An Optical and Thermal Study of Laser Production by a Parabolic Dish Solar Concentrator in Ouargla Region

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Abstract:

In this paper, based on the simulation, we concentrate the solar radiation in Ouargla region in Algeria for laser production. The parameters location of this region were the longitude is L=5.24, latitude is φ=31.57, and the height above the sea level is Z=141 m. To do so, we use a reflective dish with two different diameters in a summer day and winter day as well. The laser production is achieved by side-pumping of three lasers namely YAG:Nd rod , YAG:Nd plate and GSGG:Nd:Cr rod. To get a suitable temperature for the laser, we use a refrigeration system and a solar spectrum filter. We obtained a 7.84Mw/m^2 concentred radiation and recorded an inpower of 955.5 W and anoutpower of the laser equal to 46.43 W.

Keywords: Solar radiation, solar laser, reflective dish, YAG:Nd, GSGG:Nd:Cr.

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1 Introduction

The sun emits rays with density flow of 1 KW/m^2 on the earth's surface, which is equivalent to more than ten thousand time of the world's energy demand. This makes the solar energy widely used for different tasks (1).The laser is among the most interesting discoveries that humans made in the 20th century (2). The word 'laser' is acronym of light amplification by stimulated emission of radiation. The laser is characterized by its coherent, direct and monochromatic beam.Pumping the active laser medium, which is the source of optical gain within a laser, is the main technique to produce a laser. Pumping is the act of energy transfer from an external source into the laser. It is a process used to raise electrons from a lower energy level in an atom or molecule to a higher oneproducing excited states. When the number of particles in one excited state exceeds the number of particles in the ground statethe pump power exceeds the lasing threshold of the laser then the stimulated emission can take place and the medium can act as a laser. Pumping technique can be performed in many ways: electrical, chemical, nuclear and optical pumping.The optical pumping is a low cost compared to the remaining techniques (3)(4).

A parabolic dish concentrator system is used to concentrate the solar radiationsand provide it to a laser as pump power. This power should be higher than the lasing threshold required for excitation. In order to protect the material of the active laser medium from damage that can be caused by the high temperature of solar radiations, we add a refrigerating system. Every medium has an energy threshold above which the laser is stimulated, depending on the material used for each case (3).

In 1966, Young has made the first attempt to produce the solar laser using a primary concentrator parabolic mirror with a diameter of 61 cm, where end and side-pumping of YAG material doped with Nd produce 1Watt(5).In 2008, Yabe system has produced 80 W, using a Fresnel lens, which has a surface of 4 cm^2, with a collection efficiency of 20 W/m^2 by exploiting the YAG material which is doped by Nd and Cr (6). In 2011, Liang has performed an end-pumping laser rod using the YAG material doped with Nd, which has a diameter of 4 mm, and a Fresnel lens, which has a surface of 0.64 cm^2 to produce 12.35 W with a collection efficiency of 19.3 W/m^2 (7).In 2012 (Dinh), by using a Fresnel lens which has a surface of 0.64 cm^2 and an end-pumping laser rod with a diameter of 6 mm, achieved 30 W/m^2 of the collection efficiency (8). In 2012, Yasser has used a Fresnel lens of 60x60 cm^{2}to pump a YAG rod doped by Nd, which has a diameter 2 mm. This configuration has yielded to 6.8 W (9).

In 2015, Yasser has used a Fresnel lens of 60x60 cm in addition to pump a YAG rod doped by Nd, which has a diameter 2 mm. This configuration has yielded 7.56 W (2). In 2016, Liang has used a parabolic mirror in addition to a big semi-spherical silica lens to perform a side and end-pumping YAG rod doped with Nd, and which has a diameter of 4 mm. This configuration has yielded to 29.3 W with acollection efficiency equal to 25 W/m^2 (10). In 2021, Claudia has performed a side pumping YAG rod doped by Nd and Cr, and which has a diameter of 4 mm. This pumping has been carried out by a parabolic mirror and a semi-spherical lens. This configuration has produced a laser with a collection efficiency of 23.6 W/m^2(11). In 2022, Zitoacai has produced 74.6 W with a collection efficiency of 42.2 W/m using a parabolic mirror, which has a diameter of 1.5m and a Fresnel lens. Note that the diameter of the laser rod was 5 mm (12).

Our study based on the intensity of the solar radiation in Ouargla region in Algeria. In this region, the parameters were the longitude is L=5.240, latitude is φ=31.570, and the area altitude is Z=141 m. The average annual solar irradiance on a horizontal surface in the southern region of Algeria (Sahara) is approximately 2260 kilowatt-hours per square meter. Which is approximately 3400 hours of sunshine per year (1). We have used a solar concentrator parabolic dish with two diameters D=1 m and D=2m, withoutsun-tracking. This system is simple andcut-price. In addition, we have used end-pumping by exploiting the active medium namely YAG doped with

Nd in two forms: rod and slab, and the GSGG doped with Nd and Cr. We have calculated the ouput power, collection efficiency, temperature of the laser prior and after using the refrigerating system.

2 The proposed method

In this work, we consider a solar system which is made up of reflective dish with a parabolic shape Fig.1.We have chosen two different diameters for this reflective dish,$D = 1\ m$and$D = 2\ m$. The solar radiations fall on the reflective surface, and then they are collected in the form of concentrated rays in the focus.

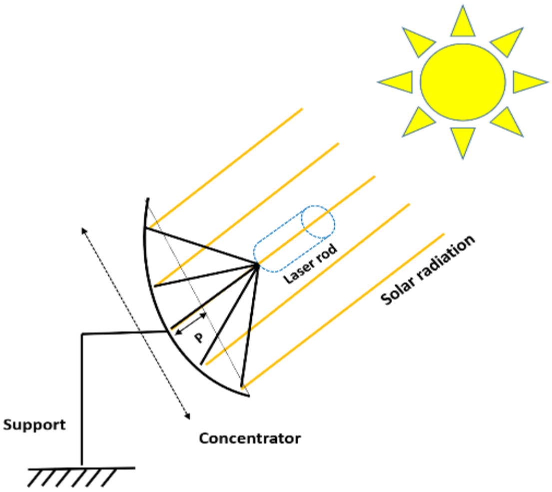


Fig. 1. The solar concentrating system using parabolic Dish.

As our solar system in this study is a concentrator, the laser crystal was installed on the focus of the reflecting dish.In this study, we have chosen two materials of lasers namely neodymium-doped yttrium aluminum garnet (YAG:Nd) and neodymium- and chromium-doped gadolinium scandium gallium garnet (GSGG:Nd:Cr). We use the YAG:Nd in two different forms, at first, in form of rod, then, in slab form. Regarding the GSGG:Nd:Cr it is used in the form of rod only. A side pumping is conducted to produce the laser.

The YAG doped with Nd has a low threshold of 926 W/cm compared to the other effective materials, meanwhile, the GSGG doped with Nd and Cr has a threshold of 2160 W/cm. TheNd:YAG laser is widely utilized as a solid-state laser due to the favorable combination of properties unique to neodymium-doped yttrium aluminum garnet. The YAG host is characterized by its high thermal conductivity and optical quality, as well as its hardness. Additionally, the cubic structure of YAG enables a narrow fluorescent line width, resulting in low laser threshold and high gain. Charge compensation is not necessary in Nd:YAG as trivalent neodymium substitutes trivalent yttrium in the lattice (13).

Nd:Cr:GSGG laser is a solid-state laser that was introduced in the early 80s [1]. It uses neodymium (Nd) and chromium (Cr) as dopants in a gadolinium scandium gallium garnet (Gd3Sc2Ga3O12: GSGG)) crystal. The large lattice parameter of Nd:GSGG co-doped with chromium enables fast and efficient energy transfer from the Cr-ion to the Nd-ion, thus improving the laser efficiency. Nd:Cr:GSGG lasers are known for their high efficiency, high output power and low threshold, and they are used in a variety of applications, including materials processing, laser surgery, and spectroscopy. This medium had been considered a good candidate for solar lasers because of the two strong and broad Cr absorption bands peaked at 450 nm and 640 nm and narrow Nd lines, which presents the strong absorption of solar radiation [1,4]. However, they can be more expensive than other types of lasers and require good thermal management due to increased heat in the crystal [14,15].

The laser crystal installed on the focal point of the reflective dish is exposed to high temperature, which, in certain cases, leads to the damage of the laser material. In addition, afilter, which pass a portion of the solar spectrum, leads to decrease the temperature of the laser crystal. To limit this effect a refrigeration system is considered. It is based on recycling the water around the laser crystal. To simplify the study of this model, we performed our study in sunny and cloudless days. In addition, we have neglected the drawbacks of the studied form. As for the solar radiation that fall on the dish, we have consider it perpendicular to the dish. Therefore, we have neglected the shading and the heat exchange with the dish as well. The reflectivity is considered the same for all waves' length Fig.2.

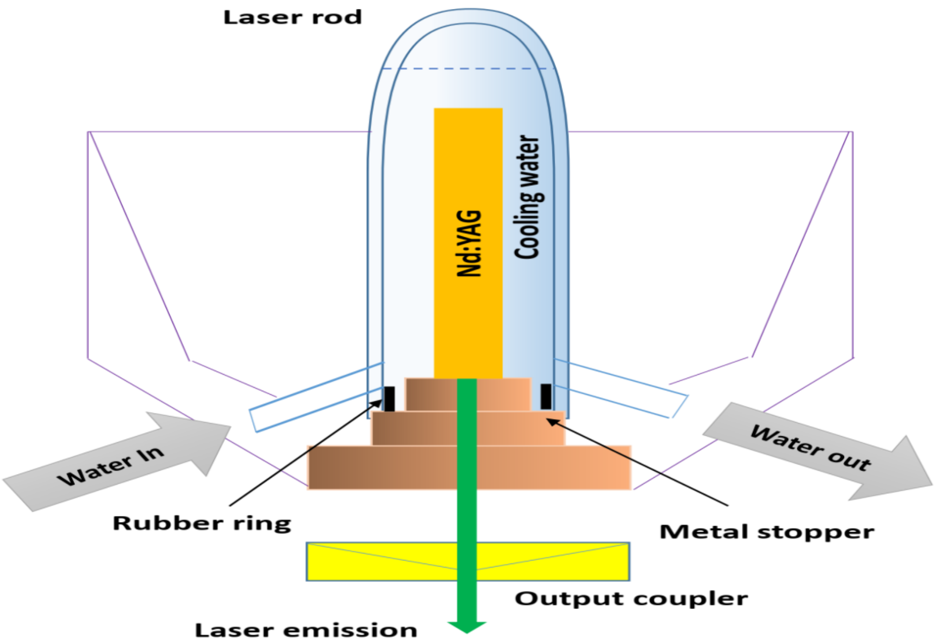


Fig. 2.The laser cooling system.

2.1 Optical study

The sun’s rays fall on the parabolic dish then they are reflected and are focused on the focus dish. Equation 1 presents the geometrical shape of the dish.

$$x^2 + y^2 = 4fz^2 \qquad (1)$$

Where $f$is the dish focal distance ($D = 2\,m,\ h = 0.5\,m,\ f = 1\,m$) ($D = 1\,m,\ h = 0.25\,m,\ f = 1\,m$). In this case, the rimangle φ will be as follows[16]

$$\tan(\varphi) = \frac{\left(f/D_{op}\right)}{2(f/D_{op})^2 - \frac{1}{8}} \qquad (2)$$

The power of the concentrated solar system $G_h$is given by

$$G_h = I \times \rho^o \times C \qquad (3)$$

$\rho^o$is the reflectance of the mirror, C is the geometrical concentration, and the ratio of the reflector aperture area to the receiver surface area, as follows

$$C = \frac{A_{ap}}{A_r} \qquad (4)$$

$A_{ap}$the reflector aperture area, and A_r is the receiver surface area. In the case of the presence of solar radiation spectre filter on the surface of the receiver, the power of the radiation, which reaches the receiver, will be$G_{(\lambda_1 \to \lambda_2)}$

$$G_{(\lambda_1 \to \lambda_2)} = I_{(\lambda_1 \to \lambda_2)} \times \rho^o \times C \qquad (5)$$

here$I_{(\lambda_1 \to \lambda_2)}$ is the power of the solar radiation on the earth surface for the concerned spectre $[\lambda_1 \to \lambda_2]$ and its value depends on the solar constant of this spectre [17]

$$I_{(\lambda_1 \to \lambda_2)} = I_{0(\lambda_1 \to \lambda_2)}[a_0 + a_1 e^{-K.AM}] \qquad (6)$$

Where

$$I_{0(\lambda_1 \to \lambda_2)} = E_{(\lambda_1 \to \lambda_2)}\left[1 + 0.033.cos\left[(N_J)\frac{360}{365}\right]\right] \qquad (7)$$

Where AM isair mass and equal to$\frac{1}{\sin(h)}$

a_0,$\alpha_1$and $K$are constants given by$Duffie$and$Beckman$relations[18]:

$$K = 1.02\,[0.2711 - 0.01858(2.5 - Z)^2] \qquad (8)$$

$$a_0 = 0.94\,[0.4237 - 0.00821(6 - Z)^2] \qquad (9)$$

$$a_1 = 0.98\,[0.5055 - 0.00595(6.5 - Z)^2] \qquad (10)$$

$Z$is thearea altitude,measured in kilometers. From Planck's law which gives the energy of the radiation emitted by the black body.

$$E_{(\lambda_1 \to \lambda_2)} = \left(\frac{D_S}{D_{S,T}}\right)^2 \int_{\lambda 1}^{\lambda 2} \frac{C_1}{\lambda^5\left[e^{\left(C_2/\lambda T\right)}-1\right]} d\lambda \qquad (11)$$

Such that $C_1 = 2\pi h c^2$and$C_2 = {hc}/{K}$

2.2 Thermal study

The laser crystal receives concentrated solar radiation then the heat is transmitted by conduction through it.A part of the heat is lost through the cooling system by forced convection with water that flows by mass flow$\dot{m}_w$ around the lateral surface of the laser. Thermal balance equation for the laser is

$$(L_f.\rho_f.C_f)\frac{\partial T_f}{\partial t} = G + k_f\frac{\partial T_f}{\partial x} + 4\frac{L_f}{D_f}h_{conv}\left(T_w - T_f\right) \qquad (12)$$

Thermal balance equation for the water

$$\dot{m}_w.C_{pw}(T_w^t - T_w^{t-\Delta t}) = \pi D_f.L_f.h_{conv}\left(T_f - T_w\right) \qquad (13)$$

h_{conv}The coefficient of heat transfer by convection is given by the relationship

$$h_{conv} = \frac{k_w}{D_f}Nu_w \qquad (14)$$

The Nusselt number is given in the turbulent flow [19]

$$Nu_w = 0.023.Re_D^{0.8}.Pr_w^{0.33} \qquad (15)$$

Re is Reynolds number and $Pr_w$is Prantel number of the water.

2.3 Optoelectronic study

We can calculate the power of the laser threshold by the following equation

$$P_{th} = \frac{A_\alpha I_s}{\eta_q \eta_{ovp} \alpha}\left(\frac{2\gamma_l - \ln R}{2\varepsilon}\right) \qquad (16)$$

Where P_{in} is the in-power, and it is given by

$$P_{in} = G_h A_\alpha e \qquad (17)$$

The outpower, it is given by the following equation

$$P_{out} = \eta_s(P_{in} - P_{th}) \qquad (18)$$

The parameters of the laser crystal used in our work are presented in Table1.

Table1.The parameters of the laser crystal

Parameters	YAG Nd (1%) rod	YAG Nd (1%) slab	GSGG Nd(1%),Cr(1%) rod
Wave length λ (µm)	1.06	1.06	1.06
Fluorescence of the crystal I_S(w/cm^2)	926	926	2.16×10^3
Overlap ratio η_{ovp}	0.06	0.1	0.24
Quantum efficience η_q	0.9	0.9	0.9
Absorption Coefficient α	0.6	0.6	0.6
Diameter D_a (cm)	0.63	0.5	0.63
Length L (cm)	3	/	3
Pumping efficiency ε	0.8	0.8	0.8

3 Analysis and discussion of results

Our modeling and numerical simulation of the laser production, using solar radiation, andof the heat transfer give better results compared to the previous works, which are more complicated (like using Fresnel lens) than our proposed system. On a summer day (July 29th) and another winter day (December 29th), using a reflective dish with a diameter of 1 meter and 2 meters, we obtain the following results.

3.1 The flow of the concentrated solar radiation

The flow of the concentrated solar radiation in the focus of the parabola increases gradually from sunrise and reaches its maximum at midday then it decreases to zero at sunset.In a winter day, on the midday, 4.39MW/m^2 of solar radiation was concentrated with a diameter of 1 meter and 17.57MW/m^2 for a diameter of 2 meters, as shown by Fig. 3. In a summer day, it achieves 7.87MW/m^2on the midday with a diameter of 1 meter and 31.5MW/m^2 for a diameter of 2 meters, as shown by Fig. 4.

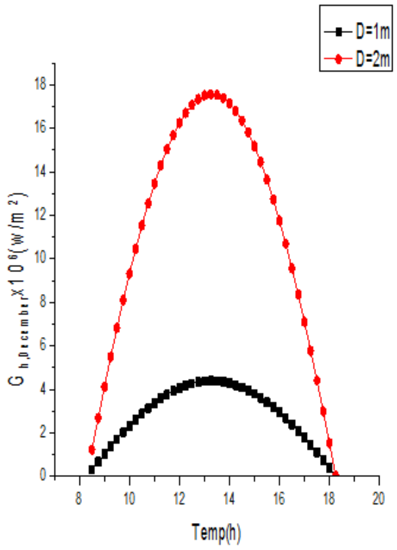


Fig. 3. Theconcentrated solar radiation flow in Ouargla on December 29th

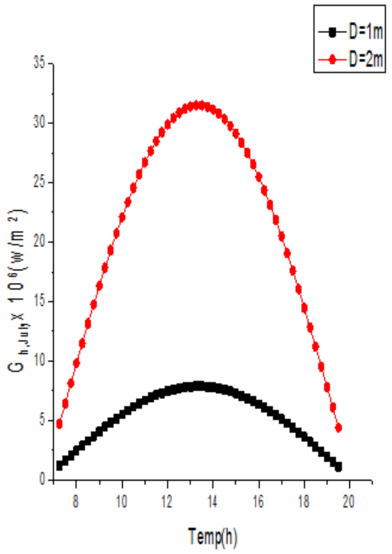
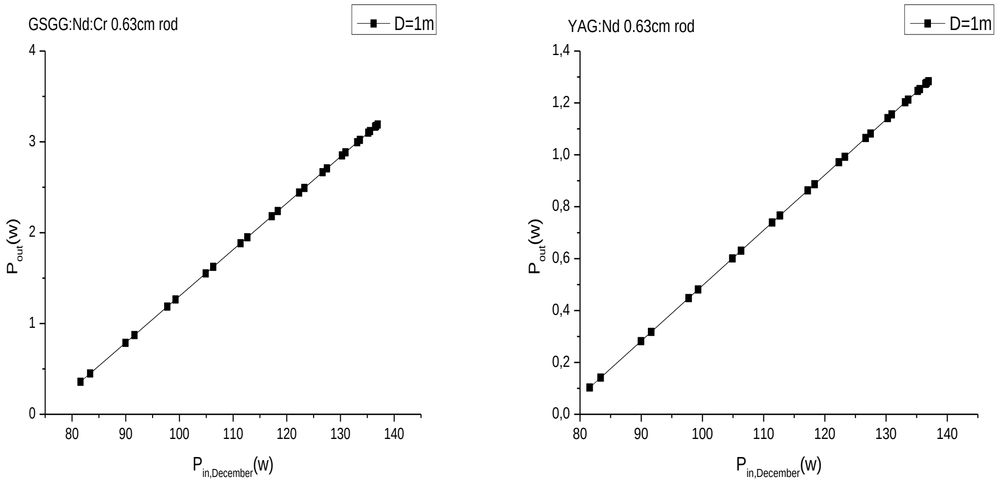


Fig. 4. Theconcentrated solar radiation flow in Ouargla on July 29th

3.2 The outpower

When the laser is installed on the focusof the dish receives a concentrated solar radiation, the outpower is proportional to the inpower according equation (11). We have drawn the simulation results for every time for the three types of laserwith two kinds of materials namely the laser rod/slabYAG:Nd and the GSGG:Nd:Cr rod. This is demonstrated by the following curves in Fig.5.In a winter day, the laser starts to appear at 10:00*a.m* with a diameter of 1 meter. We have recorded an outpower of 1.28W from the laser rod YAG:Nd, and 2.72W and 3.19W from the laser plate YAG: Nd and GSGG:Nd:Cr, respectively at 13:00*p.m*.



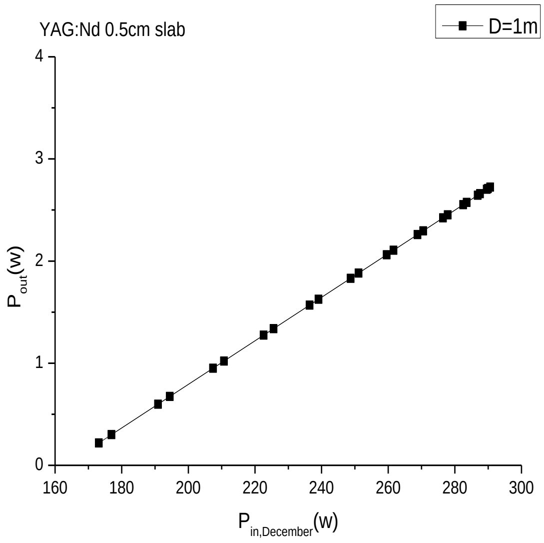
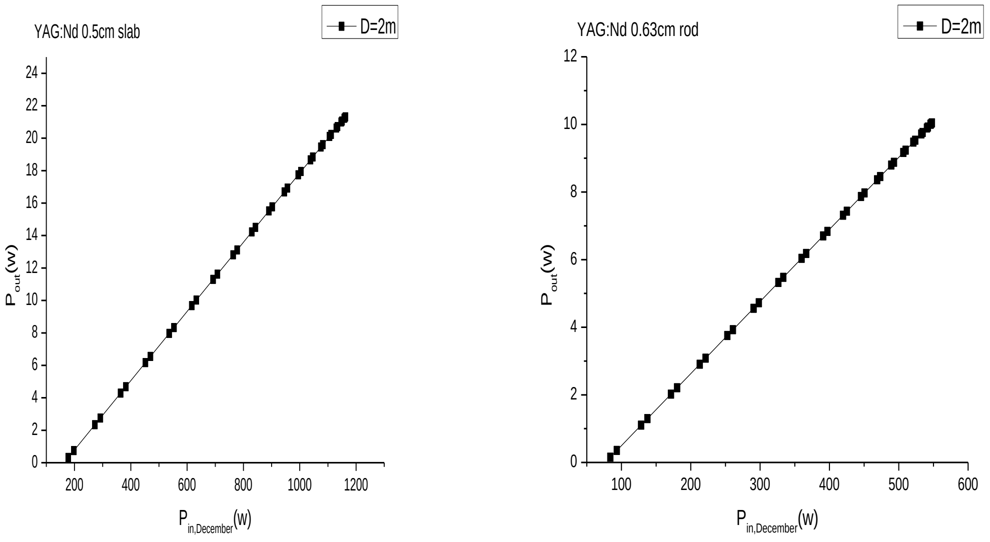


Fig. 5. Laser outpower versus laser inpower with a dish diameter of 1 meter, on December 29th.

For a diameter of 2 meters, the laser appear at 08:30$a.m$, where we have recorded and outpowerat 10.04 from the laser rod YAG:Nd and 21.31W and 24.21W from the laser plate YAG:Nd and GSGG:Nd:Cr, respectively at 13:00$p.m$(Fig. 6).In a summer day, the laser start to appear at 07:45 $a.m$ with a diameter of 1 meter, where we have recorded an outpower of 3.59W from the laser rod YAG:Nd, and 7.33W and 8.74W from the laser plate YAG:Nd and GSGG:Nd:Cr, respectively, at 13:00 $p.m$(Fig. 7).



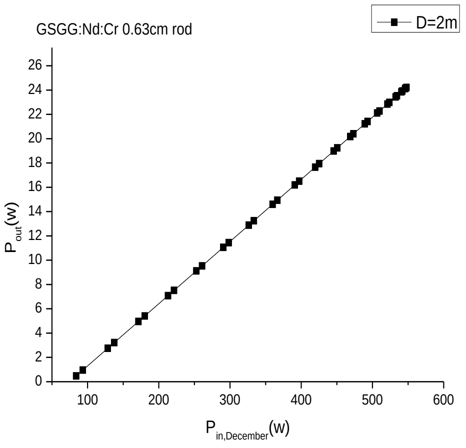


Fig. 6. Laser outpower versus laser inpower with a dish diameter of 2 meter, on December 29th.

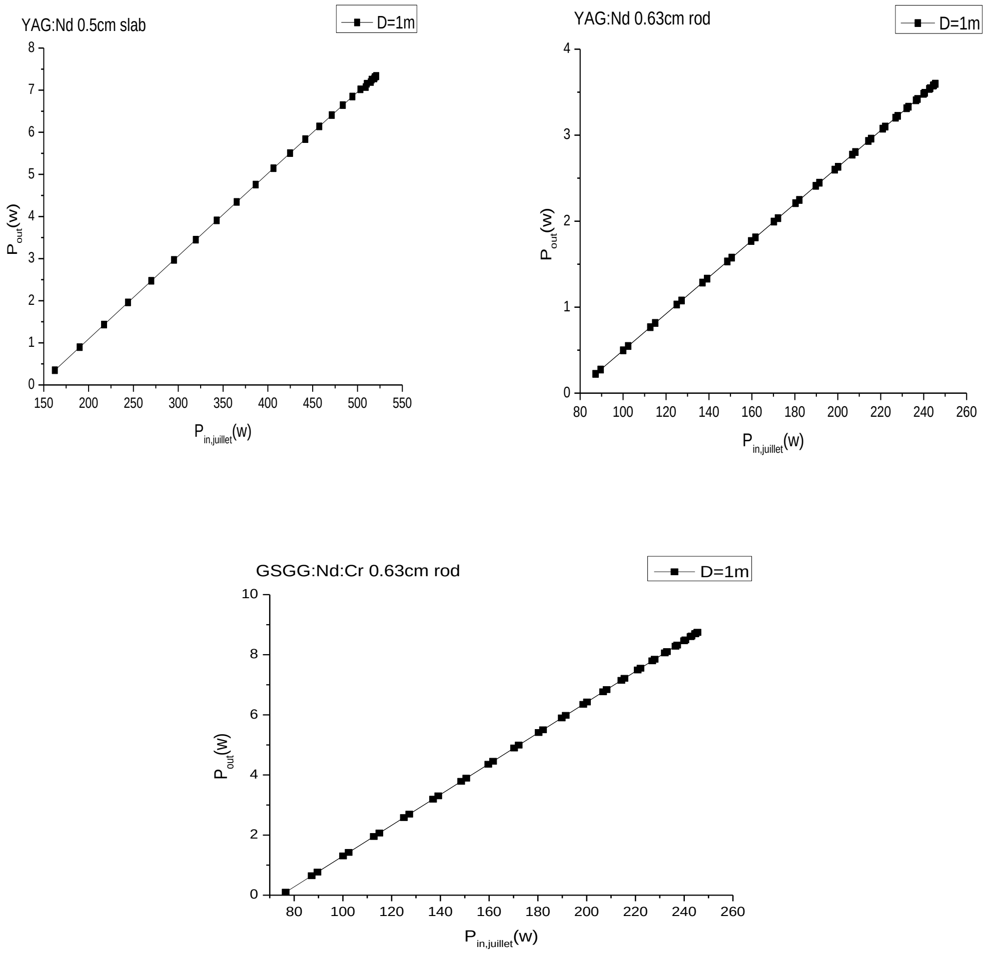


Fig. 7. Laser outpower versus the inpower with a dish diameter of 1 meter, on July 29th.

Now, for a diameter of 2 meters, we can see that the laser appear at 06:45 *a.m*, where we have recorded an outpower at $19.30W$ from the laser rod YAG:Nd, and $40.96W$ and $46.43W$ from the laser plate YAG:Nd and GSGG:Nd:Cr, respectively at 13:00 *p.m*(Fig.8).

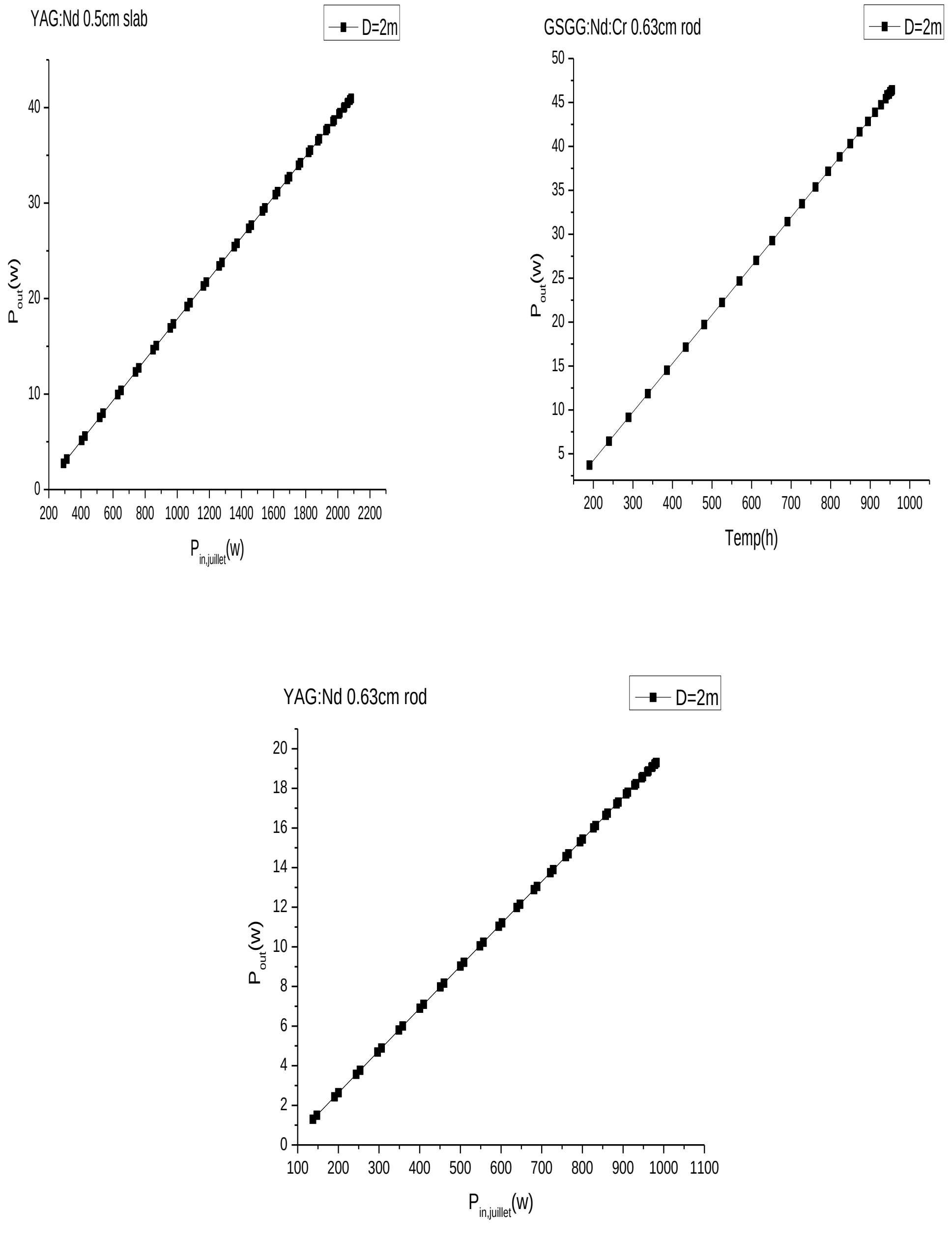


Fig. 8. Laser outpower versus the inpower with a dish diameter of 2 meter, onJuly 29th.

3.3 The temperature

By considering a refrigeration system in the laser crystal within the dish focus, we have obtained the results shown in the curves of fig.9 and fig.10. In particular, we have noticed the after refrigerating, in a winter day, the temperature of the laser crystal was 27°C and 50.33°C with the diameters of 1 and 2 meters, respectively. Before refrigerating, the temperature of the laser crystal was 50.5°C and 145°C with the diameters of 1 and 2 meters, respectively.Whereas in a summer day, we have noted that the temperature was 59°C and 101°C with a diameter of 1 and 2 meters, respectively after refrigerating. Before refrigerating, the temperature was 101°C and 272°C with the diameters of 1 and 2 meters, respectively.These temperaturesareconsidered acceptable for the laser crystal. Therefore, it is necessary to consider a refrigeration system, especially in the days with high temperature, and that to save the laser material from damage.

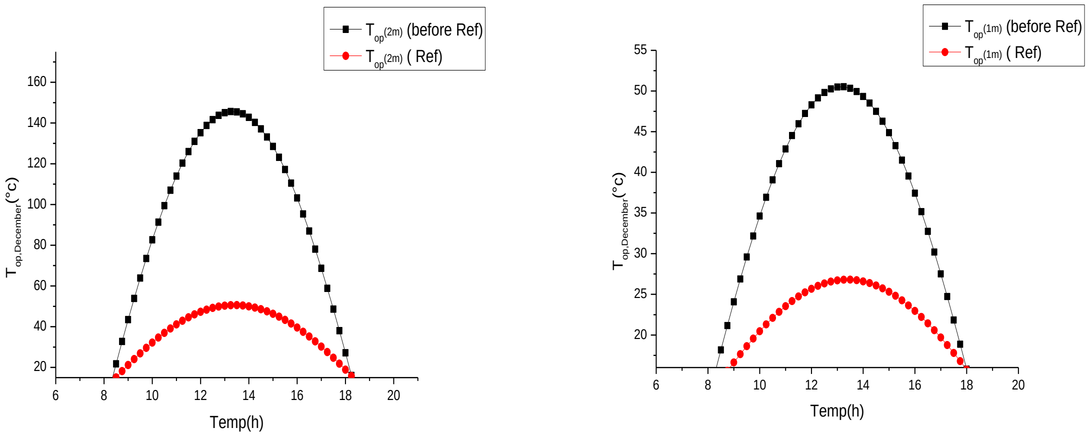


Fig. 9. The laser temperature during the day December 29th.,before and after cooling

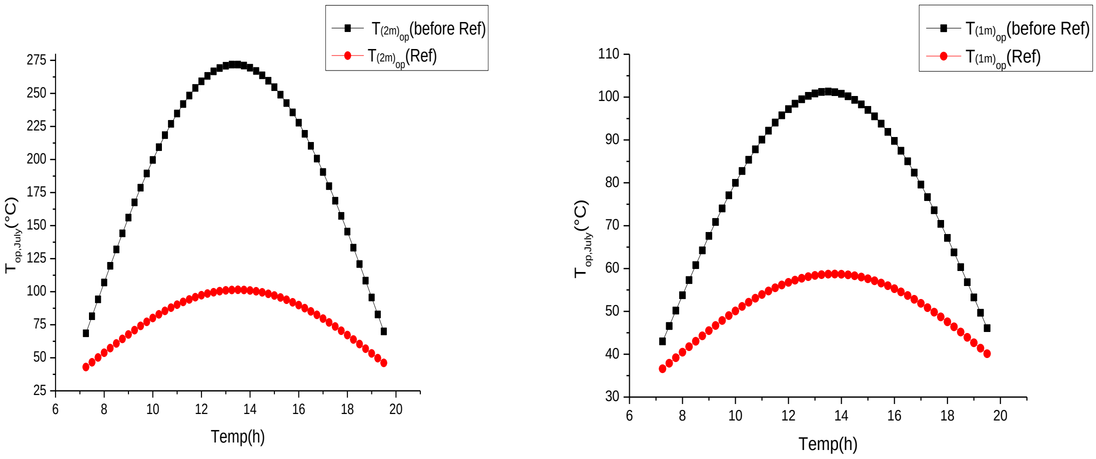


Fig. 10. The laser temperature during the day July 29th,before and after cooling.

In this study, by using simulation, we have successfully produced a solar laser, using three lasers which are rod and slab of YAG:Nd and GSGG:Nd:Cr rod,based on side pumping,using a dish with a small surface of 3.14 $m^2$with an outpower of 46.43W. With this cut-price system, a significant collection efficiency of 14.79$W/m^2$was achieved.To confirm the high efficiency of our proposed system in concentrating the solar radiation and laser production despite its simple architecture, we insert the inputs of the reference (2) in our simulation system. Reference (2)uses a concentrator consisting of a Fresnel lens and a compound parabolic concentrator (CPC). The results are givenin table 2

Table2. Comparison of our results with reference [2]

Parameters	Reference [2]results	Our simulation results
P_{in} (w)	696	1128.714
P_{out} (w)	13.86	18.44359

From these results, it appears that when changing the reference (2) concentrator, and using our concentrator instead, we have concentrated the radiation power of 1128.714 W, which is significantly greater than the power (696 *W*) obtained by the original concentrator. Thus, the outpower of our concentrator is 18.44 *W*, whereas, their outpower was 13.86 *W*. From the obtained results, it evidently appears that we have achieved better results compared to similar systems, which use Fresnel lens and heliostat-parabolic mirror.

In reference(20),the outpower was 32,5*W*using a concentratorthe heliostat-parabolic mirror solar energy concentration system and the solar laser head, consisting of the fused silica liquid light guide lens and the conical pumpin gcavity. In reference(11), the inpower was600*W*, which produces a laser power of 16,5*W*using a concentrator solar laser headwascomposed of a double-stage semisphericallens and a trapezoidal-shapedpumpingcavity, whichcoupled and redistributed the concentratedsolar radiation from the focal zone of a parabolicmirrorinto a laser rod.

It is worth mentioning that we cannotcompareour system with others, which have the structure of the primaryconcentratorconsists of a Fresnel lens and a modifiedparabolicmirror. The Fresnel lenswasplacedat the top of the concentrator system to concentrate the sunlight at the front end of the laser head. The parabolicmirrorwasmountedcoaxiallybelow the Fresnel lens to concentrate sunlight onto the sides of the laser head;itsparabolic surface wassilver-coated (reflectivity R = 95% for sunlight),which is more complicated than our system, and allow a double pumping of the laser material (side and peripheral pumping)(12).

4 Conclusion

To exploit the solar radiation in Ouargla region in Algeria, we use a reflective parabolic dish to pump a laser material with which we 7.84 MW/m^2. In particular, we have reached an in power of 955.5 W, which produces, using the GSGG:Nd:Cr laser, and out power of 46.43 W with a significant efficiency. It should be noted that our system does not require a complicated focusing system such as the use of a heliostat-parabolic mirror or a Fresnel lens.Therefore, we do not need a continuous maintenance, which is indispensable in the region due to sandy winds and dust. We have also provided a suitable temperature for the laser using the solar spectrum filterand a refrigeration system, which decreased the temperature, in the summer, from 272°C to less than 101°C. Compared to the temperature before the refrigeration, these degrees are considered appropriate to save the laser material from damage. Thereby the laser material is preventedfrombeing damaged.

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