

Numerical analysis of a four-rod Ce:Nd:YAG solar laser with 8.09% conversion efficiency

MAROUA REGUIG^{1,2}, SAID MEHELLOU^{1,2,*}, RABEH BOUTAKA³, HAMZA ADAIKA¹

¹University of El Oued, 39000 El Oued, Algeria

²LEVRES Laboratory, University of El Oued, 39000 El Oued, Algeria

³Center for Development of Advanced Technologies, Cité 20 Août 1956, BP 17, Baba Hassan, Algiers, Algeria

Solar-pumped lasers (SPLs) rely primarily on solar energy without the need for electrical power, which directly converts sunlight into laser. In this work, three end-side-pumping configurations were numerically investigated using a Ring-Array Concentrator (RAC) with an effective collection area of 0.785 m². The first configuration employed a single Nd:YAG rod (4 mm diameter, 16 mm length), achieving a collection efficiency (CE) of 49.1 W/m², a solar-to-laser conversion efficiency (SLCE) of 4.9%, and a slope efficiency of 6.1% under 1000 W/m² solar irradiance. However, thermal stress reached 182.5 N/mm², close to the fracture limit. To overcome this, a second configuration using four thin Nd:YAG rods (2 mm diameter, 16 mm length each) was designed, distributing the concentrated solar energy among four rods. This configuration achieved a total laser power of 43.9 W (CE = 55.9 W/m², SLCE = 5.59%, slope efficiency = 6.45%), while significantly reducing thermal stress to 44.92 N/mm² and maximum temperature to 326.6 K. Finally, to maximize efficiency, the active material was replaced with Ce:Nd:YAG (0.1 at. % Ce, 1.1 at.% Nd) while maintaining the same four-rod geometry. Under 890 W/m² solar irradiance, this configuration produced a record total laser power of 56.4 W (14.1 W per rod), corresponding to a CE of 71.3 W/m², an SLCE of 8.09%, and a slope efficiency of 9.33%, which are 1.73, 1.74, and 1.22 times higher, respectively, than the previous records by Liang et al. (41.25 W/m² and 4.64%) using three Ce:Nd:YAG rods. Thermal stress remained within safe limits at 75.79 N/mm². These results demonstrate that the four-thin-rod Ce:Nd:YAG configuration with an RAC concentrator offers an optimal balance between high efficiency and acceptable thermal stress, providing a practical and scalable solution for high-power solar lasers.

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1. Introduction

Recently, solar energy is attracting more attention from scientists worldwide due to its renewable, clean, and environmentally friendly nature. Sunlight is abundant, especially in space, and can be utilized both directly and indirectly for various space applications. Solar-pumped lasers (SPLs) are one of the important applications of solar energy, which can be directly pumped by sunlight, and eliminate the need for electrical equipment in the pumping process. It works by extracting narrow-band laser light from broad-band sunlight. In solid-state lasers, SPLs can be used in various applications, mainly in space, including free-space power transmission and laser communication [1,2]. Additionally, SPLs can be used effectively in solar hydrogen generation [3,4].

Over the past sixty years, numerous researchers have studied solar-pumped laser (SPL) designs to enhance solar laser performance, employing both simple and compound solar concentrators along with various pumping methods. The ratio of the primary solar concentrator's collection area to the laser's output power, known as collection efficiency (CE) [5,6], and the brightness figure, which measures laser beam quality, are critical factors in determining solar laser efficiency. Researchers focus on enhancing these factors by using advanced primary

concentrators instead of the ordinary parabolic mirrors and Fresnel lenses, such as the ring-array concentrator (RAC), or by employing advanced laser materials which capable of absorbing a largest amount of solar energy. Optimization of the solar pumping cavities and its thermal management, the multirod technics can also improve the solar laser collection efficiency.

The first SPL was reported by Young in 1966 using a parabolic mirror with an Nd:YAG rod, achieving 1 W [7]. In 1984, Arashi et al. achieved 18 W with a large parabolic mirror [8]. Using a 6.75 m² parabolic mirror with CPCs, Lando et al. reached a CE of 6.7 W/m² in 2003 [5]. In 2007, Yabe et al. used a Fresnel lens to pump a Cr:Nd:YAG rod, achieving 24.4 W [9]. Using a 0.64 m² Fresnel lens, Liang and Almeida obtained a CE of 19.3 W/m² in 2011 [10]. Dinh et al. reported 120 W with a Fresnel lens in 2012 [11], and Guan et al. achieved a CE of 32.1 W/m² in 2018 [12].

The adoption of an RAC concentrator has led to substantial enhancements in SPL efficiency. In 2018, Tibúrcio and Matos et al. designed RAC concentrators for pumping Nd:YAG rods, achieving CEs of 38.2 W/m² and 38.4 W/m², respectively [13,14]. Numerical studies on RAC concentrators, rod grooving impact, and sunlight-pumped laser performance have been conducted by Boutaka and Mehellou et al. [15-17]. More recently,

Boutaka et al. achieved a high CE of 48.4 W/m² using an off-axis mirror concentrator under a solar irradiance of 1200 W/m² [18].

Ce:Nd:YAG has recently emerged as one of the most effective laser media for improving the efficiency of solar-pumped lasers, showing notable enhancements in solar laser performance compared to the conventional Nd:YAG medium [19,20]. This improvement is primarily due to the Ce³⁺ ions, which act as efficient sensitizers owing to their two broad and strong absorption bands in the ultraviolet and blue regions (centered around 340 nm and 460 nm). These bands overlap effectively with the high-intensity region of the solar spectrum, leading to higher absorption of optical energy. The absorbed energy is then transferred from Ce³⁺ to Nd³⁺ ions through both radiative and non-radiative mechanisms, significantly increasing the number of excited Nd³⁺ ions [21,22].

The first successful use of a Ce:Nd:YAG medium in a solar laser was reported by Vistas and co-workers in 2020 using an end-side-pumping configuration, producing 6 W with a solar-to-laser conversion efficiency (SLCE) of 0.57%. However, when attempting to further increase the laser power, the crystal rod fractured due to the severe thermal issues caused by the non-uniform light distribution [23]. To overcome this problem, side-pumping configurations were adopted to alleviate the thermal load thanks to the more uniform distribution of the pump light along the active medium axis. This contributed to successive record-breaking achievements [19,24]. In 2021, Vistas and his team reported a record collection efficiency of 23.6 W/m² by side-pumping a Ce:Nd:YAG rod [24]. Despite this, end-side-pumping configurations also played a major role in improving solar laser performance [20,22,25,26]. In 2022, Garcia and colleagues achieved a remarkable solar-to-laser conversion efficiency of 4.5% by end-side-pumping a thin Ce:Nd:YAG rod using a small parabolic mirror [25]. Moreover, according to the recent review by Liang et al. [27], multi-thin-rod pumping configurations have proven their effectiveness in achieving rapid performance improvements. In the same year, Liang and co-workers set new records in collection efficiency (41.25 W/m²) and conversion efficiency (4.64%) by simultaneously pumping three Ce:Nd:YAG rods inside a single pump cavity [20]. Almeida and his team achieved a total continuous-wave laser power of 58 W by side-pumping two Ce:Nd:YAG rods, with a tracking error compensation width of 5.1° [28]. Costa and co-workers achieved an SLCE of 4.49% by pumping four Ce:Nd:YAG rods using a Fresnel lens [26].

More recently, in 2025, Wang et al. achieved a solar laser power of 89.29 W with a SLCE of 3.96% [29], and later in 2026, they reached 97.28 W with a SLCE of 4.49% [30]. For fundamental mode operation, Liang et al. reported the first simultaneous emission of three TEM₀₀-mode beams [31], while Costa et al. demonstrated the first simultaneous emission of four TEM₀₀-mode beams [32]. Tibúrcio et al. achieved the first simultaneous emission of multimode and TEM₀₀ beams from a single laser head [33]. Numerical simulations have further explored multi-

rod configurations; Matos et al. proposed a five-rod concept achieving a simulated TEM₀₀ collection efficiency of 51.7 W/m² and SLCE of 5.44% [34], while Vistas et al. simulated four-rod and three-rod configurations achieving multimode power of 134 W (CE = 49.1 W/m²) and TEM₀₀ power of 57.5 W (CE = 21.1 W/m²) [35]. Despite this remarkable progress, achieving stable, high-brightness TEM₀₀-mode operation remains a major challenge [22].

In the present work, three end-side-pumping configurations were numerically investigated using a ring-array concentrator (RAC) with a total effective collection area of 0.785 m². The first configuration consists of a single Nd:YAG rod (4 mm diameter, 16 mm length). The second configuration uses four thin Nd:YAG rods (2 mm diameter, 16 mm length each) to distribute the concentrated solar energy and reduce thermal stress. The third configuration employs four Ce:Nd:YAG rods (0.1 at.% Ce, 1.1 at.% Nd) with the same geometry to maximize laser efficiency. All configurations share the same laser head components: a curved silica cover, a conical pump cavity, and an active water cooling system. To simulate and optimize these designs, ZEMAX[®] and LASCAD[™] software were employed. The obtained results are compared with previous records from the literature, showing significant improvements in collection efficiency, solar-to-laser conversion efficiency, and slope efficiency.

2. Solar-pumped laser design

2.1. Solar concentrator system

Ring-array concentrators (RACs) were first presented by Vasylyev et al. in 2002 [36]. This design is composed of many concentric rings with different diameters and curvatures placed on the same axis and direction. Compared to the systems of heliostat-parabolic mirrors, this design is distinguished by preventing the formation of shadowed areas along the path of the solar rays to the focal point. This is accomplished by focusing the rays on a single point on the collector's backside. The RAC also offers higher CE compared to Fresnel lenses because it avoids chromatic aberration along the focal zone.

The solar concentration system consists of a Ring-Array Concentrator (RAC) comprising a central Fresnel lens and nine concentric rings, each with 95% reflectivity. In the central region of the RAC, a small Fresnel lens with a diameter of 100 mm, a conic factor of -0.1, a groove frequency of 0.3, a depth of 3 mm and a pitch of 12° is mounted, as illustrated in Fig. 1. This central lens has a thickness of 3 mm and a focal length of 529 mm. It is made of polymethyl methacrylate (PMMA) material. Table 1 summarizes the main parameters of the nine concentric rings and the central Fresnel lens, including the maximum and minimum apertures, focal length, and radius of curvature. The rings with their curvature and locations were designed using ZEMAX[®] software.

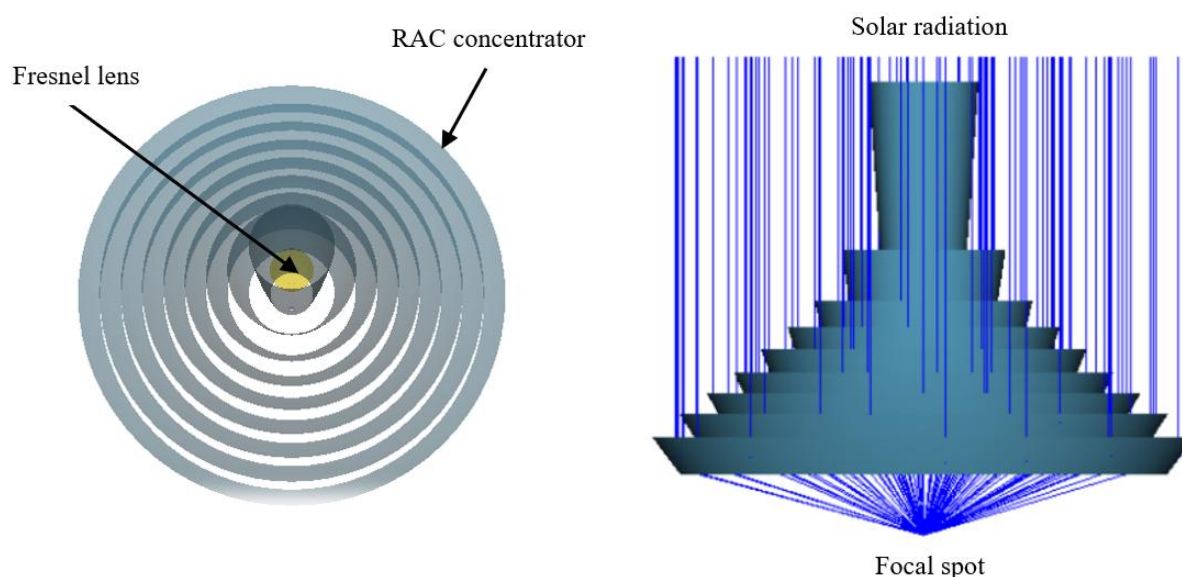


Fig. 1. RAC design featuring nine concentric rings and compact Fresnel lens (colour online)

Table 1 provides a summary of various parameters for the ring-array concentrator used in this study, including the

minimum and maximum apertures, as well as the radius of curvature for each ring.

Table 1. Specifications of all rings in the RAC and Fresnel lens

Reflective rings	Minimum diameter (mm)	Maximum diameter (mm)	Radius of curvature (mm)	Focal length (mm)
Ring 1	900	1000	350	114.3
Ring 2	800	900	278	148.77
Ring 3	700	800	215	177.4
Ring 4	600	700	160	201.25
Ring 5	500	600	112	223
Ring 6	400	500	74	233.27
Ring 7	300	400	44	233.7
Ring 8	200	300	21	227.6
Ring 9	100	200	6	205.33
Fresnel lens	0	100	260	529

The large reflective ring measures 1.0 m in diameter, providing 0.78 m² of effective collection area. As illustrated in Fig. 2, by assuming a solar irradiance of 1000 W/m², this RAC primary concentrator can concentrate a

solar power of 785 W at its focal zone (about 250 mm from the center of the RAC), in a near-Gaussian spot shape with a full-width at half maximum of 10 mm.

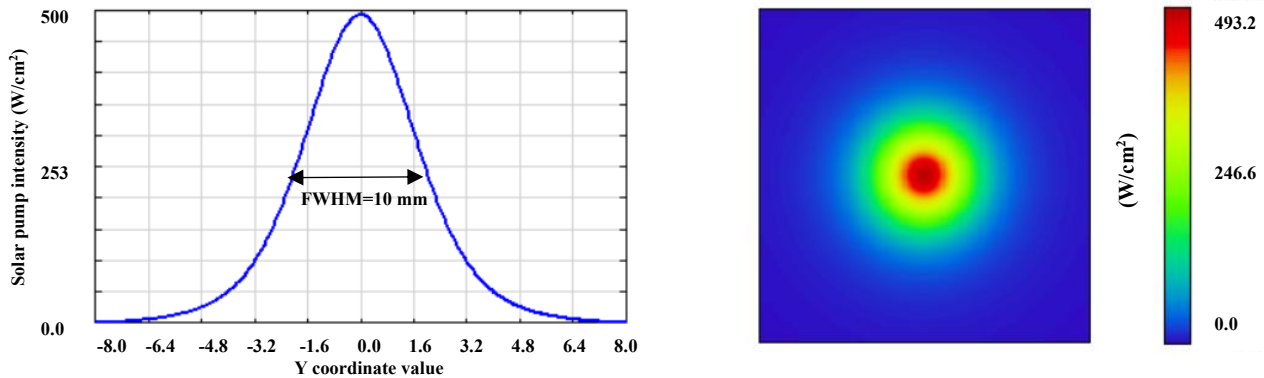


Fig. 2. Distribution of pump light intensity at the RAC focal zone (colour online)

2.2. Laser head system

The system of laser head consists of a crystal rod, a conical pump cavity, and a curved silica cover with a cooling water system, as shown in Fig. 3. Cooling the crystal rod with water is crucial for dissipating infrared heat and preventing UV-induced solarization.

In this study, two different end-side-pumped configurations were designed and investigated: a single-rod Nd:YAG configuration and a four-rod configuration using both Nd:YAG and Ce:Nd:YAG rods. Each configuration consists of a curved silica cover, a conical pump cavity, and laser rods of identical length but different diameters and numbers. The laser rods are actively cooled by water to dissipate the generated heat

and prevent UV-induced solarization. The schematic design of each laser head is illustrated in its respective figure: Fig. 3 for the single-rod Nd:YAG configuration and Fig. 4 for the four-rod (Ce:Nd:YAG and Nd:YAG) configuration. The detailed dimensions of all components for both configurations are summarized in Table 2.

The inner wall of the pumping cavity was coated with aluminum foil that has protective layer of silver, offering a reflectivity up to 98%. The crystal rod's front face was coated with a high-reflection layer at 1064 nm. Within the resonator cavity, this HR coating reflects the 1064 nm laser radiation and permits other wavelengths to pass through. At the rear end of the laser rod, an output mirror with 95% reflectance and 1000 mm radius of curvature is placed 10 mm away.

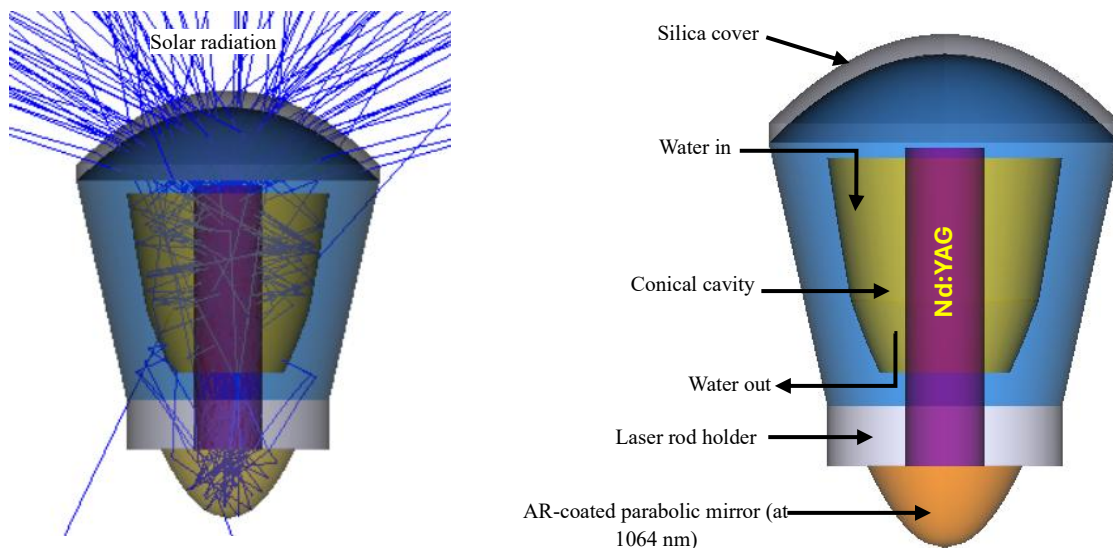


Fig. 3. Laser head design configured for end-side-pumping (single-rod Nd:YAG) (colour online)

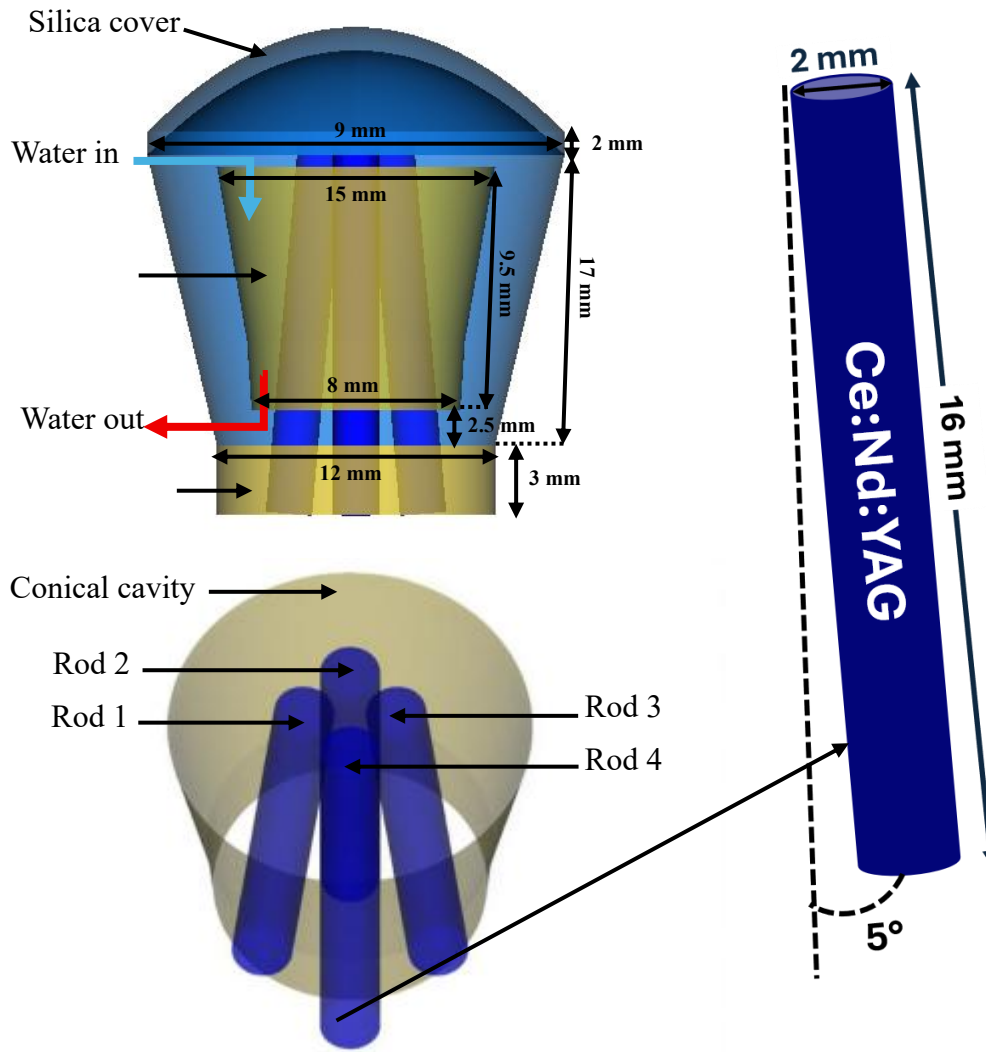


Fig. 4. Schematic of the four-rod (Ce:Nd:YAG and Nd:YAG) end-side-pumped laser head (colour online)

Table 2. Dimensions of the laser head components

Single-rod Nd:YAG configuration dimensions			Four-rod Ce:Nd:YAG and Nd:YAG configuration dimensions		
Silica cover	Conical cavity	Rod	Silica cover	Conical cavity	Rod
Diameter (9 mm)	Input diameter (12 mm)	Diameter (4 mm)	Diameter (9 mm)	Input diameter (15 mm)	Diameter (2 mm)
Thickness (2 mm)	Output diameter (8 mm)		Thickness (2 mm)	Output diameter (8 mm)	
Radius of curvature (9 mm)	Height (11 mm)	Length (16 mm)	Radius of curvature (9 mm)	Height (9.5 mm)	Length (16 mm)

3. Analytical estimation of laser output power

The output power of the laser (P_{out}) can be determined analytically using the incoming solar power ($P_{incoming}$) and other measurable factors, as expressed in the following equation [37].

$$P_{out} = \left(\frac{1-R}{1+R} \right) \left(\frac{2\eta_{ovp}\eta_T\eta_A\eta_Q\eta_S\eta_B}{2\alpha l - \ln R} P_{incoming} - A I_s \right) \quad (1)$$

where for single-rod Nd:YAG configuration;

- R ; The output coupler reflectivity (95%)
- I_s ; The saturation intensity (2.9 kW/cm² for Nd:YAG medium) [37]

- A ; The rod cross-section area (0.1252 cm^2)
- L ; The rod length (1.6 cm)
- α ; The typical scattering coefficient of the laser material (0.003 cm^{-1})
- $2\alpha l$; The two-way loss within the resonator (0.0096)
- η_{OVP} ; The overlap of the laser medium's absorption spectrum with the solar emission spectrum (0.16 for Nd:YAG) [38]
- η_T ; The transfer efficiency (0.85 Zemax)
- η_A ; The absorption efficiency by the laser medium (0.73 Zemax)
- η_S ; Stokes factor (0.62) [6]
- η_Q ; Quantum efficiency (0.90) [37]
- η_B ; The beam overlap efficiency (≈ 1 for multimode operation and ≈ 0.36 for TEM₀₀ mode) [39]

The slope efficiency η_{slope} can be obtained by calculating it from Eq. (1), and is given as Eq. (2) [37]:

$$\eta_{slope} = \left(\frac{1-R}{1+R} \right) \left(\frac{2\eta_{OVP}\eta_T\eta_A\eta_Q\eta_S\eta_B}{2\alpha l - \ln R} \right) \quad (2)$$

The threshold pump power P_{Th} is determined by Eq. (3) [37]:

$$P_{Th} = \frac{2\alpha l - \ln R}{2\eta_{OVP}\eta_T\eta_A\eta_Q\eta_S\eta_B} A I_s \quad (3)$$

In the next section, more precise laser output power calculations are presented using ZEMAX® and LASCAD™ software, taking into account the profile of absorbed pump power and the related thermal effects inside the laser medium.

3.1. ZEMAX® analysis

3.1.1. Numerical modeling of Nd:YAG configurations

To improve the absorption of pump power within the laser rod, the non-sequential method of ZEMAX® software was used to quantitatively optimize the RAC and the laser head characteristics. A number of factors were added to the ZEMAX® database, including the sun's half angle of ± 0.27 degrees and the solar irradiance of 1000 W/m^2 . For the 1.0% Nd³⁺ doped YAG, the numerical data identified 22 absorption peaks [10,40]. 527, 531, 568, 578, 586, 592, 732, 736, 743, 746, 753, 758, 790, 793, 803, 805, 808, 811, 815, 820, 865, and 880 nm are the core wavelengths of these peaks. The ZEMAX® glass catalog contained these peaks along with the absorption coefficients that corresponded to them. The conventional solar spectrum for one-and-a-half air masses (AM1.5) was utilized as a reference for the spectral irradiance values for these absorption wavelengths [41]. The numerical data also contained the wavelength-dependent refractive indices of water and fused silica as well as their absorption spectra. The ZEMAX® software was also developed to account for spectral changes, including transmission through reflecting rings and reflectance from the heliostat mirror. The 0.16 spectral overlap was taken into consideration when calculating the light source's effective pump power [38,42]. Because of its advantageous in thermal conductivity ($K = 14 \text{ W m}^{-1} \text{ K}^{-1}$) [37], tensile strength ($\sigma = 200 \text{ N mm}^{-2}$) [37], and high quantum efficiency, the Nd:YAG material has proven to be more effective for SPLs than other laser materials.

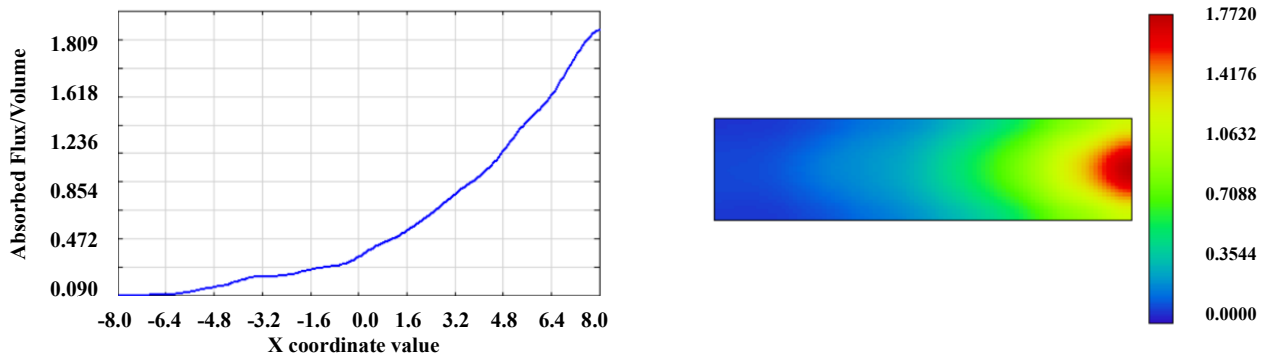


Fig. 5. Spatial distribution of absorbed pump flux in an Nd:YAG rod (4 mm diameter, 16 mm length) (colour online)

The laser medium was divided into 18,000 distinct sections in order to examine ray tracing in ZEMAX®. This allowed for the computation of the route length for each area. The total absorbed pump radiation in this rod was

calculated by adding together the absorbed pump power in each location using this data and the 1.0% effective absorption efficiency for Nd³⁺ doped YAG. The distributions of the absorbed pump flux in a 16 mm long

by 4 mm wide crystal rod are shown in Fig. 4 in one longitudinal section. Spots with almost maximum pump absorption are indicated by red spots, whereas locations with little to no absorption are indicated by blue areas.

As illustrated in Fig. 5, the end-side pumped configuration in SPLs increases the absorbed pump power by producing a more concentrated pump flux close to the upper-end region of the laser rod. ZEMAX® software was used to numerically analyze various RAC focal lengths in order to optimize the pumping flux inside the Nd:YAG rod. Following additional processing of the absorbed pump flux data from the ZEMAX® analysis, the laser resonator parameters were adjusted using LASCAD™ software.

3.1.2. Numerical modeling of Ce:Nd:YAG configurations

The design was optimized using ZEMAX® 13 (non-sequential ray-tracing) to maximize absorbed pump power, followed by LASCAD™ to determine optimal resonator parameters for maximum laser extraction [43].

As given in Table 3, two circular solar sources (total area 0.785 m², matching the RAC concentrator) were defined. Source 1 represents wavelengths absorbed by Nd³⁺ and non-radiative Ce³⁺→Nd³⁺ transfer (quantum cutting) [21]. Source 2 represents radiative Ce³⁺→Nd³⁺

transfer. A solar irradiance of 890 W/m² was assumed [43]. The source powers were calculated using Equations (4) and (5) [43]:

$$P_{\text{source 1}} = A_{\text{ef}} \times I_S \times (\eta_{\text{Nd}^{3+}} + \eta_{\text{Ce}^{3+}} \times \eta_{\text{NR}}) \quad (4)$$

$$P_{\text{source 2}} = A_{\text{ef}} \times I_S \times (\eta_{\text{Ce}^{3+}} \times \eta_{\text{R}}) \quad (5)$$

where,

- A_{ef} denotes the effective collection area (0.785 m²)
- I_S is the terrestrial solar irradiance. (890 W/ m²)
- $\eta_{\text{Nd}^{3+}}$ is the spectral overlap between the Nd³⁺ absorption spectrum and the solar emission spectrum, i.e., 16% [43].
- $\eta_{\text{Ce}^{3+}}$ is the spectral overlap between the Ce³⁺ absorption spectrum and the solar emission spectrum, i.e., 15.3% [43].
- η_{NR} is representative of the proportion of energy absorbed by Ce³⁺ ions that could be transferred non-radiatively to Nd³⁺, i.e., 70% [44].
- η_{R} is the fraction of energy absorbed by Ce³⁺ ions that could be transferred radiatively to Nd³⁺, i.e., 30% [44].

Table 3. Pump source parameters and power calculations for Ce:Nd:YAG solar laser ray-tracing simulation

Parameter	Source 1	Source 2
Mechanism	Nd ³⁺ direct absorption + Ce ³⁺ → Nd ³⁺ non radiative transfer [21, 43]	Ce ³⁺ → Nd ³⁺ radiative transfer (fluorescence) [21, 43]
Wavelength	22 wavelengths (527, 531, 569, 579, 586, 592, 732, 736, 743, 746, 753, 758, 790, 793, 803, 805, 808, 811, 815, 820, 865, 880 nm), weighted by AM1.5D. [21, 43]	6 wavelengths (527, 531, 569, 579, 586, 592 nm), weighted by Ce ³⁺ fluorescence intensity. [21, 43]
Power equation	$P_{\text{source 1}} = A_{\text{ef}} \times I_S \times (\eta_{\text{Nd}^{3+}} + \eta_{\text{Ce}^{3+}} \times \eta_{\text{NR}})$ [43]	$P_{\text{source 2}} = A_{\text{ef}} \times I_S \times (\eta_{\text{Ce}^{3+}} \times \eta_{\text{R}})$ [43]
Power (at 1000 W/m ²)	$P_{\text{source 1}} = 209.7 \text{ W}$	$P_{\text{source 2}} = 36.0 \text{ W}$
Power (at 890 W/m ²)	$P_{\text{source 1}} = 186.7 \text{ W}$	$P_{\text{source 2}} = 32.1 \text{ W}$

3.2. LASCAD analysis

To calculate and optimize the laser power, the data of the absorbed pump power obtained from ZEMAX® was further analyzed by LASCAD™ software. This analysis considered several key factors, including: fluorescence lifetime (230 μs); stimulated emission cross-section (2.8×10⁻¹⁹ cm⁻¹); absorption and scattering losses are generally about 0.003 cm⁻¹; Mean absorbed and intensity

weighted solar pump wavelength (660 nm for Nd:YAG). The upper-end face of the rod was coated for 1064 nm of the laser emission wavelength (R > 98.8%), while the bottom-end face was anti-reflection (AR) coated for 1064 nm (R < 0.2%). The output coupler was partial-reflection (PR) coated at 1064 nm. The laser resonator configuration consisted of a high reflector at 1064 nm, a laser rod, and a PR output coupler, placed 10 mm away from the bottom AR face of the rod, as shown in Fig. 6.

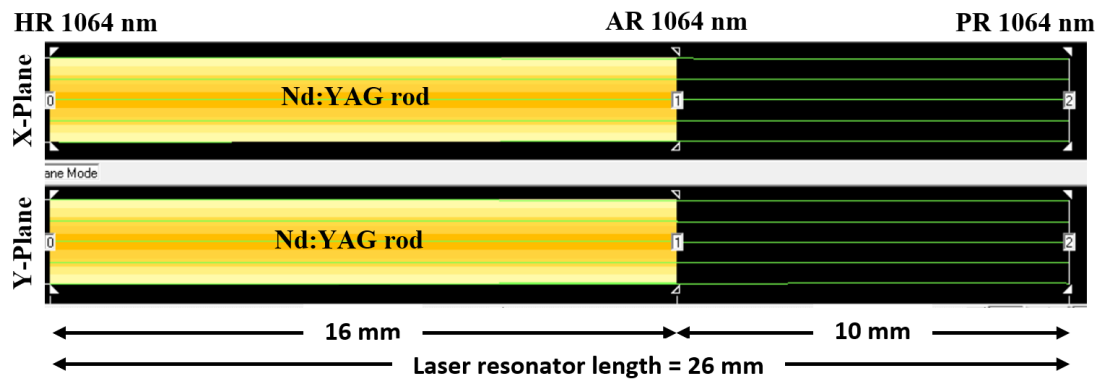


Fig. 6. SPL optical resonator for multimode laser power efficient extraction (colour online)

To determine the optimal output mirror reflectivity that yields maximum laser power, the laser output power was computed as a function of output mirror reflectivity for a 4 mm-diameter, 16 mm-length Nd:YAG rod using LASCAD™ simulation software, as shown in Fig. 6. The output mirror reflectivity values shown in Fig. 6 range from 90% to 98%.

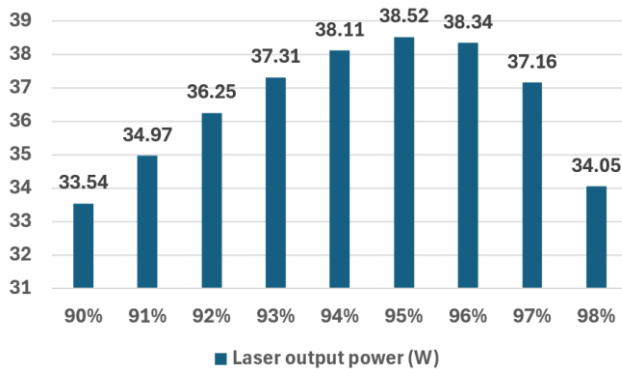


Fig. 7. Column graph of the laser output power versus the output mirror reflectivity, extracting from a 4 mm-diameter, 16 mm-length laser rod under solar light pumping (colour online)

Fig. 7 demonstrates that the highest obtained laser output power was 38.52 W for an output mirror reflectivity of 95%, while the lowest laser output power was 33.54 W for a reflectivity of 90%. These results indicate that the optimal reflectivity for maximizing laser output power is 95%.

Using 1000 W/m² of a solar terrestrial intensity, Fig. 8 illustrates the solar laser power computed as a function of the incoming solar power. For the maximum absorbed solar power of 91.4 W (which is equivalent to 785.4 W of incoming solar power) with a coupler reflectivity of 95%, a laser power of 38.52 W was achieved. 6.1% slope efficiency was then calculated based on the slope of the Fig. 7 graph.

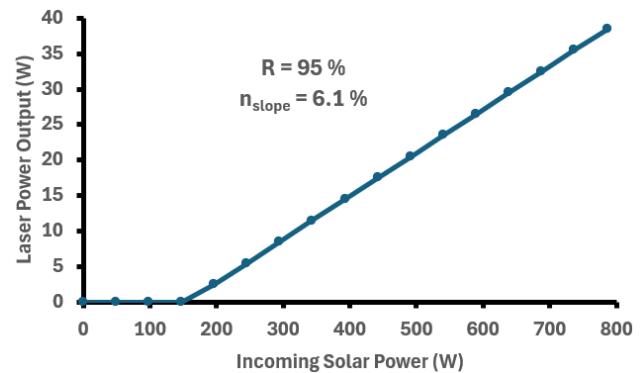


Fig. 8. Laser output power as a function of the incoming solar power (colour online)

3.3. Optimization of the Nd:YAG rod geometry

Fig. 9(a) demonstrates that under a fixed rod length of 16 mm, varying the diameter yielded peak solar energy absorption of 98.6 W at 5 mm, while the optimal output laser power of 38.5 W was attained with a 4 mm diameter. Conversely, when the rod diameter was fixed at 4 mm and the length was varied (Fig. 9(b)), maximum energy absorption of 92.1 W occurred at 18 mm, yet the highest laser output power of 38.52 W remained achievable at 16 mm length.

These findings indicate that although larger rod dimensions enhance solar energy absorption, excessively large geometries introduce parasitic losses with diminishing returns in radiative stimulation within the laser cavity. Consequently, achieving peak system efficiency necessitates balancing absorption enhancement against thermal and optical loss mitigation. Geometric optimization is therefore critical for maximizing energy conversion efficiency in SPL systems [45].

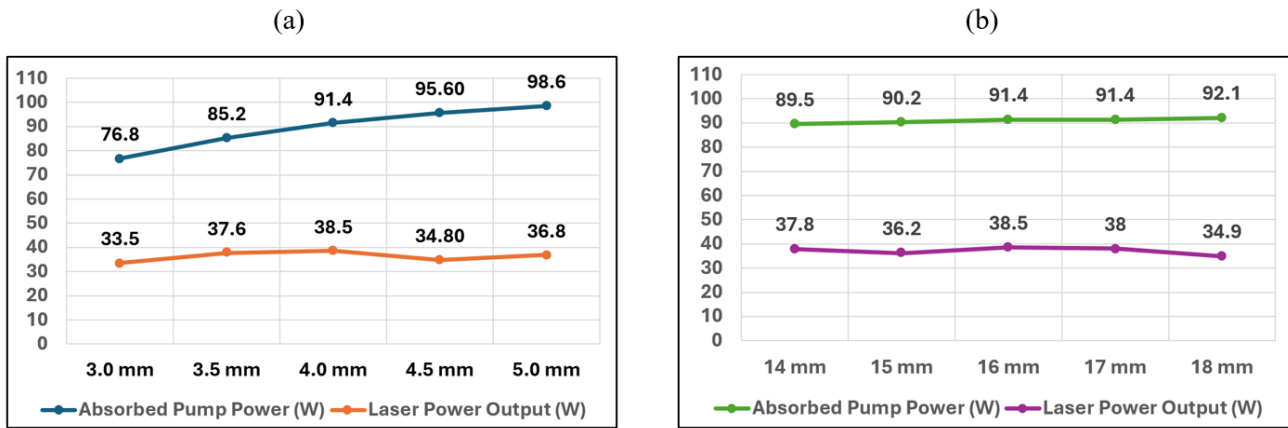


Fig. 9. Numerical calculation of absorbed pump power and laser power based on (a) the diameter and (b) the length of Nd:YAG rod (colour online)

3.4. Thermal behavior analysis of the laser rod

The LASCADTM analysis integrates the pump flux absorbed by the Nd:YAG medium, as determined by ZEMAX[®] analysis, across the entire rod volume. This analysis focuses on the thermal effects, including temperature distribution, heat load, and stress intensity, within the crystal rod as illustrated in Fig. 10.

Since the distribution of the absorbed pump flux was found nonuniform along the laser rod, remarkable thermal problems were then obtained in its upper part. A peak heat load of 1.418 W/mm³ was found by numerical analysis

using LASCADTM, raising the temperature from 399.4 K at the input end face of the rod to 295.6 K at the output end face. W. Koechner stated that 200 N/mm² is the stress fracture limit for Nd:YAG [37]. In this work, the maximum thermal stress intensity reached 182.5 N/mm², which is less than the stress fracture limit. Moreover, 84% of the solar energy is unabsorbed (only 16% of the solar emission spectrum overlaps with the Nd:YAG absorption spectrum [38,41]). Consequently, this unabsorbed radiation, which has a wavelength between 0.25 and 2.5 μ m, leads to generate more heat within the rod.

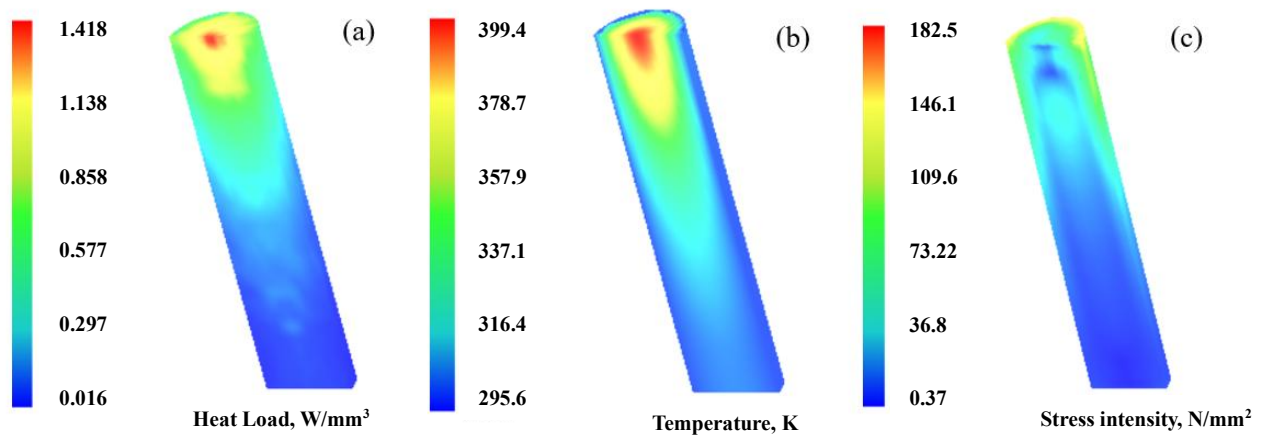


Fig. 10. Numerical results of (a) heat load, (b) temperature, and (c) stress intensity in the crystal rod, calculated through the finite element method of LASCADTM software (colour online)

The thermal effects analysis with the absorbed and output power in Nd:YAG rod using different diameters (3.0 mm, 3.5 mm, 4.0 mm, 4.5 mm and 5.0 mm) are presented in Fig. 11, all the rods are 16 mm in length. As shown in this figure, the rod with a 4 mm diameter

demonstrates a higher laser power of 38.5 W compared to all rods that used in this study. However, the lowest stress intensities were 106.6 N/mm² and 140.6 N/mm², and the lowest temperatures were 372.8 K and 385.3 K for the rods of 3.0 mm and 3.5 mm diameter, respectively.

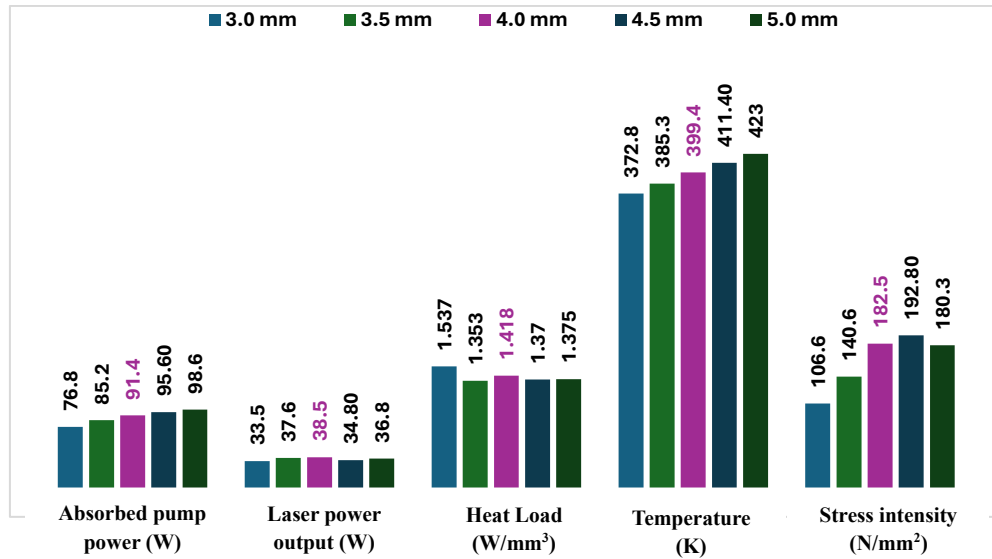


Fig. 11. Thermal effects inside the Nd:YAG laser rod for various diameters and lengths (colour online)

As observed in Fig. 11, by increasing the solar energy absorption a proportional rising in maximum temperature was obtained in the active medium. Furthermore, increasing the diameter of the rod leads to increase absorption of solar energy, which consequently results in a

more pronounced temperature rise within the medium. This behavior is attributed to the extended optical path length that enhances energy absorption according to the Beer-Lambert law [46].

Table 4. Main numerical results found in this research and in earlier works

Parameters	Ref [47] 2024	Ref [18] 2024	This work	Enhancement compared to Refs. [47] and [18] (times).	
Solar irradiance (W/m ²)	950	1200	1000	-	-
Collection area (m ²)	0.785			-	-
Rod dimensions (diameter × length) (mm)	(4 × 16)	(5 × 25)	(4 × 16)	-	-
Laser output power (W)	31.0	38	38.52	-	-
Collection efficiency (W/m ²)	39.5	48.4	49.1	1.24	1.01
Conversion efficiency (%)	4.13	4.03	4.9	1.19	1.22
Slope efficiency (%)	5.2	5.38	6.1	1.17	1.13

Table 4 summarizes the results obtained in this study alongside those of recent studies by employing the same active medium (Nd:YAG) and the same primary concentrator area of 0.785 m². Through comparison, significant improvements in SPL efficiency were observed. Compared to a study similar to ours used 0.785 m² RAC concentrator and an Nd:YAG rod with 16 mm length and 4 mm diameter, a substantial increase in collection efficiency, slope efficiency, and solar-to-laser conversion efficiency was observed, estimated at 1.24, 1.17, and 1.19 times, respectively [47], as presented in Table 4. One of the most important keys to explain the improvement of the solar laser performance achieved in our study is the use of a curved silica cover instead of a conventional fused silica aspheric lens. Although this latter can enhance the concentration of solar radiation in the

laser pumping cavity, it can also introduce significant losses at the solar radiation focal zone.

Furthermore, when compared to the most recent study that achieved the highest reported collection efficiency of 48.4 W/m² under high solar irradiance of 1200 W/m², our results demonstrate a considerable enhancement in collection, slope, and solar-to-laser conversion efficiencies, with improvements of 1.01, 1.13, and 1.22 times, respectively [18].

4. Discussion

4.1. Configuration 1: single-rod Nd:YAG

In this configuration, a single Nd:YAG rod (4 mm diameter, 16 mm length) was end-pumped using an RAC

(Ring-Array Concentrator) with an effective collection area of 0.785 m². Using a solar irradiance of 1000 W/m², the system produced a laser output power of 38.52 W, achieving a collection efficiency of 49.1 W/m², a solar-to-laser conversion efficiency of 4.9%, and a slope efficiency of 6.1%. Accordingly, this configuration achieved notable improvements in solar laser efficiency: the collection efficiency increased by 1.24 and 1.01 times compared to the previous records of studies that used the same RAC concentrator and the same effective area (0.785 m²) [17] and [18], respectively. In addition, the slope efficiency achieved a notable improvement of 1.17 and 1.13 times from the results of previous research [17] and [18], respectively, while a significant improvement in solar-to-laser conversion efficiency was observed by factors of 1.19 and 1.22 from the values recorded in previous works [17] and [18], respectively. In terms of thermal performance, the heat load reached 1.418 W/mm³, the maximum temperature was 399.4 K, while the stress intensity reached 182.5 N/mm², which is a relatively high value and indicates that the laser rod is close to the permissible thermal fracture limit (200 N/mm²), confirming the limited scalability of this design in terms of efficiency improvement.

4.2. Configuration 2: four-rod Nd:YAG

To overcome the problem of high thermal stress that appeared in the first configuration, the second configuration was designed, characterized by the use of four thin Nd:YAG rods instead of one thick rod. The four rods, having a length of 16 mm and a diameter of 2.0 mm, were fixed symmetrically around the central axis of the laser head. Some dimensions of the laser head components were modified to suit end-pumping of the four rods, as shown in Fig. 4. Using the same solar irradiance of 1000 W/m² and the same collection area (0.785 m²) of the RAC primary concentrator system. The results showed a

significant improvement, as the total laser output power reached 43.9 W (4 rods × 10.975 W per rod), with a collection efficiency of 55.9 W/m², a conversion efficiency of 5.59%, and a slope efficiency of 6.45%. These results exceed those of the first configuration by factors of 1.14, 1.14, and 1.06, respectively. More importantly, the stress intensity dropped dramatically to 44.92 N/mm² (i.e., 4 times lower than the first configuration), and the maximum temperature decreased to 326.6 K. All of this confirms that distributing the concentrated solar energy among four rods was effective in improving the thermal performance of the laser medium, which in turn contributed to the improvement of solar laser efficiency.

4.3. Configuration 3: four-rod Ce:Nd:YAG

In order to maximize laser efficiency while maintaining thermal stress within safe limits, the same design of the second configuration with four rods (same primary concentrator system, same laser head components, and same dimensions) was used, but this time replacing the active material of the laser rod from Nd:YAG to Ce:Nd:YAG (0.1 at.% Ce, 1.1 at.% Nd) with the same diameter (2.0 mm) and the same length (16 mm). Using 890 W/m² of solar irradiance, the results showed a remarkable leap in efficiency, as a total laser output power of 56.4 W (4 rods × 14.1 W per rod) was obtained, which is 1.28 times higher than the second configuration. As given in Table 5, the collection efficiency reached 71.3 W/m², the solar-to-laser conversion efficiency reached 8.09%, and the slope efficiency reached 9.33%, which are the highest values recorded in this study compared to the first and second configurations, as shown in Fig. 12. The beam quality factors were calculated using the Beam Propagation Method (BPM) in LASCADTM, yielding $M_x^2 = 52.2$ and $M_y^2 = 52.4$ for the four-rod Ce:Nd:YAG configuration.

Table 5. Summary of numerical results for the three end-side-pumped configurations (single-rod Nd:YAG, four-rod Nd:YAG, and four-rod Ce:Nd:YAG) using an RAC concentrator

Parameters	Single-rod Nd:YAG	Four-rod Nd:YAG	Four-rod Ce:Nd:YAG
Number of rods	1	4	4
Solar irradiance	1000 W/m ²	1000 W/m ²	890 W/m ²
Collection area	0.785 m ²		
Rod dimensions (diameter × length)	(4 × 16) (mm)	(2 × 16) (mm)	(2 × 16) (mm)
Laser output power	38.52 W	43.9 W	56.4 W
Collection efficiency	49.1 W/m ²	55.9 W/m ²	71.3 W/m ²
Conversion efficiency	4.9 %	5.59 %	8.09 %
Slope efficiency	6.1 %	6.45%	9.33 %
Heat load	1.418 W/mm ³	1.609 W/mm ³	2.75 W/mm ³
Temperature	399.4 K	326.6 K	345.1 K
Stress intensity	182.5 N/mm ²	44.92 N/mm ²	75.79 N/mm ²

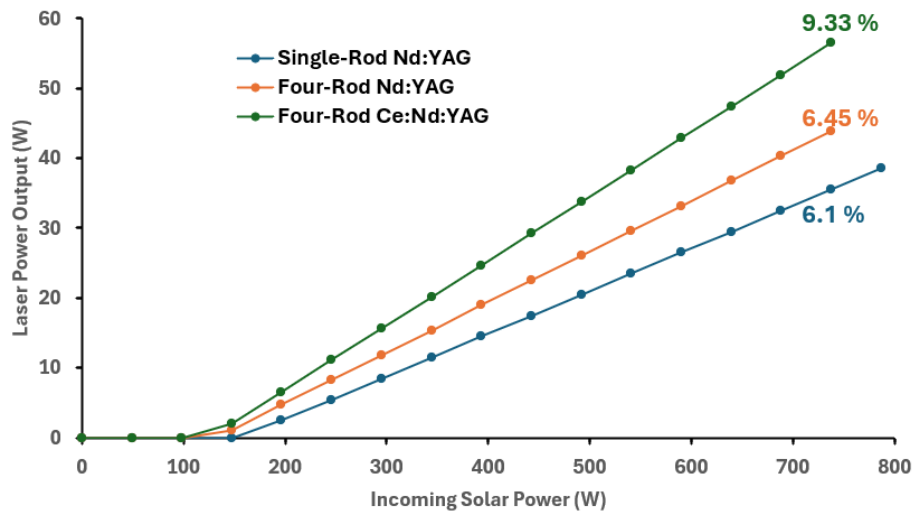


Fig. 12. Laser output power as a function of incoming solar power for the three investigated configurations: for single-rod Nd:YAG (blue line), for four-rod Nd:YAG (orange line), and for four-rod Ce:Nd:YAG (green line) (colour online)

As shown in Fig. 13, regarding thermal performance, the stress intensity recorded was 75.79 N/mm² and the maximum temperature was 345.1 K. Although these values are lower compared to the single-rod configuration, they are slightly higher than those of the second configuration with four rods, and this is due to the lower

Stokes efficiency of Ce:Nd:YAG (~0.55) compared to Nd:YAG (~0.62). Nevertheless, they remain within reasonable safe operating limits. Thus, the third configuration with four thin Ce:Nd:YAG rods is considered the optimal solution for balancing acceptable thermal performance and high efficiency.

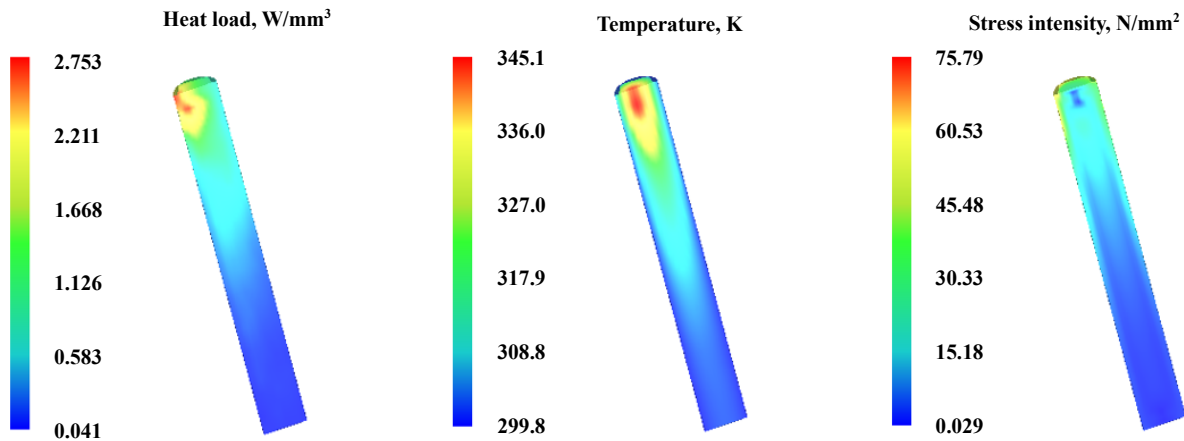


Fig. 13. Thermal behavior analysis of the four-rod Ce:Nd:YAG configuration: distribution of heat load (W/mm³), temperature (K), and stress intensity (N/mm²) along the laser rod axis (colour online)

As shown in Table 6, the results recorded in this study – collection efficiency (71.3 W/m²), conversion efficiency (8.09%), and slope efficiency (9.33%) – are 1.73, 1.74, and 1.22 times higher, respectively, than the results of the previous study by Liang et al. [20] despite using the same solar irradiance (890 W/m²). This significant improvement is due to the use of four thin rods (2 mm) instead of three rods (2.5 mm), which helps in improving thermal performance, and to the use of the RAC concentrator, which gives better concentration of light energy. Compared with the numerical results of Almeida et al. [47] (to the best of our knowledge) that simulated several

Ce:Nd:YAG rods, and despite their use of a larger collection area (1.767 m²) and higher solar irradiance (950 W/m²), this work achieved a collection efficiency that is 1.03 times higher. The conversion efficiency also exceeded the value recorded in the previous work [47] by an improvement factor of 1.11. As shown in the table, the stress intensity value in this work (75.79 N/mm²) was much lower than that recorded in reference [47] (127.4 N/mm²), confirming the superiority of the four-thin-rod design (2 mm) over the three-thick-rod design (4.5 mm) in both thermal performance and solar laser efficiency.

Table 6. Numerical results found in this research and in earlier works

Parameters	Ref, [2]	Ref, [29]		This work
Solar irradiance	890 W/m ²	950 W/m ²		890 W/m ²
Effective collection area	0.4 m ²	1.767 m ²		0.785 m ²
Rod dimensions (diameter × length)	(2.5 × 25) (mm)	(4.5 × 15) /mm)	(4.0 × 15) (mm)	(2.0 × 16) (mm)
Number of rods	3	3	4	4
Laser Power per Rod	5.5 W	40.93 W	29.99 W	14.0 W
Total laser power	16.5 W (3 × 5.5)	122.8 W (3 × 40.93)	120.0 W (4 × 29.99)	56.4 W (4 × 14.1)
Collection efficiency	41.25 W/m ²	69.5 W/m ²	67.91 W/m ²	71.3 W/m ²
Solar-to-laser conversion efficiency	4.64 %	7.31 %	7.15 %	8.09 %
Slope efficiency	7.64 %	-	-	9.33 %
Stress intensity	28.7 N/mm ²	127.4 N/mm ²	97.28 N/mm ²	75.79 N/mm ²

5. Conclusion

In this work, three end-side-pumping configurations were studied: a single-rod Nd:YAG design, a four-rod Nd:YAG design, and a four-rod Ce:Nd:YAG design. Using a modified RAC concentrator with the same area of 0.785 m², these configurations were numerically and analytically studied by optimizing the laser system parameters through ZEMAX® and LASCAD™ software. Significant improvements were consequently obtained in collection efficiency, solar-to-laser conversion efficiency, and slope efficiency. The third configuration, which uses four Ce:Nd:YAG rods (2.0 mm diameter, 16 mm length), proved to be the best solution, balancing high laser efficiency with acceptable thermal stress.

A total laser output power of 56.4 W was achieved, corresponding to a record collection efficiency of 71.3 W/m² and a record solar-to-laser conversion efficiency of 8.09%, which are 1.73 and 1.74 times higher, respectively, than the previous records of Liang et al. (41.25 W/m² and 4.64%) [20], and also exceed the previous numerical results of Almeida et al. (69.5 W/m² and 7.31%) [47] by factors of 1.03 and 1.11, respectively. A slope efficiency of 9.33% was also recorded, which is 1.22 times higher than the previous record (7.64%) [20].

Although the calculated thermal stress (75.79 N/mm²) is higher than the result recorded in Liang's system (28.7 N/mm²) [20] due to the high concentrated solar energy and the shorter pump wavelength of Ce:Nd:YAG, it remains well below the permissible limit. Compared with the numerical result of Almeida et al. (127.4 N/mm²) [48], it was 40% lower. The obtained thermal stress value in the present work is also better than the grooved Ce:Nd:YAG rod design results achieved by [49]. Thus, we conclude that the four-thin-rod Ce:Nd:YAG pumping configuration using an RAC concentrator offers a practical and scalable solution for high-power solar lasers, maintaining a high conversion efficiency (8.09%), an excellent slope efficiency (9.33%), and low thermal stress that ensures safe and proper operation of the solar laser.

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*Corresponding author: saidmeh@gmail.com