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Multi-Fresnel-Lens Pumping Approach for Simultaneous Emission of Seven TEM₀₀-Mode Beams with 3.73% Conversion Efficiency

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Abstract: TEM₀₀-mode operation is a requirement in many laser-based applications due to the small divergence and high-power density of the emitted laser beam. A solar laser scheme was designed and numerically studied with the goal of increasing the solar-to-laser power conversion efficiency in the TEM₀₀-mode operation. The collection and primary concentration of sunlight was performed via twelve sets of folding mirrors and Fresnel lenses, toward a laser head composed of a fused silica torus volume and seven Ce:Nd:YAG rods, in a side-pump configuration. With this scheme, TEM₀₀-mode laser power totaling 212.39 W could potentially be produced from seven beams, with six of them being 32.60 W each and with $M_x^2 = 1.00$, $M_y^2 = 1.01$ quality factors. Notably, 35.40 W/m² collection efficiency and, most importantly, 3.73% solar-to-laser power conversion efficiency were numerically achieved. The latter efficiency value represents a 1.81-time improvement over the experimental record, established with a prototype that had a single Ce:Nd:YAG rod in an end-side pump configuration.

Keywords: Ce:Nd:YAG; Fresnel lens; solar laser; TEM₀₀ mode



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1. Introduction

The necessity of tackling climate change has promoted a search for cleaner energy solutions, to the point where renewable power might supersede coal as the leading source of electricity generation in the foreseeable future and offer a chance of limiting global warming to 1.5 °C [1]. From a wide array of choices, harnessing solar energy is an alluring one; in fact, the amount of energy Earth receives in one hour is higher than the annual global energy consumption [2].

Directly converting broadband radiation the sun provides into coherent and narrow-band laser radiation has been gaining ever-increasing importance over the years, especially due to the efficiency, simplicity, and reliability of a process that does not require electrical equipment, except a chiller for water cooling. Solar lasers can play a significant role in materials processing [3,4], optical communications [5], and wireless electric vehicle charging [6], and they could potentially be used as tools for space-based applications, such as wireless power transmission [7], optical data transmission in deep space and networking [8], laser propulsion [9], and asteroid deflection [10].

In 1963, the first solar laser was demonstrated by Kiss et al. with a CaF₂:Dy²⁺ system at a liquid neon temperature [11], just three years after Maiman operated the first functioning laser [12]. At the beginning of the 21st century, the main goal in solar laser research changed from producing the highest laser power possible to maximizing collection efficiency, defined as solar laser output power per unit of primary concentrator area [13]. Since collection efficiency is reliant on solar irradiance, solar-to-laser power conversion efficiency emerged as another important parameter when making a fair assessment of the performance of a solar laser system, as it is defined as the ratio between the laser power generated and the total input solar pump power.

Albeit not indispensable for solar laser production [14], the use of concentration optics, especially parabolic mirrors and Fresnel lenses, has been pivotal in increasing the pump

intensity on the active medium and thus the laser efficiency [15–18]. The requirement for intricate and costly infrastructures to house heavy components, along with the obstruction of sunlight resulting from the placement of the laser head and its supporting mechanics in front of the parabolic mirror, renders this primary concentrator impractical. These reasons promote the use of Fresnel lenses which, despite having inherent chromatic aberration properties, are a low-cost, lightweight, and easily available solution that effectively minimizes obtrusive shadows. The experimental works that established record efficiency values with parabolic mirrors and Fresnel lenses are summarized in Table 1.

Table 1. Summary of the results of the experimental works that established record values in efficiency with parabolic mirrors and Fresnel lenses, in both multimode and TEM₀₀-mode regimes [15–18].

Parameter	Multimode Regime		TEM ₀₀ -Mode Regime	
	Liang et al. (2022) [15]	Cai et al. (2023) [16]	Liang et al. (2017) [17]	Liang et al. (2024) [18]
Solar concentrator	Parabolic mirror	Fresnel lens	Parabolic mirror	Fresnel lens
Effective collection area (m ²)	0.40	0.694	1.18	0.085
Type of rod	Conventional	Grooved	Conventional	Conventional
Rod material	Ce:Nd:YAG	Ce:Nd:YAG/YAG bonded	Nd:YAG	Ce:Nd:YAG
Number of rods	3	1	1	1
Configuration	End-side pump	End-side pump	End-side pump	End-side pump
Total laser power (W)	16.50	26.93	9.30	1.41
Collection efficiency (W/m ²)	41.25	38.81	7.88	16.49
Solar-to-laser power conversion efficiency (%)	4.64	3.88	0.79	2.06

Despite the significant efforts to achieve high efficiency, the accumulation of excessive heat within the active medium owing to a high concentration of radiation has always remained a concern, as it can lead to thermal lensing and thermal stress effects and affect laser beam quality. To mitigate this issue, the total amount of concentrated radiation can be uniformly distributed among multiple thinner laser rods [15,19,20]. The synchronization of multiple laser beams, each contributing to a portion of the entire process, has yielded outcomes that were unattainable with a single beam in several laser-based applications [21–25]. Opting for a side-pump configuration instead of an end-side pump configuration can also help in mitigation; it ensures a more uniform pump light distribution along the rod axis. The unrestricted access to both rod ends facilitates the optimization of more laser resonator parameters as well, leading to the efficient extraction of laser at low-order modes and enhanced beam quality [13]. Operation in the TEM₀₀ mode would be more feasible, attaining a laser beam profile favorable for numerous laser-based applications, namely in materials processing [26]. This is attributed to its minimal beam divergence, maximum power density, and, consequently, highest brightness, which allows for a small, focused spot. Its smooth profile could also obviate damage to resonator optics [27].

In 2023, our research group designed a seven-grooved-Ce:Nd:YAG rod solar laser scheme with the aim of enhancing the TEM₀₀-mode laser efficiency [28]. With the help of folding mirrors, the collection and concentration of sunlight were performed through seven circular Fresnel lenses, one with a 0.99 m diameter and the other six with a 0.95 m diameter, totaling a collection area of 5.0 m². A laser head was placed at the focal spot of the Fresnel lenses, comprising seven aspheric lenses, a hexagonal window, and seven grooved Ce:Nd:YAG rods in an end-side pump configuration, with which a better efficiency is typically attained [29]. 34.52 W/m² collection efficiency and 3.63% solar-to-laser power conversion efficiency were numerically achieved with this scheme. Nevertheless, it had a few shortcomings that affect both solar laser efficiency and practicality, namely the following:

- Large Fresnel lenses are highly susceptible to slight movements due to wind, affecting the position and shape of the focal spot and thus making it difficult to maintain the same solar laser power for a relatively long period of time during experimental work.
- Some of the components responsible for the mechanical fixation of laser resonator mirrors would have ended up obstructing a portion of the concentrated sunlight coming from the 0.99 m diameter Fresnel lens.

A novel seven-rod solar laser scheme was conceptualized and optimized via the Zemax[®] 13 ray tracing in non-sequential mode and LASCAD[™] 3.3.5 software and is presented here to improve the TEM₀₀-mode laser efficiency while overcoming the shortcomings of our previous work [28]. The solar rays were collected and concentrated using twelve sets of folding mirrors and smaller rectangular Fresnel lenses, each with only $0.57 \times 0.88 \text{ m}^2$ ($\approx 0.5 \text{ m}^2$) area to considerably reduce the wind load, toward a much simpler laser head composed of a fused silica torus volume and seven laser rods in a side-pump configuration. Ce:Nd:YAG was chosen as the material for the active media since Ce³⁺ ions serve as sensitizers of the Nd³⁺ ion emission and can be incorporated as co-dopants within the doped YAG host. This addition enhances laser efficiency by improving sunlight absorption and facilitating the transfer of the excitation energy to the Nd³⁺ ions [30]. Through this simulation work, it was found that this scheme could produce 212.39 W total TEM₀₀-mode laser power, which corresponds to a 35.40 W/m² collection efficiency and a 3.73% solar-to-laser power conversion efficiency. This is the first time a side-pump solar laser has been reported that is superior in terms of efficiency in relation to an end-side pump scheme [28]. The design parameters of the collection and concentration system and the solar laser head are described in Section 2. Section 3 presents how the overall system was modeled through Zemax[®] 13 and LASCAD[™] 3.3.5. Section 4 describes how the optimization of the design parameters was conducted to obtain the laser output and the thermal performance results. A discussion of the results is presented in Section 5, followed by conclusions in Section 6.

2. Description of the Concept

As presented in Figure 1a, the collection and concentration of solar rays were performed with twelve sets of folding mirrors and Fresnel lenses arranged in a ring. Each folding mirror had a $0.57 \times 1.24 \text{ m}^2$ area and was tilted 45° to redirect the incoming solar radiation toward the respective Fresnel lens of polymethylmethacrylate material, a lightweight, clear, and stable polymer, which makes it sunlight-resistant, and it is thermally stable up to at least 80 °C and possesses spectral transmissivity that aligns with the solar spectrum [31]. Each lens had a 1.09 m focal length and a $0.57 \times 0.88 \text{ m}^2$ area, totaling a 6.0 m² collection area, and concentrated the solar rays toward a laser head positioned 1.11 m away from it.

The laser head (Figure 1b,c) incorporated a fused silica torus volume to further concentrate solar radiation. By opting for this material, it acted as a filter of undesired radiation while being transparent over the absorption spectrum of Ce:Nd:YAG, in addition to having a low thermal expansion coefficient and high resistance to scratching and thermal shock [32]. The torus volume was created by revolving a 23 mm radius circle about an axis that was coplanar with a 24 mm radius circle. A Boolean difference was then performed between it and an 8.5 mm radius cylinder so that the output face of the resultant object would end up not having a curvature that negatively impacted the concentration of the rays.

In the middle of the torus volume, seven 3.7 mm diameter, 15 mm length Ce:Nd:YAG rods were placed. One rod (R_C in Figure 1c) was placed at the center, whereas the optical axes of the other six (R₁–R₆) were 4.2 mm away from that of the former. Furthermore, two 2.5 mm thick rod holders were used for the mechanical fixation of both ends of the seven rods. The rods and the output face of the torus volume were in direct contact with cooling water so that the heat generated within the rods and the optical components would wane. In experimental studies conducted by our research team, the cooling water was provided using a chiller at a 6 L/min flow rate [18].

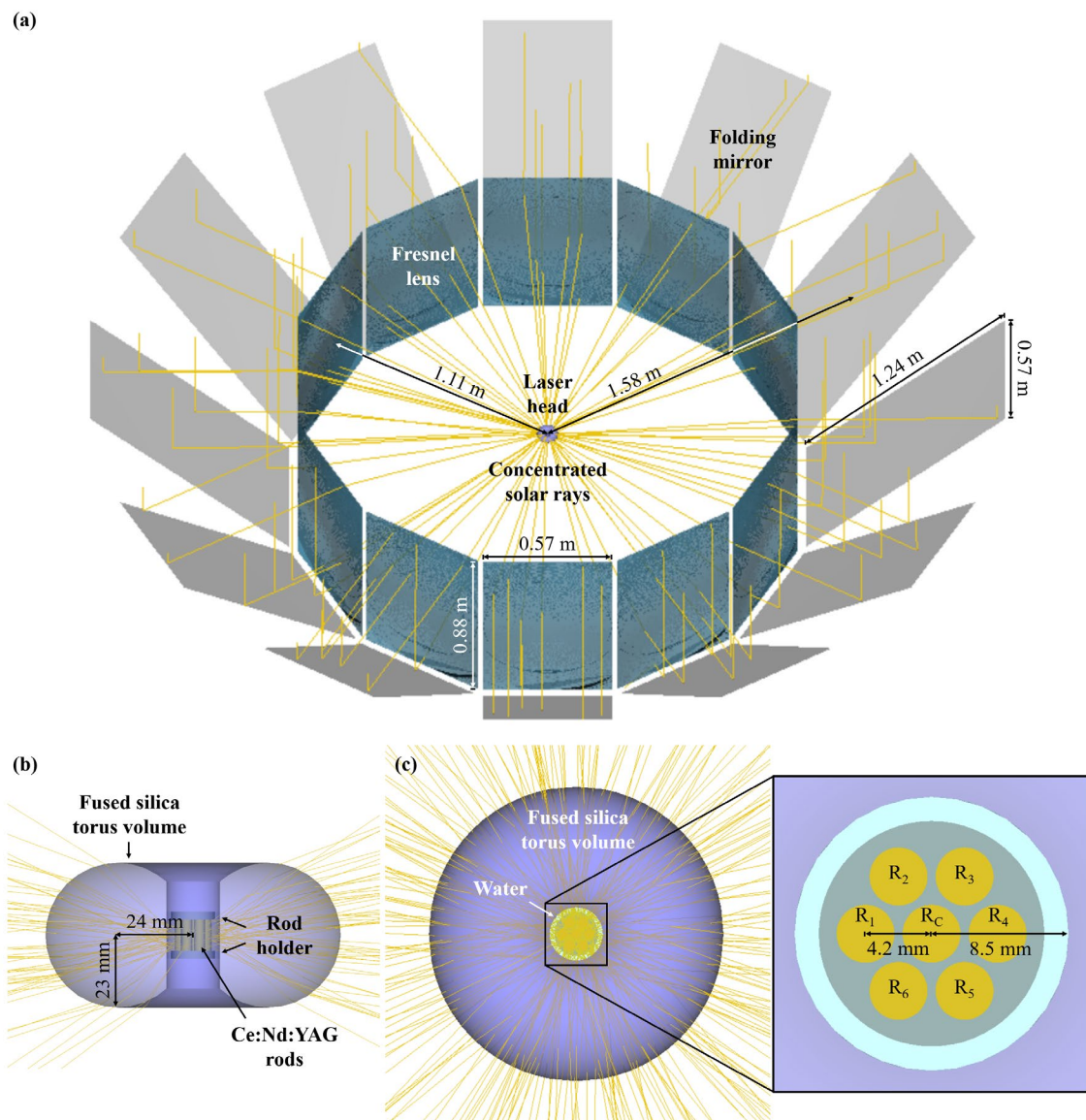


Figure 1. (a) Overview depiction of the solar laser system; (b) side and (c) top view of the laser head. The top holder was hidden in (c) for better visualization of the laser rods.

3. Numerical Modeling

3.1. Modeling of the Design Parameters through Zemax®

The Ce:Nd:YAG active medium has been proven to be more effective in enhancing solar laser performance in comparison to the Nd:YAG medium [15,16,30,33–35]. Within the ultraviolet and blue wavelength ranges, Ce^{3+} ions exhibit a strong absorption of sunlight, and the energy transfer from Ce^{3+} to Nd^{3+} ions occurs with high efficiency. Figure 2 illustrates both the solar emission and the Ce:Nd:YAG absorption spectra. The broad absorption bands centered at 339 nm and 460 nm are associated with transitions of Ce^{3+} ions from the $^2\text{F}_{5/2}$ ground state to the $5d_1$ and $5d_2$ excited states [36], respectively. The other absorption bands at >500 nm wavelengths are indicative of the characteristic absorptions from the $^4\text{I}_{9/2}$ ground state of the Nd^{3+} ions. The fluorescence displayed by Ce^{3+} ions is characterized by a broad green–yellow (500–720 nm) emission band resulting from a radiative decay from the $5d$ excited levels to the $^2\text{F}_{5/2}$ ground state [36]. This emission band aligns effectively with the two green–yellow Nd^{3+} absorption bands at 515–540 nm and 565–595 nm. The absorption coefficient reaches a maximum of 9.0 cm^{-1} for the Ce^{3+} absorption band centered at a wavelength of 460 nm, while another Ce^{3+} band at 339 nm

exhibits a coefficient of 4.5 cm^{-1} . Additionally, the Nd^{3+} absorption bands, which are located at 531 nm, 586 nm, 736 nm, 746 nm, 793 nm, 808 nm, 865 nm, and 880 nm, have corresponding absorption coefficients of 2.3 cm^{-1} , 3.7 cm^{-1} , 5.0 cm^{-1} , 4.6 cm^{-1} , 4.2 cm^{-1} , 4.9 cm^{-1} , 3.1 cm^{-1} , and 4.2 cm^{-1} .

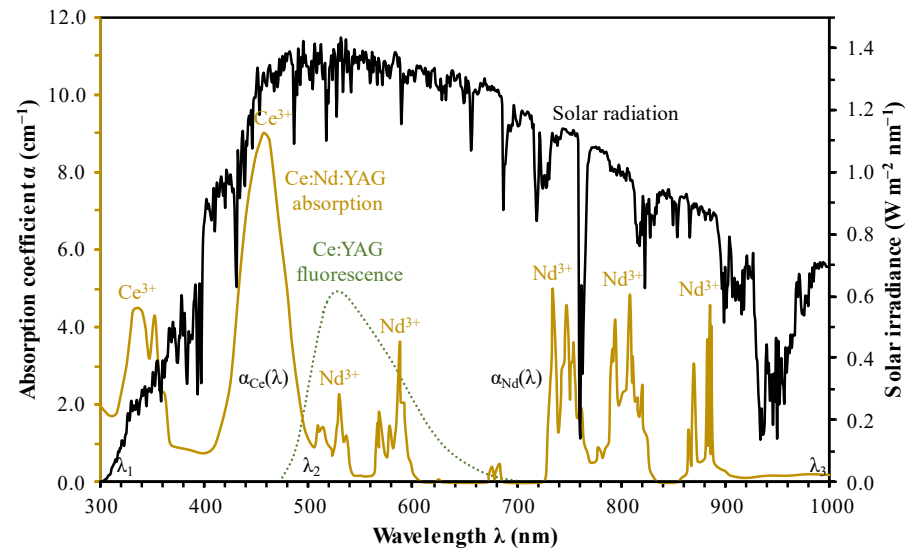


Figure 2. Standard solar emission [37] (black line), Ce^{3+} fluorescence (green line), and Ce^{3+} , Nd^{3+} absorption (golden line) spectra (adapted from [15,35], respectively).

By introducing the solar spectrum irradiance $I(\lambda)$ in short wavelength (λ) range and dismissing the weak absorption lines of Nd^{3+} , the calculation of the total absorbed power ($P_{\text{Nd}^{3+}}$) per unit area can be performed through

$$P_{\text{Nd}^{3+}} = \int_{\lambda_1}^{\lambda_2} I(\lambda) \left[1 - e^{-\alpha_{\text{Ce}}(\lambda) L} \right] \eta_{\text{non-radiative Ce}^{3+} \rightarrow \text{Nd}^{3+}} d\lambda + \int_{\lambda_1}^{\lambda_2} I(\lambda) \left[1 - e^{-\alpha_{\text{Ce}}(\lambda) L} \right] \eta_{\text{radiative Ce}^{3+} \rightarrow \text{Nd}^{3+}} d\lambda + \int_{\lambda_2}^{\lambda_3} I(\lambda) \left[1 - e^{-\alpha_{\text{Nd}}(\lambda) L} \right] d\lambda \quad (1)$$

with wavelength ranges $\lambda_1 = 320 \text{ nm}$ to $\lambda_2 = 500 \text{ nm}$ and $\lambda_2 = 500 \text{ nm}$ to $\lambda_3 = 1000 \text{ nm}$ to account for the solar power absorption performed by Ce^{3+} and Nd^{3+} ions, respectively. The additional absorption channels for Nd^{3+} ions arising from the $\text{Ce}^{3+} \rightarrow \text{Nd}^{3+}$ energy transfer by non-radiative and radiative pathways are described by the first and second integrals, respectively, while the direct absorption of solar radiation by the Nd^{3+} ions is represented by the third integral. The $\text{Ce}^{3+} \rightarrow \text{Nd}^{3+}$ non-radiative and radiative energy transfer efficiencies are designated by $\eta_{\text{non-radiative Ce}^{3+} \rightarrow \text{Nd}^{3+}}$ and $\eta_{\text{radiative Ce}^{3+} \rightarrow \text{Nd}^{3+}}$. $\alpha_{\text{Ce}}(\lambda)$ and $\alpha_{\text{Nd}}(\lambda)$ are the absorption coefficients of Ce^{3+} and Nd^{3+} ions, whereas L represents the effective absorption length within a laser rod [15]. It can be determined that the solar emission spectrum displays a 15.3% overlap efficiency with the Ce^{3+} absorption spectrum and an overlap efficiency with the Nd^{3+} absorption spectrum of 16.0%, corroborating the reported 14–16% spectral overlap between solar emission and Nd^{3+} absorption in previous studies [38,39].

In Zemax[®] 13, each set of folding mirrors and Fresnel lenses collected and concentrated solar rays emitted by two solar sources of identical area. For a solar irradiance of 950 W/m^2 and each Fresnel lens of 0.5 m^2 collection area, while taking into account the 15.3% overlap between Ce^{3+} absorption and direct standard solar spectra for one-and-a-half air mass, an effective solar power of 72.68 W was determined for the Ce^{3+} ion pumping. Due to the approximately 70% $\text{Ce}^{3+} \rightarrow \text{Nd}^{3+}$ non-radiative energy transfer efficiency [40], 50.88 W ($=72.68 \text{ W} \times 70\%$) was assigned to a Source 1 in Zemax[®] 13. Moreover, considering the 16.0% overlap between the spectra of Nd^{3+} absorption and solar emission, 76.00 W was incorporated into that same solar source to reflect the direct pumping of the Nd^{3+} ions. This totals an effective power of 126.88 W ($=50.88 \text{ W} + 76.00 \text{ W}$) attributed to Source 1, with

22 narrow Nd^{3+} ion absorption peak wavelengths of 527 nm, 531 nm, 568 nm, 578 nm, 586 nm, 592 nm, 732 nm, 736 nm, 743 nm, 746 nm, 753 nm, 758 nm, 790 nm, 793 nm, 803 nm, 805 nm, 808 nm, 811 nm, 815 nm, 820 nm, 865 nm, and 880 nm [41]. The weight for each peak wavelength of Source 1 was based on the $I(\lambda)$ value. Since approximately 30% of solar energy absorbed by Ce^{3+} ions can be emitted as green–yellow color fluorescence, which can subsequently be absorbed by Nd^{3+} ions because of their absorption wavelengths centered at 527 nm, 531 nm, 568 nm, 578 nm, 586 nm, and 592 nm [15], a Source 2 was also programmed in Zemax[®] 13 to emit an effective solar power of 21.80 W ($=72.68 \text{ W} \times 30\%$). The weight of each peak wavelength of Source 2 was assessed using the fluorescence irradiance values corresponding to each peak wavelength [15].

To acquire the data regarding the absorbed pump power in each rod, a detector volume comprised of 37,500 voxels was used for each one. This, along with 7.2×10^6 analysis rays, facilitated the attainment of precise results and good image resolution from each detector. Figure 3 illustrates the distribution of absorbed pump flux in five transversal cross-sections of the seven Ce:Nd:YAG rods, as well as in the longitudinal cross-sections of rods R_C and R_1 . Longitudinal profiles for rods R_2 – R_6 are not presented, as they are identical to that of rod R_1 . The areas of maximum pump flux are indicated in red, while blue denotes regions of the rods with minimal or no absorption. Significantly higher absorbed pump flux was observed in the profiles of rods R_1 – R_6 , with the flux in the middle section being nearly double that in R_C .

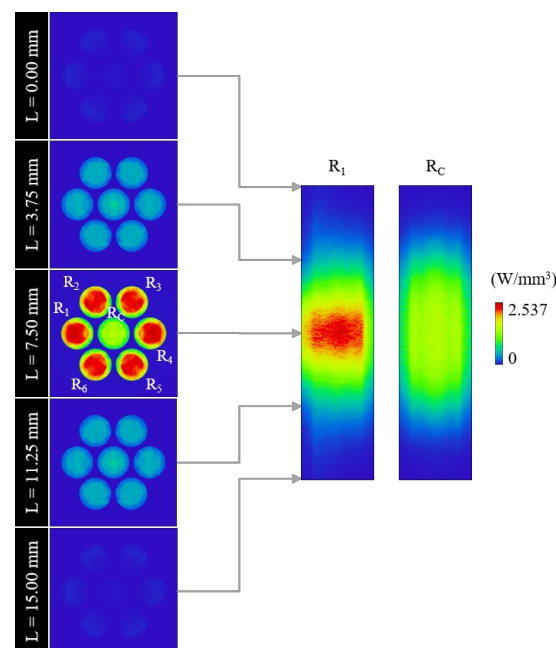


Figure 3. Absorbed pump flux distribution in five transversal cross-sections of the seven 3.7 mm diameter, 15 mm length Ce:Nd:YAG rods, in addition to the longitudinal ones of the rods R_C and R_1 .

Upon the completion of each ray tracing operation, the absorbed pump flux data were transferred from Zemax[®] 13 to the LASCAD[™] 3.3.5 software. The assessment of the thermal effects on the active media, the maximum solar laser output power, and the laser beam quality factors (M_x^2 , M_y^2) dictated by the optimal resonator beam parameters in each instance determined how to proceed afterward to further optimize the design parameters in Zemax[®] 13.

3.2. Modeling of the Laser Resonator Parameters through LASCAD[™]

In LASCAD[™] 3.3.5, the data analysis incorporated a stimulated emission cross-section of $2.8 \times 10^{-19} \text{ cm}^2$, a fluorescence lifetime of 230 μs [29], an absorption and scattering loss of

0.002 cm^{-1} for the Ce (0.1 at.):Nd (1.1 at.):YAG rod medium [15], and the mean-absorbed and intensity weighted solar pump wavelength of 660 nm [38].

Each laser resonator was composed of two mirrors, one with a highly reflective (HR) coating and the other with a partially reflective (PR) coating specifically designed for the 1064 nm laser emission wavelength, with reflectivity rates of 99.9% and 90–99%, respectively. The optical axes of these mirrors were precisely aligned with that of the rod. Furthermore, both end faces of the rod had a coating that was anti-reflective (AR) to the 1064 nm wavelength. Long resonators were utilized as they enable efficient extraction of TEM₀₀-mode laser beams; an increase in the length also leads to an increase in the TEM₀₀-mode beam size and diffraction losses at the rod edges, eliminating higher-order modes. Otherwise, the TEM₀₀ mode would poorly match the active region, and the laser would oscillate in a myriad of modes, producing laser beams with worse M_x^2 , M_y^2 . Therefore, the selection of long resonators in conjunction with relatively small-diameter laser rods, which act as apertures, allows for the exclusive oscillation of the TEM₀₀ mode, enhancing the beam quality [29]. Both the radius of curvature (RoC) of the resonator mirrors and the separation length were optimized.

Figures 4 and 5 show the laser resonator design for the extraction of a TEM₀₀-mode laser beam from rods R_C and R₁, respectively. The laser resonators for rods R₂–R₆ are similar to that for R₁. To achieve the most efficient extraction of the TEM₀₀-mode laser beam from rod R_C, HR and PR 1064 nm mirrors with a 5000 mm RoC were employed, with a 591.8 mm separation length on each side. This facilitated the generation of a 16.79 W laser beam with quality factors of $M_x^2 = 1.99$, $M_y^2 = 1.00$. Additionally, the laser resonators for R₁–R₆ had 1500 mm RoC mirrors and 535.4 mm separation lengths, which resulted in laser beams of 32.60 W each with better quality factors of $M_x^2 = 1.00$, $M_y^2 = 1.01$. Due to this, the thermal lensing was more pronounced, and the stabilization in the LASCAD™ 3.3.5 beam propagation method was much quicker.

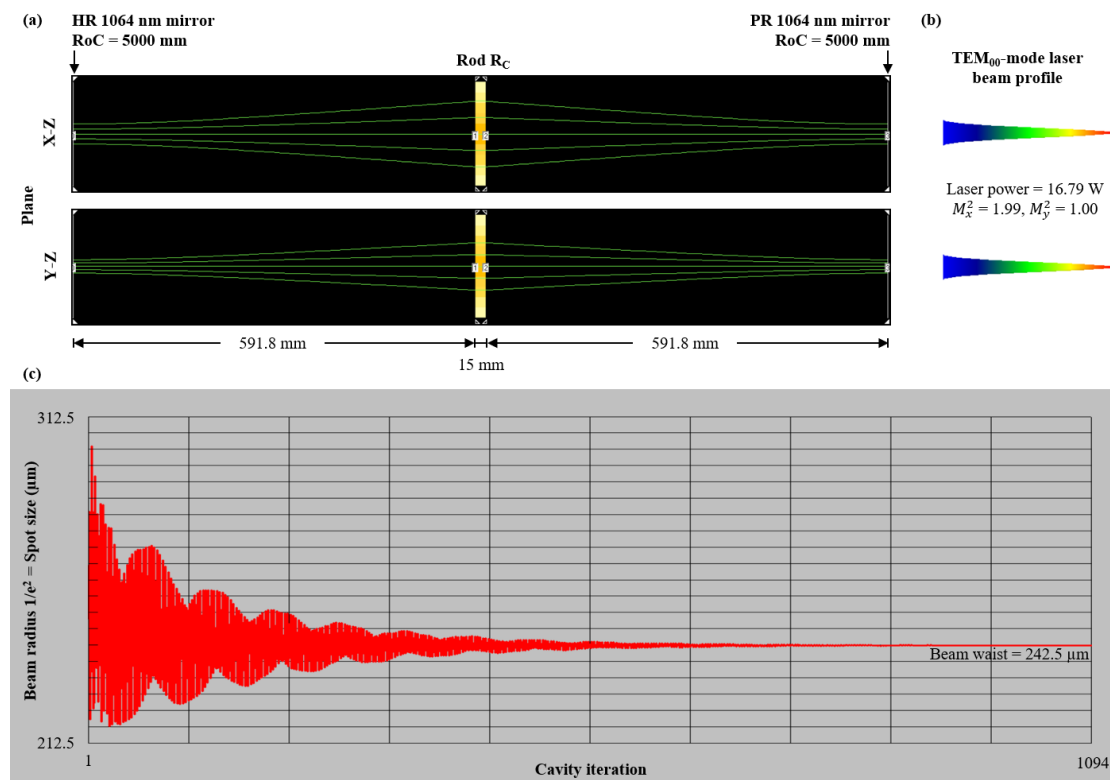


Figure 4. (a) Laser resonator design in LASCAD™ 3.3.5 for the extraction of a TEM₀₀-mode laser beam from rod R_C, with (b) the respective beam profile; (c) laser beam waist radius obtained at the PR 1064 nm output mirror, through the LASCAD™ 3.3.5 beam propagation method.

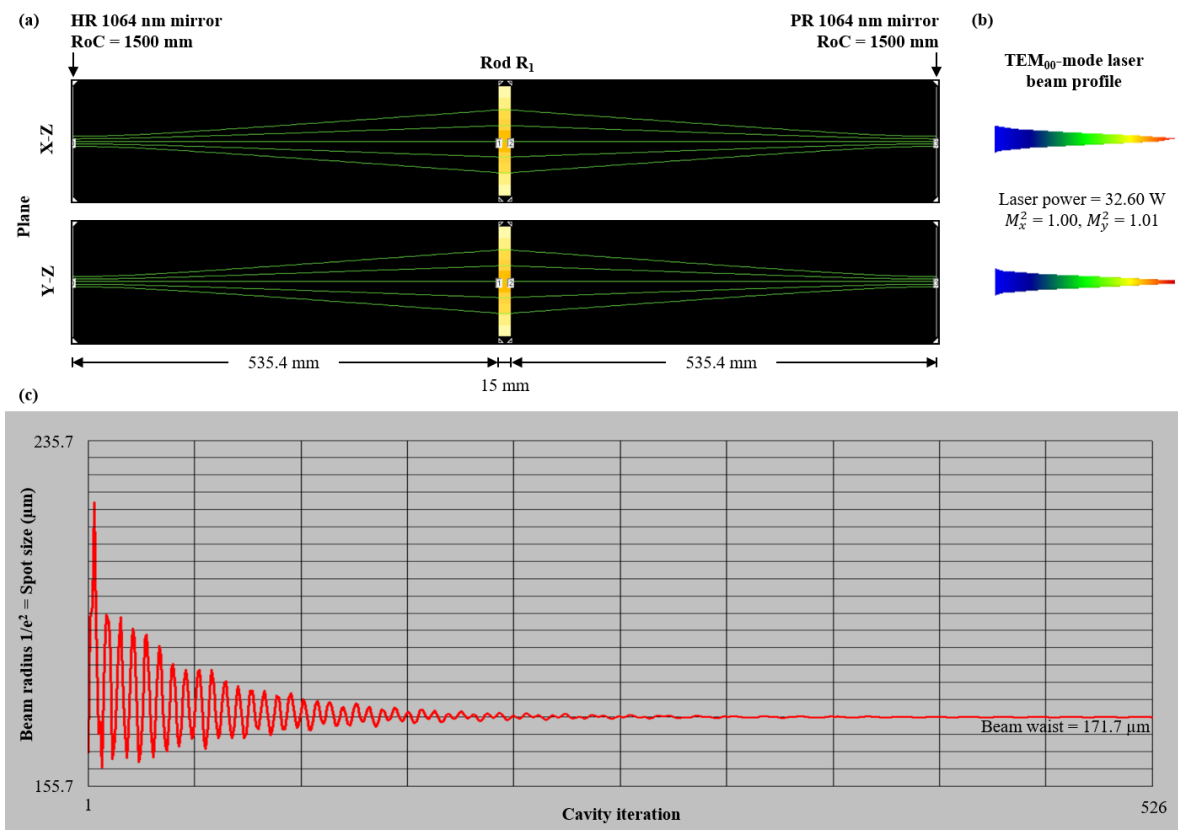


Figure 5. (a) Laser resonator design in LASCAD™ 3.3.5 for the extraction of a TEM₀₀-mode laser beam from rod R₁, with (b) the respective beam profile; (c) laser beam waist radius obtained at the PR 1064 nm output mirror, through the LASCAD™ 3.3.5 beam propagation method.

4. Numerical Optimization of the Solar Laser System

4.1. Solar Laser Output Performance

Before the optimization process started, the number of laser rods was fixed at seven since it is one of the multirod configurations with the best performance under intense solar pumping [42]. Since rods R₁–R₆ presented higher pump power absorption, as shown in Figure 3, and thus higher contribution toward the total TEM₀₀-mode laser power than rod R_C, more effort was put into enhancing the laser power that they would produce and the quality of the resultant laser beams.

Different total collection areas and rod diameters were tested in order to find the optimal conditions that led to a higher solar-to-laser power conversion efficiency in the TEM₀₀ mode. In Figure 6, the variation in the efficiency with the rod diameter is presented, for total collection areas of 5.5 m², 6.0 m², and 6.5 m². With the 6.0 m² area and seven 3.7 mm diameter rods, the system's maximum conversion efficiency was found to be 3.73%, corresponding to a 212.39 W (=16.79 W + 6 × 32.60 W) total TEM₀₀-mode laser power and 35.40 W/m² collection efficiency. The highest conversion efficiency attained for a total collection area of 5.5 m² was 3.54% with a rod diameter of 3.3 mm, equivalent to a total TEM₀₀-mode laser power of 185.18 W (=16.94 W + 6 × 28.04 W) and a collection efficiency of 33.67 W/m². For the total collection area of 6.5 m², a 4.1 mm rod diameter led to the highest conversion efficiency of 3.47%, corresponding to a total TEM₀₀-mode laser power of 214.07 W (=16.25 W + 6 × 32.97 W) and a collection efficiency of 32.93 W/m².

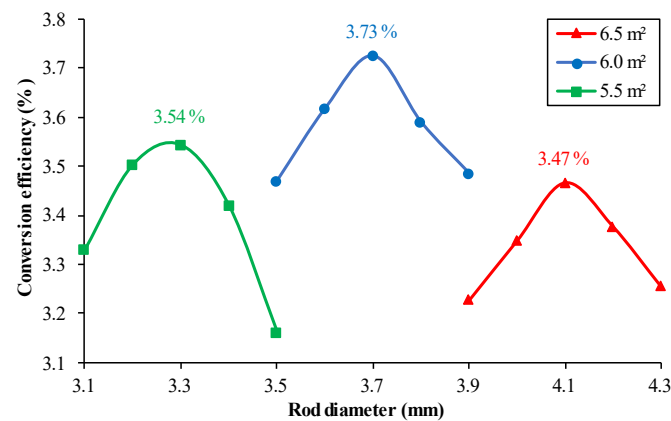


Figure 6. Numerically calculated solar-to-laser power conversion efficiency as a function of rod diameter, for total collection areas of 5.5 m², 6.0 m², and 6.5 m².

4.2. Thermal Analysis of the Ce:Nd:YAG Rods

Through LASCAD™ 3.3.5, the analysis of the thermal-induced effects—heat load, temperature, and stress intensity—on rods R_C and R₁ was conducted, and the results are presented in Figure 7. Since rod R₁ absorbed the most pump power, heat load, temperature, and stress intensity were also more intense (1.367 W/mm³, 395.3 K, and 141.30 N/mm², respectively) in comparison with the values observed in R_C (0.902 W/mm³, 363.7 K, and 87.28 N/mm²). Nonetheless, these results mean that, under a highly intense solar pump, the moderately good thermal performance of the system could be verified.

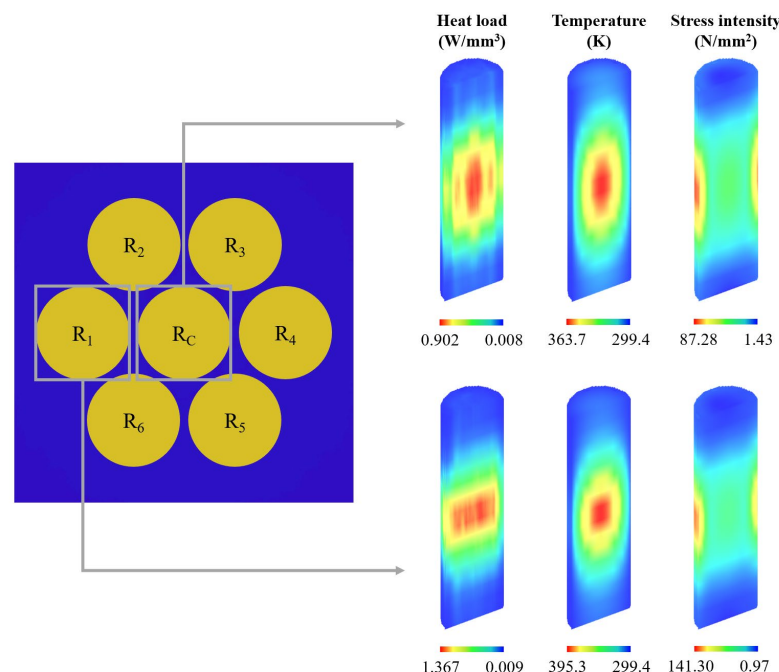


Figure 7. Heat load, temperature, and stress intensity for rods R_C and R₁.

5. Discussion

The results attained with the proposed numerical work represented improvements in comparison not only with the experimental work performed by Liang et al. [18] but also with our previous scheme [28]. In the former, a record-breaking solar-to-laser power conversion efficiency was obtained during TEM₀₀-mode operation by pumping a single Ce:Nd:YAG rod placed inside a laser head composed of a fused silica aspheric lens and a conical cavity [18]. A summary of the results from the three works is presented in Table 2.

Table 2. Summary of the results of the present work, from Ref. [18], and from our previous seven-Ce:Nd:YAG-grooved rod scheme [28].

Parameter	Experimental Work		Numerical Work	
	Liang et al. (2024) [18]	Costa et al. (2023) [28]	Present Scheme	
Type of rod	Conventional	Grooved	Conventional	
Number of rods	1	7	7	
Configuration	End-side pump	End-side pump	Side pump	
Number of Fresnel lenses	1	7	12	
Effective collection area (m ²)	0.0855	5.0	6.0	
Solar irradiance (W/m ²)	800	950	950	
Total TEM ₀₀ -mode laser power (W)	1.41	172.59 (=22.89 + 6 × 24.95)	212.39 (=16.79 + 6 × 32.60)	
Solar-to-laser power conversion efficiency (%)	2.06	3.63	3.73	
M_x^2, M_y^2	1.08, 1.08	1 × (1.69, 1.00), 6 × (1.04, 1.00)	1 × (1.99, 1.00), 6 × (1.00, 1.01)	

As previously mentioned, in solar-pumped lasers, the end-side pump configuration is generally the one that leads to better efficiency [29]. Still, with the proposed scheme, solar-to-laser power conversion efficiency was 1.81 times higher than that attained by Liang et al. [18]. In addition, even though adopting grooved rods can further improve both efficiency and beam quality [43], the present scheme was 2.75% more efficient than the end-side pump scheme with grooved rods [28]. It could also enable the production of six laser beams (from rods R₁–R₆) whose quality was 1.07 times better than the one from the single-rod prototype and 1.49% higher than those attained with the previous scheme.

The side-pump configuration with multiple laser rods makes the use of the proposed scheme more advantageous than the single-rod prototype. The total amount of concentrated radiation was distributed among the seven rods, with each presenting a more uniform pump light distribution. This makes the seven-rod side-pump concept more suitable for laser power scaling, considering that the main part of the concentrated sunlight directly focusing on one of the end faces of the prototype's single rod would cause strong thermal lensing and thermally induced birefringence as the pump power increases. Furthermore, in single-rod systems, a more precise alignment of the components is required, as it is a configuration that has low tracking error compensation capacity; since the single rod occupies a relatively small space within the pump cavity, a slight misalignment could lead to a large depletion of the laser output power. With seven rods, however, that problem is alleviated. The rods end up occupying more space, and a decrease in absorbed pump power in one rod may lead to an increase in that in a different rod. The total laser power usually ends up being more stable due to the high tracking error compensation capacity that this configuration has [44].

6. Conclusions

A proposal for a seven-rod solar laser scheme, conceptualized and optimized through the Zemax[®] 13 and LASCAD[™] 3.3.5 software with the aim of improving the TEM₀₀-mode laser efficiency, was presented. Twelve folding mirrors redirected incoming sunlight toward twelve Fresnel lenses, with a 6.0 m² total collection area, which in turn concentrated it toward a single laser head. The laser head comprised a fused silica torus volume and seven Ce:Nd:YAG laser rods. From it, a 3.73% solar-to-laser power conversion efficiency was numerically calculated, corresponding to a 212.39 W total TEM₀₀-mode laser power and a 35.40 W/m² collection efficiency. The conversion efficiency was 1.81 times higher than the experimental record, set by a prototype in which a single Ce:Nd:YAG rod was used in an end-side pump configuration [18], and 2.75% more than that of the solar laser approach using seven Ce:Nd:YAG-grooved rods with a more complex configuration [28]. Moreover, six laser beams could be extracted with beam quality factors of $M_x^2 = 1.00$, $M_y^2 = 1.01$, in conjunction with one with factors of $M_x^2 = 1.99$, $M_y^2 = 1.00$.

This is the first time a side-pump solar laser has been reported that is superior in terms of efficiency in relation to an end-side pump scheme [28]. The proposed solar laser configuration provides an effective solution to reach high TEM₀₀-mode laser power through seven laser beams of good quality, appealing to many laser-based applications. Further improvements could be made by adopting different geometries for the active media, such as grooved rods [43], slabs [45], or disks [46].

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