Thermal behavior in Highly Efficient pulse Nd: YAG Laser pump chamber using Yellow ceramic Reflector

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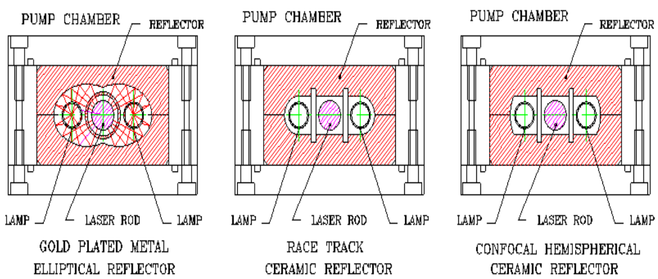
Abstract –We report the study on development of high efficient long pulse double flash lamp pumped Nd: YAG rod laser of 1.1% doping concentration. In pulse Nd: YAG laser system thermal behavior is controlled by transient heat flow. Theoretical and experimental investigations have been performed and the results are reported in terms of thermal lensing effect caused by radial thermal gradients present in the optically pumped system in the Nd: YAG laser rod. The results show that in Nd: YAG rod under lamp pumping behaves as negative lens at single shot operation and behaves as a positive lens when it pumping in repetitive mode. The temperature of laser rod be stabilized or go in thermal run-away condition when the repletion rate increases together with the high pulse energy. We also compare the 1.1% doping Nd: YAG laser rod of with Nd: Ceramic laser rod of 2% Nd atoms doping for high power laser generation. The thermal lensing effects depend on the refractive indices of laser rod materials and the temperature distribution inside the rod. Another crucial parameter is the thermal stress generated due to temperature gradient present in the rod during heating by the pumping.

1. INTRODUCTION

In recent years, high power solid state Nd: YAG lasers are widely applied for various industrial applications such as laser cutting in air and under water environments, drilling, grooving surface cleaning, sheet metal template cutting, sheet metal welding, thick materials welding, bi- materials welding and many more application in medical as well as automobile industries. These days, long pulse Nd: YAG laser is used in dismantling and construction in shipping and nuclear industries. The Nd: YAG laser can be transported through laser optical fiber without loss of energy, so this laser can be used for remote and narrow passage/gap area. The quality of laser cutting and welding is very good and fast. These processes can be automated so that they can be used in all the industries where quality and accuracy are very important. Some of the examples are pacemaker shell welding, Breachy therapy capsule welding and auto car body sheet profile cutting and welding. The long pulse Nd: YAG laser provides certain advantages over CW lasers for laser cutting such as lower thermal distortion and minimum heat affected zone in the cut materials. The long pulse laser pumped by flash lamps has more potential than the diode laser, since the high peak power operation in laser diodes in millisecond regime is restricted due to thermal run away problem. Further, flash lamps are much more rugged and cost effective over diode pumped lasers in industrial environments.

During the past year, a lot of work has been done to improve the performance of lamp pumped long pulse Nd: YAG laser systems in terms of high output energy and power with good beam quality which can be coupled and transported through optical fiber, with high slope efficiency. Long pulse Nd: YAG laser of 2.2 kW average power and pulse energy of 60 Joule has been demonstrated by Menghua Jiang [1] et al. in their work. They showed an electrical to laser conversion efficiency of 3.49% for input pump power of 58 kW. They used Xenon filled flash lamp pumped laser chamber. XueSheng Liu [2] et al. had demonstrated a Krypton lamp-pumped Nd: YAG laser delivered 80 Joule energy in 10 msec. pulse duration with a slope efficiency of 3.3%. In this experiment, they used gold plated reflectors. Amber choubey [3] et al. demonstrated 520-watt average power of long pulse energy using 1.1% doped Nd: YAG rod laser of slope efficiency of 5.4%, However, most of the commercially available fiber coupled lamp pumped long pulse Nd: YAG lasers provides maximum pulse energy in the range of 50 J-150 J, with the maximum slope efficiency of 4-4.5% with the limited pulse repetition rate and energy.

In our design of the pump chamber, the reflector used for optical pumping is yellow glazed alumina ceramic reflector. The laser pulse duration can have varied from 2-40 msec. and repetition rate from 1 to 100 Hz. Parameters like thermal lensing, coolant water flow rate, thermal behavior and resonator stability were optimized to achieve higher slope efficiency. A laser maximum output energy of 380 Joule @ 40 msec. pulse width. The maximum output average power 680 Watt has been achieved with slope efficiency of 6.85%.



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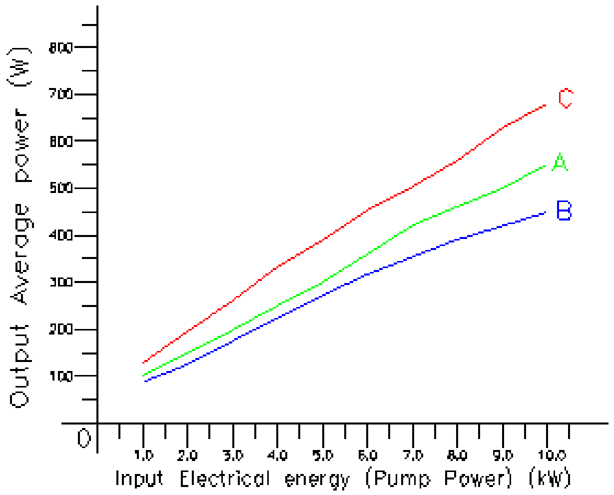
Cross section of the laser cavities, investigated experimentally

(A). Double Elliptical cavity (Gold Plated) EC 1, a = 14, e = 0.5, cavity length l = 140; ή= 5.5% [6]
(b). Double Racetrack cavity (White Ceramic) RTC 2, c= 14, l = 140; ή= 4.5%
(c). Double Hemispherical cavity (Yellow Ceramic) HRC 3, C = 13, cavity length l = 140; ή= 6.8%
(Dimensions are in mm).



Slope Efficiency curve of different geometry measured

2. THEORY

Wall Plug Efficiency: The wall-plug efficiency of a laser system is its total electrical-to-optical power efficiency, i.e., the ratio of optical output power to consumed electrical input power. [4]

CW:-Continuous-wave operation of laser means that the energy pumping continuously to active medium and its continuously emits laser light.

Birefringence is the optical property of a material having a refractive index that depends on the polarization and propagation direction of light. When the refractive index changes the divergence of laser beam changes. These optically anisotropic materials are said to be **birefringent** (or birefractive).[4]

Slope efficiency: The slope efficiency is an important property of a laser. It is obtained by plotting the laser output power against the input pump power. Above the lasing threshold, the resulting curve is usually close to a straight line. The **slope efficiency** is the **slope** of this line. [4]

For the cylindrical rod with optical pumping of fixed energy and repetition rate, photons are uniformly absorbed in the volume of the laser rod known as volumetric heating.

Right combination of volumetric heating from outer circular boundary and surface cooling are required for heat management. The heat extraction leads to a non-uniform radial temperature distribution in the rod. The effect of non-uniform heating of the laser rod manifests in thermal lensing and thermal stress to give rise to induce birefringence (the beam quality of photon resonate in resonator is non-uniformity which give more divergence of laser beam). An additional issue associated with thermal loading is stress fracture of laser rod. The stress fracture occurs when the stress induced by temperature gradient in the laser rod exceeds the tensile strength of laser rod. The stress-fracture limit is given in terms of maximum power per unit length heat dissipated in the laser rod. In this condition the general heat transfer equation is

$$\left(\frac{d2T}{dr2}\right)+\left(\frac{1}{r}\right)\left(\frac{dT}{dr}\right)+Q/K=0 \quad \text{eq. (1) [4]}$$

By solving this equation

$$T(r) = T(r_0) + Q/4K\,(r_0^2 - r^2) \quad [4] \qquad \text{eq. (2)}$$

And total energy dissipated per unit volume are

$$Q = P_h / \pi r_0^2 l.$$

Where Q = heat dissipated per unit volume, P_h = Total heat dissipated in rod,

r_0 = radius of rod, r = radius, T(r) = Temp. at radius r.
$T(r_0)$ = Temperature at surface of the rod.
$T_{(0)} - T_{(r0)} = P_h / 4\pi K l$, or $P_h = 4\pi K l \{ T_{(0)} - T_{(r0)} \}$

This is the total heat produced (absorbed) in the laser rod and the heat removed from
The rod from the surface of rod

$$P_h = 2\pi.\, r_0.l.h.\, \{T_{(r0)} - T_F\}$$

Where h = surface heat transfers coefficients. W/m.

K, T_F = Coolant temperature,

Suppose surface cooling area is $A = 2\pi r_0 l$. cm^2
So by all above equation

$$T_{(r0)} = T_F + P_h\,(1/4\pi K l + 1/Ah)$$

By the conventional method for surface heat transfer equation is

$$h = 0.023\,\{K/(D_2 - D_1)\}\,(N_{Re})^{0.8}\,(N_{pr})^{0.33}\,(D_2/D_1)^{0.53} \; [5]$$

$(W/cm^2 K)$, eq. (2)

Where D_1 =inner diameter of flow tube D_1= rod diameter,
N_{Re} = Reynolds's Number = $\rho (D_2- D_1).V/\mu$,
ρ = density of coolant, μ = Viscosity of coolant
V = coolant speed in cm/sec = Q/A
(Area of water flow) = $4Q / (D_2^2- D_1^2)$
N_{pr} = Prandtl Number = Cp μ/K,
Where Cp = specific heat of coolant,
K= thermal conductivity
So for the Nd: YAG rod as active medium and coolant as DM water

The surface heat transfer equation are modified as given below

$$h = 10.47 \times 10^{-3} \{(D_2/D_1)^{0.53} / (D_2-D_1) (D_2+D_1)^{0.8}\}.fr^{0.8} \quad (W/cm^2K), [5]$$

Where fr = flow rate cm^3/sec

The Nd: YAG rod having diameter 10mm x 150mm length and doping 1.1% of Nd atoms.

The thermal shock parameter is the stress generated by thermal elongation. Thermal shock parameter is defined as the stress generated due to the non-uniform thermal coefficient of expansion caused by the stress produce in the laser rod. This is given below: -

$$6_{max} = \frac{2\alpha E}{3(1-\nu)} \Delta T = \frac{2\alpha E d2}{12(1-\nu)K} Q \ [4]$$

Or we can say that $\Delta T_{max} = \frac{3Rs}{2K}$ [4]

$$\Delta T_{max} = 3 \times 7.9 /2 \times 0.052 = 227.88\ ^0C$$

By the experiments the thermal focal length at the pumping of 10 kW, F = 3.15cm

r = 0.5 cm, $dN/dT = 6.5 \times 10^{-6}$, $\alpha = 7.9 \times 10^{-6}$,
l = 15 cm, n_o = 1.82
$\Delta T = 382.29\ ^0C$

(This is by experimental measured focal length at highest input power and calculated.)

$$\Delta T_{max} = 529.289-147.126 = 382^0C$$

(This is by analyzed and calculated on ANSYS program.)

$$\Delta T_{max} = 3 \times 7.9 /2 \times 0.052 = 227.88\ ^0C$$

(This value is calculated by the laser rod properties.)

3. The parameter measured during experiments: -

1) Water flow rate = 80 LPM =80/60= 4/3 Kg/sec or 1333.3cm^3/sec.
   Water inlet temperature T_F=23 ^0C

This flows in three parallel water flow channels as per design.

So the flow rates on the rod surface (through one channel only) are 1333.3/3,
f_r = 444.4 3cm^3/sec or 0.444 Kg/sec.

2) Diameter of rod D_1=1 cm. (restricted available in the manufacture size)
3) Water channel diameter is approx... D_2 = 1.47 cm. (restricted available in the manufacture size)
4) The power dissipated in the lamp are maximum 5000W, so the maximum heat
   Dissipated in the rod is 20% of total lamp input power ie. = 1000W

So the numerical calculation of the laser rod heat dissipation and temperature distribution are

$$h = 10.47 \times 10^{-3} \{(D_2/D_1)^{0.53} / (D_2-D_1) (D_2+D_1)^{0.8}\}.f_r^{0.8}\ W/cm^2\ K$$

$$h = 10.47 \times 10^{-3}[(1.47/1)^{0.53}/ (1.47-1) (1.47+1)^{0.8}] \times 444.4 = 1.74\ W/cm^2\ K$$

Area of cooling surface A = $2\pi rl$ = 2 x 3.14 x 0.5 x 15 = 47.1 cm^2
Volume of the rod V =$\pi r^2 l$ = 3.14 x 0.5^2 x 15 = 11.775 cm^3
Mass of rod m = ρ V =4.56 x 11.775 = 53.694 gm.
Specific heat 0.59 W/gm.K, Thermal conductivity = 0.14 W/cm K

$$T_{(0)} = T_F+ P_h (1/4\pi Kl + 1/Ah) = 23 + 1000(1/4 \times 3.14 \times 0.14 \times 15 + 1/1.74 \times 47.1) = 23 + 46.93 = 69.93\ ^0C$$

And the

$$T(r) = T (r_0) + (Q/4K) (r_0^2-r^2)$$ at r=0 means center of the rod

$$T_{(0)} = 69.93 + (1000/4 \times 0.14) (0.5^2) = 69.93 + 446.43 = 516.36\ ^0C \text{ at the center}$$

The duty cycle of the lamp pumped power are 10% only. In this condition the temperature difference between center and surface temperature are very high, which is crosses the thermal shock temperature difference, results show on the 1.1% doping Nd: YAG rod is break at this power rating.

The value of lamp power input are 10kW having pulse energy of 200 J of 2 msec. at 50 Hz.
Duty cycle 10%.

Nd: YAG rod of diameter 10mm length 150mm

Table -1:

S. No.	R (radius) cm. (r_0^2-r^2)		Q/4K	T_F (^{0}C)	T_R (^{0}C)
01	0.0	0.25	1785.72	69.93	516.36
02	0.1	0.24	1785.72	69.93	498.46
03	0.2	0.21	1785.72	69.93	444.93
04	0.3	0.16	1785.72	69.93	355.65
05	0.4	0.09	1785.72	69.93	230.62
06	0.5	0.0	1785.72	69.93	69.93

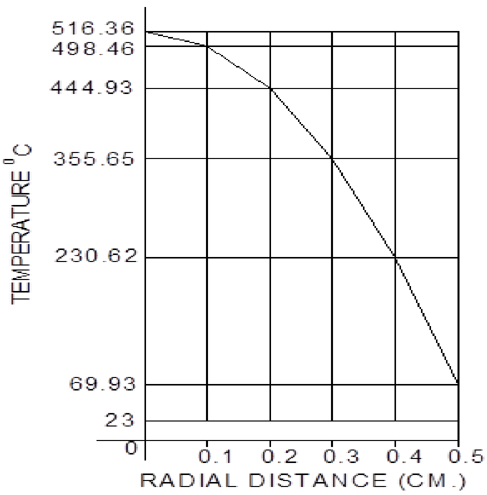


Fig: 1 Nd: YAG rod thermal profile

Nd: Ceramic rod of diameter 8mm length 150mm

Table- 2:

S. No.	R (radius) cm. (r_0^2-r^2)		Q/4K	T_F (^{0}C)	T_R (^{0}C)
01	0.0	0.16	1785.72	73.96	359.68
02	0.1	0.15	1785.72	73.96	341.82
03	0.2	0.12	1785.72	73.9	288.25
04	0.3	0.07	1785.72	73.96	198.96
05	0.4	0.0	1785.72	73.96	73.96

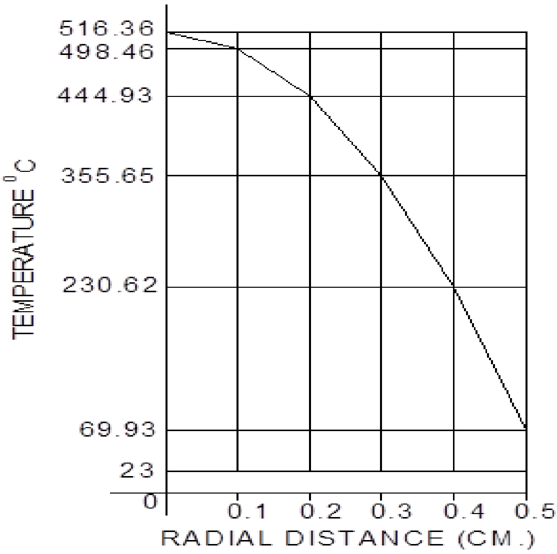


Fig: 2 Nd: Ceramic rod thermal profile

Figure 1&2: Temperature v/s time variation curve inside (center) the Nd: YAG rod crystal Temperature v/s time variation curve inside the laser rod crystal

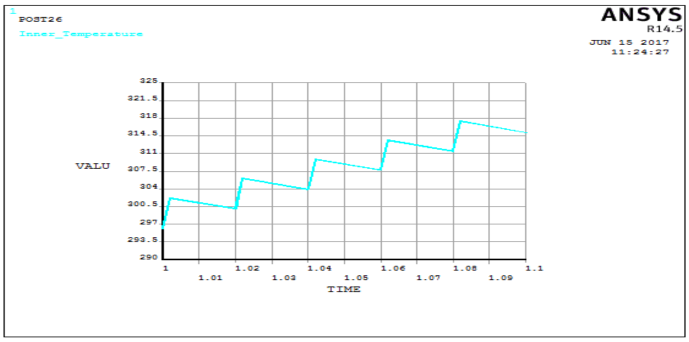


Fig: 3 Transient heat loads in laser rod

4. The thermal profile analysis on ANSYS software is given bellow:-

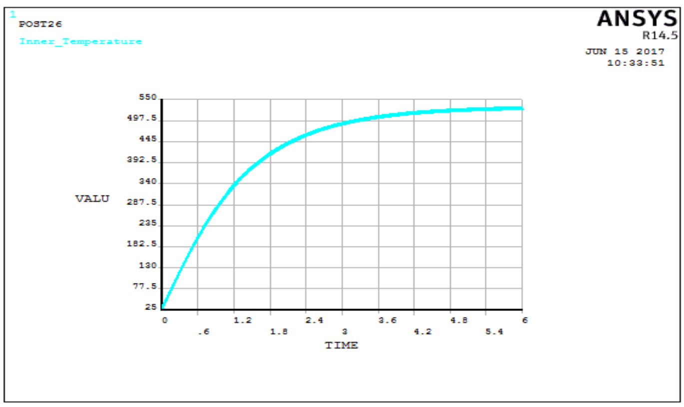


Fig: 4 Nd: YAG rod of diameter 10mm length 150mm

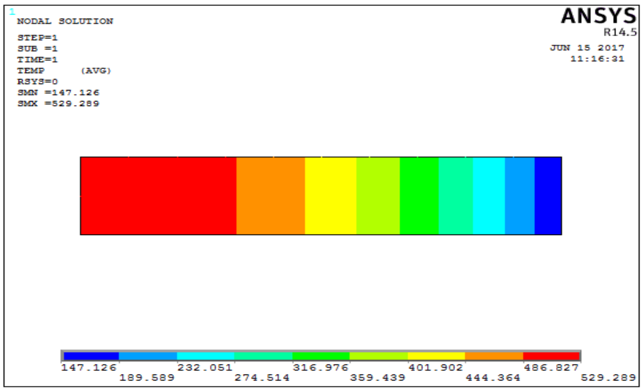


Fig: 5 Nd: YAG rod of diameter 10mm length 150mm

The value of lamp power input are 10kW having pulse energy of 200 J of 2 msec. at 50 Hz.
Duty cycle 10%.
This data calculated on ANSYS software for the Nd: Ceramic rod of diameter 8mm length 150mm.

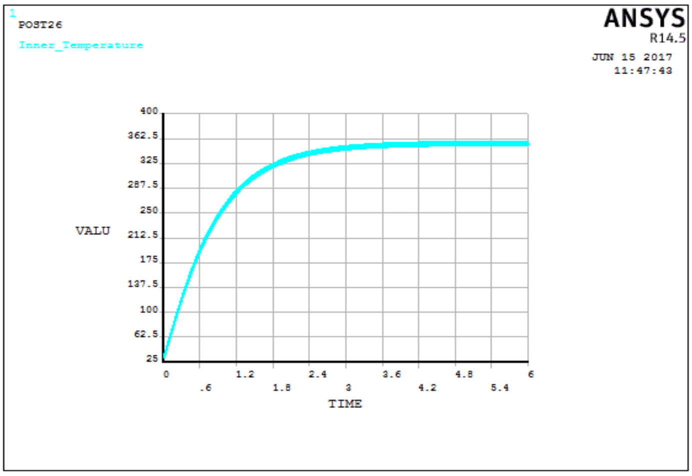


Fig: 6 Nd: Ceramic rod of diameter 8mm length 150mm

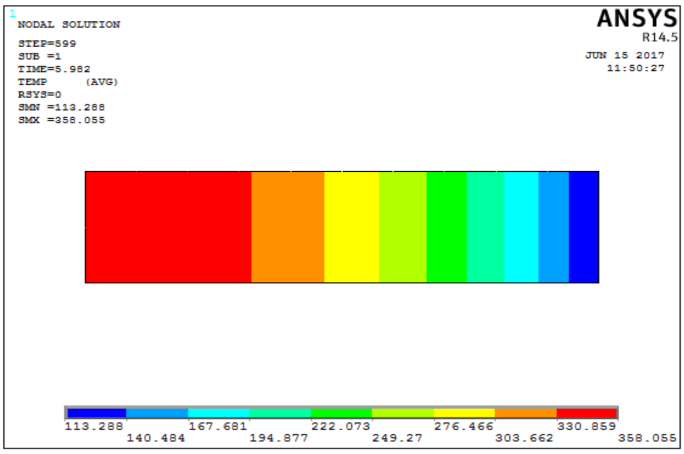


Fig: 7 Nd: Ceramic rod of diameter 8mm length 150mm

5. CONCLUSION

1. The new design of laser pump chamber is optimized for the high power laser system operation. It gives highest measured wall plug efficiency of 6.8%.
2. The doping concentration in YAG crystal is only1.1% of Nd in laser rod, therefore the number of Nd atoms per unit volume cannot be increased. For high power generation, more atoms required so more volume of the rod is required as results diameter of rod increases. However, the temperature gradient increases with increase in diameter, therefore the size of rod plays a crucial role in high power laser generation.
3. Thermal loading of rod in pulsed laser is very high. The temperature rise in center of rod can be considerably higher than that at the outer surface. This can cause fracture if the stresses cross the thermal fracture limit. This situation can arise easily if we select larger diameter rod to produce high pulse energy and run at high repletion rate i.e. more than 50 Hz frequencies.
4. The thermal time constant of the Nd-YAG laser is of the order of second whereas the pulse flat top duration is in a few milliseconds. Therefore, the temperature rise is inevitable pulse after pulse unless the ND: YAG rod is operated at low power and low repetition rate.
5. The more doped 2% Nd: Ceramic rod (Dia. = 8mm) is better than 1.1% Nd: YAG rod (Dia. = 10mm) as it gives more number of Nd atoms per unit volume. This facilitates use of a lower diameter rod. As a result, it can withstand higher repletion rate operation and it can also be pumped by high average power to produce the high laser power. The thermal fracture limit of Nd: Ceramic rod is also higher than that of Nd: YAG rod.
6. The yellow glazed diffused ceramic reflector with hemispherical geometry is very helpful in maximizing the optical pumping efficiency of laser system with respect to the previous white ceramic based reflector.

6. ACKNOWLEDGEMENT

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