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Theoretical Study of the Effects Type of Host's Crystal on the Lasing Output of High – Power Thin –Disk Laser

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Abstract

Ytterbium-doped (Y2O3), (Sc2O3) and (YAG) crystals are very important for high-power thin-disk lasers. These lasers have shown their ability to operate quasi-three-level materials with high efficiency as well as high thermal conductivity ratio for crystalline hosts. All these reasons have required studying this type of laser. In the present work, the analytical solution was found for the equation of laser output power, pumping threshold power, and efficiency of a quasi-three-level thin disk laser. The numerical solution of these equations was also found through the Matlab program at the fundamental transverse mode, at a temperature of $299K^0$ and with high pumping capabilities in order to know the effect of the type of crystal host (YAG, Sc_2O_3,Lu_2O_3) on the laser production of this design and thermal effect when operating continuously. We found out that the crystal host (Lu_2O_3) was the best type of these hosts in obtaining the highest laser output power and efficiency at all values of pumping power.

Keywords: thin disk laser, high power, continuous wave, beam quality, ytterbium yb^{3+}.

1.Introduction

It is not surprising that the laser has become an important element in the industry. During the past years, many laser operations were performed with standard production techniques characterized by reliability and high productivity. This led to the presence of thousands of thin-disk lasers, and the demand for them still exists [1].

The thin-disk lasers give high beam quality, high output power, and low investment, as well as low operational cost, so that thin disk laser has been considered for several years the best and optimal choice for most high-power material processing applications in CW in addition to short and ultra-short pulse systems [2].

Thin-disk lasers are a standard tool for all industrial applications due to their high efficiency, accuracy, and power, as well as great ease of operation. Accordingly, broad prospects were opened in the field of laser-based industry, such as remote welding, high-speed cutting, brazing, cladding, and mixed welding [2, 3].

In addition to the interest in new applications, for example in lightweight designs (aluminum and copper welding), the interest in cost was clear as well. In this article, we present theoretical modern recording parameters obtained from thin disk lasers [2].

The fifth generation of thin disk lasers used in industry was produced in large quantities in continuous-wave operating systems (CW) at the work piece, delivering 6 kilowatts per disk. As for the laboratory results, they easily reached 10 kilowatts/disk [2].

2.Disk Laser Principles

Perhaps, what Adolf Giesen and his colleagues introduced more than two decades ago as a basic principle behind the thin-disk laser architecture was to use a cooled medium with a large surface relative to its volume [1].

As a result, the device has effective cooling, resulting in high average power. In addition, an effective axial heat flow is generated, which leads to the termination of the internal thermal lens and its effects. In most cases, only low constraints on pump brightness occur [2, 4].

The product of a beam modulus of 500 mm mrad is sufficient to have high energy in a thin disk laser, but fiber lasers require a higher degree of brightness [5].

To compare the 6 kW/disc laser generation with the previous generation, the improved pump cavity increases the efficiency to more than 72%, which means an increase of 10% over the previous generation. In outline, there are five important characteristics for improving the performance of lasers in the industry [2]:

1. High brightness of thin disc lasers due to their low thermal lenses.
2. The use of laser beams in converting electrical efficiency into optical, especially in high-medium power systems, is becoming more popular because of the low brightness constraints on pumping diodes..
3. The broadening of the energy range while maintaining the internal intensity is due to the scaling of the region to the beam size.
4. In fiber laser systems that have harmful back reflection problems, they are removed due to the deep saturation of the gain in the thin disk.
5. In general, the beam diameters are large when compared to the longitudinal extension of the gain medium.
6. Accordingly, there are no problems due to non-linearity, and the power sources are of high intensity. Cost and brightness are the focus of today's technology for two important reasons: first, the possibility of increasing the quality of the beam and thus improving performance; second, the possibility of reducing the number of laser diodes required and increasing the laser output power [6].

3.Theoretical Treatment

The gain material in a solid-state laser consists of a host material doped with optically active ions. The spectral properties of gain materials for doping are determined using energy levels. The individual Stark levels are coupled with phonons, and a thermal equilibrium is obtained for occupying energy levels. Depending on the active cleavage, discussion of this work will be on quasi-tri-level systems. The Boltzmann occupation [7]:

$$f_{Lp} = \frac{e^{-\frac{b}{KT}}}{A} \quad (1)$$

$$f_{up} = \frac{e^{-\frac{g}{KT}}}{A} \quad (2)$$

Where $A = \sum_{i=1}^{4} e^{\frac{E_i}{KT}}$

$$f_{LL} = \frac{e^{-\frac{f}{KT}}}{B} \quad (3)$$

$$f_{uL} = \frac{e^{-\frac{d}{KT}}}{B} \quad (4)$$

Where $B = \sum_{j=1}^{3} e^{\frac{E_j}{KT}}$

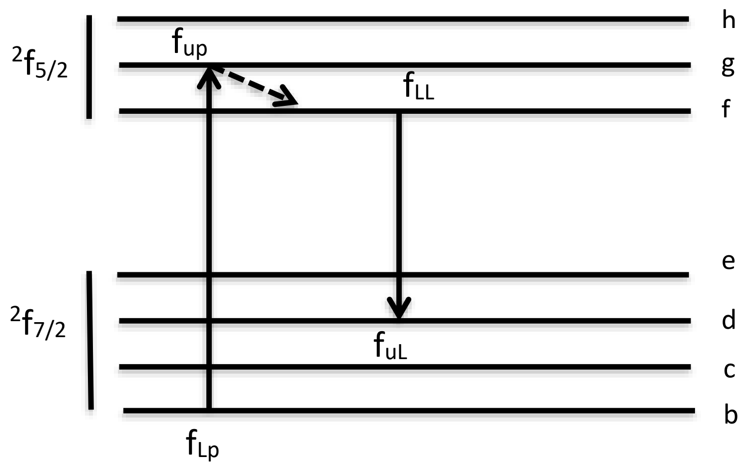


Figure1. The energy levels of the three crystals

The configuration of the resonator determines the quality of the beam, which has a time-spacing limit factor M^2[8].

At a thin-disk laser, M^2 is proportional to the radius of the pump spot rp, and inversely proportional to r_0, where ($r_0 = 0.7r_p$) if TEM_{00}, as shown in the equation below [9]:

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

The laser material used to prepare the thin-disk is

(Yb^{3+}:YAG,Sc_2O_3,Lu_2O_3), at room temperature is a quasi-three-level laser material.

The energy level system of (Yb^{3+}:YAG,Sc_2O_3,Lu_2O_3), consists of the stark split ($^2F_{7/2}$) ground state and ($^2F_{5/2}$) state of excitement.

Because of the tiny split of power levels for each forked, it is assumed to be very small. This excuses the use of a dual model, the energy ground state (E_1), the population N_1, the excited state energy (E_2), and the population N_2. The rate equation for the ground state (N_1) and excited state (N_2) can be written in the following way [10,11]:-

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

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

$N_1 - N_2 = N_t(8)$

At N_2=N_{2th}

So

$\therefore N_{2th} = \frac{I_{pth}\eta_a\lambda_p\tau}{dhc}(9)$

$P_p = A_p\ I_p$ (10)

Replaced with the threshold condition (N2=N2th ,Ip=Ipth and IL=0) in eq.(6), the pump power at the threshold (Pth) can be qualified as [11]:

$P_p^{th} = I_{pth}A_p(11)$

In the steady–state condition $\frac{dN_2}{dt} = 0$

$P_{out} = \frac{T}{[-\ln(1-T) - \ln(1-\gamma)]} * \eta_a\eta_s(p_p - p_{pth})$ (12)

$\eta = \frac{T}{\delta}\eta_a\,\eta_s(13)$

4.Numerical Simulation

In this study, the Matlab program is used to find the numerical solution for each of the equations of the pumping power at the threshold (P_{pump}^{th}) computed through equation (11). The laser output power (Pout) is computed through equation (12), and the efficiency of the laser device that we are going to study (η) calculated through equation (13).

Three types of crystal hosts have been selected: (YAG), (Sc_2O_3), (Lu_2O_3) which are common for using in Yb: thin disk lasers, to determine the best hosts that can be used to get the best laser output power. Table (1) shows the parameters used to find the numerical solution for these three crystals.

In view of the high value of the pumping power at the threshold of some hosts, a range of pumping power between 1150-25000 W is chosen to find out the effect of low and high pumping powers on the laser output power in these hosts.

Table 1. The parameters used for these three crystals[12–14].

parameter	YAG	Sc_2O_3	Lu_2O_3	unit
λ_p	$940*10^{-9}$	$942*10^{-9}$	$950*10^{-9}$	m
σ_{ap}	$0.737*10^{-24}$	$0.755*10^{-24}$	$0.788*10^{-24}$	m^2
σ_{ep}	$0.147*10^{-24}$	$0.073*10^{-24}$	$0.333*10^{-24}$	m^2
λ_L	$1030*10^{-9}$	$1041*10^{-9}$	$1032*10^{-9}$	m
σ_{aL}	$1.482*10^{-24}$	$1.179*10^{-24}$	$0.703*10^{-24}$	m^2
σ_{eL}	$0.079*10^{-24}$	$0.062*10^{-24}$	$0.069*10^{-24}$	m^2
N	$1.38*10^{26}$	$3.3*10^{26}$	$2.9*10^{26}$	Ion/m^3
Ti	$940*10^{-6}$	$800*10^{-6}$	$820*10^{-6}$	sec

4.1.Effect of Crystal Type on the Laser Output Power for Each Pumping Power

In order to know the effect of crystal on the power of the laser output, we use the typical values of these coefficients (as in shown in **Table2)** that have an impact on the work of this laser design, the values of these coefficients that can be used when using them to obtain the highest laser output power and efficiency for this laser design which what we call (typical values) to build the laser design.

Table 2. The typical values of the parameters used to obtain the highest output power, the highest efficiency, and the lowest amount of heat.

Parameters	value	unit
Crystal	YAG,Lu_2O_3,Sc_2O_3	/
T	290	K^0
M^2	1	/
r_p	$1*10^{-3}$	M
D	$300*10^{-6}$	M
M_p	80	/
R_2	0.95	/
ʊ	0	m^{-1}
P_p	$25*10^3$	W
N	1 at%	/

The **Figure (2)** below shows the effect of the crystal type on the laser output power for each pumping power at the optimum values, showing that a (Lu_2O_3) crystal can extract the highest laser output power from it.

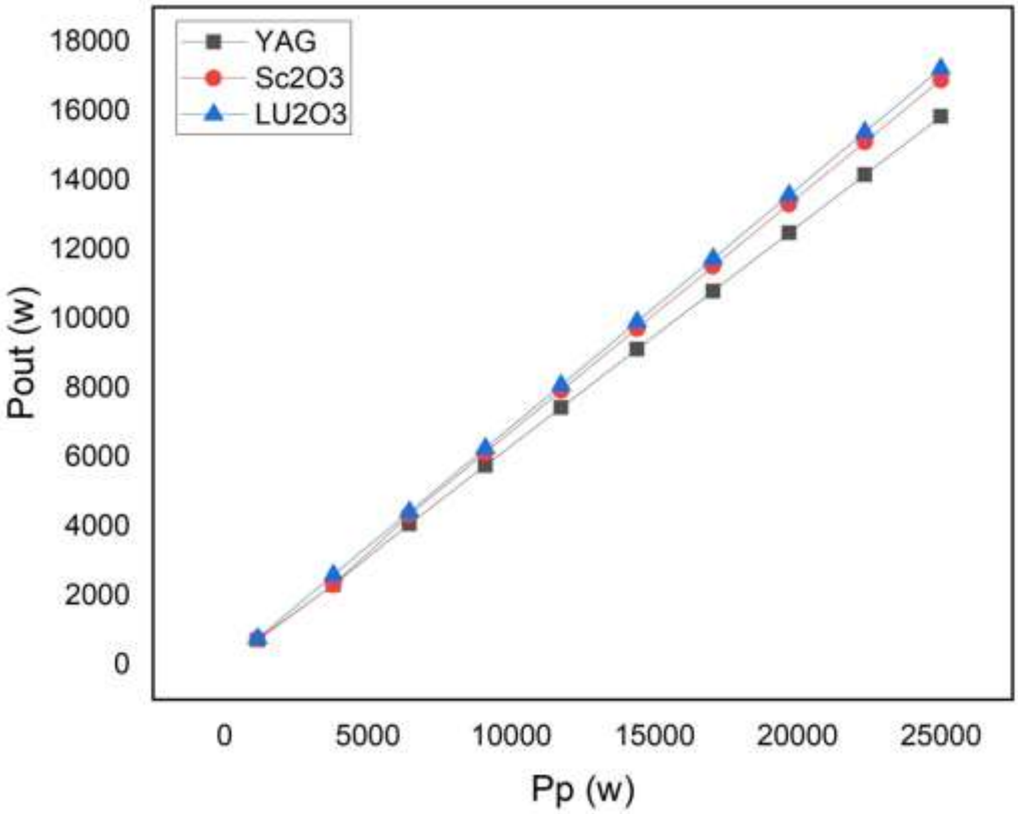


Figure 2. values of output power versus pumping power at typical value for three crystals.

4.2.Effect of Crystal Type on the Pumping Threshold Power and efficiency.

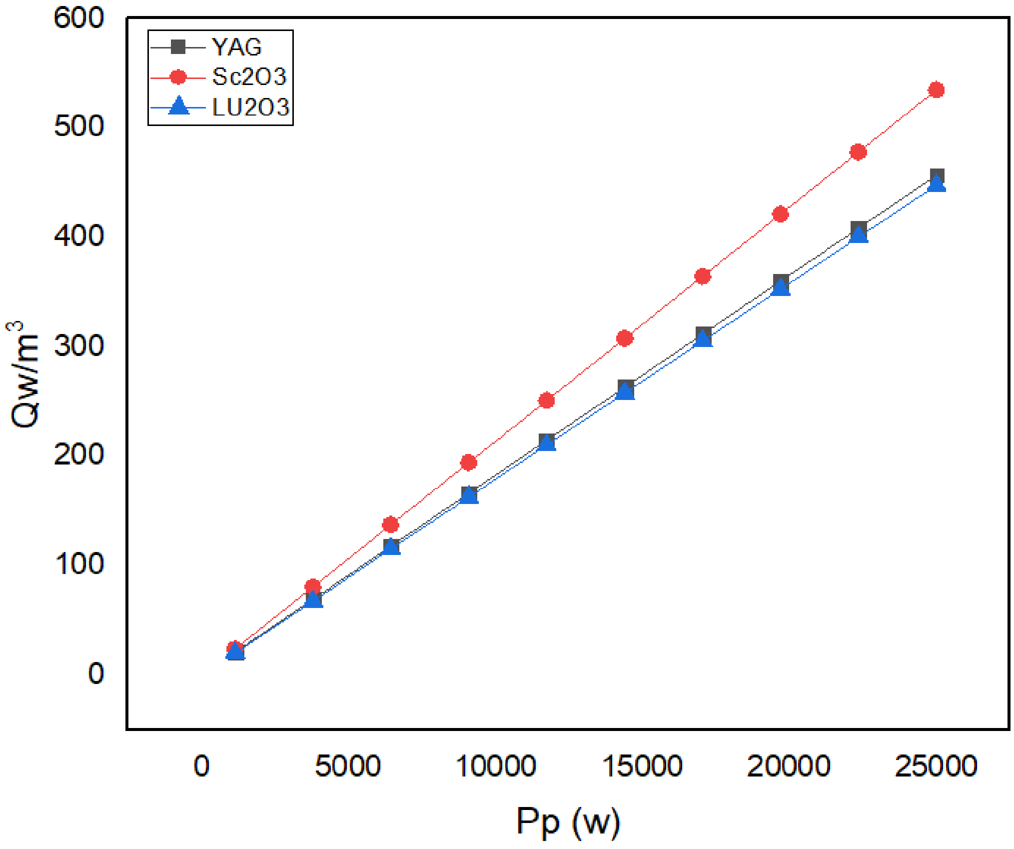
Table 3 below shows that the threshold pumping power varies with the crystal type and that the lowest pumping threshold power is at the crystal (YAG). It also shows the efficiency of the three crystals, where it is found that the crystal of (Lu_2O_3) is the most efficient.

Table 3. shows the threshold pumping capacity and efficiency of three crystals.

Par.	YAG	Sc_2O_3	Lu_2O_3	unit
P_{pth}	17.019	40.718	36.097	W
η%	63.41	67.69	68.99	/

4.3.The Effect of the Crystal Type on the Heat Generated in the Thin Disk.

Figure 3 illustrates the graphic relationship between the Quantity of heat per unit volume from the active medium of the thin disk and the pumping power in the five hosts, where we note that the Quantity of heat increases with the increase in the pumping power in all these hosts. The lowest value for this quantity is in the crystal (Lu_2O_3) of all these hosts.



Figures 3. Relationship between the Quantity of heat per unit volume from the active medium of the thin disk and the pumping power three crystals.

5.Discussion

This design's laser output power value varies according to the type of crystals grafted with (Yb^{3+}) at typical values. We note that the value of the output power for this laser design increases with the increase in pumping power at the typical values. The highest value is at the crystal (Lu_2O_3), while the crystal (Sc_2O_3) is less. The crystal (YAG) has the lowest value for the output power for the specific crystals. The difference in the crystal leads to a difference in the pumping power threshold, which is the lowest power at which the laser occurs. At the pumping power (25 kw), the highest value of the laser output power is at the crystal (Lu_2O_3), while the crystal (Sc_2O_3) is less. The crystal (YAG) has the lowest value for the output power of the specific crystals. We noticed that (YAG) crystal has the lowest pumping threshold capacity than (LuO) and finally (ScO). We notice the difference in efficiency between the three crystals, where we find that (Lu_2O_3) crystal is the most efficient, and (YAG) is the least efficient.

The amount of heat generated per unit volume in the effective medium of the thin-disk in the three hosts varies according to their types. We note that the heat quantity increases with the increase in the pumping power in all these hosts and that the lowest value for this quantity at the pumping power (25 kW) is in the crystal (Lu_2O_3) of all these hosts. Therefore, the crystal change has an effect on the heat quantity generated within the active medium of this laser design.

6. Conclusions

We conclude from this work that the type of crystal has a significant impact on the laser output power as well as on the amount of heat generated per unit volume within the laser system. By studying the three crystals, it is found that the best crystal is (Lu_2O_3), giving a high output power and a small amount of heat.

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