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Theoretical Investigations of High Power Yb^{3+}: YAG Thin-Disk Laser

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Abstract

The present study includes a theoretical treatment to derive the general equations of pumping threshold power (P_{pump}^{th}), laser output power (P_{out}), and laser device efficiency (η) of the element-doped thin-disk laser (Yb^{3+}) with a quasi-three-level pumping scheme in the continuous wave mode at a temperature of (299K°). In this study, the host crystals (YAG) were selected as typical examples of this laser design in a Gaussian transverse mode. The numerical solution of these equations was made using Matlab software by selecting the basic parameters from the recently published scientific articles for the laser design of these crystal hosts. According to this simulation, this article studied the effect of concentration (N), pumping spot radius (r_p), the number of times the pumping beam passes over the disk (M_p), and the pumping power on the laser output power.

Keywords: pumping power, quasi-three-level, Yb: YAG, wave Continuous

1. Introduction

One of the successful designs of high-energy thin-disc lasers is based on Ytterbium-doped YAG because of its high efficiency and beam quality. One disc can give a laser power of (1) kilowatts [1]. Thin disk lasers mostly consist of a Yb-doped YAG disk with a thickness ranged from 100 µm to several hundreds of µm [2].

Depending on the obtained energy, the diameter of this disk ranges from few millimeters to few centimeters. There are different techniques to join the disk to the heat sink (usually water) where alternative supporting structures are used [2].

The heat sink is a technical necessity in thin-disk installation because of high density of heat energy. This heat sink significantly improves the thermal lens behavior and makes it small and typical for disk lasers [2].

The gain medium in diode-pumped solid-state lasers is in the shape of thin disk, and its axial dimensions are very small compared to the cross-section and back surface mounted on the heat sink. This surface also acts as one of the laser mirrors, and this is another advantage, and through the axial length of the laser, the heat is removed very efficiently because the cooling surface is large compared to the size [1].

Also, we can get a laser by a simple resonator in this lasing design because there is no transverse heat flux in the gain medium. Consequently, the thermal lens is small, so the laser works with excellent beam quality [3]. The absorption of the pumping beam depends on the thickness of the crystal and the doping concentration to ensure absorption efficiency and, thence, the efficiency of lasing light [1].

In high-energy laser, there must be a high balance between the parameters to obtain multiple passes through the disk, thus achieving multiple times pumping scheme [4]. The design of a thin-disc with quasi-three levels such as Yb: YAG requires high pumping intensity to overcome the threshold limit, where a laser can be obtained with the highest efficiency, but on other hand, it is difficult to operate due to the relatively high absorption because the minimum laser level is very close to the ground level at room temperature (299k$^{\circ}$) [5].

Also the concentration of Yb should be high, and the gain medium must be pumped with high pumping power along with low temperature of the crystal. This makes the absorption sufficient in the disk of a thickness (100-300 µm) [1]. The refractive index is an essential parameter in designing this type of laser, as it changes with the concentration of impurities and, therefore, must be considered [1].

When the active medium is pumped with pumping beams, the pumping beam of low brightness is converted into a laser beam of high brightness, governing the conversion efficiency of the second law of thermodynamics. This states that if the brightness increases, a part of the pumping power must be ejected into the environment. This part of the power called the quantum defect is the difference in energy between the pumping photon and the laser photon, and it comes out as heat. Therefore, most of the quantitative defects are the heat source inside the laser and thus lead to a dissimilar heat distribution in the gain medium, so the quality of the laser beam decreases [5].

But, what distinguishes the quasi-three-level Yb: YAG laser is that it has small quantum defects, but this does not mean that it should not be pumped strongly to obtain a laser emission at room temperature. Only two-electron states are contained in the Yb^{3+} ion: the excited state $^2F_{5/2}$ and the ground state $^2F_{7/2}$. However, the Stark effect divides the ground state into four sub-levels and the excited state into three. In the Yb: YAG laser, the pumping is at 940 nm, and the laser beam is at 1030 nm, showing a quantum defect of 8.7% [6].

2. Materials and Methods

2.1. Analytical model

2.1.1. Boltzmann occupation factors

The energy level of Yb: YAG in our model (see **Figure 1)** can be described as two-fold system, with the ground $^2F_{7/2}$ divided into four levels and the excitation state $^2F_{5/2}$ divided into three levels. The laser and pumping states lie within small spaced manifolds with groups, N1 and N2 lie the laser and pumping states [7].

The population of each state within a manifold is described By Boltzmann occupation factors assuming that the population is moved to a level thermally redistributed in a short time via phonon interactions given by [6]:

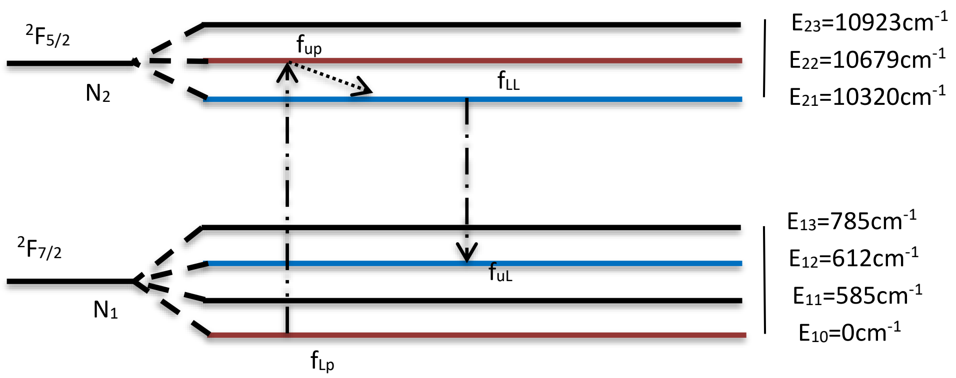

Figure 1. Illustrates the energy levels of a (Yb: YAG) crystal, $^2F_{7/2}$ ground state, and $^2F_{5/2}$ excited state.

$$f_{Lp} = \frac{e^{-\frac{E_{10}}{KT}}}{\sum_{i=1}^{4} e^{\frac{E_i}{KT}}} \tag{1}$$

$$f_{up} = \frac{e^{-\frac{E_{22}}{KT}}}{A\sum_{i=1}^{4} e^{\frac{E_i}{KT}}} \tag{2}$$

$$f_{LL} = \frac{e^{-\frac{E_{21}}{KT}}}{\sum_{i=1}^{3} e^{\frac{E_j}{KT}}} \tag{3}$$

$$f_{uL} = \frac{e^{-\frac{E_{12}}{KT}}}{\sum_{i=1}^{3} e^{\frac{E_j}{KT}}} \tag{4}$$

Where (f_{up}) and (f_{Lp}) are the thermal Boltzman factor in the lower and upper laser levels at pumping, respectively, (f_{uL}) and (f_{LL}) is the thermal Boltzman factor in the lower and upper laser levels at lasing, respectively, and (k) is the Boltzman constant (1.3806488*10-23 J/k^0).

2.1.2. Beam quality coefficient

In the Yb: YAG laser, due to the low direct quantum defect at room temperature (299k^0), the lowest laser level has a thermally induced population of about 4%[8]. But, this means an increase in the pumping power density threshold. This thermal array creates a soft aperture for the resonator modes. The beam quality is greatly improved due to this effect[9]. Weber and Hodgson suggested a functional equation that could be used to calculate the approximate beam quality [3]:

$$M^2 = K\frac{r_p}{r_0} \qquad (5)$$

Where ($r_0=0.7r_P$) if TEM_{00}

2.1.3. Steady-state equation for Yb: YAG

At wave mode continuous, the transient demeanor of the density of population of the excited state N_2 and the intra-cavity laser intensity I_L is described via[10]:-

$$\frac{dN_2}{dt} = \left[\,\sigma_{ap}N_t - \left(\sigma_{ap}+\sigma_{ep}\right)N_2\right] * \frac{I_p\eta_a\lambda_p}{\alpha_p dhc} + \left[\sigma_{aL}N_t - (\sigma_{aL}+\sigma_{eL})N_2\right] * \frac{I_L M_L \lambda_L}{hc} - \frac{N_2}{\tau} \qquad (6)$$

$$\frac{dI_L}{dt} = I_L M_L d\left[(\sigma_{aL+\sigma_{eL}})N_2 - \sigma_{aL}N_{2t}\right] * \frac{c}{2L} - \frac{I_L c}{2L}\left[-\ln(1-T) - \ln(1-\gamma)\right] \qquad (7)$$

$$N_t = N_1 - N_2 \qquad (8)$$

At $N_2=N_{2th}$

So

$$\therefore N_{2th} = \frac{I_{pth}\eta_a\lambda_p\tau}{dhc}$$

Where (λ_p) is the pump wavelength, (λ_L) is the laser wavelength, (τ) is the fluorescence lifetime of the upper manifold, (N_t) is the doping concentration, (T) is the transmission of the output coupler, (γ) is the internal loss of the resonator, (I_p) is the effective pump intensity, (d) is the thickness of thin disk, (c) is the velocity of electromagnetic waves in vacuum, (h) is Planck's constant, (σ_{ep}, σ_{eL}) are the dependence of the stimulated cross-section of pumping and lasing transition on wavelength, (σ_{ap}, σ_{aL}) are the dependence of the absorption cross-section of pumping and lasing transition on wavelength, (α_p) is the pump transition absorbance, (L) is the optical length of the resonator, (M_L) is the number of passes of the Laser beam in crystal per resonator round trip

And (A_{eff}) is the spot area of the pumping and is given by equation[11]: -

$$A_{eff} = \frac{\pi}{2}\omega_f^2$$

$P_p = A_{eff}\, I_p$

Where (I_p)is the Intensity of Pumping.

By replacing the threshold condition (N_2=N_{2th}, I_p=I_{pth}, and I_L=0) in eq. (6) the pump power at the threshold (Pth) can be qualified as [10]:

$$p_{pth} = I_{pth}\, A_{eff} \tag{9}$$

2.1.4. The efficiency of laser design

For each laser design, there is a pumping power, an output power, and an efficiency are [10]: -

$$P_{out} = \frac{T\eta_a\eta_s\,(p_p - p_{pth})}{[-\ln(1-T) - \ln(1-\gamma)]} \tag{10}$$

When the steady-state condition $\frac{dN_2}{dt} = 0$

(η_s) is the stokes efficiency, and (η_a) is the absorption efficiency

The efficiency can be defined as:

$$\eta = \frac{T}{\delta}\,\eta_a\,\eta_s \tag{11}$$

2.2. Numerical imulation

In this article, the Matlab program was used to find the numerical solution of the equations of pumping power at the threshold (P_{pump}^{th}) computed from equation (9), the laser output power (Pout) computed from equation (10), and the efficiency of the laser device that we are going to study (η) calculated from equation (11), at the wave mode continuous at temperature (299K^0)

The selected host crystal (YAG) is commonly used in Yb: thin-disk laser, **Table (1)** shows the values of parameters of (Yb: YAG) crystal to know the best laser output power for this crystal host. Giveg the high value of the pumping power at the threshold of this host, a range of pumping power (1150-25000) W was chosen to find out the effect of low and high pumping power on the laser output power in this host.

Table1.shows the value of parameters of (Yb: YAG) crystal.

parameter	value	unit
λ_p	$940*10^{-9}$	m
σ_{ap}	$0.737*10^{-24}$	m^2
σ_{ep}	$0.147*10^{-24}$	m^2
λ_L	$1030*10^{-9}$	m
σ_{aL}	$1.482*10^{-24}$	m^2
σ_{eL}	$0.079*10^{-24}$	m^2
N	$1.38*10^{26}$	Ion/m^3
Ti	$940*10^{-6}$	sec

3.Results

3.1. Concentration effect

Table (2) shows the concentration values, pumping threshold power, laser output power, as well as the amount of heat per unit volume. The laser output power changes with concentration at percentage with the stability of the other parameter at the ideal values. **Figure (2)** shows that the output power increases with increasing concentration until it reaches the highest value at 10% and then begins to decrease until it reaches the lowest value at 25%.

Table2. Shows the concentration values, pumping threshold power, output power, and Quantity of heat.

N at (%)	$N*10^{26}$ (ion/ms)	P_{th} w	Q $*10^{13}$
5	13.33	3.6479	1.6424
10	26.66	5.7479	1.6464
15	39.99	7.7080	1.6463
20	53.32	9.8702	1.6461
25	66.65	13.1178	1.6459

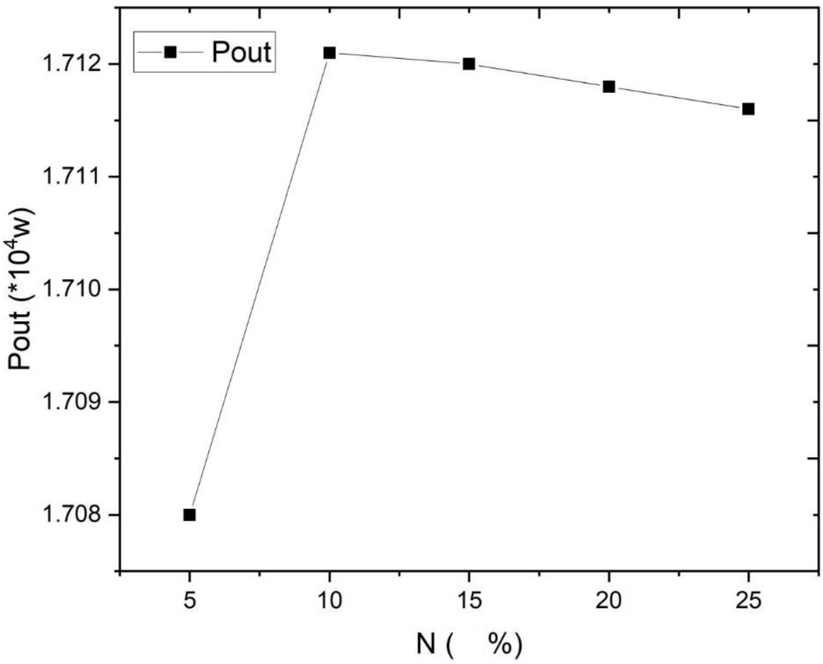

Figure 2. Illustrates the effect of concentration on the output power.

3.2. The effect of radius of pumping spot

Table (3) shows the change in the values of radius of pumping spot and the values of pumping spot power, which leads to a change in the laser output power. **Figure (3)** illustrates that the highest value of the laser output power is when the radius of pumping spot is as small as possible ($r_p=1*10^{-3}$m). Then, it decreases until it reaches the lowest value at ($r_p=4.6*10^{-3}$m). This means that the smaller the radius of the pumping spot, the higher the output power.

Table 3. Shows the values of the pumping spot radius, pumping threshold power, and output power

r_p *10^{-3}m	P_{th} w
1	5.7479
1.4	11.2660
1.8	18.6233
2.2	27.8200
2.6	38.8560
3	51.7314
3.4	66.4461
3.8	83.0002
4.2	101.3936
4.6	121.6263

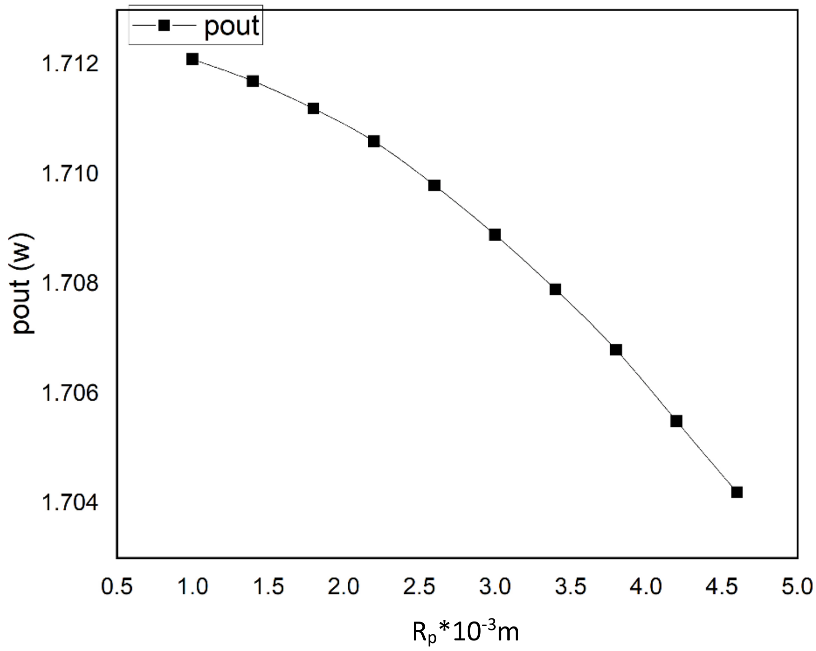

Figure 3. Illustrates the relationship between the radius of the pumping spot and the laser output power.

3.3. Effect of Number of Passes of Pump Beam.

The number of times the pumping beam passes through the crystal for thin disk (Mp) affects the output power. In **Table (3**), it can be seen that the change in the pumping power at the threshold changes the laser output power.

Figure (4) illustrates that the value of the output power increases with increasing (M_p) until it reaches (M_p = 40). The increase is slight until it reaches (M_p =64), where the value of the laser output power is constant.

Table4. Shows the value of (Mp), the pumping threshold power, and laser output power for (Yb: YAG).

M_p	P_{th} (w)
8	8.2293
16	6.3228
24	5.9099
32	5.7958
40	5.7623
48	5.7522
56	5.7492
64	5.7483
72	5.7480
80	5.7479

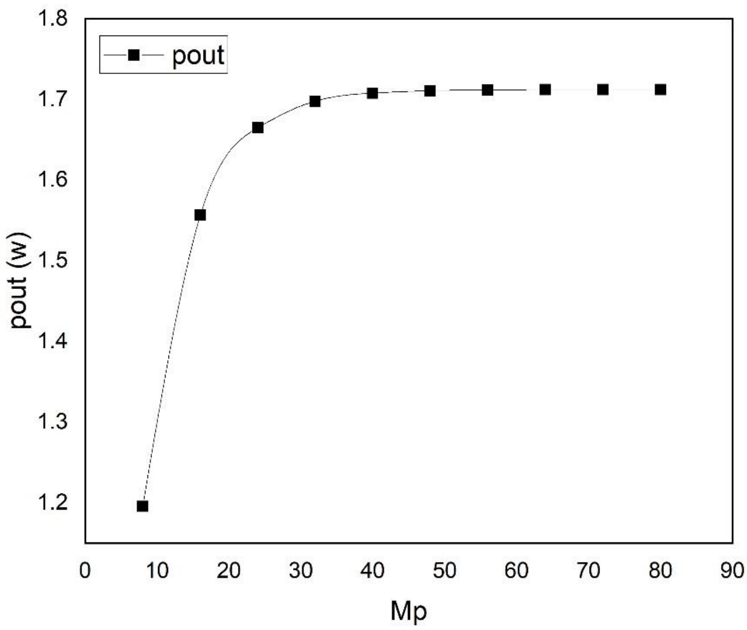

Figure 4. Illustrates the relationship between the value of (M_p) and the laser output power of (Yb: YAG).

3.4. The effect of pumping power

Table (5) shows the pumping power used in thin disk laser (Yb: YAG), and the laser output power for this design. **Figure (5)** shows the relationship between the output power and the pumping power. An increase in the pumping power leads to an increase in the output power. The highest value of the laser output power is at pumping power of 25000 W.

Table 5. Shows the values of the pumping power and laser output power of the thin disk laser for (Yb: YAG).

P_{pump}(w)	P_{out} (w)
1150	718
3800	2319
6450	4079
9100	5760
11750	7440
14400	9121
17050	10801
19700	12482
22350	14162
25000	15843

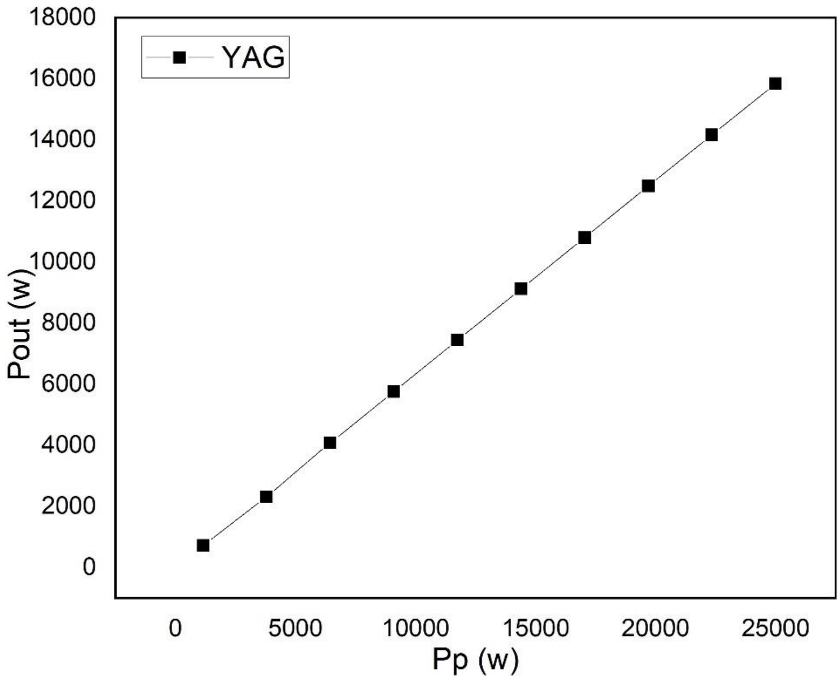

Figure 5. Shows the relationship between the pumping threshold power and the laser output power of the (Yb: YAG) thin-disk laser.

4. Discussion

The results of the numerical calculation of the laser output power increased. The results of the numerical calculation of the laser output power increased with increasing the doping concentration. They then began to decrease as the concentration increased, as the change in concentration affects the pumping ability at the threshold (P_{pump}^{th}) and the absorption efficiency (η_a) thus affects the output capacity.

The second parameter is the radius of the pumping spot in **Figure (3)**. Increasing the value of the radius of the pumping spot leads to an increase in the pumping power at the threshold (P_{pump}^{th}). This leads to a decrease in the laser output power and efficiency. We noticed a decrease in the laser output power with an increase in the radius of the pumping spot, and the highest value was at (rp = 1 * 10-3).

The third parameter is the number of times the pumping beam passes through the crystal **in Figure (4),** which shows an apparent increase in the output power and then it tends to stable with a negligible increase.

The last parameter is the pumping power, which increases the laser output power, as shown in **Figure (5)**, because the output power directly depends on the pumping power, as shown in equation (10).

5. Conclusion

The results at ideal parameters showed a strong dependence of the laser output power on the doping concentration. The laser output power decreases with the change in concentration. The highest output power was at a concentration (10%) quickly, as the output power rapidly reduced with the increase in the doping concentration. There was a significant increase with the decrease in the radius of the pumping spot, so the highest output power value was at (rp=1* 10-3). The number of times the pumping power beam passes affected the output power so that there was an increase in the output power with an increase in (Mp) until it reached a constant value that did not change (Mp = 80). The other parameter is the pumping power, as its increase showed an increase in the laser output power.

In conclusion, we can conclude the importance of the dependence of the doping concentration and the radius of the pumping spot, as well as the number of times the pumping beam passes through the crystal on the material parameters of the numerical simulation that must be taken into account to obtain a high output power.

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