

Effect of Rod Crystal Dimensions on Thermal Stress in Nd: YLF Laser with 20 W End-Diode Pumped

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ABSTRACT

Theoretical results are reported on thermal stress effects along the π 1047 nm and σ 1053 nm polarizations in an a cut Nd: YLF rod crystal by using 20 W diode-end-pumped. The effects of rod crystal length and radius on the distribution of radial temperature and thermal stress are studied. The result from this study has shown that the temperature in a center of rod is decreased when the length of crystal increases. The center of the rod is under compression, while the surface of the rod is under tension. Furthermore, the effect of thermal stress for π polarized 1047 nm is stronger than σ polarized 1053 nm.

Keywords: Thermal effects; Nd: YLF laser crystal; Thermal stress; Heat dissipated power in crystal; End-diode pumped

INTRODUCTION

Thermal lens effect was discovered by Gordon et al. [1] in 1964. When a laser crystal is absorbed pumping light energy, fluorescent light is produced. A part of pumping light will be converted into thermal energy and created a variation in refraction index and mechanical properties for laser crystal [2,3].

Thermal distortion is caused when a field of a temperature gradient formed in the crystal. The thermal effects will make laser crystal as a thermal lens. This lens had most limitations the laser beam quality and resonator stability range. There are different ways to reduce thermal lens effects such as, by using composite crystal and designing the variable configuration resonator [2].

Nd: YLF uniaxial, birefringent crystal with two main lasing line in the 1 μ m wavelength region namely 1047 nm and 1053 nm both the π and σ polarized. To minimize the effects of thermal lens and stress induced birefringence, Nd: YLF crystal was used as laser material because of its good thermo optical properties [3,4].

The aim of this paper is to present theoretical results for studying the effects of rod crystal dimensions on the thermal stress for π 1047 nm and σ 1053 nm polarization in a cut Nd: YLF crystal with 20 W end pumping power.

MATERIALS AND METHODS

Proposed geometry and basic equations

The proposed geometry consists of Nd: YLF crystal rod, whose axis corresponds with the pump symmetry axis, with a radius r_0 which is surrounded by a cylindrical with water for cooling, which leads to conduction heat transfer from rod surface to the ambient medium. The schematic figure of the rod and cooling system geometry is shown in **Figure 1**.

The absorbed power P_a in crystal is given by [2]:

$$P_a = \eta_a P_{in} \quad (1)$$

$$\eta_a = 1 - \exp(-\alpha L) \quad (2)$$

where P_{in} and η_a are the fraction of optical input power and the absorption efficiency respectively, is the absorption coefficient of the laser crystal at a wavelength emitted by the laser diode, and L is the crystal length.

In the case of diode pumped, the heat dissipated power P_h is given by:

$$P_h = \eta_h P_a \quad (3)$$

The fractional thermal load in the crystal η_h can be calculated

$$\eta_h = 1 - \frac{\lambda_p}{\lambda_L} \quad (4)$$

where λ_p is the pump wave length and λ_L is the laser wave length.

The heat conduction equation is given by [5]:

$$\rho c_p \frac{dT}{dt} = K \nabla^2 T + Q \quad (5)$$

where ρ is the density of the material (kg m^{-3}), C_p is the specific heat ($\text{J kg}^{-1} \text{K}^{-1}$), T is the temperature in (K), t is the time (s), K is the thermal conductivity ($\text{Wm}^{-1} \text{K}^{-1}$), ∇ is the gradient operator, and Q is the heat generated in crystal per unit volume in (W/m^3) [6]. Eq. 5 can be solved at steady - state gives, the temperature at any point along a radius of length r (radial temperature), at the boundary condition $T(r_o)$ for $r=r_o$ where $T(r_o)=T_s$ is the temperature at the surface of the rod, then:

$$T_{(r)} = T_s + \frac{Q}{4K} (r_o^2 - r^2) \quad (6)$$

where T_s is the temperature at the surface of the crystal given by:

$$T_s = T_f + \frac{P_h}{Ah} \quad (7)$$

where h is the surface heat transfer coefficient, T_f is the coolant temperature, and A is the surface area of the crystal rod. The uniform heat generated per unit volume is given by:

$$Q = \frac{P_h}{\pi r_o L} \quad (8)$$

Thermal stress deformation occurs as the temperature of material increases since the vibration of the constituent atoms or molecule's increases. This effect causes the material to expand. When this expansion is constrained it

$$\left. \begin{aligned} \sigma_r &= QS(r^2 - r_o^2) \\ \sigma_\phi &= QS(3r^2 - r_o^2) \\ \sigma_z &= 2QS(2r^2 - r_o^2) \end{aligned} \right\} \quad (9)$$

where σ_r , σ_ϕ , σ_z are radial, tangential and axial stress respectively, and S is given by:

$$S = \alpha_T E [16K(1-\nu)]^{-1} \quad (10)$$

where α_T is the thermal coefficient of expansion; E is young's modules and ν is Poisson's ratio. The photo elastic effect is a minor importance in Nd: YLF because of its strong natural birefringence.

RESULTS AND DISCUSSION

In our previous works [7,8], general theoretical calculations were established to study and determine the variations of surface temperature, refractive index and the focal length for π (1047 nm) and σ (1053 nm) polarization in a cut Nd: YLF crystal with 20 W end pumping power using the model under study in **Figure 1** and the information and essential parameters for the crystal in **Table 1** [2].

According to Eq. 6, the radial temperature distribution as a function of a radius for Nd: YLF crystal for different values of crystal length is shown in **Figure 2**.

It can be seen that radial temperature with a parabolic profile, has a maximum temperature in the center of crystal and of minimum value on the surface of crystal. Also, by increasing the crystal length, the radial temperature begins to converge in values.

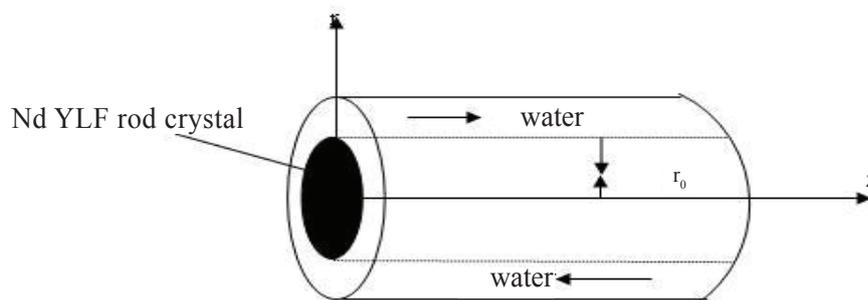
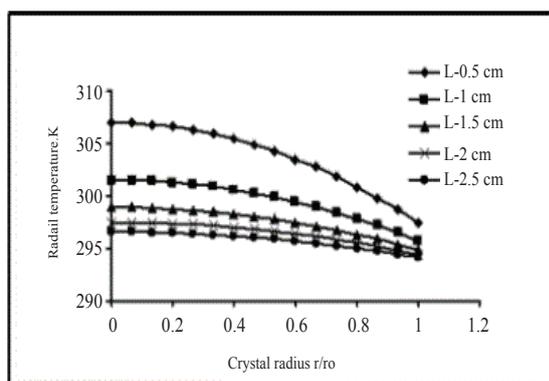


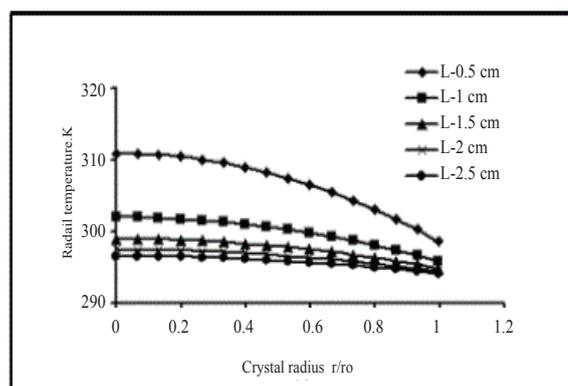
Figure 1: A simple drawing of Nd: YLF rod crystal and cooling system geometry

Table 1: Basic parameters of Nd: YLF laser crystal [2]

Parameter	Value	Parameter	Value
Thermal conductivity K	0.06 (W/cmK)	Elastic modulus	7.5×10^{10} (N/m ²)
Peak absorption coefficient α (for 1% Nd)	π : 10.8 cm ⁻¹ ; σ : 3 cm ⁻¹	Surface heat transfer coefficient	1.8 W/cm ² K
Refractive indices n_o	π : 1.477; σ : 1.448	Crystal radius r_o	0.15 cm
Thermo-optical coefficient dn/dt	π : -4.3×10^{-6} K ⁻¹ ; σ : -2.0×10^{-6} K ⁻¹	-	-

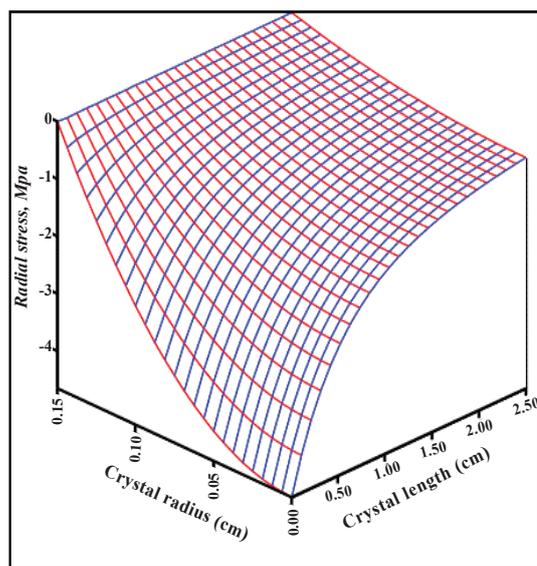


(a)

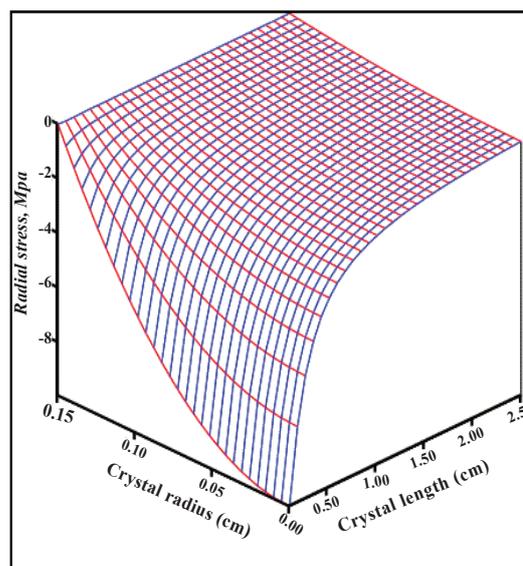


(b)

Figure 2: Radial temperature distribution T_r of Nd: YLF crystal as a function of radius for different crystal length (a) for σ polarized laser 1053 nm (b) for π polarized laser 1047 nm



(a)



(b)

Figure 3: Radial stresses component as a function of crystal radius (a) for σ polarized laser 1053 nm (b) for π polarized laser 1047 nm

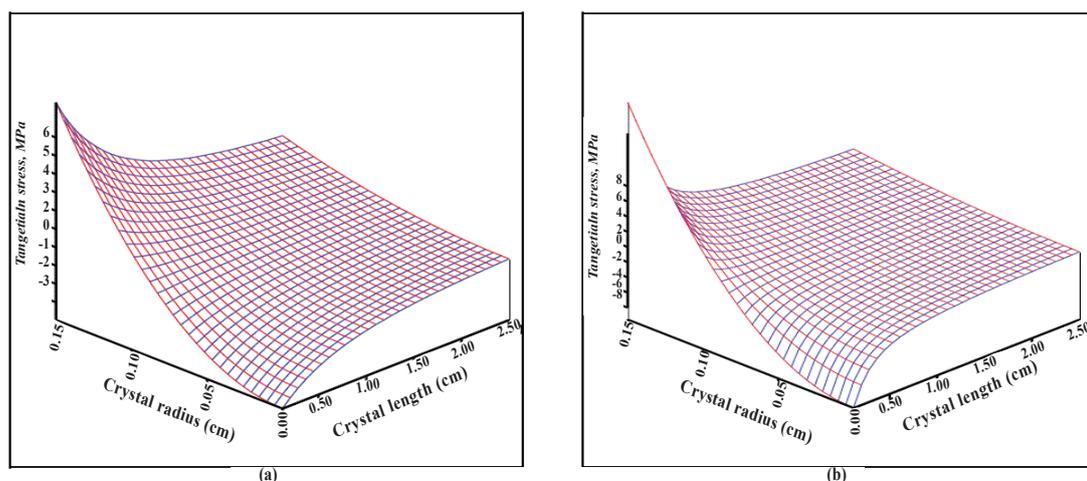


Figure 4: Tangential stresses components as a function of crystal radius (a) for σ polarized laser 1053 nm (b) for π polarized laser 1047 nm

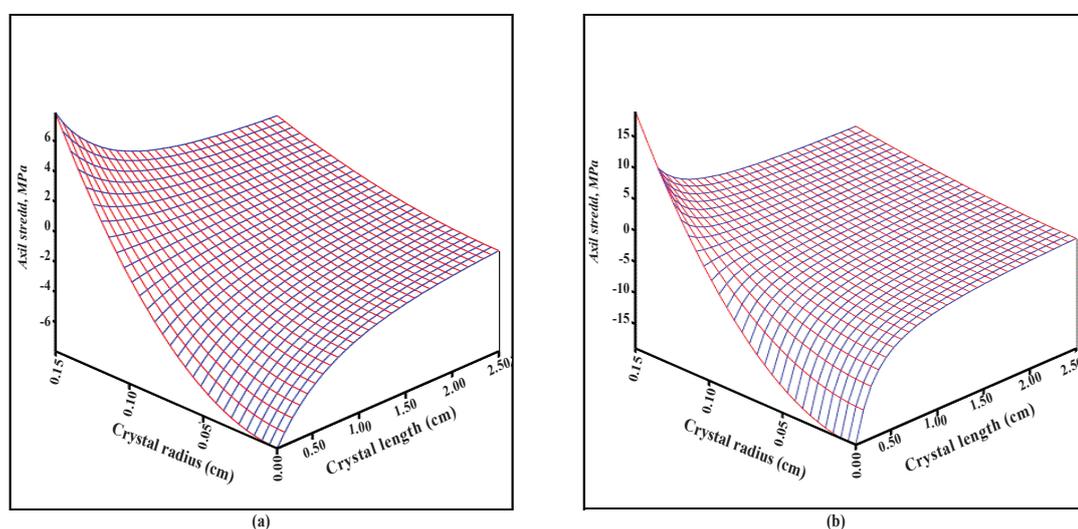


Figure 5: Axial stress component as a function of crystal radius (a) for σ polarized laser 1053 nm (b) for π polarized laser 1047 nm

The thermal stress components are studied for different crystal length for and polarized using Eq. 9 as shown in **Figures 3-5**.

It is found that the stress distribution profile is parabolic for all the three compounds. The center of the rod is under compression (negative value) while the surface of the rod is under tension (positive value). The stress component is affected by the crystal length while it decreases when the crystal length increases; the stress distribution of σ polarized 1053 nm is less than π polarized 1047 nm.

CONCLUSION

The numerical calculation in the present work has produced some exact results, which have classified the importance of thermo-optic effect for Nd: YLF crystal. When the crystal length is increased, the radial temperature begins convergence in values, furthermore, the temperature at the center of rod decreases. The center of rod under compression, the radial stress component vanishes at the rod surface, and the tangential and axial stress component had the same magnitude on the pumped rod surface reaching a maximum value. Also, the results are showing that thermal stress effects of π polarized is stronger than σ polarized.

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