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Simulation and Analysis of a High Power Diode-End-Pumped Nd:YVO_4 Solid-State Laser

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Abstract

Nd:YVO_4 is widely and commercially available laser material for diode-pumped lasers. Compared to Nd:YAG, Nd:YVO_4 has a larger stimulated emission cross-section, larger absorption coefficient and broader absorption bandwidth. It has lower threshold and its output power is less sensitive to the drifting of the diode pump wavelength. In this paper a Nd:YVO_4 crystal at 1064nm pumped with a high power diode laser at 808nm is modeled and simulated using LasCAD software tool package. These models investigate the optimum cavity design parameters (length of the cavity, output coupler reflectivity, the beam overlap key parameter and crystal dimensions). The geometry of the cavity is optimized to produce maximum TEM_{00} laser output, taking into consideration the thermal gradient on the rod structure. The cavity optimum configuration neglecting the insignificant effect of changing rod length was; 66mm in length, 90% of output coupler reflectivity. The pumping beam spot size affects on the laser output and the final optical conversion efficiency. Controlling the pumped spot size (w_g) to be equal the mode spot size (w_g) the maximum beam overlap efficiency and consequently the maximum optical slope efficiency with the highest laser output were achieved. The Nd:YVO_4 Crystal with dimension of (1-3mm) diameter and (7-10mm) length with 1% doping concentration (1at.%) is the suitable choice for the DEPSS (Diode End Pumped Solid State) laser configuration. A final optical conversion efficiency of 52% and a maximum slope efficiency of 54% were obtained. These results can be improved by rescaling the transfer efficiency to become around 90%.

1- Introduction :

Three decades of solid-state laser research have contributed to the development of a unique family of powerful photonic tools. Solid-state laser media, such as neodymium-doped crystal, is used in applications like laser fusion, material processing, optical communications, product marking, remote sensing and surgery [1-2].

In recent years; development in high power diode pumping contributed in a significant advancement in solid-state laser design, improvement and applicability. Optical pumping using a semiconductor laser diode instead of conventional flashlamp provides more efficient, reliable, stable laser o/p and compact all solid-state laser sources. In contrast to flashlamp pumping (the conventional method for generating a population inversion in solid-state gain media); excitation using a monochromatic and spatially coherent laser pump source offers lower threshold, higher o/p efficiency, reduction of thermal loading and improving the mode quality.

At the time; diode pumping was first proposed, semiconductor lasers were in their formative years, providing low powers (a few milliwatts); they were not competitive with flashlamps, until efficient high power AlGaAs laser diode became available in the mid-1980 [3-4]. Today; reliable one and two-dimensional laser diode arrays are commercially available with continuous-wave and quasi-cw peak powers up to 100W and 10kW respectively [5].

The output spectra of the first high power diodes are well matched to the absorption peak of neodymium ion ($\lambda \sim 800nm$) [4]. Development of these laser diode pump sources is ongoing with increasing output powers, increasing brightness and new wavelengths.

Simulation using LasCAD tool package provides complex engineering tools; developed on purpose for ease-of-operation. The graphical user interface of the program can be used like an optical work-bench on the PC, allowing intuitive design of laser resonators. In this way LasCAD helps users in laboratories and workshops process experimental results without wasting valuable time.

In this paper; a performance modeling of a diode single end pumped Nd:YVO_4 laser is presented in section (2); to investigate the dependency and inter-relation between the various design parameters. In section (3) the simulation tool was overviewed and the DPSS laser system setup was shown. In section (4) the optimization of the DPSS (Nd:YVO_4) Laser system design is discussed; these included; optimizing cavity design, optimizing system design by pumped beam waist size controlling and finally optimizing Nd:YVO_4 crystal dimension. In section (5) a discussion and results for the temperature effect on the Nd:YVO_4 crystal is simulated.

2- Performance modeling of a Diode End pumped Nd:YVO_4 laser :

In this section a performance model for Diode End Pumped Solid State (DEPSS) Nd:YVO_4 laser will be presented. That model will lead to a good estimate for the dependency and inter-relation between the various design parameters. This will help in optimization of the overall laser efficiency (maximizes system efficiency).

I. Nd:YVO_4 crystal parameters optimization :

For a high power-diode-pumped Nd:YVO_4 laser ; the relation between the output optical power (laser out from the DPSS system) and the input one (laser from the diode) can be described as [2], [6-7]

$$P_{out} = \sigma_{optical} \times P_{in} \qquad (1)$$

$$\sigma_{optical} = \eta_T \eta_A \eta_R \qquad (2)$$

Where P_{out} is the laser output power at 1064nm, P_{in} is the diode laser input power at 808nm, $\sigma_{optical}$ is the optical slope efficiency given by eqn. (2.2); as η_T is the transfer efficiency, η_A is the total absorption efficiency and η_R is the resonator efficiency.

The transfer efficiency is defined as the fraction of the laser pumping radiation leaving the laser diode source and intersects with the laser rod.

$$\eta_T = {}^{P_T}/_{P_{in}} \qquad (3)$$

Where P_T is the fraction of this radiation transferred into the laser active medium. Transfer efficiency can be controlled to get maximum efficiency by the design issues based on the geometrical shape of the pump cavity, these included; the rod diameter and separation of the pump source and laser rod, reflectivity of the laser rod's input face and finally the reflection losses at the coolant jacket.

In the case of end pumping solid state laser the radiation transfer is much simpler as the transfer system consists of antireflection lenses which collimating and focusing the pumping radiation to the laser crystal. Thus we can define the transfer efficiency in terms of reflection losses over all optics and active medium represented by the parameter (r).

$$\eta_T = (1 - r) \qquad (4)$$

Since in our case the laser crystal and optical components are all anti-reflection coated and the radiation transfer losses are very small ($r = 5 \sim 20\%$) [6-7].

The absorption of pumped radiation by the solid state active medium represented by η_A is defined as

$$\eta_A = \eta_a \times \eta_Q \times \eta_S \qquad (5)$$

Where

$$\eta_a = 1 - \exp(-\alpha L) \qquad (6)$$

$$\eta_s = \frac{\lambda_P}{\lambda_E} \qquad (7)$$

Where α the absorption coefficient of the Nd:YVO_4 crystal, L is the path length of the gain medium, η_Q is the quantum efficiency and η_S is the stokes shift factor (the ratio of the photon energy emitted at the laser transition to the energy of the pumped photons) and is given by eqn. (7); λ_P is the pumped laser wavelength (808nm) and λ_E is the emitted laser wavelength (1064nm).

Equation (6) is a good approximating formula that describes the relation between the absorption efficiency and the absorbed coefficient of the solid state active medium [7-8]. The higher absorbed coefficient makes it easier to obtain single longitudinal mode operation by using a short monolithic cavity and lead to a higher slope efficiency for the TEM_{00} mode [9].

The final efficient design parameter η_R was obtained by the multiplication of the two factors; the beam overlap efficiency (η_B) and the coupling efficiency (η_C).

Where η_B describes the spatial overlap between the resonator modes and the gain distribution in the gain medium, so in case of End-pumped laser; where the output beam from the diode laser is circulated and focused onto the gain medium; the perfect beam overlap is achieved.

The beam overlap efficiency can be expressed in terms of the beam profile spot size (w_B) and the pumped waist spot size (w_g) [1],[7],[10].

$$\eta_B = \frac{2w_B^2}{w_B^2 + w_g^2} \quad for\ w_g > w_B \quad (8)$$

And

$$\eta_B = 1 \qquad for\ w_g \le w_B \qquad (9)$$

Finally; the coupling efficiency is being considered as an indication to the reduction of the available output power due to losses in the resonator [2],[7].

$$\eta_C = \frac{T}{(l+T)} \qquad (10)$$

Where l is the round trip losses factor and T is the output coupler transmission factor.

II. The 808 nm pumped Nd^{3+}:YVO_4 modeling result :

A discussion for the end pumping solid state laser configuration advantages was clarified and the calculation for the overall Optical system efficiency according to the previous performance model were done. As the radiation from the high power laser diode module is focused on a small spot on the end of the Nd:YVO_4 laser rod with a suitable antireflection coated focusing optics. The laser diode module pump radiation can be adjusted to be coincident with the diameter of the resonator modes to produce a prefect overlap. The key parameter that determines the laser efficiency and the output power is the spatial overlap; it will be shown in section (4.II) that the size of the pump distribution with respect to size of the Gaussian laser mode is usually the most important factor that determines the TEM_{00} resonator mode and the maximum o/p power.

The end pumping configuration allows the maximum use of the energy from the laser diode; this configuration is the best manner of operation in producing fundamental spatial mode without entracavity apertures [7],[10].

In this work we will consider the configuration illustrated in figure (1).

Figure (1) is a Plano-concave resonator configuration with an anti-reflection coated i/p mirror at 808nm and high reflection coated at 1064nm and an o/p coupler with partially reflected coated at 1064nm.

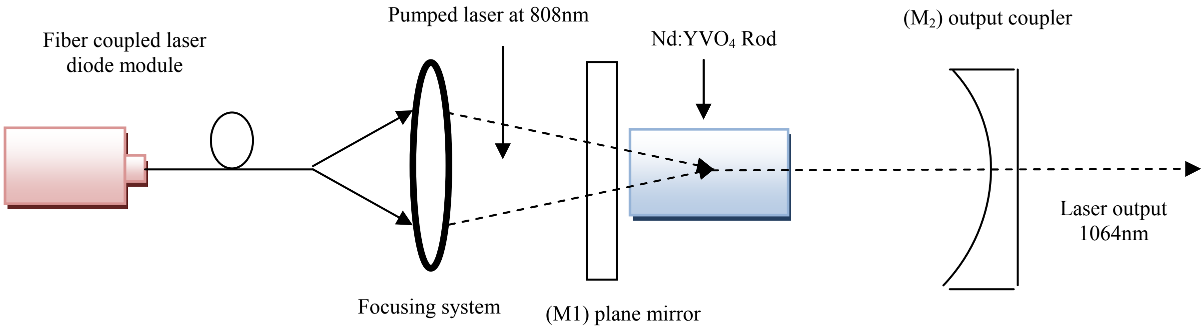


Figure (1) the DPSS Nd:YVO_4 laser with the a single End pumping configuration

The output from the laser diode module with a maximum of 7.8 cw watt at 808nm is collimated and focused onto 3mm diameter × 10 mm long of Nd:YVO_4 laser Rod with 1at.%.
The transfer efficiency η_T will be around 80-98% [2],[6-7] depending on the anti-reflection coating on the i/p mirror and the distance between the diode and the gain medium. The pump radiation will be absorbed according to the totally absorbed efficiency that determined before, where the absorption coefficient factor for the Nd:YVO_4 (1at.%) crystal is equal to 31.4 cm^{-1} [11], $\eta_Q = 0.95$ [7][11], $\eta_s = 0.759$ producing total absorbed efficiency $\eta_A = 0.72$. By evaluating the beam overlap efficiency η_B in eqn. (9) and calculating η_C for an o/p coupler of 90% reflectance at 1064nm; one can calculated the Optical slope efficiency to be equal 48%[1], figure (2) shows the optical to optical power curve calculated through eqn. (1).
The attractive features of 808nm end pumped 1064nm Nd:YVO_4 is its very compact design, in addition to the high beam quality and efficiency as a result of the good overlap between the pumped region and the TEM_{00} laser mode.

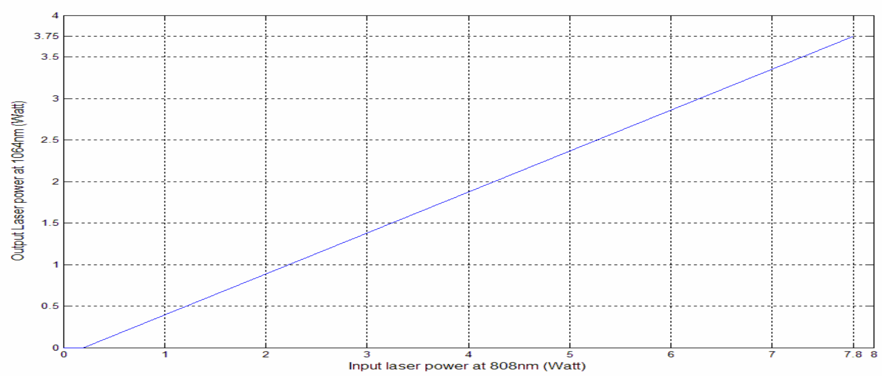


Figure (2) the calculated o/p laser power as a function of i/p laser one.

3- Simulation studies:
LasCAD software simulating tool package was use to simulate and analysis the setup shown in figure(1). LasCAD provides multiphysics analysis of the complicated interaction between thermal and optical fields in solid state lasers commonly known as thermal lensing effect. Modeling of this effect and its influence on beam quality, cavity stability and laser efficiency is essential for analysis and optimization of laser resonators.
In this section we will discussed the single end pumping configuration as a design issue using solid state Nd:YVO_4 rods with different dimensions and ideal two mirror resonator as shown in figure (1).

[1] We considered the worst case of the transfer efficiency to be 80% in case of end pumping configuration.

The Nd:YVO_4 crystal was pumped by a high power fiber coupled diode laser module at 808nm, with a maximum pumped power of 7.8 Watt, The pumped beam focused into the laser crystal had spot size of the beam waist around 150µm.
Nd:YVO_4 (a-cut) crystal (a1at.%) was used with different dimensions; to study the effect of:-

a. The rod length on the performing output power.
b. The rod geometrical dimension on the temperature gradients and the catastrophic face damage.
c. The variation of beam waist spot size Vs. output power.

The crystal was AR coated for wavelengths of 808nm and 1064nm; which are the absorbed and output laser wavelengths respectively. The input mirror (M1) was a flat mirror (HR) coated at 1064nm, (HT) coated at 808nm. The output coupler was (M2) a concave mirror with radius of curvature of (100mm); HR at 808nm with 10% transmission factor at 1064nm.

4- Optimizing DPSS (Nd:YVO_4) Laser system :

I. Optimizing Cavity design :

The interaction between thermal effect and optical system denoted by the thermal lens of the laser crystal, it is an important parameter for optimizing the laser system and performing the high power laser operation. When a fiber-coupled diode laser pumped Nd:YVO_4 solid state crystal in cw mode of operation, the resonator experienced a strong thermal lensing effect with Nd:YVO_4. The thermally induced focusing lens drove the laser resonator out of the stable regime.
In the absence of laser action; the thermal loading on the medium is strong because of the strong heat absorption within the material. Therefore, the thermally induced focusing lens of the material is stronger during non-lasing operation [12-13].
The main point is to determine the pump-induced thermal lens of the Nd:YVO_4 laser medium under lasing condition by using a diode laser pump. After the thermally induced focusing lens was identified, the resonator would be redesigned to achieve a stable laser oscillation. The effective focal length for the entire Nd:YVO_4 crystal is given by [1],[14].

$$f = \frac{\pi K_c W_g^2}{P_{ph}\left({dn}/{dT}\right)}\left(\frac{1}{1-e^{(-\alpha l)}}\right) \qquad (11)$$

Where P_{ph} is the fraction of the pumped power that results in heating and given by eqn. (12) [1].

$$P_{ph} = \left(1-\frac{\lambda_p}{\lambda_E}\right)P_{in} \qquad (12)$$

Where P_{in} is the input pumped power, λ_p and λ_E are the pumped and emitted laser wavelength as mentioned in section (2), l is the rod length, w_g is the spot size of the pumped beam waist (in this case w_g=150µm, but we will try a different size to observe the effect on the output power in section(4.II). Table (1) shows the optical and thermal parameters of Nd:YVO_4 1.0% doping concentration (a-cut) lasers.

Name	Symbol	Units	Typical Value
Atomic Density	N	Atoms/cm^3	$1.26x10^{20}$(Nd 1.0 at.%)
Peak Emission Wavelength	λ	nm	1064
Stimulated Emission Cross-Section	σ	cm^2	$25x10^{-19}$@1064
Fluorescent lifetime	τ	µs	90
Peak Absorption Coefficient	α	cm^{-1}	31.4@810
Refractive Index at 1064nm	n_a		2.17
Thermal Conductivity (300K)	K	W/(m.K)	5.10
Thermal Optical Coefficient (300K)	$^{dn}/_{dT}$	1/K	$2.9x10^{-6}$

Table (1) characteristics of the optical and thermal properties of Nd:YVO_4 1.0% doping concentration (a-cut) lasers [11].

Applying all these parameters in the first main equation (11); getting the effective focal length for the entire crystal equal to (6.65cm). The importance of this result is that the effective focal length of the required pumping rod actually comparable to the resonator length [2]. To verify this condition we simulated different cavity lengths with the same rod of dimension 3mm*10mm; with the same output coupler of reflectivity of 90% at 1064nm; considering the previous worst case of the transfer efficiency η_T to be 80%[2]. The simulation results are summarized in figure (3).

Figure (3) shows the dependence of the output laser power on the designed cavity length; getting the maximum output power (3.965W) denoted by solid curve at the cavity length of 66mm with an optical conversion efficiency of 51% and maximum slop efficiency of (54%). This result is in a good agreement with the previously calculated one in section (2).

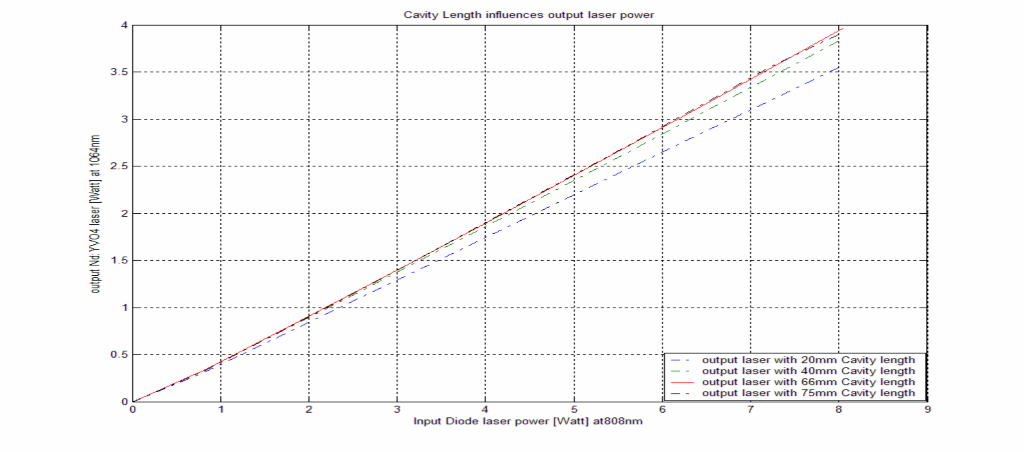


Figure (3) the effect of the cavity length design on the Extract output laser; solid red line was the highest slope efficiency with a maximum extracting laser output up to 3.965 Watt.

We notice that; cavity length above 75mm bringing the resonator to unstable condition; figure (4) shows the stability diagram for each simulated case using LasCAD simulating tool package.

[2] Transfer efficiency is not an accurate measuring quantity so we toke the worst percentage in case of end pumping system.

II. Optimizing System design by controlling the pumped beam waist :

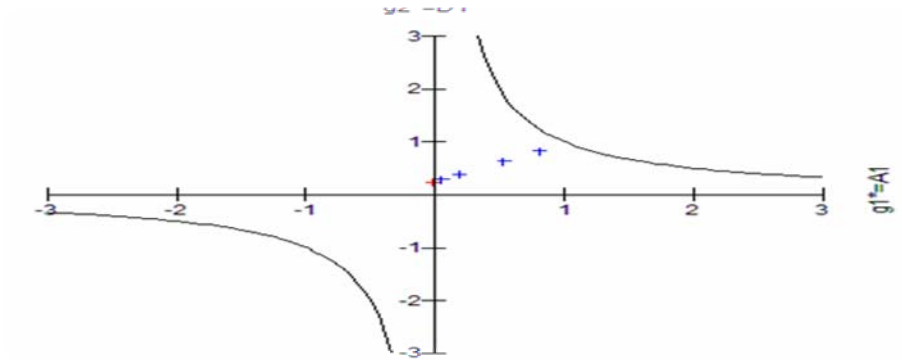


Figure (4) the stability realization of the Nd:YVO_4 designed cavity with (20,40,66 and 75mm) in length (from right to left) and shows the unstable case at the cavity total length above 75mm denoted by the extreme lift cross.

As mentioned before the resonator length considered to be an important factor in the end pumping design issues. It depends on the square input beam radius of the waist spot size and independent on the rod length.

So the only parameter that can optimize our cavity design is the input beam waist which maximizes the performance of the output laser (1064nm) at the given pumped power. As proved before in section (2) the beam overlap efficiency is the most important parameter.

In end Pumping solid state laser controlling w_g achieved the benefits of the TEM_{00} with extracting maximum possible output power. The ratio between w_B and w_g affects the DPSS laser system performance output, this will be simulated using LasCAD software package.

By simulating a diode end pumped Nd:YVO_4 (1at.%) with variation in w_g (pumped waist spot size) at the same crystal dimension 3*10mm and output coupler of 90% reflectivity at 1064nm; the importance of this ratio can be shown.

Figure (5) shows the effect of the ratio between the mode spot size w_B and the controlled w_g on the extracted laser power at 1064nm.

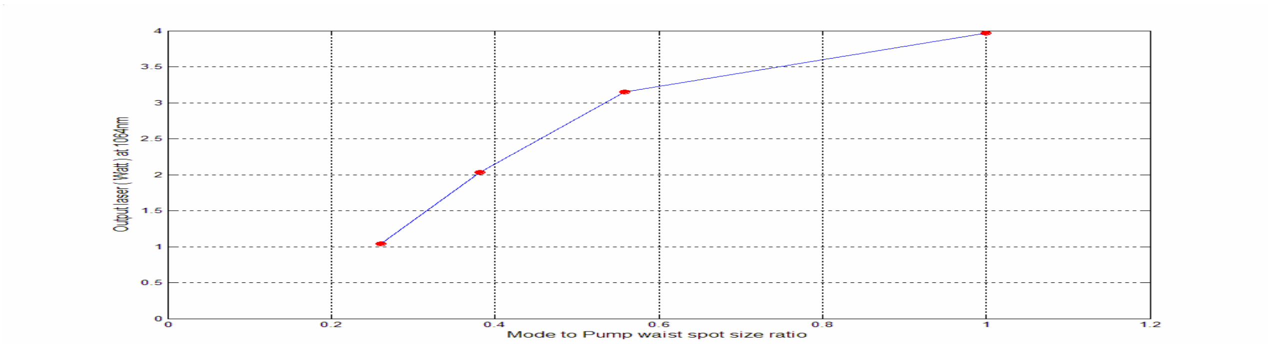


Figure (5) simulated results of the laser output Vs. the mode to pumped beam waist spot size ratio.

From figure (5) and our previous performance analysis work in section (2); the ratio between w_B and w_g can now show its effect on the system output performance; as the maximum output power (3.965W) can be extracted when this ratio exactly equal to 1.0 ($w_B \approx w_g \approx 150\mu m$). As this ratio became smaller than 1.0; the performance laser output would be affected by; and the extracted power will be much less than expected (case of $\eta_B < 1$); this effect is shown at a given w_g = 250, 350 and 500µm.

From the above figure the effect of the mode to pump ratio on the output laser power fulfilled the great importance of the beam overlap efficiency.

III. Optimizing Nd:YVO_4 Crystal geometry :

In this work; we will investigate the effect of changing the crystal geometry on the extracting laser o/p. First we simulated Nd:YVO_4 crystal with different lengths.
Figure (6) shows the laser output power (Watt) Vs. different crystal lengths (2, 4, 7, 10 and 15mm). It illustrates the independency of the laser output on changing rod length, moreover; increasing the length of the gain medium will produce insignificant changing in the extracting power; this change is inversely proportional to the rod length.

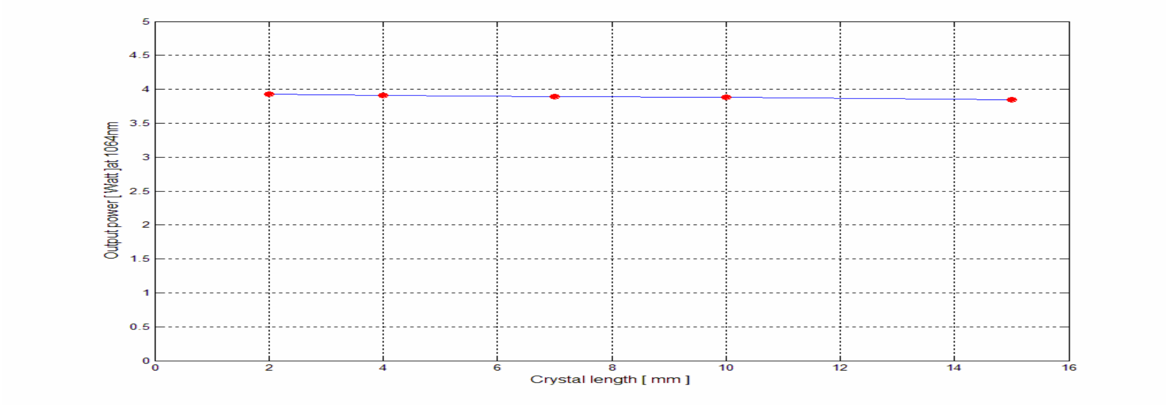
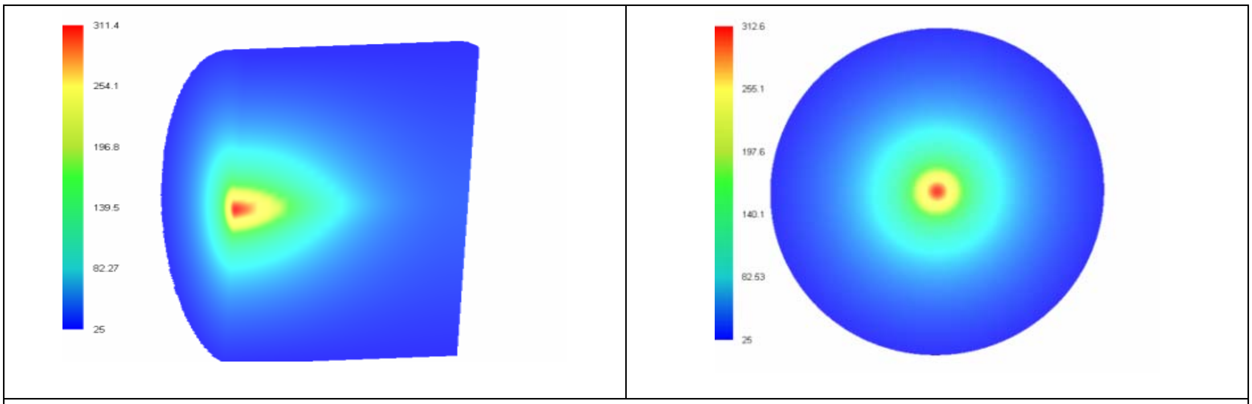


Figure (6) Laser output power Vs. Crystal length curve

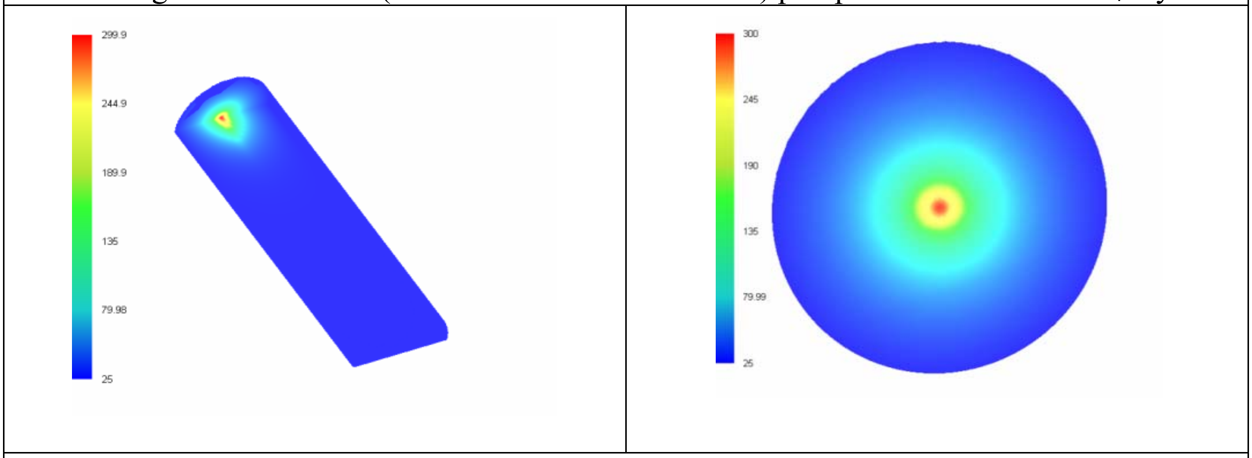
As mentioned in [7] and the previous performance analysis in section (2); the total absorption efficiency in case of end pumping solid state laser will be around 72% of the input 808nm laser disregarding to the rod length; so using the previous treatment made only 2mm length of Nd:YVO_4 crystal provided laser output power slightly higher than crystal of 15mm. Figure (6) illustrates the results of this study which was in an excellent agreement with the numerical model of the Nd:YVO_4 laser and its calculated results in[9].

5- Temperature effect on the solid state crystal (thermal fracture):

From the most recent researches in DPSS lasers and especially in case of end pumping process; progress in scaling the output power while maintaining operation in the TEM_{00} mode is limited by the formation of an aberrated thermal lens within the active medium [15], moreover; the maximum input pump power is restricted by thermal fracture of laser crystal [16].
Since a large amount of thermal energy converted from the absorbed pump power is accumulated near the pump region of the end pumped geometry; so the temperature distribution inside the laser crystal became gradually more serious as the pump power increases. The maximum output power for DEPSS laser is fundamentally limited by thermal fracture of laser crystals [7]. Moreover; it is so difficult to reduce thermal stress in an end-pumped geometry compared to side-pumped one. Therefore, it is important to simulate the temperature gradient on the front face and inside the pumped Nd:YVO_4 crystal to avoid thermally induced fracture and evaluate the maximum pumped power.
Figure (7) shows the simulated results of two rods of different dimensions (3*2mm and 3*10mm). It illustrates the thermal gradient on the front face and inside the Nd:YVO_4 crystal. The results show a central maximum temperature of 312^{o}C and 300^{o}C for the first and the second rod respectively (other cavity parameters considered to be constant values with 7.8 W cw laser input power).



Thermal gradient for 7.8W(focused on the front rod face) pumped 3*2mm Nd:YVO_4 crystal

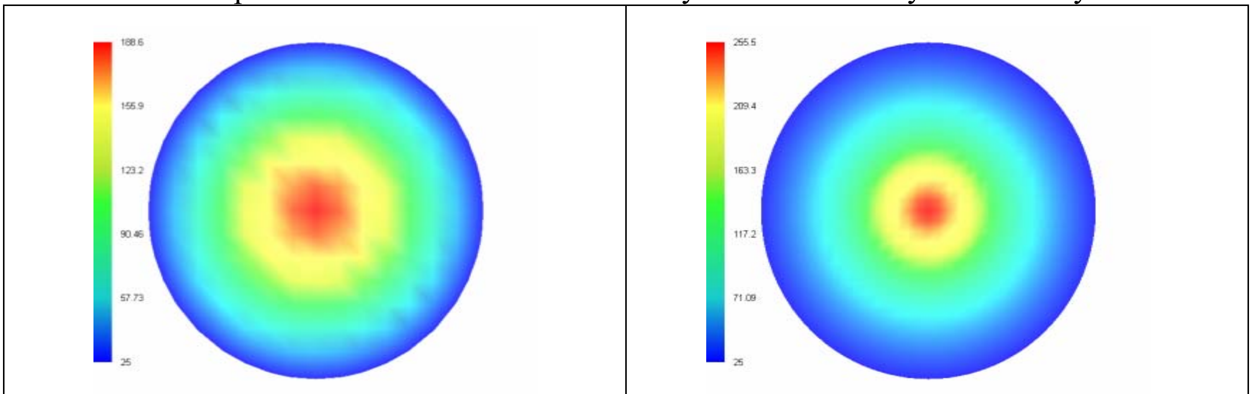


Thermal gradient for 7.8W(focused on the front rod face) pumped 3*10mm Nd:YVO4 crystal

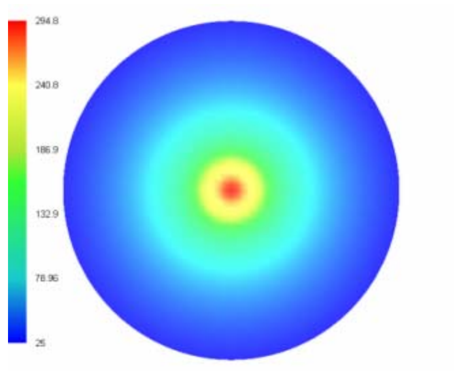
Fig.(7) The Temperature gradient within two different Nd:YVO_4 dimensional rod length

This simulation was deliberated to confirm that; the longer crystal is useful in heat removal, but it increases the intacavity absorption losses as shown in figure (6).

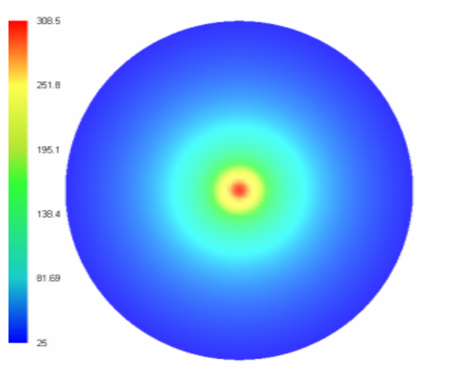
The temperature gradient is also affected by The radial change of the crystal diameter; simulating Nd:YVO_4 with different rod diameter is strongly recommended, figure(8) illustrated this important effect; as the crystal diameter became smaller the minimum storage temperature case is obtained; this is because the deposited heat can be more effectively removed radially from the crystal.



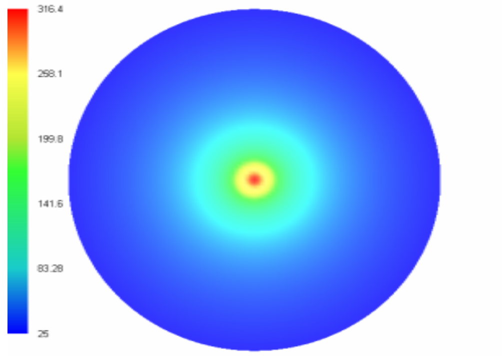
Nd:YVO_4 Crystal with dimension of 0.5*10mm and central temp. of 188^{o}C	Nd:YVO_4 Crystal with dimension of 1*10mm and central temp. of 255^{o}C



$Nd:YVO_4$ Crystal with dimension of 2*10mm and central temp. of 295°C



$Nd:YVO_4$ Crystal with dimension of 3*10mm and central temp. 308°C



$Nd:YVO_4$ Crystal with dimension of 4*10mm and central temp. 316°C

Figure (8) the simulating results of the temperature gradient through radial change of the $Nd:YVO_4$ crystal diameter

These simulated results manifested the reason of increasing the fracture limit as the crystal diameter became smaller as shown in figure (9).

Figure (9) shows the maximum pumped power (W) Vs. the crystal width (mm); it clarifies that more pumping power can be tolerated with smaller radial diameter.

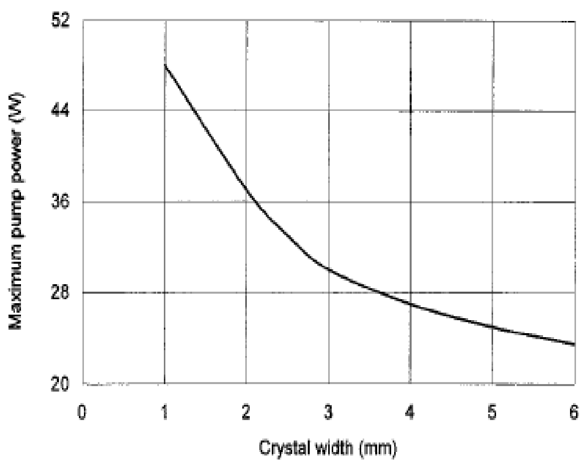


Fig.(9) The Calculated fracture limited pump power as function of crystal $Nd:YVO_4$ width [9].

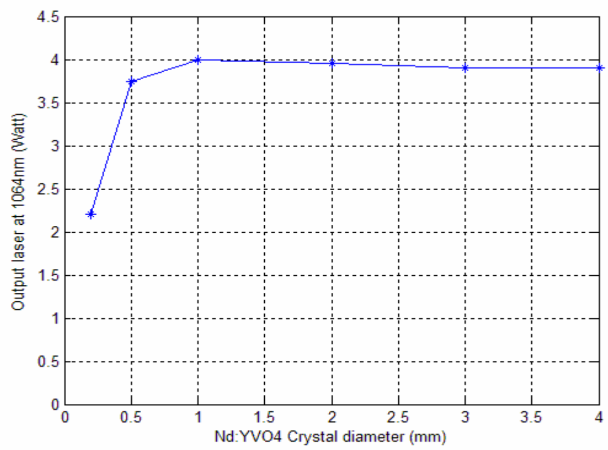


Fig.(10) the simulating results of the laser o/p power (W) Vs. crystal diameter (mm)

Figure (10) shows the effect of the crystal radial changing on the laser output; these simulated results were in excellent agreement with the numerical solution given by [9].
Figure (10) illustrates that Nd:YVO_4 rod with dimension of 1*10 mm is the suitable choice with 1at.% of doping percentage; getting maximum output power 4.03 Watt with 52% of the optical conversion efficiency[3] and maximum optical to optical slope efficiency of 54%.

6- Conclusion

The DPSS Nd:YVO_4 Laser was simulated using LasCAD and its performance was analyzed. Nd:YVO_4 crystal with dimension of (1-3mm) diameter and (7-10mm) length with 1at.% doping percentage is optimized to achieve the highest o/p performance at 1064nm (optical slope efficiency). This is done through DEPSS of a plano-concave cavity configuration with an optimized 66mm length. The spot size of the pumping beam was optimized to achieve the maximum o/p power as the mode to pumped spot size ratio equal to 1 ($w_B = w_g$) producing maximum beam overlap efficiency and consequently maximum optical to optical slope efficiency with the highest final laser output. The analysis of the thermal gradient on the rod enabled the suitable choice of the crystal dimension.
Final optical conversion efficiency around 52% and maximum slope efficiency around 54% were obtained at the transfer efficiency of the pumped beam of 80%.

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[3] These results were simulated at 80% of the transfer efficiency.