Thermal Lensing Reduction in Conventional and Composite Nd:YAG Laser Rod

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ABSTRACT:
A finite-element method (FEM) was used to simulate numerically the effect of thermal lensing in YAG rods doped with Nd ion using LASCAD software. The temperature distribution and thermal lensing focal length of the composite laser rod (YAG/Nd:YAG) with one undoped end cap was considered and compared with conventional laser rod (Nd:YAG) by applying software. Results show that thermal lensing effects were reduced by a factor of 2 using (YAG/Nd:YAG) composite rod at pump power of 20W.
Keywords: composite Laser Rods, Thermal Lensing, Finite Element Method, Diode End-Pumping Geometry.

INTRODUCTION

Laser-diode-pumped solid-state lasers may offer high performance, compactness, and reliability, especially in an end-pumped setup. In order to acquire higher powers by continuous (CW) end-pumped solid-state lasers, one should consider thermal lensing phenomenon (result by temperature-induced changes in the refractive index of the laser active medium) that will influence optical efficiency [1–7].

Throughout high-power solid-state lasers, pump-induced thermal focusing can be of principal importance due to its significant impact on most major facets of solid-state lasers, for instance efficiency, resonator stability, oscillating mode sizes, and output beam quality. Therefore, it is necessary in solid-state laser design in addition to optimization to look for the thermal lens focal length occurring inside the gain medium at a variety of pump power levels. A possible strategy for reducing this effect and improving the overall laser performance is to use a composite rod with sections of undoped host material on a single or the two ends [8, 9]. Composite active element enlarges the cooling surface and decreases the temperature gradients inside the rod. This can diminish the bending of the front active element surface and consequently decrease the contribution of end-face curvature to the focal length of thermal lens [10].

In this paper, finite-element method was used to simulate temperature distribution field and thermal lensing in both conventional and composite YAG rods. Compared to 2x5mm^2 conventional laser rod, thermal lensing of a composite structure of 2x6mm^2 with one undoped end cap was investigated.

Thermal Model:

The following equation governs the temperature distribution in steady-state heat problems [10]:

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

Where $T(r,z)$ is the temperature field of laser rod, K is the heat conductivity in the solid which is equal to 13 $(W.m^{-1}..K^{-1})$ 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 generation source $Q(r,z)$ can have different profiles, but in our simulation a pump beam with a Gaussian transverse profile has been used, so $Q(r,z)$ has the form[9]:

$$Q(r,z) = \left\{ \begin{matrix} 0, z < \ell^* \\ \dfrac{2\eta\alpha P}{\pi w_p^2} \exp\left(-\dfrac{2r^2}{w_p^2}\right) \exp\left(-\alpha\left(z-\ell^*\right)\right) \end{matrix} \right\}, z \geq \ell^* \qquad \ldots(2)$$

Where η denotes the part of pump beam radiation converted to heat, which is equal to 32% for Nd:YAG [10], α is the absorption coefficient ($350m^{-1}$) for Nd:YAG [10], P and w_p are the power and the radius of the Gaussian pump beam.

With the boundary conditions of:

$$T(r,z) = T_o, \frac{\partial T(r,z)}{\partial r}\bigg|_{r=0} = 0, \frac{\partial T(r,z)}{\partial z}\bigg|_{z=0,\ell+\ell^*} = \infty \qquad \ldots(3)$$

Where T_o is the temperature of the ambient air, r is the rod radius, and z is the axial coordinate, ℓ is the length of the doped rod, and ℓ^* is the length of the undoped cap, the temperature distribution can be calculated using finite element method (FEM).

The inhomogeneous distribution of temperature, strain and displacement cause a change of the refractive index at each point at the active medium, this result in a variation of the optical path difference (OPD).

The optical path difference (OPD) theory is a bridge between the imaginary lens and the thermal effect [11]. For a paraxial coherent beam propagating in the z-direction, the optical path difference (OPD) is given in [12]. By neglecting the contribution from thermal stress induced birefringence which is small for most cases [12], the OPD can be expressed as:

$$OPD(r) = 2\left[\int_L \frac{\partial n}{\partial T} T(r,z) dz + \int_L n\varepsilon_z dz\right] \qquad \ldots(4)$$

Where n is the refractive index of the rod, and ε_z is the longitudinal strain.

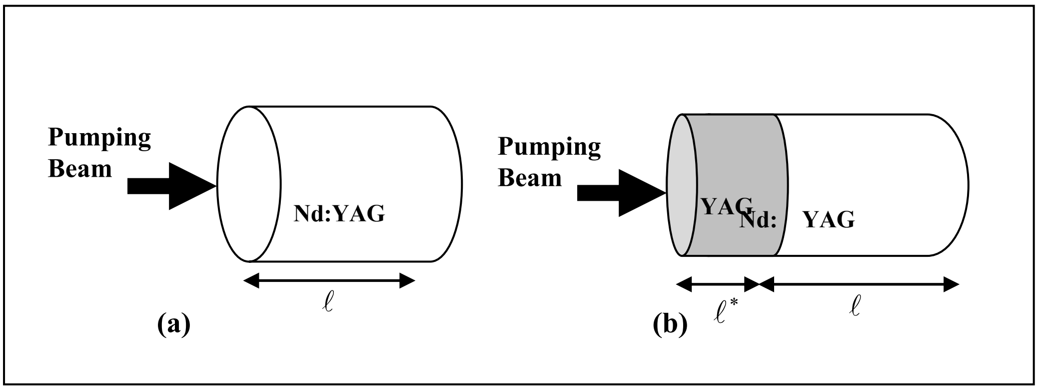
For laser rod operating in steady state, the focal length due to temperature – induced variation of refractive index, can be written by [13]:

$$f = \frac{r^2}{2[OPD(0) - OPD(r)]} \qquad \ldots(5)$$

Where OPD(0) is the OPD in the center and OPD(r) is the OPD at the effective radius of the pump light.

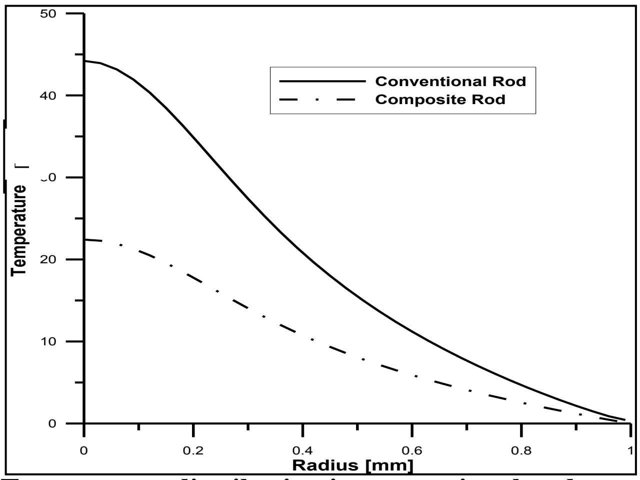
Results and Discussion:

Two different laser active medium have been used as shown in fig.1. The first one (conventional rod) has the size of $2x5mm^2$, and the second (composite rod) has the dimensions of $2x6mm^2$, with an undoped front end cap. In the composite rod, an undoped YAG cap of $2x1mm^2$ was thermally bonded with the conventional active element. The results were calculated with heat load ηP=6.4W, and Gaussian pump beam with waist radius w_p = 0.3mm.



Figure(1). Schematic of two Nd:YAG laser rods (a) Conventional rod (b) Composite rod

Figure (2) shows the simulation results of temperature distribution. It can be seen that the temperature peak value was reduced from 44.21K to 22.41K when a conventional rod was replaced by a composite rod which is about 49% smaller than temperature rise in conventional rod.

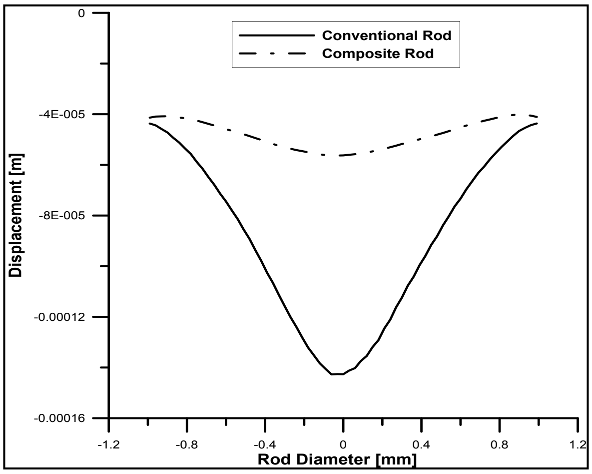


Figure(2). Temperature distribution in conventional and composite rod

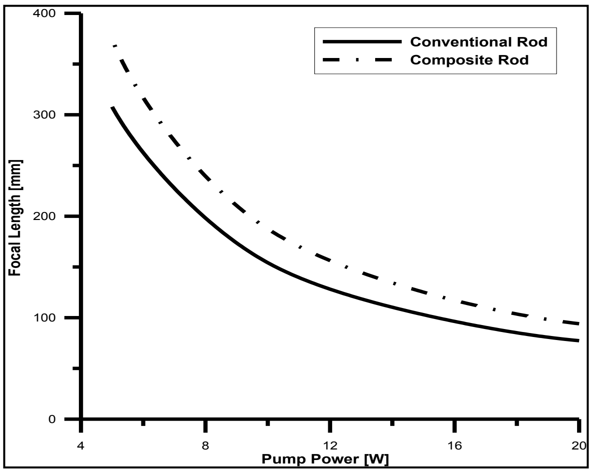
The thermally induced mechanical displacement profile at the entrance face of the rod (z=0) was presented in fig.3. The maximum displacement occurs in the middle of the rod. For a composite rod the displacement is larger than in the case of conventional rod due to a longer composite rod as shown in fig.3.

The change of the thermal focal length of the rod with the pump power is shown in fig.4. Because the birefrengent effects from the thermal temperature field and from the Nd:YAG oneself will counteract each other, it can be seen that the deviation will decrease when the pump power rises.

When compared to conventional laser rod, the thermal lensing focal length of the YAG/Nd:YAG composite rod is 94.038mm at a pump power of 20W, while it is 73.28mm for a single Nd:YAG rod in the same conditions. Because the undoped cap host material (YAG) absorbs the heat from the Nd:YAG rod, it can be seen that not only the temperature evidently decreases but also the thermal lensing focal length evidently increases. So the thermal lens effect of the Nd:YAG rod is evidently decreasing for the YAG/Nd:YAG composite rod, that is highly advantageous to the thermal stability of output power and the beam quality of the output laser beam.



Figure(3). Displacement profile of the end face for conventional and composite rods.



Figure(4). Thermal focal length as function of pump power for conventional and composite rods.

CONCLUSIONS:

The two Nd:YAG rods (one conventional, and one with undoped end cap) intended for longitudinal diode pumping were investigated. At the same level of the pump power (20 W - continuous pumping), and in the case of the rod with one undoped end, the temperature gradient inside the rod will be more than once below the value measured for the conventional rod, and the thermal focal length was reduced by a factor of two as compared with the conventional rod. The results show that composite laser rod is attractive for the possibility of improving thermal management, especially of high power diode-pumped solid state lasers.

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