



Theoretical Study of a Nd: YAG Solar Laser with 2.5% Efficiency

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Abstract

This study explores the direct conversion of sunlight into laser light using a neodymium-doped yttrium aluminum garnet (Nd:YAG) crystal as the active medium. A side-pumping technique was employed, and a theoretical Nd:YAG model was developed to assess the influence of key parameters on solar laser performance. The results indicate that the Nd:YAG medium achieved a laser gain of 4% and a conversion efficiency of 2.5%. These findings align with previous studies, validating the proposed model and confirming the feasibility of solar-pumped lasers as a sustainable energy source.

Keywords: Laser, Solar Energy, Solar Pumping, Solar Laser, Conversion Efficiency.

1. Introduction

The growing demand for energy, rising costs, and concerns about the depletion of conventional fuels have driven the search for sustainable alternatives. However, fossil fuel combustion releases harmful emissions, contributing to environmental pollution and global warming. Among renewable energy sources, solar energy is a promising option due to its availability and potential for efficient energy conversion. One of its advanced applications is optical pumping for lasers (LASER—Light Amplification by Stimulated Emission of Radiation), a process that enables the generation of coherent light for various technological uses.

Optical pumping is a widely used method to achieve population inversion, a necessary condition for laser operation. In this process, atoms absorb energy and transition to an excited state, where they can undergo stimulated emission, producing a focused and monochromatic laser beam. This process takes place in an active medium, which can be a solid, liquid, or gas, enclosed within a resonator that amplifies the emitted light.

Solar energy can be harnessed for laser generation through two main approaches:



a. Indirect Pumping

Photovoltaic cells convert sunlight into electricity, which then powers a laser diode to excite the active medium. While diode-excited lasers (DELs) can achieve high efficiencies, solar cells typically operate at 12%–15% efficiency, reducing overall performance [1,2].

b. Direct Pumping

Sunlight is directly concentrated onto the active medium, eliminating intermediate electrical conversion. This technique includes:

- Side Pumping: Solar radiation is focused onto the side of the laser medium, improving energy absorption and efficiency [3].
- End Pumping: Sunlight is directed at one end of the active medium, enhancing energy transfer for improved laser output.

Solar-powered lasers present a promising integration of solar energy and laser physics, with applications in space communication, industrial processing, medical treatments, and precision measurements.

This study aims to develop a solar-driven optical pumping system to replace conventional methods, improving energy efficiency, reducing maintenance costs, and enhancing adaptability across various environments. The focus is on direct solar-to-laser conversion, eliminating electrical intermediates to maximize performance.

2. Characteristics of Nd:YAG Laser

The neodymium-doped yttrium aluminum garnet (Nd:YAG) laser is a four-level laser system, requiring lower pumping energy than three-level lasers. It primarily emits at a wavelength of 1064 nm [4]. The active medium consists of yttrium aluminum garnet (YAG) crystals doped with neodymium ions (Nd^{3+}) at concentrations between 0.5% and 2%. In this structure, neodymium ions replace yttrium atoms in the YAG crystal lattice, forming laser-active energy states. This system supports three key laser emission lines at 1359 nm, 1064 nm, and 914.2 nm. Although the YAG host crystal itself does not emit laser light, it provides structural stability. When Nd^{3+} ions are incorporated into the lattice, they interact with the periodic electric field of the host material. This interaction affects the electronic energy levels of the neodymium ions, influenced by factors such as field intensity, crystal symmetry, and electronic configuration. In free space, neodymium ions possess multiple closely spaced energy levels. However, inside the YAG crystal, the crystal field effect induces energy level splitting, creating distinct laser-active states. This interaction also modifies the selection rules governing electronic transitions, enabling transitions that would otherwise be forbidden in isolated Nd^{3+} ions. Due to these enhanced optical properties, Nd:YAG lasers are widely used in



industrial, medical, and scientific applications, valued for their high efficiency and stable output.

3. Four-Level Laser Energy Transition Process

In a four-level laser system, excitation of the active medium promotes atoms or molecules from their ground state (E_4) to a higher excited state (E_3) within a broad frequency range. However, these excited particles quickly undergo a non-radiative transition to a lower-energy metastable state (E_2), where they accumulate due to its relatively long lifetime.

The key to laser operation lies in population inversion, which occurs when the number of atoms at E_3 exceeds those at the lower laser level E_2 . This imbalance allows stimulated emission to dominate over absorption. As atoms transition from E_3 to E_2 , they release coherent photons—identical in frequency, phase, and direction—leading to the amplification of laser light.

Following photon emission, atoms rapidly return to the ground state (E_1) via a non-radiative process, ensuring continuous energy cycling and sustained laser operation. The fast depopulation of E_2 prevents the reabsorption of emitted photons, further improving laser efficiency. This four-level mechanism is favored in solid-state lasers due to its low threshold energy and high operational stability.

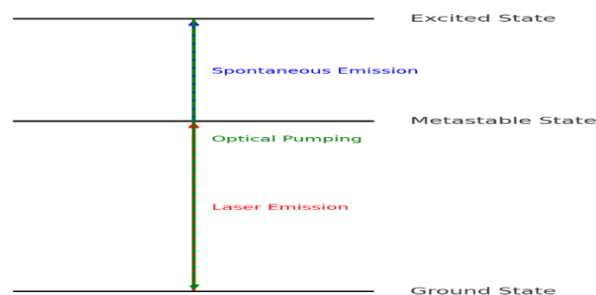


Figure 1: Schematic Representation of Energy Levels and Transitions in an Nd:YAG Laser

The time-dependent rate equations governing the population dynamics of ions N_1 , N_2 , N_3 , and N_4 per unit volume in a four-level laser system are expressed as:

$$\frac{dN_4}{dt} = W_{14}(N_1 - N_4) - \frac{N_4}{\tau_{43}} - \frac{N_4}{\tau_{42}} - \frac{N_4}{\tau_{41}} \quad (1)$$

$$\frac{dN_3}{dt} = W_{13}(N_1 - N_3) + \frac{N_4}{\tau_{43}} - \frac{N_3}{\tau_{32}} - \frac{N_3}{\tau_{31}} - W_{32}(N_3 - N_2) \quad (2)$$

$$\frac{dN_2}{dt} = W_{12}(N_1 - N_2) + W_{32}(N_3 - N_2) + \frac{N_3}{\tau_{32}} + \frac{N_4}{\tau_{42}} - \frac{N_2}{\tau_{21}} \quad (3)$$



$$\frac{dN_1}{dt} = W_{14}(N_4 - N_1) + W_{13}(N_3 - N_1) + W_{12}(N_2 - N_1) + \frac{N_3}{\tau_{32}} + \frac{N_4}{\tau_{42}} - \frac{N_2}{\tau_{21}} \quad (4)$$

where:

W_{ij} represents the transition probability between levels i and j .

τ_{ij} denotes the spontaneous emission lifetime between levels i and j .

The photon lifetimes corresponding to spontaneous transitions between different energy levels are defined as:

$\tau_{41}, \tau_{42}, \tau_{43}$: photon lifetimes for spontaneous transitions from energy level E_4 to lower levels.

τ_{31}, τ_{32} : photon lifetimes for spontaneous transitions from energy level E_3 to E_2 and E_1 .

τ_{21} : photon lifetime for spontaneous transitions from energy level E_2 to E_1 .

The time-dependent rate equation describing the photon density ρ within the laser cavity, assuming the cavity volume V_R is equal to the active laser medium volume V_L , is given by:

$$\frac{d\rho}{dt} = W_{32}(N_3 - N_2) - \frac{N_3}{P\tau_{32}} - \frac{\rho}{\tau_C} \quad (5)$$

where:

P is a parameter related to the stimulated emission process.

τ_C is the photon lifetime in the laser cavity:

$$\tau_C = \frac{L_R}{\gamma C} \quad (6)$$

where:

L_R is the length of the laser cavity, γ is the loss rate along the active medium and C is the speed of light in the medium.

The population inversion density, defined as:

$$N = N_3 - N_2 \quad (7)$$

evolves according to the following expression:

$$\frac{dN}{dt} = \frac{dN_3}{dt} - \frac{dN_2}{dt} = \eta W N_1 - 2W_{32}N - 2\frac{N}{\tau_T} \quad (8)$$



where:

η is the excitation efficiency.

τ_T is the total lifetime of the population inversion.

The temporal evolution of N is determined by the excitation of atoms from the ground state and their depletion due to stimulated emission and spontaneous relaxation. The total inversion lifetime is given by:

$$\frac{1}{\tau_T} = \frac{1}{\tau_{32}} + \frac{1}{2\tau_{31}} \quad (9)$$

This formulation accounts for the contributions of spontaneous emission from different energy states to the overall inversion dynamics.

When $N_2 \ll N_3$, it can be assumed that $N_3 \approx N$. Considering a specific number of modes, the photon density evolves as:

$$\frac{d\rho}{dt} = W_{32}N - \frac{nN}{P\tau_{32}} - \frac{\rho}{\tau_C} \quad (10)$$

The rate of stimulated emission per unit time and volume is expressed as:

$$N_S = W_{32}N = I_L\sigma N \quad (11)$$

I_L is the intensity of emitted laser radiation or photons from the active medium per unit area and time.

σ represents the intensity of the pump radiation per unit area and time.

The photon density is defined as:

$$I_L = \rho \times C \quad (12)$$

The number of pumping photons per unit time and volume is expressed as:

$$N_P = WN_1 = I_P\sigma_P N_1 \quad (13)$$

where:

I_P represents the intensity of emitted laser radiation or photon flux from the active medium per unit area and time.

σ_P denotes the stimulated emission cross-section of the laser ions.

Given that ϕ_p represents the total number of photons emitted from the pump source, the pump photon flux for side-pumping is given by:



$$I_p = \frac{\Phi_p}{Ld} \quad (14)$$

where:

L is the length of the active medium.

d is the diameter of the active medium.

Using equations (5), (10), (11), (12), (13), and (14), the governing equations for the emission process in an Nd:YAG laser can be derived as follows:

$$\frac{dN}{dt} = \eta N_p - 2C\sigma\rho N - 2\frac{N}{\tau_T} \quad (15)$$

$$\frac{d\rho}{dt} = \frac{V_L}{V_R} 2C\sigma\rho N - \frac{nN}{P\tau_{32}} - \frac{\rho}{\tau_C} \quad (16)$$

To solve equation (15) and (16), we consider the steady-state condition, where:

$$\frac{dN}{dt} = \frac{d\rho}{dt} = 0$$

Under this assumption, the expression for photon density is obtained as:

$$\rho = \frac{L_R}{\gamma C} \frac{nN_p}{2} \frac{V_L}{V_R} - \frac{1}{C\sigma\tau_T} \quad (17)$$

This equation describes the steady-state photon density, balancing pumping power, losses, and stimulated emission, which are critical factors in determining the efficiency of the solar-pumped Nd:YAG laser.

Using equation (12), the laser photon flux density is determined by:

$$I_L = \frac{L_R}{\gamma} \frac{\eta N_p}{2} \frac{V_L}{V_R} - \frac{1}{\sigma\tau_T} \quad (18)$$

If A represents the laser beam cross-sectional area and T the mirror transmittance coefficient, the laser output power is given by:

$$P_{OUT} = \frac{I_L}{2} T A h\nu_1 \quad (19)$$

Substituting the expression for I_L gives:



$$P_{OUT} = \frac{T}{\frac{2\sigma\tau_T}{Ah\nu_l}} \left[\frac{\frac{L_R\tau_T N_P\sigma V_L\eta}{2V_R}}{\gamma} - 1 \right] \quad (20)$$

Two key parameters are defined [7]:

- Small-signal gain coefficient:

$$g_0 = \frac{L_R\tau_T N_P\sigma V_L\eta}{2V_R} \quad (21)$$

- Output coupling parameter:

$$\beta = \frac{2\sigma\tau_T}{Ah\nu_l} = \frac{2}{Al_s} \quad (22)$$

By substituting these parameters, Equation (20) simplifies to:

$$P_{OUT} = \frac{T}{\beta} \left(\frac{g_0}{\gamma} - 1 \right) \quad (23)$$

T represents the mirror transmittance, which accounts for both total cavity losses and active medium losses, the overall optical loss coefficient along the active medium is given by:

$$\gamma = \frac{T}{2} + \gamma_0 \quad (24)$$

The laser energy inside the cavity is defined as:

$$P_C = \frac{I_L}{2} A \quad (25)$$

The output laser energy, expressed in terms of T and P_C , is given by:

$$P_{OUT} = TP_C \quad (26)$$

Higher values of T lead to increased output power, albeit at the cost of reduced intracavity energy storage.

Using equations (23) and (26), the following expressions are derived:

- Laser energy inside the cavity:

$$P_C = \frac{1}{\beta} \left(\frac{g_0}{\gamma} - 1 \right) \quad (27)$$



- Relation between gain and intracavity energy:

$$\frac{g_0}{\gamma} = 1 + \beta P_C \quad (28)$$

- Total loss coefficient expression:

$$\gamma = \frac{g_0}{1 + \beta P_C} \quad (29)$$

In this case, the condition is analyzed where the gain (g) equals the total optical losses (γ), ensuring laser operation at the threshold [8]:

$$g = \frac{g_0}{1 + \beta P_C} = \frac{g_0}{1 + I_L/I_s} \quad (30)$$

To establish the connection between population inversion (N) and gain (g_0), two specific cases are considered:

- Steady-State Condition: $\frac{dN}{dt} = 0$
- Specific Photon Density Condition: $\rho=0$

Thus, by applying equations (15) and (16), the expression for population inversion density is derived as:

$$N = \frac{\eta N_P \tau_T}{2} \quad (31)$$

Using equation (26) and assuming the cavity and active medium have the same diameter, the relevant expressions are substituted into equation (31) to determine the gain coefficient [9]:

$$g_0 = \sigma L N \quad (32)$$

4. Theoretical Model of Nd:YAG Laser

This study establishes a mathematical framework that defines the relationship between input pump power, photon flux density, gain coefficient, and laser output power. Focusing on the side-pumping configuration, the model incorporates key parameters governing energy conversion and threshold conditions, forming the basis for the following equations.

Relationship Between Laser Output Power and Input Power

The laser output power, P_r , within the specified spectral range, is given by:

$$P_r = k_r (p_{in} - p_0) \quad (33)$$



where:

k_r is the conversion efficiency to the desired radiation.

p_{in} represents the input pump power.

p_0 is the threshold pump power required to sustain lasing.

Photon Flux and Pump Light Conversion Efficiency

The total number of photons reaching the active medium is given by:

$$\phi_p = k_p \frac{P_r}{h\nu_p} \quad (34)$$

k_p is the pump light conversion efficiency within the cavity (also referred to as pumping efficiency).

$h\nu_p$ is the photon energy required to pump the active medium.

Using this relationship, the pump light flux density in the active laser medium can be expressed as:

$$I_p = \frac{K_p K_r (p_{in} - p_0)}{h\nu_p L d} \quad (35)$$

where L and d are the cavity length and diameter, respectively.

Absorbed Pump Photons and Gain Coefficient

The number of absorbed pump photons per unit time and volume is expressed as:

$$N_p = \frac{K_p K_r \sigma_p N_1 (p_{in} - p_0)}{h\nu_p L d} \quad (36)$$

where N_1 is the density of ground-state ions per unit volume. Assuming that the cavity and the active medium share the same diameter, d , the gain coefficient is defined as:

$$g_0 = \frac{K_p K_r \sigma_p \eta N_1 \sigma \tau_T}{2h\nu_p d} (P_{IN} - P_0) \quad (37)$$

Defining the gain coefficient factor:

$$K = \frac{K_p K_r \sigma_p \eta N_1 \sigma \tau_T}{2h\nu_p d} \quad (38)$$



Thus, the intrinsic gain coefficient can be rewritten as:

$$g_0 = k(P_{IN} - P_0) \quad (39)$$

Laser Output Power and Conversion Efficiency

By substituting the gain coefficient equation into the power equation, the laser output power is expressed as:

$$P_{OUT} = \frac{KT}{\gamma\beta} \left[P_{IN} - \left(P_0 + \frac{\gamma}{K} \right) \right] \quad (40)$$

where:

γ and β are system-dependent parameters,

T denotes the transmission coefficient.

The conversion efficiency is given by:

$$\eta_d = \frac{KT}{\gamma\beta} = \eta\eta_{OVP}\alpha k_p \left(\frac{T}{2\gamma - \ln R} \right) \quad (41)$$

η_{OVP} denotes the overlap efficiency between the laser absorption spectrum and the solar spectrum.

Threshold Pump Power

The threshold pump power, P_{th} , is determined using the following equation:

$$P_{th} = P_0 + \frac{\gamma}{K} = \frac{AI_s}{\eta_{OVP}\eta\alpha} \left(\frac{2\gamma - \ln R}{2K_p} \right) \quad (42)$$

The overlap efficiency, η_{OVP} , is defined as:

$$\eta_{OVP} = \frac{\int_a^b g_\lambda d\lambda}{\int_0^\infty g_\lambda d\lambda} \quad (43)$$

g_λ represents the solar spectral radiation flux density.

$\int_0^\infty g_\lambda d\lambda = I_0$ corresponds to the total incident solar radiation intensity over all wavelengths.

Mean Absorbed Solar Wavelength

The mean absorbed solar wavelength (λ_s) is given by:



$$\lambda_s = \frac{\int_a^b g_\lambda \lambda d\lambda}{\int_a^b g_\lambda d\lambda} \quad (44)$$

where:

λ_s represents the weighted average wavelength of the absorbed solar spectrum.

The integration limits a and b define the spectral range relevant to the laser absorption region.

Final Expression for Laser Output Power

The laser output power is also expressed as:

$$P_{OUT} = \eta_d [P_{IN} - P_{th}] \quad (45)$$

By rearranging the equation:

$$\frac{K_p K_r \sigma_p \eta N_1 \sigma \tau_T}{2h\nu_p} = \left(\frac{\beta A}{2}\right) \left(\frac{N_1 \sigma_p \eta}{2}\right) \left(\frac{\lambda_p}{\lambda_L}\right) K_p K_r \quad (46)$$

All parameters in this equation depend on the active laser medium or the pumping method. Under the assumption that the parameter dK remains constant within the studied range:

$$dK = \text{constant}$$

Equation (20) simplifies to [9]:

$$\frac{2}{A\beta} = \frac{h\nu_1}{\sigma\tau_T} = I_s \quad (47)$$

Since the characteristics of the Nd:YAG laser medium remain unchanged for the studied system, the following assumption is made:

$$\frac{2}{A\beta} = \text{constant}$$

5. Physical Parameters of the Studied Model

The following table summarizes the key physical parameters used in the studied solar laser model:

Value	Symbol	Description
40 mm	L	Length of the active medium
3 mm	D	Diameter of the active medium



0.59	A	Absorption coefficient of the Nd:YAG laser
0.63	η	Quantum efficiency
0.67	k_p	Pump efficiency
0.14	η_{OVP}	Overlap ratio between the solar radiation emission spectrum and the laser absorption spectrum
0.016	γ	Optical loss coefficient in the laser rod
12.5 W/mm ²	I_s	Laser radiation intensity emitted from the crystal

This set of parameters provides a detailed characterization of the laser system, ensuring accurate modeling and performance evaluation.

6. Results and Discussion

a. High Efficiency of Solar Laser

Figure 2 illustrates the linear relationship between solar laser output power and input pumping power. For an active medium with a 3 mm diameter and a pumping power of 4000 W, a conversion efficiency of 2.5% ($\eta_d=0.025$) was achieved, corresponding to a maximum laser output power of 93 W at a front mirror reflectivity of 90%. These results align with previous studies [10], validating the proposed model and reinforcing the potential of solar-pumped lasers for high-efficiency energy conversion.

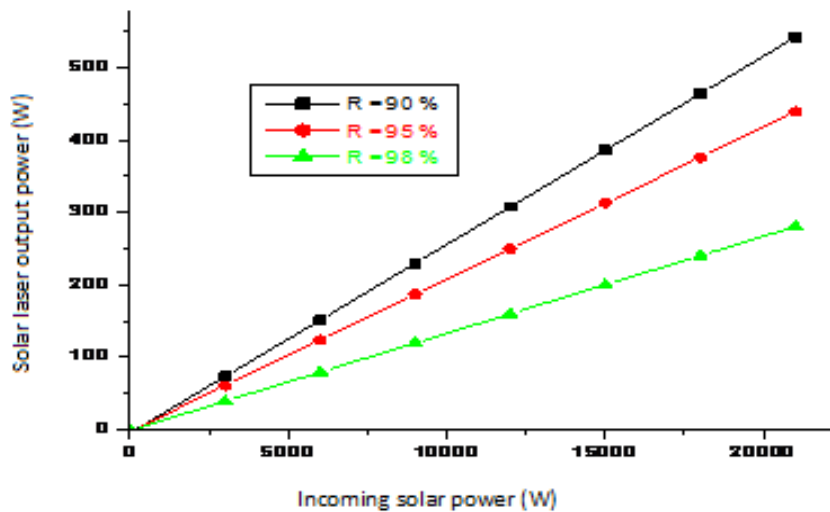


Figure 2: solar laser output power as a of fonction inconing solar power.



b. Gain of the Studied Solar Laser

Figure 3 depicts the variation in solar laser gain as a function of solar pumping power for an active medium with dimensions $3 \times 40 \text{ mm}^2$. The findings indicate that at a specific solar pumping power, the laser gain reaches 4% ($g_0 = 4\%$). This demonstrates the direct correlation between pumping power and gain, highlighting the efficiency of the studied solar-pumped laser system.

c. Influence of the Active Medium Diameter on Solar Laser Output Power, Gain, and Threshold Pumping Power

To assess the impact of active medium diameter on solar laser performance, a systematic variation in size was conducted, with corresponding effects on output power, laser gain, and threshold pumping power presented in Figures 4, 5, and 6, respectively. The results show that for a laser rod with dimensions $3 \times 40 \text{ mm}^2$, the laser gain reaches 4% ($g_0 = 4\%$), while the maximum solar laser output power is 93 W ($P_{\text{OUT}} = 93 \text{ W}$). These findings align with previous research [11], further validating the proposed model and confirming the strong dependence of solar laser performance on active medium dimensions.

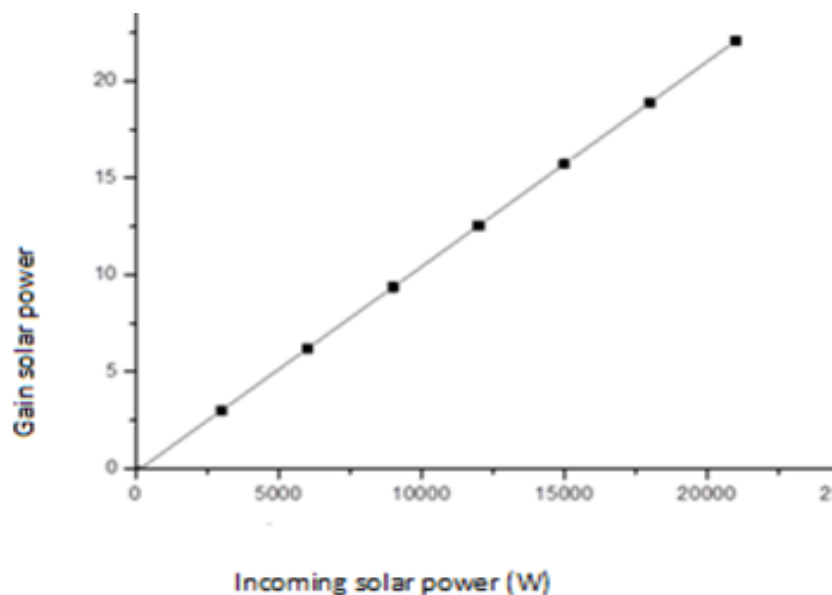


Figure 3: depicts the variation in solar laser gain as a function of solar pumping power

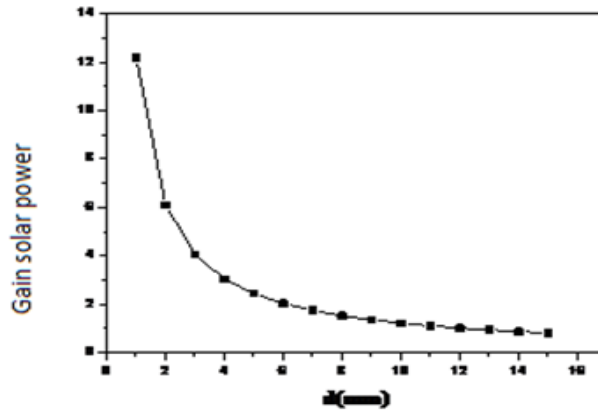


Figure 4: solar laser gain as a fonction of the active medium diameter.

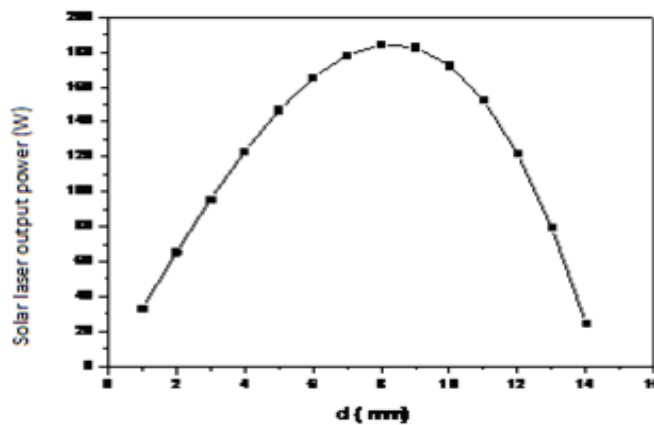


Figure 5: solar laser output power as a fonction of the active medium diameter

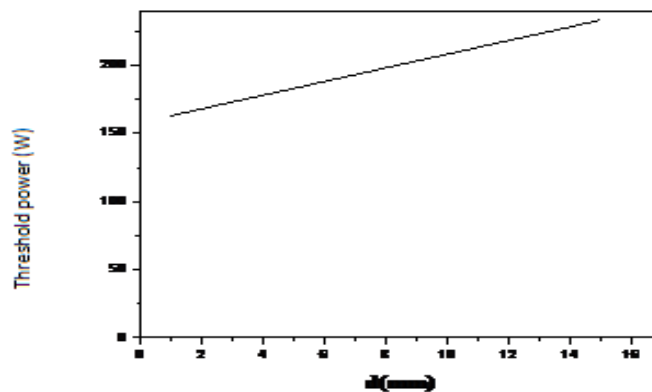


Figure 6: Threshod power as a fonction of the active medium diameter

7. Conclusion

This study investigated the direct conversion of sunlight into laser light through solar pumping, utilizing an Nd:YAG crystal as the laser medium. Nd:YAG was selected for its low pumping



threshold, making it highly efficient for solar laser applications. The side-pumping technique was implemented to excite the active medium, and a theoretical model was developed to evaluate the impact of key parameters on solar laser system performance.

The findings demonstrate that using an Nd:YAG laser medium of $3 \times 40 \text{ mm}^2$, with a laser cavity front mirror reflectivity of 90% and an input solar power of 4000 W, the system achieves a solar laser gain of 4% ($g_0 = 4\%$) and a maximum output power of 93 W ($P_{\text{OUT}} = 93 \text{ W}$), corresponding to a conversion efficiency of 2.5% ($\eta_d = 0.025$). These results align with previous studies, validating the feasibility and efficiency of solar-pumped Nd:YAG lasers for sustainable energy applications.

Overall, this following work confirms that solar-pumped laser technology offers a promising pathway for high-efficiency, renewable energy conversion. Future research should focus on optimizing active medium dimensions, enhancing light absorption techniques, and improving system scalability to further advance solar laser applications in various scientific and industrial fields.

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