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Numerical Thermal Model of Diode Double-End-Pumped Solid State Lasers

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Abstract

In this work, a numerical analysis based on finite element method (FEM) has been used to predict both the temperature distribution and focal length in CW Nd:YAG laser rod. The double end-pumped utilizing two different pumping profiles, namely, Gaussian and super-Gaussian beam profiles are adopted in this simulation. In addition, four different super-Gaussian beam profiles (N = 4, 6, 10, 30) have been studied and compared with the Gaussian (N = 2) pump profile. At Gaussian pumping power of 40 W (20 W for each face), maximum center temperature is observed for each face of the two end-pumped faces were found, and start to decrease in the super-Gaussian case as the exponent factor N increases. The thermal lensing effect strongly depends on different factors, namely, power of the pump source, and distribution profile of the pump through the laser medium geometry. Therefore, the double-end-pumped method may be considered as important to reduce temperature gradiant in the laser rod while choosing the type of pumping profiles.

Keywords: Thermal lens effects; Finite Element Method (FEM); End-pumping Geometry; super-Gaussian pumping profile.

1. Introduction

Diode end pumped solid-state lasers are of great interest due to their compact package, reliability, high beam quality and high optical-to-optical efficiency due to a high overlap of the spatial distribution of the pump mode and the resonator’s fundamental eigenmodes. However, high-pump intensities are required sufficiently to achieve population inversion in the laser material, which, in turn produced high peak thermal loading in laser materials, and leads to undesirable thermal effects, such as variation of the refractive index with temperature,thermal stresses, and distortion of the end-surface. All these effects are described as a thermal lensing phenomena in laser material. Therefore, one of the important issues in designing and optimizing of a diode-end-pumped solid-state laser is the thermal analysis of the gain medium [1–5].

The thermal lens depends on a number of parameters, including laser material properties, such as the thermal conductivity (K), thermal expansion coefficient α_p, thermo-optic coefficient (dn/dT) and the cross sections of the absorption and emission at the pump and laser wavelengths. Hence, for thermal analysis, we need to develop a simulation framework that takes into account all these parameters in addition to heat source density.

In this paper, the thermal lensing in double end-pumped Nd:YAG laser rod under two different pumping profiles are simulated and investigated via LASCAD software [6]. The FEM has been used to predict both the temperature distribution and thermal focal length of the proposed laser rod with non-uniform distribution of pump beam and constant thermal conductivity. The variation of the thermal lensing focal length due to thermal effects and different pump profiles versus pump power are analyzed in details and the obtained results have been compared to earlier work reported in the literatue [4].

2. Simulation of Temperature Distribution

The resulting temperature distributions are calculated by solving the Poisson equation:[7]:

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

Where $T(r,z)$ is the laser rod temperature field, K is the heat conductivity in the solid, for Nd:YAG rod heat conductivity is about (13 W/m.K), $Q(r,z)$ is the density of the heat source which is a function of the pump power density, and r is the radial coordinates.

The beam of pumping source can be assumed to have a Gaussian profile with an inhomogeneous intensity along the z-direction. By adopting the propagation along the z-axis, the heat power density can be given in several forms, namely, Gaussian, super-Gaussian and top-hat depending on the pump shape and written as [5]:

$$Q(r,z) = \left[Q_1 \exp\left[-\left(\frac{r}{w_p} \right)^N \right] \exp(-\alpha z) + Q_2 \exp\left[-\left(\frac{r}{w_p} \right)^N \right] \exp(-\alpha(\ell - z)) \right] \qquad \ldots(2)$$

Where α is the absorption coefficient for Nd:YAG is about (350m^{-1}) [7]. Q_1 and Q_2 are the left and right heat power density and can be calculated as [5]:

$$Q_1 = \frac{\eta P_1}{2\pi \int_0^r \int_0^\ell \exp\left(-\, r/w_p\right)^N \exp(-\alpha z) r\,dr\,dz} \quad \text{…. (3)}$$

$$Q_2 = \frac{\eta P_2}{2\pi \int_0^r \int_0^\ell \exp\left(-\, r/w_p\right)^N \exp(-\alpha(\ell - z)z) r\,dr\,dz} \quad \text{…. (4)}$$

In the above equations, η is the fractional thermal load (ratio of heat produced to absorbed pump power or energy), which is equal to (32 %) for Nd:YAG[7], P_1 and P_2 are the left and right pump power, N is the exponent factor (an even integer and equal 2 for Gaussian) and w_p is the pump radius. With the boundary conditions:

$$T(r_o, z) = T_o, \left.\frac{\partial T(r,z)}{\partial r}\right|_{r=0} = 0, \left.\frac{\partial T(r,z)}{\partial z}\right|_{z=0,\ell} = \infty \quad \text{…. (5)}$$

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 FEM.

3. Simulation of Thermal Lensing

In solid state lasers, the thermal lens is formed due to several parameters, namely, thermal expansion induced change of the laser rod length, and the change of refractive index with temperature and birefringence [8, 9]. Since, the Nd:YAG rod is a uniaxial birefringence crystal, then the refractive index change due to birefringence can be neglected. Therefore, mainly thermal lensing effect results from the thermal expansion and thermal change of refractive index. These parameters will produce an additional optical path difference (OPD) and hence the total additional OPD is approximately expressed by [10]:

$$OPD(r,z) = \left[(n-1)\alpha_p + \frac{dn}{dT}\right] \times \int_0^r \int_0^z T(r,z)\,dr\,dz \quad \text{…(6)}$$

Where dn/dT is the thermo-optic coefficient ($9.86\times10^{-6}K^{-1}$) for Nd:YAG elements [7], n is the rod refractive index, and α_p is the thermal expansion coefficient along the z-direction. The thermal focal length associated with temperature refractive index change can be calculated from [8, 11]:

$$f = \frac{r^2}{2[OPD(0)-OPD(r)]} \qquad \ldots(7)$$

Where r is the effective radius of light beam, OPD (0) and OPD (r) are the optical path difference in the center and at the effective radius of the pump light respectively.

3. Results and Discussions

As mentioned before, the temperature distribution inside the laser rod in an end pumping geometry is a function of the distributed absorbed power density along the rod length. Figure 1, shows the distribution of the absorbed power density for different cases studied at pumping power of 40 W.

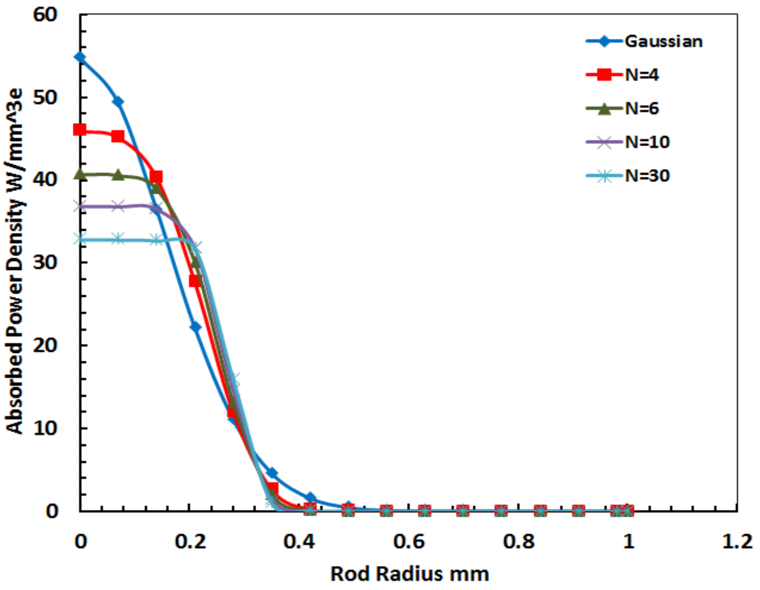


Figure 1: Distributed power density considered at a pump power of 40 W (20 W for each face).

According to finite element code incorporated in LASCAD software that has been used to calculate the temperature distribution in Nd:YAG laser rod, a-3D thermal model of ½ Nd:YAG rod ($r = 1\,mm$) and ($l = 4\,mm$) is shown in figure 2, for the different cases studied.

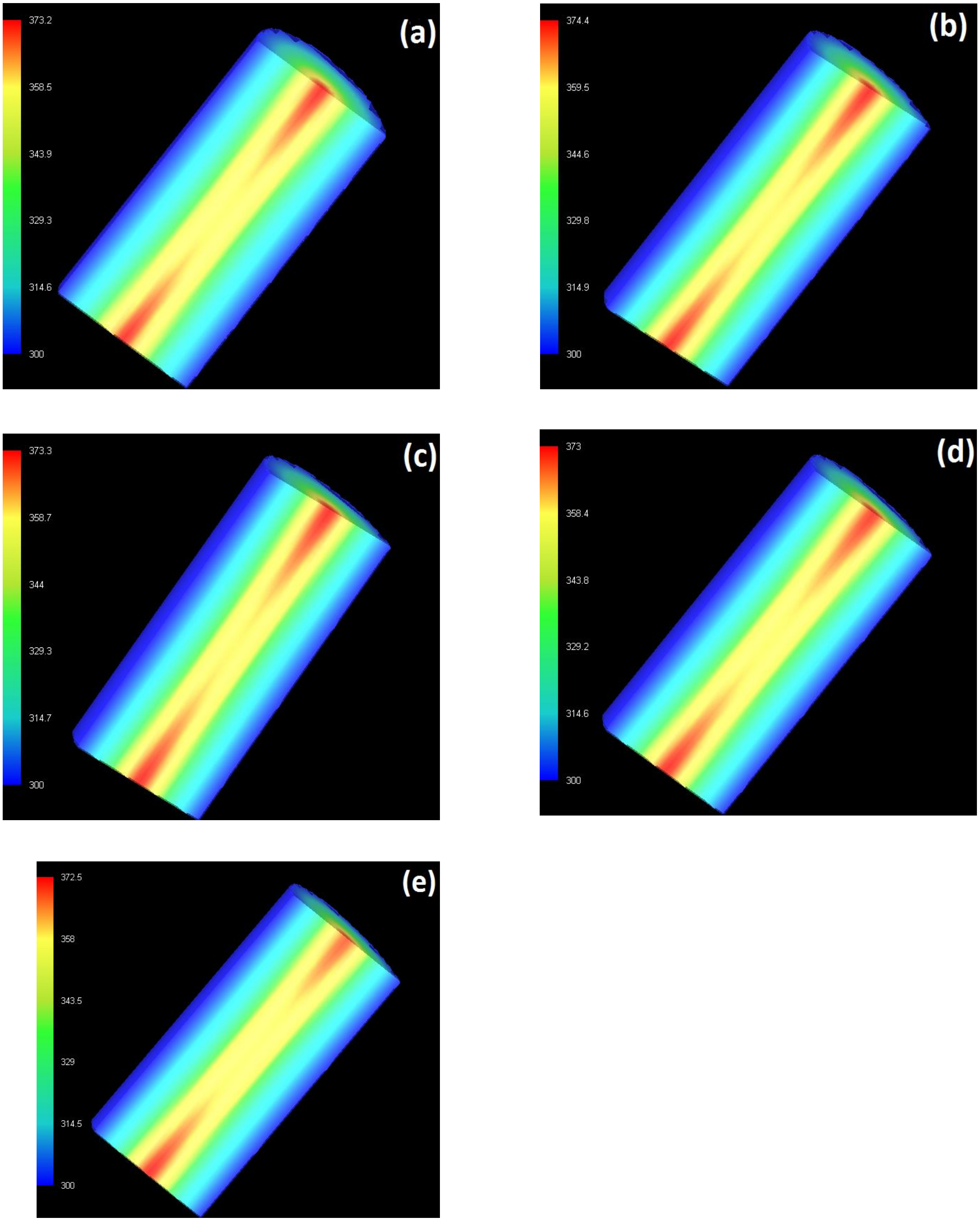
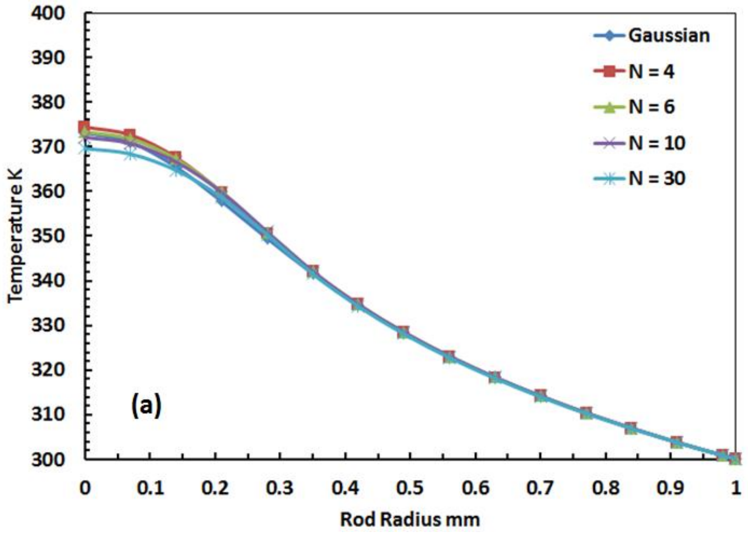

(a)
373.2
358.5
343.9
329.3
314.6
300
(b)
374.4
359.5
344.6
329.8
314.9
300
(c)
373.3
358.7
344
329.3
314.7
300
(d)
373
358.4
343.8
329.2
314.6
300
(e)
372.5
358
343.5
329
314.5
300

Figure 2: ½ Rod simulation thermal model foe (a) Gaussian, (b) N = 4, (c) N = 6, (d) N = 10, and (e) N = 30.

From figure 3 (a), it can be seen that temperature gradient exists in the rod and the maximum temperature is 374.4 K which located at the center of each face of the laser rod.To validate the obtained results, a comparison has been made with other previos work [1], and a good agreement was obtained as shown in fig3(b).Also the results show that the temperature is maximum in the case of Gaussian pumping beam and decreased in the case of super-Gaussian beam as the exponent factor N increased ,so we can suggest that, the larger the factor N, leads to a more uniform temoerature distribution in comparsion to the Gaussian case (N=2) .



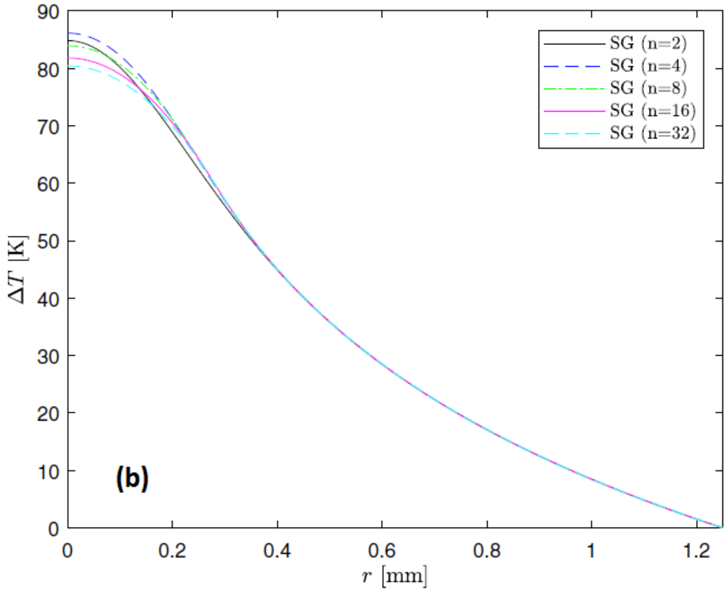


Figure 3: Temperature distribution versus rod radius at z = 0 (a) present work, (b) reported work [1].

As the order of the exponent N increases (N>>2), the pump beam approaches to top-hat distribution. The influence of the order N on the thermal lensing focal length is quantitatively studied and compared to previos work [4] for a radius of the Super-Gaussian pump beam of 0.3mm is shown in figure 4(a) and (b). In this figure, with the help of equ(7), the exponent factor N is varied from Gaussian profile to top-hat profile. Four velues of N (4,6,10,and 30) used to calculate the thermal focal lens of the laser rod and compared to the Gaussian case. It can be seen that for the same pumping radius, the effect of thermal lensing appears to be more influential on the resonator stability and the rod is under stress for the case of Gaussian profile (N=2), while for the other cases (N=4,6,10, and 30) the focal thermal length becomes longer and the fracture limit of the rod will be minimized [12]. So, the exponent factor N is important in controling the absorbed power power and to obtaine a uniform temperature distribution in the laser rod.

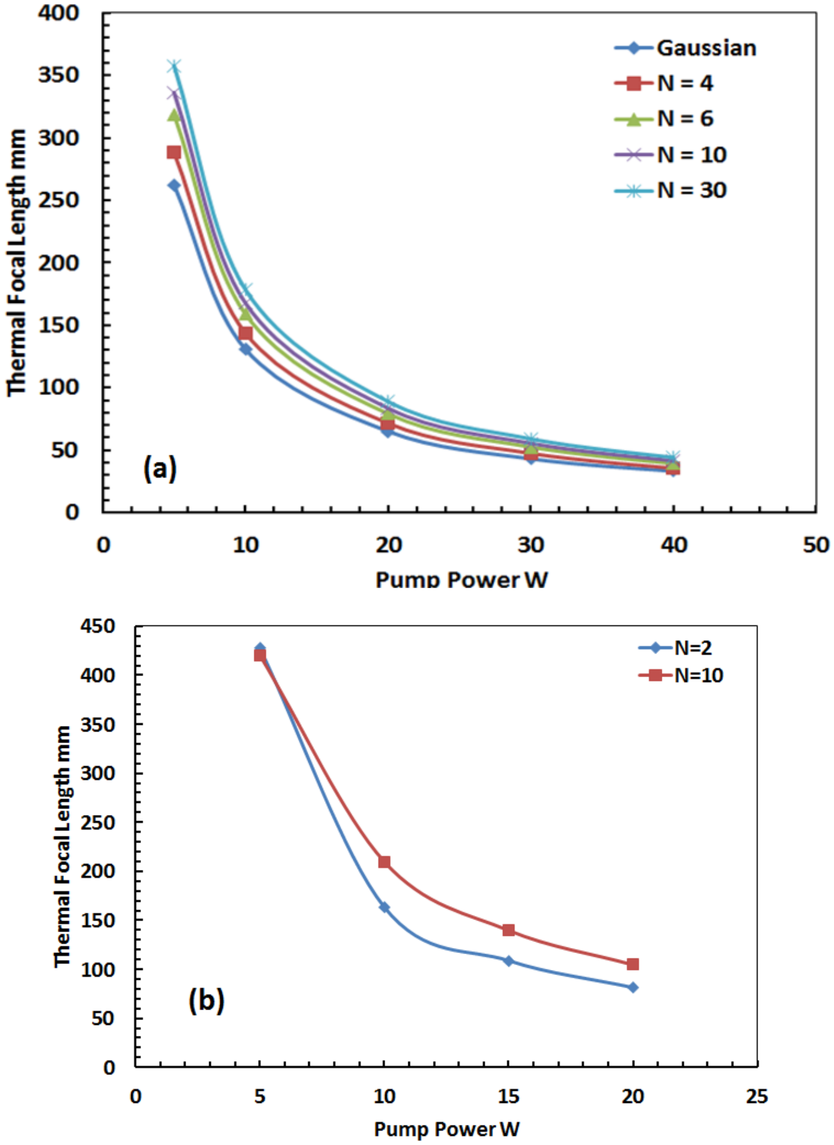


Figure 4: Influence of factor N on the thermal focal length (a) present work, (b) reported work [4].

4. Conclusions

In conclusion, the FEM code incorporated in LASCAD software has been used to solve the heat equation in laser rod. At a pump power of 40W (20W for each face), the temperature distribution and the thermal lens focal length of an Nd:YAG laser rod double-end-pumped were obtained. Different commonly used pump beam profiles were studied and compared to previous work [1,4]. The results obtained show that the maximum temperature is located at the rod center, a maximum in tha case of Gaussian and decreased in the case of super-Gaussian pumping profile as the exponent factor N increased. Additionally, the results show that the double-end-pumped geometry reduces the fracture limit as reported in the literature work [12]. Finally, it can be conculed that the thermal lensing sensitivity depends on several factors, namely, pump power and the shape of pumping beam profiles.

Abbreviations

FEM: Finite Element method.

LAS-CAD software: Laser cavity analysis and design software.

Nd:YAG: Neodymium-doped Yttrium Aluminium Garnet (Nd:$Y_3Al_5O_{12}$).

OPD: Optical path Difference.

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