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Simulation of thermal lensing in an end-pumped Nd:YAG laser rod with Gaussian and super-Gaussian pump beam profile

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Abstract

A numerical simulation is made on the thermal lensing effect in an laser diode end-pumped Nd:YAG laser rod. Based on finite element method (FEM), the laser rod temperature distribution is calculated and the focal length is deduced for a Gaussian and super-Gaussian pump beam profiles.

At the pump power of 20W, the highest temperature located at the center of end-pumped face was 345K, and the thermal lens focal length was 81.4mm along the x-z axis.

The results indicate that the thermal lensing effect sensitively depend on the pump power, waist radius of the pump beam and the pump distribution in a laser rod geometry.

Key words

Thermal lensing, Finite Element Method (FEM), End-Pumping Nd:YAG Laser Rod.

Article info

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محاكاة البعد البؤري الحراري لليزر النديميوم-ياك المضخ من نهايته لنمط الضخ الكاوسي والفائق الكاوسي

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الخلاصـــة

تم اجراء محاكاة عددية للتأثير الحراري لليزر النديميوم- ياك المضخ من نهايته باستخدام ليزر الدايود. اعتماداً على نظرية العناصر المحددة تم حساب توزيع درجات الحرارة والبعد البؤري للتأثير الحراري في ليزر النديميوم- ياك لنمط الضخ الكاوسي والفائق الكاوسي.

عند قدرة ضخ 20 واط ، اعلى درجة حرارة في قلب وجه الضخ النهائي كانت بحدود 345 درجة كلفن وكان البعد البؤري للتأثير الحراري بحدود 81.4 ملم عند المحور x-z .

أظهرت النتائج ان حساسية التأثير الحراري تعتمد على قدرة الضخ، نصف قطر تخصر حزمة الضخ وكذلك توزيع الضخ في القضيب الليزري.

Introduction

Laser-diode-pumped solid-state lasers can offer high efficiency, compactness, and reliability, especially in an end-pumped configuration, while in endeavoring to obtain higher output powers from continuous (CW) end-pumped solid-state lasers, one must consider thermal lensing effects (result from temperature-induced changes in the refractive index of the laser gain medium) that will impact optical performance [1–4].

In high-power solid-state lasers, pump-induced thermal focusing is of primary importance because of its significant influences on almost all major aspects of solid-state lasers, such as resonator stability, oscillating mode sizes, efficiency, and output beam quality.

Therefore, it is essential in solid-state laser design and optimization to determine the focal length of the thermal lens occurring in the laser crystal at various pump power levels.

The thermal lens depends on a number of parameters, including material properties such as the thermal conductivity of laser material, thermo-optic coefficient $({dn}/{dT})$ and the absorption and emission cross sections at the pump and laser wavelengths.

The calculation of the thermal lens involves three critical factors: Firstly, the optical, thermal, and mechanical properties of the laser rod. Secondly, the corresponding boundary conditions of the simulated model, which include intricacies in the geometry of the rod and cooler. And thirdly, the generation of heat inside the laser rod due to the pump condition.

In this work, based on fundamental theory of heat transfer in a cylinder, temperature distribution in a laser rod is numerically calculated by the FEM with the non-uniform distribution of pump beam and constant thermal conductivity. The variation of the focal length of thermal lensing versus the pump power, waist radius of the pump beam and the pump distribution in laser rod geometry are analyzed in detail.

Theoretical analysis and numerical simulation of thermal effects

Simulation of temperature distribution

The resulting temperature distributions are calculated by solving the Poisson equation [5]:

$$\nabla^2 T(r,z) = -\frac{Q(r,z)}{K} = \frac{\partial^2}{\partial r^2}T(r,z) + \frac{1}{r}\frac{\partial}{\partial r}T(r,z) \qquad (1)$$

where $T(r,z)$ is the temperature field of laser rod, K is the heat conductivity in the solid which is equal to 13 in $(Watt.m^{-1}.K^{-1})$ for Nd:YAG laser rod, $Q(r,z)$ is the heat source density that is a function of the pump power density, r is the radial coordinates.

The heat density can have different profiles, but most simulation was conducted using a pump beam with a Gaussian transverse profile:

$$Q(r,z) = \frac{2\alpha\eta P_{in}}{\pi w_p^2\left[1-\exp(-\alpha\ell)\right]}\exp\left[-2\left(\frac{r}{w_p}\right)^N\right]\exp(-\alpha z) \qquad (2)$$

where P_{in} is the pump power entering the rod, α is the absorption coefficient (350m^{-1}) for Nd:YAG [5], η is the fractional thermal load (the fraction of the absorbed pump power converted into heat which is equal to (32%) for Nd:YAG [5], N is the exponent factor (2 for Gaussian) and w_p is the pump beam radius.

With the boundary conditions of:

$$T(r_o,z) = T_o, \left.\frac{\partial T(r,z)}{\partial r}\right|_{r=0} = 0, \left.\frac{\partial T(r,z)}{\partial z}\right|_{z=0,\ell} = \infty$$

Where T_o is the temperature of the coolant (300K), r_o is the rod radius, and z is the axial coordinate, and ℓ is rod length, the temperature distribution can be calculated using finite element method (FEM).

Simulation of Thermal Lensing

The change in refractive index caused by temperature gradient can be described by:

$$\Delta n(r,z) = \left[T(0,z) - T(r,z)\right].\left({dn}/{dT}\right) \qquad (3)$$

Where ${dn}/{dT}$ is the thermo-optic coefficient, which is $9.86\times10^{-6}K^{-1}$ for Nd:YAG [5]. Then the focal length due to temperature-induced variation of refractive index can be written as [6]:

$$f_T = \frac{r^2}{2OPD} = \frac{r^2}{2\,{dn}/{dT}\left[T(0)-T(r)\ell\right]} \qquad (4)$$

Results and Discussion

According to parameters given before, temperature distribution in the rod is numerically calculated by the finite element method. The thermal model of ½ Nd:YAG rod $(r = 1mm)$ and $(\ell = 4mm)$ is shown in Fig.1a, and the rod temperature distribution in Fig.1b, in which different gray-scales express different temperature values. From Fig.1b, we find that maximum temperature is 345K which appears in the rod pump end center and temperature gradient exists in the rod.

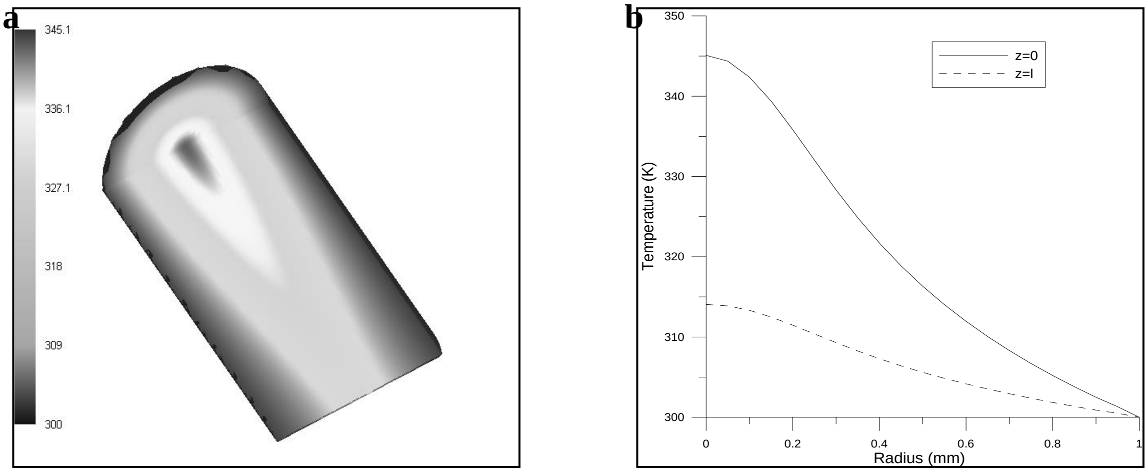

Fig.1 ½ Rod simulation model and the calculation result: (a) Thermal model and (b) Temperature distribution.

When the pump power is 5, 10, 15 and 20W respectively, the variation of the focal length is shown in Fig.2. When the waist radius of the pump beam is 0.3, 0.4 and 0.5mm, respectively, the variation of the focal length versus pump power is shown in Fig.3. It can be seen that the higher the pump power and the smaller the beam waist radius, the shorter the focal length is.

The above figures was simulated for a Gaussian pump beam profiles (N=2). With the increase the exponent N, the pump beam approaches to flat-top distribution, as shown in Fig.4. It is assumed that the radius of the Super-Gaussian pump beam equal to 0.3mm.

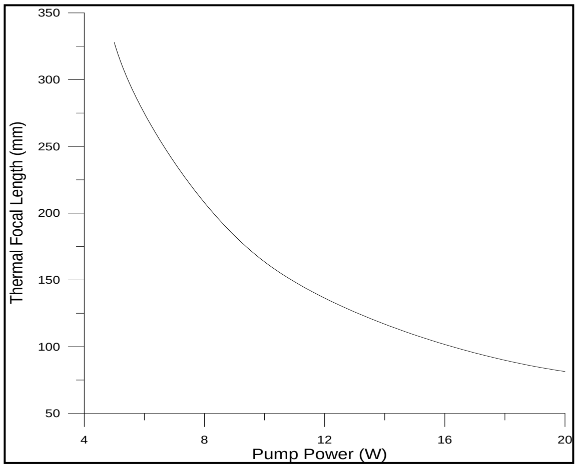

Fig.2: Thermal focal length vs pump power

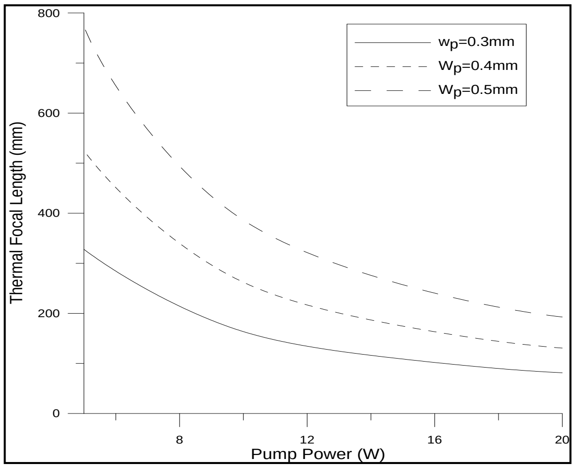

Fig.3: Thermal focal length vs pump power for different waist radius

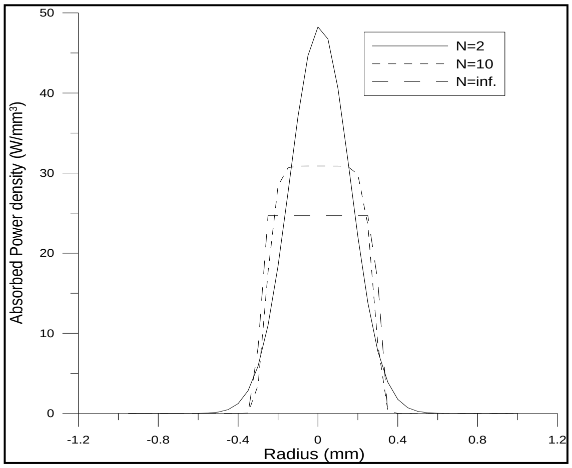

Fig.4: Absorbed power density of the Gaussian and Super-Gaussian beam profile.

The influence of the order N on the focal length of the thermal lensing is quantitatively studied, and the final results are shown in Fig.5 for N=2, 10, and ∞ respectively. It can be seen that the larger the factor N, the longer focal length is.

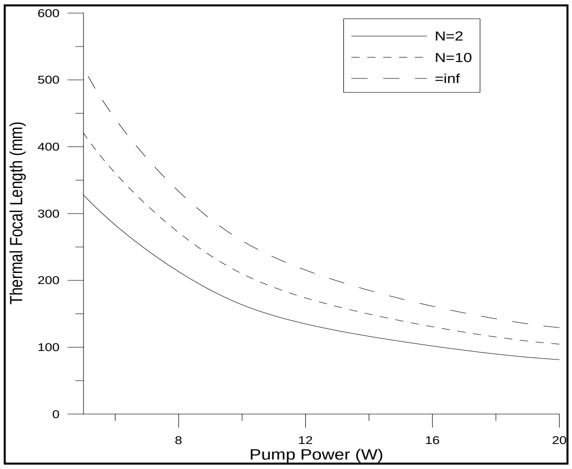

Fig.5: The influence of factor N on the focal length.

Conclusions

In conclusion, by using FEM to solve Poisson equation, the temperature distribution, thermal lens focal length of Nd:YAG laser rod pumped by laser diode at a maximum power of 20W were obtained based on the thermal conductivity, and thermo-optic coefficients,. The maximum temperature is located at the center of the end-pumped face. The results indicate that the thermal lensing effect sensitively depend on the pump power, waist radius of the pump beam and the pump distribution in a laser rod geometry.

References

[1] L.J. Li, B.Q. Yao, C.T. Wu, Y.L. Ju, Y.J. Zhang, Y.Z. Wang, Laser Phys., 19 (2009) 1213–1216.

[2] H. Chen, Q. Liu, X. Yan, M. Gong, Laser Phys.. 20 (2010) 1594–1598.

[3] M.J. Moritz, Radial distribution of temperature in a thin lens due to absorption of light and heat conduction, Optik (2010), doi:10.1016/j.ijleo.2010.06.043.

[4] C. Li, L. Liu, L. Xu, J. Bi, X. Zhang, M. Zhao, J. Feng, Optik 121 (2010) 1735–1738.

[5] W. Koechner, Solid-state laser engineering, in: Arthur L. Schawlow (Ed), Springer Series in Optical Sciences, Springer, Berlin, 1999, fifth revised and updated edition.

[6] Liang Liu, Xiaobo Wang, Shaofeng Guo, Xiaojun Xu, Qisheng Lu, Optics Communications, 284(2011) 1274-1277.