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# IMPROVEMENT OF LASER BEAM QUALITY BY COMPENSATING THERMALLY INDUCED LENS IN SOLID-STATE LASERS

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## ABSTRACT

Numerical simulations for compensation of thermally induced lens in diode pumped Nd : YLF laser rod are presented. We have proposed a design for intra-cavity compensation of thermally induced lens for π-polarization. The numerical calculations showed that the Nd : YLF laser rod can be pumped up to 850 W before rod fractured. Temperature and stress distributions around pumped are in the Nd : YLF laser rod are also presented.

**Key words**: Laser beam, Thermally induced lens, Solid-state lasers.

## INTRODUCTION

Diode pumped solid-state lasers (DPSSL), especially Nd doped different hosts like YAG, YLF and Glass, are important high-power laser sources for material-processing applications[1-9]. A great advantage of (DPSSL) is reduced thermal load in the laser crystal compared to the flash-lamp pumped case[1]. During the last decade, research committed for the development of high power (DPSSL) lasers has been performed[10-18]. The thermal lens is a critical issue for developing high-power DPSSL lasers. Creation of thermal lens is mainly due to the change of the refractive index with temperature, $dn/dT$ (positive in the case of Nd : YAG and negative for Nd : YLF), in addition to thermal expansion of the laser rod. The thermal lens affect badly on the laser performance by limiting the stability range of the resonator and degradation of the of the beam quality.

Several studies have been reported on the compensation of positive thermally induced lens in Nd : YAG laser rods[1-27]. A Nd : YLF laser rod has one attractive feature of

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its weaker thermal lens compared to Nd : YAG for the same pumping conditions[9]. This is resulting from a YLF showing a decrease of refractive index with increasing temperature, creating a negative thermal lens, which is partly reduced by the positive lens due to the thermal expansion rod end faces[9]. The Nd : YLF is a natural birefringence crystal, and has a long fluorescence lifetime. The degree of compensation of these opposite contributions to thermal lensing is particularly evident for the σ-polarization (corresponding to 1.053- μm operation), where the net thermal lensing is ~17 times weaker than for a comparable 1064 nm Nd : YAG laser[9]. Compensation of negative thermally induced lens in Nd : YLF is not presented yet. Therefore, thermally induced lens in diode pumped Nd : YLF laser rod for the π-polarisation has the priority to compensate for.

In this work, we have introduced for the first time (to the best of our knowledge) a new design to compensate for negative thermal lens in a Nd : YLF laser rod. Numerical simulations were used to calculate dioptric powers of thermally induced lens in Nd : YLF and compensating element (glass SK2). The compensating element is heated via intra-cavity of 1% of the produced laser, for Nd : YAG[20]. Temperature and stress valued in end pumped Nd : YLF laser rod are also presented.

## Temperature and stress distributions in end-pumped laser rod

End pumped laser rod has an advantage for good beam quality laser oscillation, since the small pump beam radius comparable to side pumping where the medium allows higher order of modes to oscillate[23], resulting in bad beam quality. Concentrating of pump beam on a small area on the laser rod in end pumped gives raise to limitation of power due to risk of rod fracture, also complicated calculations of temperature distributions than in side pumped where the temperature distribution is uniform.

In an end-pumped laser rod the temperature distribution depends on the pump distribution. The temperature has a higher value at the center of the laser rod and decays logarithmically to the rod edges. A uniform heat load over a pump radius $r_p$ of a laser rod of radius $r_{rod}$ leads to a temperature distribution given by –

$$T - T_0 = \frac{P_a}{4\pi KL} \times \begin{cases} -2\ln\left(\frac{r_p}{r_{rod}}\right) + 1 - \left(\frac{r}{r_{pump}}\right)^2, & r \le r_{pump} \\ -2\ln\left(\frac{r}{r_{rod}}\right), & r > r_{pump} \end{cases} \quad \ldots(1)$$

Where $P_a$, $T_0$, K and L are absorbed pump power, rod edge temperature, rod thermal conductivity and rod length, respectively.

The non-uniform temperature distribution gives raise to different stresses distributions. The maximum tensile stress $\sigma_{max}$ across the rod section is given by (1):

$$\sigma_{\max} = \frac{1}{2} \cdot (T - T_0) \cdot \frac{\beta \cdot E}{1 - \nu} \quad \ldots(2)$$

where β, E and ν are the expansion coefficient, Young's modulus and Poisson ration, respectively.

## Thermally induced lens and resonator stability

The resulting non-uniform temperature distribution from the centre to the rod surface is responsible for the creation of thermally induced lens in the laser medium. This distribution changes the refractive index across the rod (thermal dispersion *dn*/*dT*). Also, appearance of bended end faces due to thermal expansion with thermal stresses.

The focal length *f* of the laser rod in an end-pumped case is given by the following Equation:

$$f = \frac{\pi \cdot K \cdot r_p^2}{P_{heat} \cdot \left( dn/dT \right)} \left( \frac{1}{1 - e^{-\alpha \cdot L}} \right) \quad \ldots(3)$$

Where, $P_{heat}$ is the part of absorbed pump power that converted to heat and α is the absorption coefficient of the laser medium.

Presence of thermal lens of focal length *f* inside laser resonator changes the optical path and affect the stability of resonator. This effect can be modeled by a simple thin lens with an effective focal length of *f*. With the focal length *f*, it is possible to determine resonator stability using two resonator parameters. These parameters are functions of the resonator length and the optical components within the resonator, they are defined as:

$$g_1 = 1 - \frac{L_2}{f} - \frac{L_0}{R_1} \quad \ldots(4)$$

$$g_2 = 1 - \frac{L_1}{f} - \frac{L_0}{R_2} \quad \ldots(5)$$

Where $R_1$ and $R_2$ is the radii of each mirror, $L_0$ is defined as -

$$L_0 = L_1 + L_2 - \left( \frac{L_1 \cdot L_2}{f} \right) \qquad \ldots(6)$$

and $L_1$ and $L_2$ are the distances from each mirror to the thermal lens. The focal length of the lens can be used to determine the resonator parameters that are frequently used to define resonator stability on the stability diagram[1,25] with well-known stability condition $-1 \leq g_1 g_2 \leq 1$.

## RESULTS AND DISCUSSION

### Nd : YLF laser rod

The numerical modeling calculations were performed to predict the limits imposed power scaling in diode pumped Nd : YLF laser rod. In the first step we calculated the dioptric powers (D=1/f m-1) of Nd : YLF laser rod under non-lasing condition and without compensations and compared with previous work[9], to validate our calculations.

For calculations, the pump light (λ = 797 nm) is focused on the laser rod end of radii 340 µm 220 µm. The Nd : YLF is 6-mm long 4 mm-diameter Nd : YLF rod with dopant concentration of 1.15 at %. The rod axis is placed parallel to the resonator plane and water cooled at 298 K. Equation (3) was used to calculate the dioptric power of thermally induced lens in Nd : YLF rod. The optical and mechanical parameters of the Nd : YLF crystal are in Table 1.

**Table 1: The parameters used in calculations for Nd : YLF[1]**

| Heat conductivity (W/mK) | Expansion coefficient ($10^{-6}$/K) | Young's modulus (GPa) | Poisson's ratio | Refractive index | | dn/dT ($10^{-6}$/K) | |
|---|---|---|---|---|---|---|---|
| | | | | σ | π | σ | π |
| 8.3 | 8 | 85 | 0.33 | 1.448 | 1.47 | -2 | -4.3 |

Figure 1 shows the dependence of the negative dioptric power of thermally induced lens in Nd : YLF laser rod with pump power. The absorbed pump power assumed 85% on incident pump and 35% of it is converted to heat. The calculated results presented in Fig. 2 are in a good agreement with measurements for π-polarisation[9].

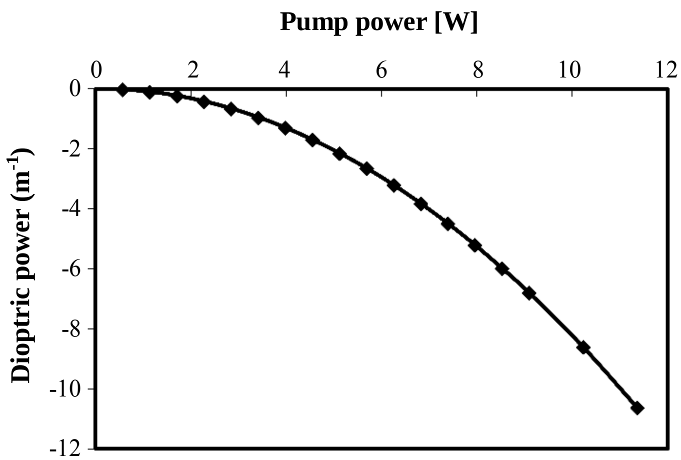


**Fig. 1: Calculations of dioptric power of thermally induced lens in Nd : YLF laser rod versus pump power**

In the next, we have extended the calculations for different pump powers and rod geometry under lasing condition where the dioptric is ~6 weaker than in lasing condition. And, to predict the fracture limit imposed the power scaling.

Figure 2 shows the calculated normalized temperature distribution using Eq. (1), for a typical ratio rpump/rrod = 0.2.

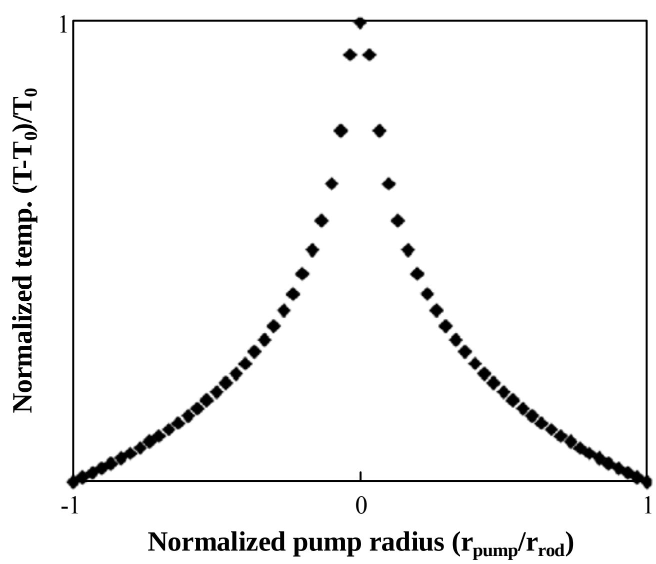


**Fig. 2: Normalized temperature for Nd : YLF rod pumped at 40 W with rpump/rrod = 0.2.**

The calculations showed by increasing the ratio of the pump diameter to the rod diameter from approximately 1/2 to 1/3 causes decrease in temperature from the rod centre to the circumference. On one hand, increasing the pump spot diameter much beyond 1/2 of the rod diameter leads to excessive aperture losses if the mode and pump spot diameters are equal. On the other hand, in a short rod, the pump power on one end is absorbed through the length and produces a rise in temperature and stress at the opposing end. Thus, preferable using long rods in which the ends are thermally independent can be pumped at higher powers before reaching the thermal fracture limit.

To examine the effect of dioptric power of negative thermally induced lens on resonator stability, we analyzed the laser operation performance by using the ABCD matrix formalism based on the standard Gaussian propagation theory after consideration of thermal lens effect[23]. For calculations, we have used rod length of 6 mm and diameter of 4 mm, $L_1$ = 6 mm and $L_2$ = 6 mm. The equivalent matrix for free space and each element are presented in Fig. 3.

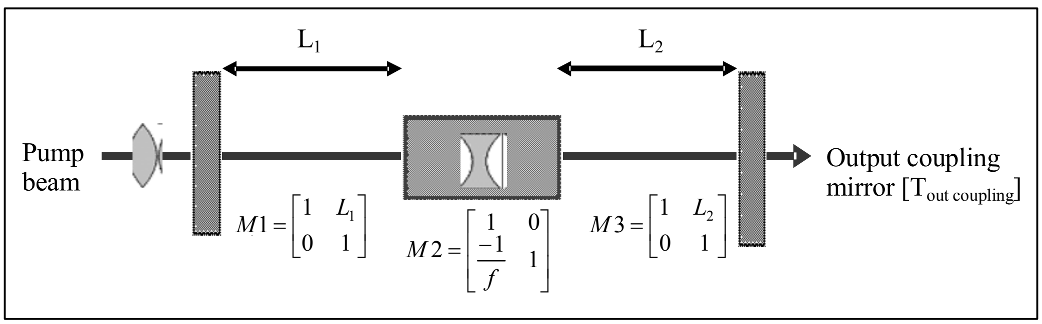


**Fig. 3: Shows negative thermally induced lens with equivalent matrices**

The equivalent matrix for single and round trip is given by[23] –

$$M_{\sin gletrip} = M_3 M_2 M_1 \quad \ldots(7)$$

$$M_{roundtrio} = M_1 M_2 M_3 M_3 M_2 M_1 \quad \ldots(8)$$

$$M_{roundtrip} = \begin{bmatrix} g_1 & L \\ \frac{g_1 g_2 - 1}{L} & g_2 \end{bmatrix} \quad \ldots(9)$$

By applying the stability condition $-1 \le g_1\, g_2 \le 1$, we can calculate the resonator stability for different pump power and as a function of negative dioptric power of negative thermally induced lens.

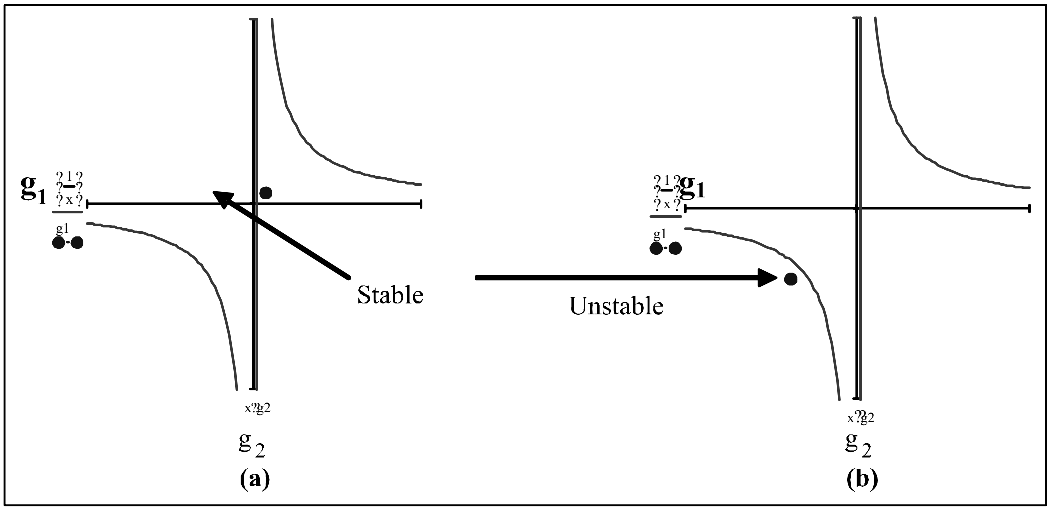


**Fig. 4: Stability diagram for Nd : YLF at two different pump powers (a) 10 W (with Dioptric power D = -8 $m^{-1}$), (b) 20 W (with D = -16 $m^{-1}$)**

Figure 4 shows the two stability regions of the laser resonator at two different pump powers, 10 W in (5 a) where the resonator is stable and 20 W unstable resonator as in (5b). To bring down the resonator to the stability region the negative dioptric power of thermally induced lens in the Nd : YLF laser has to be balanced. Clearly, to scale end-pumped Nd : YLF lasers to stable high powers while simultaneously maintaining high efficiency and good beam quality that requires compensation of the thermally induced lens.

## Proposed design for correction of thermally induced lens in Nd : YLF laser rod

Figure 5 shows the proposed design for compensation of thermally induced lens in Nd : YLF laser rod with a compensating element glass SK2 with positive dn/dt[26]. The compensating glass element SK2 is doped with Thuium ($Tm^{+3}$) ions[28-30], the dopant of $Tm^{+3}$ is adjusted to absorb 1% of the laser beam from Nd : YLF laser rod at wavelength of 1047 nm corresponding to π-polarization. The glass SK2 is chosen, because its thermal dispersion + dn/dT ≅ -dn/dT (Nd : YLF for π-polarisation). The Nd : YLF laser rod is end pumped with laser diodes adjusted at wavelength of ~797 nm. This wavelength is chosen to reduce the risk of rod fracture, since the fracture limit of Nd : YLF is ~5 times lower than for the Nd : YAG[9]. The pump light is focused on the Nd:YLF laser rod end with a convex lens. The barrel of the Nd : YLF laser rod is water cooled at 298 K and the two end faces are air cooled. The distances between Nd : YLF laser rod and compensating element SK2 glass with mirror reflectivities are denoted in the Fig. 5. The numerical values of glass SK2 are tabulated in Table 2 with 35% of absorbed pump power converted to heat.

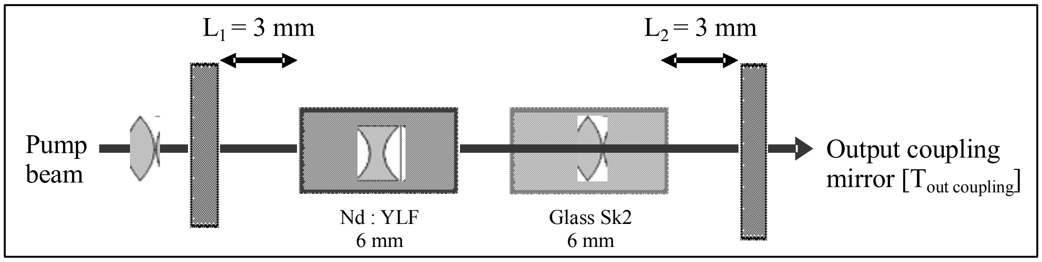


**Fig. 5: The proposed design for compensation of thermally induced lens in Nd : YLF laser rod**

**Table 2: The parameters used in calculations for SK2[26]**

| Heat conductivity (W/mK) | Expansion coefficient ($10^{-6}$/K) | Young's modulus (GPa) | Poisson's ratio | Refractive index | dn/dT ($10^{-6}$/K) |
|---|---|---|---|---|---|
| 0.771 | 7 | 87 | 0.261 | 1.61 | 3.9 |

The glass SK2 is heated via intra-cavity laser at 1047 nm and produce a positive thermally induced lens to compensate for the negative lens in the Nd : YLF section. The dioptric power of the thermally induced lens in the glass SK2 section is given by[20]:

$$f_{SK2} = \frac{\pi \cdot K_{SK2} \cdot T_{Outcoupling}}{L_{SK2} \cdot \eta_{Effeciency} \cdot \left(P_{Laserpump} - P_{Threshould}\right)} \cdot \frac{1}{\left(\frac{\left(dn/dT\right)_{SK2}}{2 \cdot R_{SK2}} + \frac{\alpha_{exp}\left(n_0 - 1\right)}{L_{SK2}}\right)} \quad \ldots(10)$$

Where, $K_{Sk2}$, $L_{SK2}$, $n_0$, $\alpha_{expansion}$ are thermal conductivity, length, refractive index and expansion coefficient of glass SK2. With, pump threshold ($T_{hreshold}$ = 45 W), slope efficiency ($\eta_{Efficiency}$ = 40%) and transmittance of output coupling mirror $T_{Outcoupling}$ = 5%).

Figure 6 shows the dioptric powers of thermally induced lenses in the Nd : YLF, glass SK2 and the sum of them at different pump powers using Equations 3 & 10. The length of the glass SK2 is important, since the dioptric power is a function of it. The Nd : YLF can be pumped up to 1000 W. Thermal stresses that lead to rod fracture is the main drawback for power scaling for both Nd : YLF and SK2 rods.

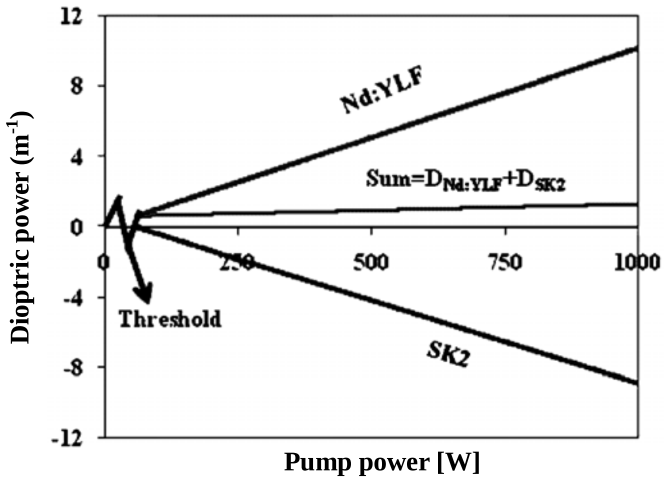


**Fig. 6: The dioptric powers of thermally induced lens against pump power for Nd:YLF laser rod and compensating element glass SK2 and the sum of them**

Figure 7 shows values of maximum thermal stresses for Nd : YLF laser rod at different pump powers by using equation 2. The calculations showed the Nd : YLF can be pumped up to 850 W before rod fractured, where $\sigma_{max}$ ~80 MPa (for Nd:YLF $\sigma_{max}$ ~85 MPa).

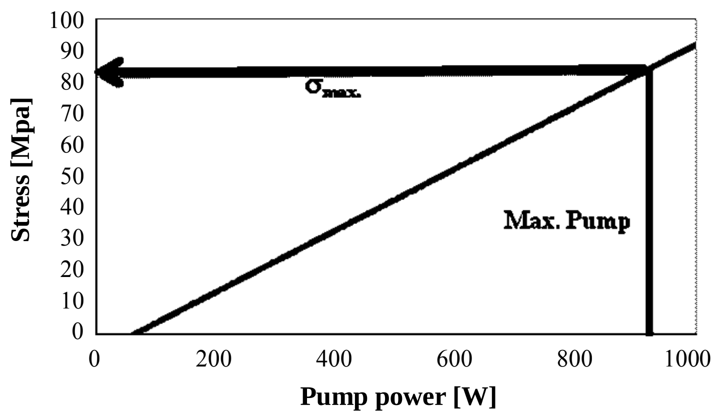


**Fig. 7: Calculated values of thermal stresses in end pumped Nd : YLF laser rod**

## CONCLUSION

Compensation of negative thermally induced lens in end pumped Nd : YLF laser rod is presented numerically. Stability of laser resonator without and with compensation is addressed. Temperature and stress distribution inside Nd : YLF laser rod is showed. The Nd :

YLF laser rod can be pumped up to 850 W before rod fractured with nearly complete compensation of thermally induced lens and stable resonator.

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