta T \right) \quad \dots (4)$$

$$\sigma_z = \frac{\alpha_T E}{1-\nu} \left(\frac{2}{r_o^2} \int_0^{r_o} \Delta T r dr - \Delta T \right) \quad \dots (5)$$

Where r_o is the rod radius, α_T is the thermal expansion coefficient in (1/K), E is the Young's modulus in (Kg/cm²), ν is Poisson's ratio, and ΔT is temperature difference relative to the rod side surface.

The optical path difference (OPD) theory is a bridge between the imaginary lens and the thermal effect [12]. For a paraxial coherent beam propagating in the z -direction, the optical path difference (OPD) is given in [8]. By neglecting the contribution from thermal stress induced birefringence which is small for most cases [8], the OPD can be expressed as:

$$OPD(r) = 2 \left[\int_L \frac{\partial n}{\partial T} T(r, z) dz + \int_L n \varepsilon_z dz \right] \quad \dots (6)$$

Where n is the refractive index of the rod, and ε_z is the longitudinal strain, which is given by [13]:

$$\varepsilon_z = \frac{1}{E} (\sigma_z - \nu(\sigma_r + \sigma_\theta)) + \alpha_T \Delta T \quad \dots (7)$$

For laser rod operating in steady state, the focal length due to temperature – induced variation of refractive index, can be written by [14]:

$$f_T = \frac{r_o^2}{2OPD} \quad \dots (8)$$

SIMULATION OF RESULTS AND DISCUSSION

In the calculation process, radius of the laser medium is 1.5mm; Young’s modulus E is $3 \times 10^4 \text{ Kg/cm}^2$; Thermal expansion coefficient α_T is $6.9 \times 10^{-6} \text{ K}^{-1}$; Poisson’s ratio ν is 0.25; absorption coefficient α is 3.5 cm^{-1} ; thermal conductivity $K = 13 \text{ W/m.K}$; the cooling temperature $T_c = 300 \text{ K}$; heat transfer coefficient $h = 20 \text{ W/cm}^2 \cdot \text{K}$; and the refractive index of the rod is 1.82, respectively.

Figure (3) shows the 2D and 3D calculated result of relative temperature distribution for central uniform distribution under an input power of 90W.

It is clear that, the temperature difference is maximum at the rod center, and this value gradually decreased while moving toward the convection surface as shown in Figure (3). Due to the surface cooling effect, this figure also indicates that the temperature difference for partially side pumping structure is higher than totally pumping structure as shown in Figure (4a, b, and c) .

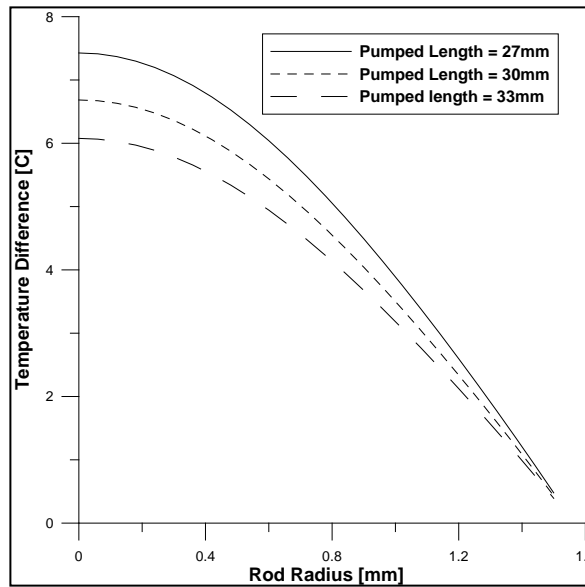
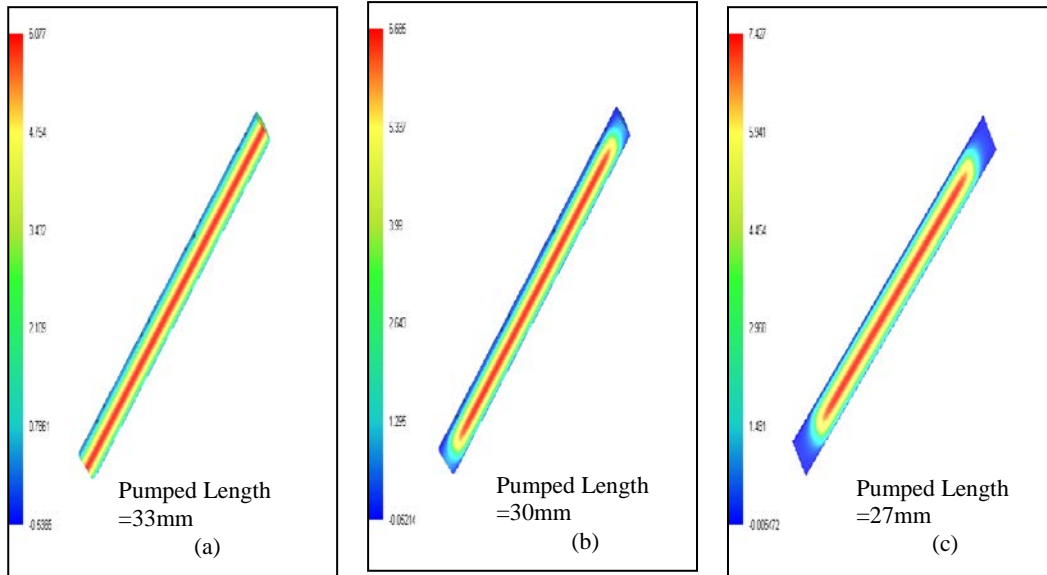
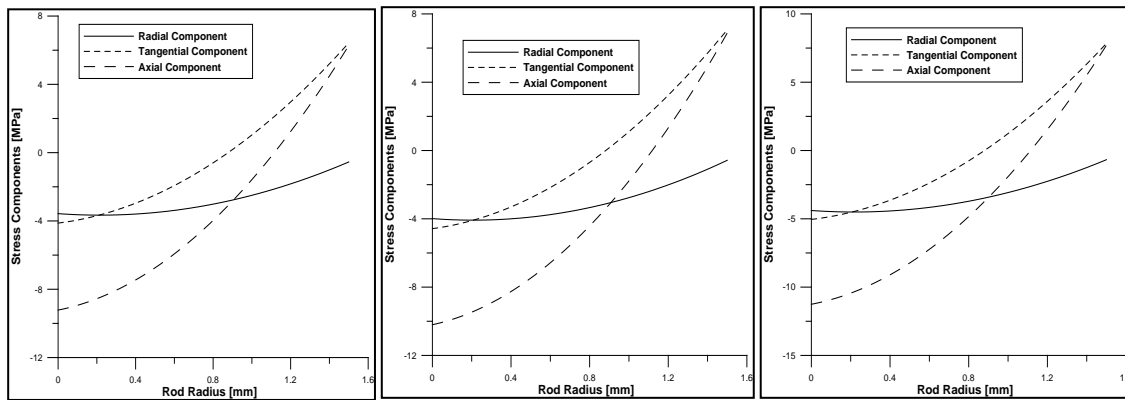


Figure (3) 2D Temperature distribution of laser rod cross section along radius for totally and partially side pumping structure.



Figure(4): 1/2 Rod 3D Temperature distribution of laser rod.

Figure (5) gives the stresses as a function of radius inside the Nd: YAG rod whose temperature profile was shown in Figure (4). From these curves it follows that the highest. Tensile stresses occur at the center and at the surface of the rod. Also it can be seen that for different pumping lengths the hoop stress does not exceed the fracture tensile strength of Nd:YAG material, which is equal to 137.88MPa, as suggested in [8].



-a-

-b-

-c-

Figure (5) Stress distribution within laser rod as a function of radius for (a) 33mm, (b)30mm, and (c)27mm pumped length, respectively.

Figure (6) shows the longitudinal displacement calculated using the parameters given before, while suppose the pump length are equal to 33mm , 30mm, and 27mm. It is shown that the displacement mainly consist of elongation, rather than end-face curvature. For the pump length of 33mm, 30mm, and 27mm, the displacements are 0.362 μ m, 0.342 μ m, and 0.339 μ m, respectively. The corresponding OPDs are 2.49 μ m, 2.38 μ m, and 2.36 μ m, respectively. So according to these optical paths difference, the corresponding focal lengths are 450.405mm, 472.034mm, and 475.287mm, respectively. It is shown that the expansion for partially side pumping structure does not occur within the whole rod length. Namely, strain does not occur in the whole rod, so the OPD is less than totally side pumping structure.

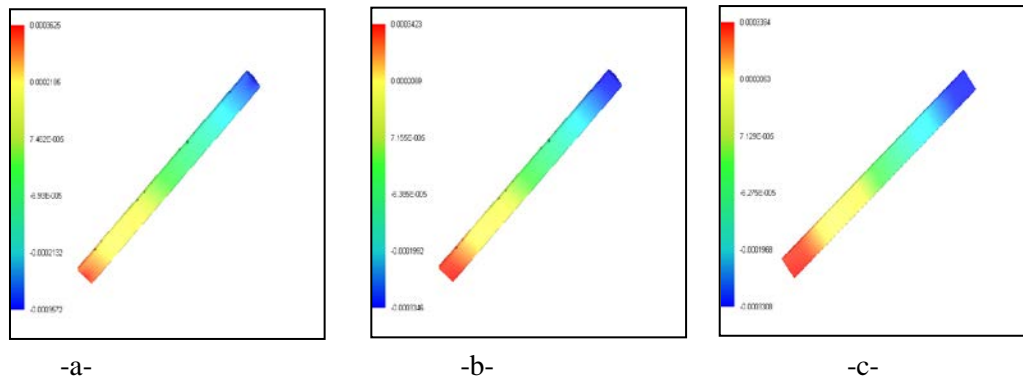


Figure (6) Displacement distribution on the rod cross section for (a) 33mm, (b)30mm, and (c)27mm pumped length, respectively.

By doubling pumping power for totally pumped laser rod from 90W to 180W, the displacement, OPD and subsequently thermal focal length increased due to increased in the temperature distribution as the pumped power increased as shown in Figure (7).

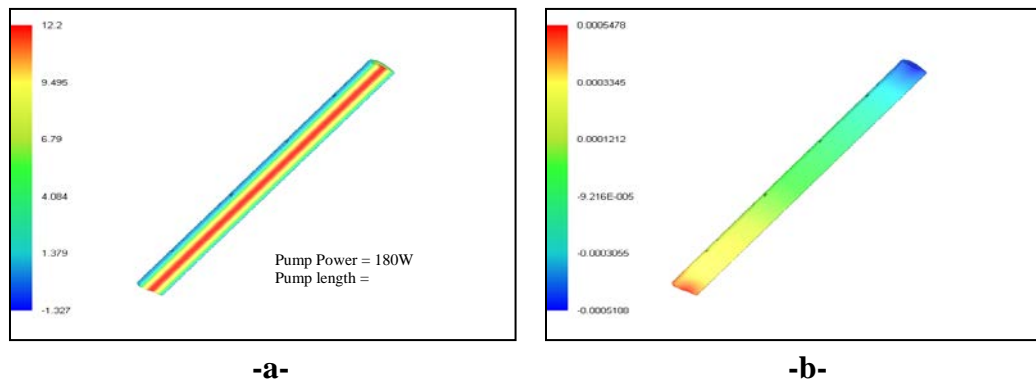


Figure (7) Results for 180W pumped power (a) 2D Temperature distribution of laser rod cross section along radius for totally side pumping structure (b) Displacement distribution on the rod cross section.

Table (1) shows summery of the obtained results for laser rod pumped by 90W and 180W for different pumping lengths.

Table (1) Summery of the obtained results.

<i>Pumped Power (W)</i>	<i>Pumped length (mm)</i>	<i>Displacement (μm)</i>	<i>Thermal Focal length (mm)</i>	<i>OPD (μm)</i>
90	27	0.339	475.287	2.36
	30	0.342	472.034	2.38
	33	0.362	450.405	2.49
180	33	0.547	225.999	4.97

SUMMERY AND CONCLUSIONS

In summery the temperature field in the directly side- pumped Nd:YAG laser rod is numerically simulated under totally and partially side pumping structures. Results show that the maximum temperature rise and the maximum thermal distortion both decrease with the totally pumping structure, while the OPD increased. Moreover, the directly close-pumping configuration is helpful to increase efficiency of the LD-pumped laser system. Results in this paper can be applied to the other quantitative calculation and analysis of thermal effect of laser crystal, and offer theoretical basis for the stability design of LD-pumped solid state laser.

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