



Advancements in Nd:YAG Solar Laser Stability Under Solar Tracking Error Conditions

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DOCTORATE IN PHYSICS ENGINEERING
NOVA University Lisbon
March, 2024

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ACKNOWLEDGMENTS

I am profoundly grateful to Professor Dawei Liang, my supervisor and leader of the Solar Laser Lab. Since 2017, he has not only taught me laser physics but has also been an unwavering guide in developing my approach to problem-solving, articulating ideas, and inspiring others, all while steering a globally recognized research team. Professor Liang's influence has been instrumental in my journey, and I owe much of my growth and accomplishments to his wisdom.

I extend my heartfelt appreciation to Dr. Cláudia Vistas, my co-supervisor, whose insights have been invaluable, and to all my colleagues at the Solar Laser Lab: Dr. Bruno Tibúrcio, Dr. Dario Garcia, and Hugo Costa, with a special acknowledgment to Dra. Joana Almeida. Her unwavering dedication and inspirational presence have been instrumental throughout my research journey. Dra. Almeida not only offered invaluable assistance but consistently demonstrated a keen interest in contributing innovative ideas to propel our work forward. I am sincerely appreciative of her commitment to fostering a collaborative spirit in the lab, which cultivates an atmosphere of creativity and collective achievement.

I am deeply grateful to the esteemed professors, dedicated researchers, and aspiring students comprising CEFITEC, whose collective passion for physics has not only inspired me but has also unveiled the extraordinary applications within each distinct realm. The remarkable enthusiasm demonstrated by this community has been a constant source of motivation, igniting my own fascination for physics and its incredible applications. I extend my gratitude to the Department of Physics and FCT NOVA where, over the past decade, I've gleaned far more than engineering knowledge. Additionally, I express my sincere appreciation to the FCT foundation for funding my PhD program.

Thanks to the PROMES-CNRS personnel for planning and receiving us during our trips to Font-Romeu, with special appreciation to Dra. Anita Haeussler and MSc. Emmanuel Guillot.

And finally, thanks to my friends and family, all the weekends that I was on the lab, thanks for understanding and continuing to support me. Obrigado!

ABSTRACT

Solar-pumped lasers represent a promising frontier in laser technology, offering the ability to convert incoherent solar radiation into coherent laser radiation without relying on traditional pump light sources. This dissertation explores methods and strategies to develop and adapt solar-pumped laser technology, tailoring it to meet both scientific and industrial challenges. Firstly, solar laser configurations are applied to lamp-pump lasers commonly utilized in industry, with the objective of boosting efficiency and brightness while addressing thermal concerns. Additionally, the investigation of alternative beam profiles, such as top hat and doughnut-shaped, showcases the potential of solar lasers in diverse applications, including material processing and biomedical imaging. Moreover, efforts to improve the stability and efficiency of solar-pumped laser systems, particularly under solar tracking error condition, are discussed. By utilizing end-side pump configurations and incorporating a solar flux homogenizer, significant advancements have been made towards achieving uniform and stable solar laser emissions. Experimental validation of these advancements at the PROMES-CNRS solar facility in Odeillo, France, demonstrates the feasibility of building stable solar laser systems with low-cost solar tracking systems. Even when the tracking system was turned off, the total output power extracted from the solar-pumped laser remained stable for 1 min, representing, to the best of our knowledge, the first successful demonstration of stable multibeam solar laser operation without solar tracking.

Keywords: solar laser, Nd:YAG, multibeam, solar tracking error, parabolic mirror,

RESUMO

Os lasers alimentados por energia solar representam uma promissora fronteira na tecnologia laser, oferecendo a capacidade de converter radiação solar incoerente em radiação laser coerente sem depender de fontes de bombeamento tradicionais, como lâmpadas ou díodos. Esta dissertação explora métodos e estratégias para desenvolver e adaptar a tecnologia de lasers solares, adaptando-a para enfrentar desafios científicos e industriais. Em primeiro lugar, as configurações de lasers solares são aplicadas aos lasers bombeados por lâmpadas comumente utilizados na indústria, com o objetivo de aumentar a eficiência e o brilho ao mesmo tempo que reduzem preocupações térmicas. Além disso, a investigação de perfis de feixe alternativos, como o perfil plano e em forma de donut, destaca o potencial dos lasers solares em diversas aplicações, incluindo processamento de materiais e imagens biomédicas. Também são discutidos os esforços para melhorar a estabilidade e a eficiência dos sistemas de laser alimentados por energia solar, particularmente em relação a erros de rastreamento solar. Ao bombear os cristais pela extremidade e incorporar homogeneizadores de fluxo solar, foram feitos avanços significativos em direção à obtenção de emissões de laser solar uniformes e estáveis. A validação experimental desses avanços na instalação solar PROMES-CNRS em Odeillo, França, demonstra a viabilidade de construir sistemas de laser solar estáveis com sistemas de rastreamento solar de baixo custo. Mesmo quando o sistema de rastreamento foi desligado, a potência total de saída extraída do laser alimentado por energia solar permaneceu estável por 1 minuto, representando, até onde sabemos, a primeira demonstração bem-sucedida de operação estável de laser solar multifeixe sem rastreamento solar.

Palavras-chave: laser solar, Nd:YAG, multifeixe, erro de rastreamento solar, espelho parabólico.

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INTRODUCTION

Lasers are ubiquitous in modern society, playing a critical role in a wide range of applications such as manufacturing [1], material processing [2], telecommunications [3], defense [4] and healthcare [5]. Multimode laser systems are used in industrial processes such as cutting, welding, and drilling due to their high power and large beam size [6]. They also serve as efficient pumping sources for other laser systems, delivering monochromatic light to the gain media [7]. The presence of multiple transverse electromagnetic modes (TEM modes) within its resonant cavity makes them susceptible to mode competition and instability often associated with poor beam quality and high divergence [8]. In contrast, the TEM₀₀ mode, known as the fundamental mode or single mode, is typically the most stable mode in a laser resonator, as it experiences minimal mode competition and exhibits a well-defined Gaussian shaped intensity profile over time [9]. These laser systems present also superior beam quality (M_x^2 , M_y^2), being particularly well-suited for applications that require high precision, such as micromachining, engraving, and lithography [10]. It is also extensively used in laser spectroscopy, where its high spatial coherence enables accurate measurements of absorption, fluorescence, and others spectroscopic phenomena [11]. The single mode also exhibits the lowest beam divergence, propagating over extended distances, particularly useful in free-space optical communications and laser-based measurements [12].

Intensive electricity consumption is a constraint for the above-mentioned laser large-scale applications considering the cost and environmental impacts. For instance, laser additive manufacturing offers potential environmental benefits such as the elimination of molds, dies, cutting tools, and cutting fluids; however, it can consume up to 100 times more energy when compared to conventional manufacturing methods [13]. As such, there has been a growing interest in the

development of solar-pumped lasers, which represent a sustainable and cost-effective alternative [14]. They directly convert the natural sunlight into narrowband. The collimated solar laser radiation does not require electrical pumping sources, such as arc lamps and laser diodes, along with their mandatory power consumption and conditioning equipment, potentially leading to higher efficiency, simplicity, and reliability. Solar-pumped laser systems are particularly well suited for space-based applications, including long-range optical communication and networking [15], atmospheric remote sensing and pollution control [16], laser-induced asteroid trajectory deviation [17], probe photonic acceleration [18] and wireless energy transmission [19]. Furthermore, by completely avoiding semiconductor laser arrays and their inherent limitations, such as limited lifetime and performance degradation over time, reliable spaceborne laser operation could be achieved for extended durations. On Earth, they have potential for renewable energy cycles and laser material processing, particularly in off-grid locations with abundant sunlight [20,21].

Solar laser emission was firstly reported in 1963 by Kiss et al.[22], not long after the invention of laser [23]. Gas, liquid and solid laser media have been studied [24–26]; however, solid-state media's inherent high energy density, compactness, and potential for efficient solar-to-laser power conversion have made them widely used [27–35]. Particularly, Nd:YAG material has been proven to be quite effective in solar-pumped lasers due to its suitability for solar pumping of high intensity as a result of the spectroscopic properties of the dopant [36], and good thermo-mechanical properties, making it durable and resilient to thermal fractures [9], along with its availability and relatively low cost. In the first Nd:YAG solar laser systems, efforts were made to increase the laser output power from 1.0 W in 1966 to 60.0 W in 1988 [26–28].

Efficiency is generally regarded of primary importance to evaluate the laser performance, while researchers continued to improve solar-pumped lasers using either highly focusing parabolic mirrors, or lightweight, low-cost, and easily available Fresnel lenses [27–35]. In order to compare the solar laser output performance obtained from different primary concentrators, the valuation of their efficiency has been essentially done through the solar laser collection efficiency and solar-to-laser conversion efficiencies [37–39]. The first provides a very straightforward way to find out the amount of solar laser power produced from each square meter of collector area, although it may be misleading since this parameter is dependent on the solar irradiance, which can vary largely with geographical location. Solar-to-laser conversion efficiency is defined as the percentage of laser power produced from the total disposable input

solar pump power. A clear advantage of this parameter lies in its independency on the solar irradiance.

In 2011, 19.3 W/m² solar laser collection efficiency and 2.2% solar-to-laser conversion efficiency were achieved by exciting a 4.0 mm diameter, 25 mm length Nd:YAG rod with a Fresnel lens with 0.64 m² collection area [31]. 30.0 W/m² solar laser collection efficiency and 3.3% solar-to-laser conversion efficiency were attained by pumping a 6.0 mm diameter, 100 mm length Nd:YAG rod through a large Fresnel lens with 4 m² collection area in 2012 [32]. In 2017, 37.2 W of continuous-wave (CW) multimode 1064 nm solar laser power was produced from a 4.0 mm diameter, 35 mm length Nd:YAG rod through a parabolic mirror with 1.18 m² collection area, resulting in 31.5 W/m² solar laser collection efficiency and 3.1% solar-to-laser conversion efficiency [38]. In 2018, a 4.5 mm diameter, 35 mm length Cr:Nd:YAG ceramic rod was efficiently pumped through a parabolic mirror with 1.0 m² effective collection area, leading to a collection efficiency of 32.5 W/m² and solar-to-laser conversion efficiency of 3.7% [40]. In 2022, 11.2 W multimode solar laser were extracted from a 2.5 mm diameter, 25 mm length Ce:Nd:YAG rod efficiently pumped through a parabolic mirror with 0.293 m² effective collection area, leading to the state-of-the-art single-rod solar-to-laser conversion efficiency of 4.5% [41]. The single thin laser rod mitigated the serious thermal lensing and thermal stress issues associated with classical single-thick-rod solar lasers [9]. In 2023, Cai et al. improved the single-rod solar laser collection efficiency to the state-of-the-art of 38.8 W/m² by pumping a 6 mm diameter, 95 mm length Ce:Nd:YAG rod through a Fresnel lens with effective collection area of 0.69 m² [42]. More recently, Liang et al. achieved the state-of-the-art TEM₀₀-mode solar-to-laser conversion efficiencies of 2.06% by using a single Ce:Nd:YAG rod and a small area Fresnel lens as the primary concentrator [43].

All the above-mentioned achievements were accomplished with solar laser schemes based on single-laser/single-beam concept. However, the industry has shown significant interest in multibeam laser systems due to their potential for reducing processing time. By employing techniques such as beam overlapping or tailoring each beam for specific tasks within the overall procedure, these systems can rapidly perform tasks that would normally take days or even weeks using a single beam [44–47]. Moreover, laser output power and its beam quality are strongly influenced by the thermal lensing and thermal stress problems of the single-laser source [9]. To avoid these limitations, solar laser systems based on a multi-rod/multi-beam concept from a single solar laser head have been studied [48–54]. This is significant for solar

laser research, since solar pump rays not completely absorbed by one of the rods can be furtherly absorbed by other rods, leading to more passages through the active media. This increases the path length of the rays inside the rods and hence the amount of energy absorbed, while avoiding the serious thermal fracture, thermal lensing and thermal stress issues associated with classical single-thick-rod solar lasers [55]. In 2020, the first simultaneous emission of three 1064 nm solar laser beams was reported by end-side-pumping three 3.0 mm diameter, 25 mm length Nd:YAG rods within a single conical pump cavity with a heliostat-parabolic system [49]. Substantial improvement in the laser rods' thermal performance was achieved, when compared to that of the single rod pumped within the same pump cavity. 18.3 W total multimode solar laser power was measured at an effective collection area of 1 m², resulting in 18.3 W/m² collection efficiency and 2.2% solar-to-laser conversion efficiency [49]. In 2022, Liang et al. achieved the state-of-the-art multimode solar laser collection and solar-to-laser conversion efficiencies of 41.3 W/m² and 4.6%, respectively, by end-side-pumping three 2.5 mm diameter, 25 mm length Ce:Nd:YAG rods through an effective collection area of 0.40 m² [56].

In order to maintain the solar laser system performance throughout the day, it is of paramount importance to incorporate a highly accurate solar tracking system (STS) [57]. However, an STS with an error below 0.2° can cost about 10 times more than a similar system with the double of that solar tracking error [58]. Additionally, if the STS is programmed to continuously track the path of the Sun, it will imply recurrent operation of the driver motors which increases the energy consumption and reduces the lifetime of the system. Therefore, it is economically beneficial to develop solar laser systems that can maintain their performance during a couple of minutes using low-cost STS's like those usually employed on photovoltaic energy systems. The solar tracking error compensation capacity of solar laser systems has been evaluated based on the solar tracking error width at 10% laser power loss (TEW_{10%}). In 2022, a dual-rod side-pumping prototype was experimentally studied, achieving up to 1.40° TEW_{10%}. Dual-rod side-pumping approaches have been numerically [51] and experimentally studied [54] for stable solar laser emission with a heliostat-parabolic system, achieving a high tracking error tolerance of 1.40° TEW_{10%}, but only 14.1 W/m² collection efficiency and 1.8% solar-to-laser conversion efficiency were attained. In fact, the current record in Nd:YAG solar laser collection efficiency with a side-pumping configuration is only 17.6 W/m² [59].

For these reasons, the main objective of this thesis is to achieve multibeam Nd:YAG stable solar laser operation by exploring the end-side-pumping solar laser configuration, usually

associated with higher efficiencies [56]. Therefore, multi-rod end-side-pumping solar laser designs were numerically studied, through Zemax[®] and LASCAD[™] software [60–63]. The incorporation of a solar flux homogenizer was numerically studied to achieve uniform and stable multimode solar laser emissions [62]. Multibeam TEM₀₀ solar laser operation under tracking error conditions was also studied [62]. An end-side-pumped four-rod solar laser head was then designed and built for testing at PROcédés Matériaux et Energie Solaire - Centre National de la Recherche Scientifique (PROMES-CNRS) solar facility in Odeillo, France [64]. Significant progress in Nd:YAG solar laser power stability is here reported. By reducing the solar laser head's sensitivity to variations in solar angles, the STS's stepper motor does not need to be continuously running, thus reducing the power consumption and extending the lifetime of the system. Moreover, the end-side-pumped four-rod solar laser approach offers a cost-effective solution to build a stable solar laser system with a cheap, low-accuracy STS.

This thesis is divided in six chapters, as follows:

Chapter 2 describes the fundamental ideas and concepts about solid-state lasers, from the basic light matter interaction to the laser oscillator.

Chapter 3 describes the modelling tools used for the numerical simulations of the solar lasers.

Chapter 4 presents the achieved progress on numeric models, from lamp-pumped to solar pumped lasers.

Chapter 5 describes in detail the experimental work developed in the frame of this thesis to attain stable multibeam solar laser emissions.

Chapter 6 presents the conclusions of the work and future perspectives.

The published papers are cited and explained in detail throughout the document, providing detailed insights and comprehensive analysis on the topics discussed.

ND:YAG SOLAR LASER THEORY

In this chapter, the basics of solid-state laser physics that are necessary in order to understand this work will be presented. It will start with the definition of photons, followed by its interaction with matter. The concept of spontaneous emission, stimulated absorption, stimulated emission and Einstein coefficients are then explained, leading to the definition of important parameters such as stimulated emission cross section. Upper level laser rate equation, light increment along an active medium and laser oscillation threshold condition are consequently defined. To calculate solar laser output power, important definitions like solar concentration ratio, transfer efficiency, absorption efficiency, upper state efficiency, beam overlap efficiency and output coupling efficiency are explained. The topics discussed in Chapter 2 are comprehensively detailed in the following books [9,65,66].

2.1 Photons

Photons are fundamental subatomic particles that carry the electromagnetic force. As quanta of light, photons are the smallest possible packets of electromagnetic energy. Photons are integer spin-1 ($\pm\hbar$) particles (making them bosons) and does not obey the Pauli Exclusion Principle like other half-integer spin-1/2 ($\pm\hbar/2$) fermions (electrons, protons and neutrons), but obeys the Bose-Einstein statistics.

Photons have no electric charge or rest mass. Therefore, they are electrically neutral and are not deflected by electric and magnetic fields. Photons travel at the speed of light in empty space; however, in the presence of matter, a photon can be slowed or even absorbed, transferring energy momentum proportional to its frequency. Like all quanta, the photon has both wave and particle properties; it exhibits wave – particle duality.

Photons are emitted in many natural processes, e.g., when a charge is accelerated, when an atom or a nucleus jumps from a higher to lower energy level, or when a particle and its antiparticle are annihilated (for example, electron-positron annihilation). They are absorbed in the time-reversed processes which correspond to those mentioned above. Photons can have particle-like interactions (i.e. collisions) with electrons and other particles, such as in the Compton Effect in which particles of light collide with atoms, causing the release of electrons.

2.1.1 Photon energy

Each photon has a definite energy E depending upon the frequency ν of the incident radiation. If the intensity of light of a given wavelength is increased, there is an increase in the number of photons emitted by the incident radiations on a given area in a given time. But the energy of each photon remains unchanged.

$$E = h\nu = \frac{hc}{\lambda} \quad (2.1)$$

Where $h = 6.626 \times 10^{-34}$ J.s is Planck's constant, $c = 2.998 \times 10^8$ m/s is the speed of light and λ is the wavelength of light. All photons travel at the speed of light. The energy of a photon depends on radiation frequency; there are photons of all energies from high-energy gamma - and X-rays, through visible light, to low-energy infrared and radio waves. The photon energy is inversely proportional to the wavelength of the electromagnetic wave. The shorter the wavelength, the more energetic is the photon. The longer the wavelength, the less energetic is the photon.

2.1.2 Photon momentum

There is a relationship between photon energy E and photon momentum p and that is consistent with the relation for the relativistic total energy of a particle:

$$E^2 = (p c)^2 + (m c)^2 \quad (2.2)$$

Where m represents the mass of the particle, zero for a photon, but p is not zero, so that (2.2) becomes:

$$E = p c \quad (2.3)$$

From (2.1), the momentum of a photon is related to its wavelength λ and can be calculated using the following formula:

$$p = \frac{E}{c} = \frac{h\nu}{c} = \frac{h}{\lambda} \quad (2.4)$$

Photons carry linear momentum and spin angular momentum when circularly or elliptically polarized. During light - matter interaction, transfer of linear momentum leads to optical forces, whereas transfer of angular momentum induces optical torque. Optical forces including radiation pressure and gradient forces have long been used in optical tweezers and laser cooling. Space sails have been proposed that use the momentum of sunlight reflecting from gigantic low-mass sails to propel spacecraft in the solar system.

2.2 Light and matter interactions

In the early 20th century, Max Planck formulated the theory of spectral distribution of thermal radiation. Albert Einstein, by combining Planck's theory and the Boltzmann statistics gave a theory of stimulated emission which is the governing principle of lasers. Let us assume that the material is placed in a blackbody cavity whose walls are kept at a constant temperature T . Once thermodynamic equilibrium is reached, energy density with a spectral distribution $\rho(\nu)$ will be established and the material will be immersed in this radiation. In this material, both stimulated-emission and absorption processes will occur, in addition to the spontaneous-emission process. There are three ways in which an incident radiation can interact with the energy levels of atoms: spontaneous emission A_{21} , stimulated absorption B_{12} and stimulated emission B_{21} .

To describe these light and matter interactions, let us consider two energy levels, lower level 1 and upper level 2, of some atom or molecule of a given material, their energies being E_1 and E_2 ($E_1 < E_2$) (Fig. 2.1) and population N_1 and N_2 , respectively. It is important to note that the two levels could be any two out of the infinite set of levels possessed by the atom.

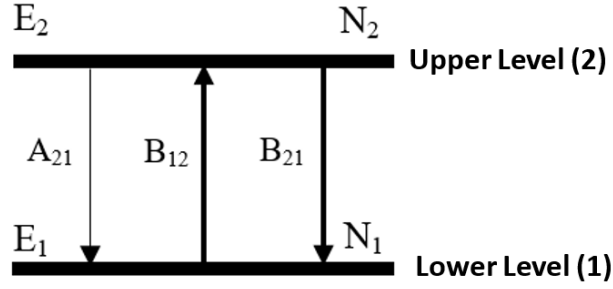


Figure 2-1. Simplified 2-energy level diagram. Adapted from [66].

2.2.1 Spontaneous emission probability

Atoms which are in excited states are not in thermal equilibrium with their surroundings. Such atoms will eventually return to their ground state by emission of a photon. The population of the upper level will decrease due to spontaneous transition to the lower level with emission of radiation. The rate of emission will depend on the population of the upper level. Spontaneous emission is a statistical function of space and time. With a large number of spontaneously emitting atoms, there is no phase relationship between the individual emission processes; the quanta emitted are incoherent. Spontaneous emission probability A_{21} is only related to the properties of the atom itself and does not depend on with the radiation field $\rho(\nu)$, defined as radiation energy density per unit frequency in unit $\left[\frac{J \cdot s}{m^3} \right]$.

By definition:

$$A_{21} = \left(\frac{dN_{21}}{dt} \right)_{sp} \frac{1}{N_2} \quad (2.5)$$

(2.5) has a solution for a time t

$$N_2(t) = N_{20} e^{-A_{21}t} = N_{20} e^{-\frac{t}{\tau_s}} \quad (2.6)$$

Where τ_s is the lifetime for spontaneous radiation of level 2 ($\tau_s = 230 \mu s$). This radiation lifetime is equal to the reciprocal of the Einstein's coefficient:

$$A_{21} = \frac{1}{\tau_s} \quad (2.7)$$

2.2.2 Stimulated absorption probability

In the presence of an electromagnetic field, an atom in a lower level can undergo transitions to the upper level provided that the frequency of the radiation field $\rho(\nu)$ satisfies (2.8)

$$E_2 - E_1 = h \nu \quad (2.8)$$

However, this process is not a spontaneous one, because the atom is stimulated to absorb by the incident light field $\rho(\nu)$. W_{12} is the stimulated absorption probability of radiation, as defined below:

$$W_{12} = \left(\frac{dN_{12}}{dt} \right)_{st} \frac{1}{N_1} \quad (2.9)$$

$$W_{12} = B_{12} \rho(\nu) \quad (2.10)$$

W_{12} is related not only to Einstein absorption constant B_{12} but energy density of radiation $\rho(\nu)$ as well.

2.2.3 Stimulated emission probability

In 1917, Einstein showed that under certain conditions, emission of light may be stimulated by radiation incident on an excited atom. This happens when an electron is in an excited state and a photon whose energy is equal to the difference between the energy of upper and lower energy levels. The incident photon induces the electron in the excited state to make a transition to the lower level by emission of a photon. The emitted photon travels in the same direction as the incident photon. The new photon has the same energy as that of the incident photon and is perfectly in phase with it. When a sizable population of electrons resides in upper levels, this condition is called a population inversion, and it sets the stage for stimulated emission of multiple photons. This is the precondition for the light amplification which occurs in a laser, and since the emitted photons have a definite time and phase relation to each other, the light has a high degree of coherence.

W_{21} is the stimulated emission probability, as defined below:

$$W_{21} = \left(\frac{dN_{21}}{dt} \right)_{st} \frac{1}{N_2} \quad (2.11)$$

$$W_{21} = B_{21} \rho(v) \quad (2.12)$$

W_{12} is related not only to Einstein emission constant B_{21} but to energy density of radiation $\rho(v)$ as well.

2.2.4 Einstein's Relations

Although Einstein coefficients A_{21} , B_{12} , and B_{21} are associated to different transition processes, they are all directly related to each other. Considering the contribution of the three transitions processes, the laser rate equation of upper level can be defined as:

$$\frac{dN_2}{dt} = \rho(v)B_{12}N_1 - \rho(v)B_{21}N_2 - A_{21}N_2 \quad (2.13)$$

Under steady state of transition $\frac{dN_2}{dt} = 0$:

$$\rho(v)B_{12}N_1 - \rho(v)B_{21}N_2 = A_{21}N_2 \quad (2.14)$$

Therefore:

$$\rho(v) = \frac{A_{21}N_2}{B_{12}N_1 - B_{21}N_2} = \frac{\frac{A_{21}}{B_{21}}}{\frac{N_1 B_{12}}{N_2 B_{21}} - 1} \quad (2.15)$$

From Boltzmann equation:

$$\frac{N_1}{N_2} = e^{-\left(\frac{E_1 - E_2}{kT}\right)} = e^{\left(\frac{E_2 - E_1}{kT}\right)} = e^{\frac{h\nu}{kT}} \quad (2.16)$$

By inserting (2.16) into (2.15)

$$\rho(v) = \frac{\frac{A_{21}}{B_{21}}}{\frac{B_{12}}{B_{21}} \frac{h\nu}{e^{kT}} - 1} \quad (2.17)$$

By comparing (2.17) with Planck's formula (2.18):

$$\rho(v) = \frac{8\pi h\nu^3}{c^3} \frac{1}{e^{\frac{h\nu}{kT}} - 1} \quad (2.18)$$

We can finally find the following relations of Einstein coefficients A_{21} , B_{12} , and B_{21} :

$$\frac{B_{12}}{B_{21}} = 1 \quad (2.19)$$

$$\frac{A_{21}}{B_{21}} = \frac{8\pi h\nu^3}{c^3} = \frac{8\pi h}{\lambda^3} \quad (2.20)$$

2.3 Population inversion

To attain laser radiation, stimulated emission probability should be higher than the spontaneous emission probability $W_{21} > A_{21}$, or photon degeneracy should be more than unity.

2.3.1 Stimulated Emission Cross Section and Laser Gain

One of the most important parameters of laser physics: Stimulated Emission Cross Section $\sigma(\nu)$ is defined as:

$$\sigma(\nu) = \frac{\lambda^2}{8\pi n^2 \tau_{21}} g(\nu) \quad (2.21)$$

Stimulated emission cross-section is purely related to the property of laser active medium, depending only on upper level lifetime τ_{21} , refractive index n , laser wavelength λ and line shape function $g(\nu)$ of the laser medium. Consequently, laser gain $G(\nu)$ can be more simply defined as the product of the stimulated emission cross section $\sigma(\nu)$ and the population inversion $N_2 - N_1$:

$$G(\nu) = \sigma(\nu) (N_2 - N_1) \quad (2.22)$$

2.3.2 Upper Level Laser Rate Equation

In a four-level laser, a pump excites atoms, molecules, or other atomic systems from the ground state level to an excited state (pump level) (Fig. 2.2). A sustained laser emission can be achieved by using atoms that have two relatively stable levels between their ground level and pump level. The atoms first drop to a long-lived metastable state (Upper level with population N_2) where they can be stimulated to emit excess energy. However, instead of dropping to the ground level, they stop at lower level with population N_1 above the ground level from which

they can more easily be excited back up to the higher metastable state, thereby maintaining the population inversion needed for continuous laser operation.

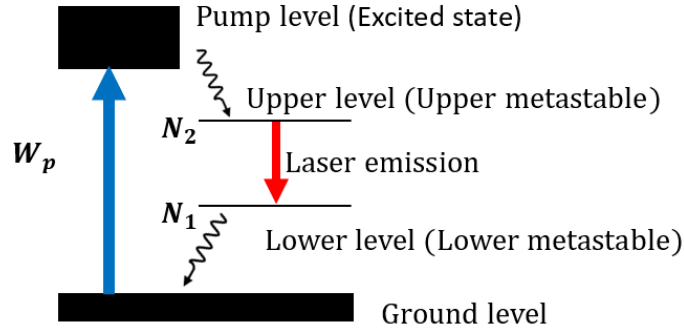


Figure 2-2. Schematics of a four-level laser system. Wiggly lines indicate fast non-radiative transitions. Blue solid line for pump transition and red solid line for slow laser transition. Adapted from [66].

By taking into account the contribution of pumping W_p , the stimulated emission cross section $\sigma(\nu)$, the number of photons per unit area per unit time $\frac{I(\nu)}{h\nu}$, the upper level population N_2 , lower level population N_1 and spontaneous emission constant A_{21} :

$$\frac{dN_2}{dt} = W_p - \sigma(\nu) \frac{I(\nu)}{h\nu} (N_2 - N_1) + A_{21}N_2 \quad (2.23)$$

2.3.3 Laser Resonant Cavity

For a laser device, in addition to a laser material and pump energy to maintain a non-equilibrium state, it is also necessary to have a feedback mechanism for radiation to build up the amplified optical field. This requirement can be obtained by placing the laser medium into a laser resonator, as shown in Fig. 2.3. The pump energy inverts the electron population in the laser material, leading to energy storage in the upper laser level. The role of the resonator, or resonant cavity, is to maintain an electromagnetic field configuration whose losses are replenished by the amplifying medium through stimulated emission. Thus, the resonator defines the spectral, directional, and spatial characteristics of the laser radiation, and the amplifying medium serves as the energy source. It is composed of two (or more) opposing mirrors (plane-parallel or curved) at right angles to the axis of the active material, enabling the laser beam to travel back and forth through the laser material, increasing the amplification of stimulated radiation. The amount of feedback is determined by the reflectivity of the mirrors. Lowering the

reflectivity of the mirrors is equivalent to decreasing the feedback factor. One cavity mirror is high-reflection coated (about 100% reflectivity) for the laser emission wavelength, while the mirror (output coupler) must be only partial reflection coated for the same wavelength, for a fraction of the radiation to "leak out" from the oscillator. Laser output emission occur if the feedback and the gain are sufficiently large to compensate the internal losses of the system.

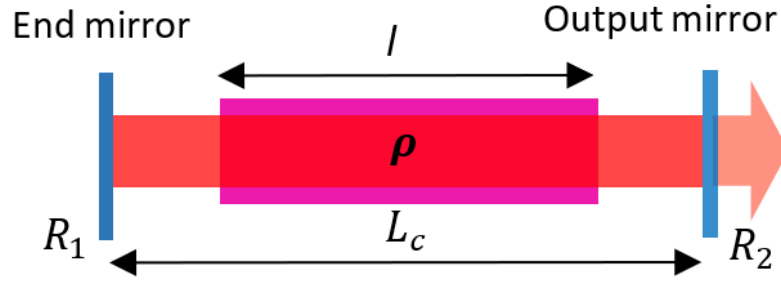


Figure 2-3. Simplified schematics of a laser resonant cavity. Adapted from [66].

For a laser resonator with an active medium, γ represents the logarithmic loss by the scattering and absorption of the laser light in the laser material and by the transmission of the two laser cavity mirrors, γ is thus given as:

$$\gamma = \alpha l + \frac{1}{2} \left[\ln \left(\frac{1}{R_1} \right) + \ln \left(\frac{1}{R_2} \right) \right] \quad (2.24)$$

Where α is the scattering and absorption losses per unit length, l is the length of the laser material, R_1 is the reflectance of the full mirror, and R_2 is the reflectance of the output coupler mirror.

2.4 Solar-to-laser power conversion

To achieve a desired output performance with the maximum system efficiency it is of utmost importance to understand the dependency and interrelationship of the laser system design parameters and design issues which may help in the optimization of the overall laser efficiency.

2.4.1 Solar Concentration Ratio

The ratio between the concentrated flux on the receiver and the ambient flux from the Sun is called the optical concentration ratio. Geometric concentration ratio C is defined as the area of solar collector aperture S_a divided by the surface area of the receiver S_r . The laser rod surface can be considered as a receiver.

$$C = \frac{S_a}{S_r} = \frac{S_a}{\pi D l} \quad (2.25)$$

Where S_a is primary solar collector area, $\pi D l$ is the laser rod side surface area exposed to concentrated solar pump rays.

2.4.2 Transfer Efficiency

Transfer Efficiency η_T can be defined as the ratio between the solar power incident on laser active medium and the incoming solar power reaching the primary solar collector [67].

$$\eta_T = \frac{\int_{\lambda_1}^{\lambda_2} \eta_{tg} \eta_{tl}(\lambda) I(\lambda) d\lambda}{\int_{\lambda_1}^{\lambda_2} I(\lambda) d\lambda} \quad (2.26)$$

Where η_{tg} is a geometrical transfer factor from the solar collector to the surface of the laser medium and is usually independent of wavelength, while $\eta_{tl}(\lambda)$ takes into account the reflection and transmission losses of primary, secondary solar concentrators and laser pump cavity. The absorption by cooling liquid, the reflection and scattering losses at the laser medium and flow tube should be considered.

The integral in (2.26) is taken over the wavelength range between λ_1 and λ_2 , which are useful for pumping the upper laser level. As an example, solar spectral irradiance $I(\lambda)$ and complex absorption spectra $\alpha(\lambda)$ of 1.0% at Nd:YAG medium are presented by orange and blue lines, respectively in Fig. 2.4. For this case, $\lambda_1 = 530 \text{ nm}$ to $\lambda_2 = 880 \text{ nm}$.

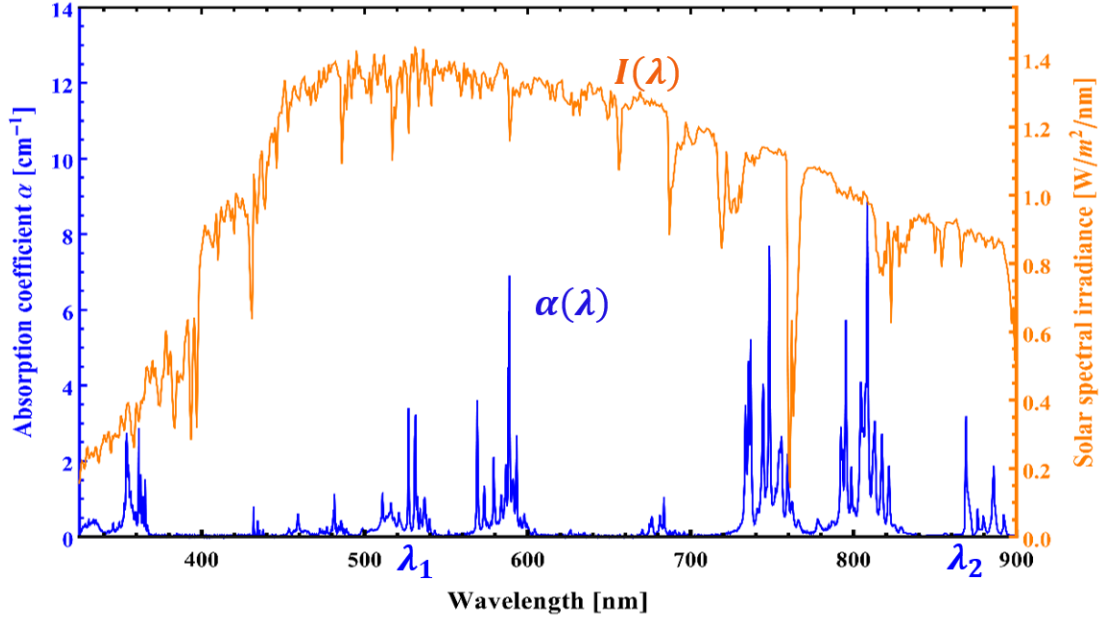


Figure 2-4. Standard solar emission spectrum $I(\lambda)$ (orange line), Nd:YAG absorption spectrum $\alpha(\lambda)$ (blue line)
Adapted from [66].

2.4.3 Absorption Efficiency

Absorption Efficiency η_A describes conversion of incident solar power incident on the surface of the active medium to the total absorbed pump power by the same medium. Absorption efficiency η_A can be defined as [67].:

$$\eta_A = \frac{P_a}{\int_{\lambda_1}^{\lambda_2} P_{e\lambda} d\lambda} \quad (2.27)$$

Where P_a is the total absorbed solar power by the active medium, and $P_{e\lambda}$ is the power per unit wavelength incident on the medium. Similar to transfer efficiency calculations, absorption efficiency calculations require the absorption spectra of the laser material and the solar emission spectra, as shown in Fig. 2.4, where pump source is characterized by solar spectral distribution $I(\lambda)$, and the laser material is characterized by absorption coefficients $\alpha(\lambda)$ with $\lambda_1 = 530 \text{ nm}$ to $\lambda_2 = 880 \text{ nm}$ for Nd:YAG solar lasers. In addition, the angular distribution of the concentrated solar light on the laser material, as well as the geometry of the laser material and its refractive index also need to be known.

2.4.4 Upper State Efficiency

Upper State Efficiency $\eta_U(\lambda)$ is defined as the product of two contributing factors:

$$\eta_U(\lambda) = \eta_Q(\lambda) \eta_S(\lambda) \quad (2.28)$$

Where $\eta_Q(\lambda)$ is the quantum efficiency and $\eta_S(\lambda)$ is the quantum defect, also referred as Stokes factor.

Quantum Efficiency $\eta_Q(\lambda)$ can be defined as the ratio of the number of atoms raised to the upper laser level to the number of absorbed pump photons [67].. It relates the probability of an absorbed photon producing an atom in the upper laser level. We can thus write:

$$\eta_Q(\lambda) = \frac{h\nu \int \frac{dN_2}{dt} dV}{P_a} = \frac{\frac{hc}{\lambda} \int \frac{dN_2}{dt} dV}{P_a} \quad (2.29)$$

Photons absorbed in a pump manifold may bypass the upper laser manifold by radiative decay to a lower manifold. In all probability, the decay from the pump to the upper laser manifold occurs by non-radiative transitions. If the upper laser manifold is directly below the pump manifold, the quantum efficiency is approximately [68]:

$$\eta_Q = \frac{\frac{1}{\tau_{NR}}}{\left[\frac{1}{\tau_{NR}} + \frac{1}{\tau_{RAD}} \right]} \quad (2.30)$$

Where τ_{NR} and τ_{RAD} are the pump manifold non-radiative and radiative lifetimes, respectively.

Quantum Defect Efficiency $\eta_S(\lambda)$, also called Stokes factor, is the ratio of the photon energy emitted at the laser transition, to the energy of a pump photon:

$$\eta_S = \frac{h \nu_L}{h \nu_p} = \frac{\lambda_p}{\lambda_L} \quad (2.31)$$

Where λ_p and λ_L are the pump transition and laser wavelengths, respectively.

In solar-pumped solid-state lasers, the pump wavelength is defined as the mean absorbed and intensity-weighted solar radiation wavelength:

$$\lambda_p = \frac{\int_{\lambda_1}^{\lambda_2} I(\lambda) \lambda d\lambda}{\int_{\lambda_1}^{\lambda_2} I(\lambda) d\lambda} \quad (2.32)$$

Where the integration is performed over the laser absorption bands between λ_1 and λ_2 and $I(\lambda)$ is the standard solar spectral irradiance, as shown in Fig. 2.4.

Since the laser wavelength of Nd:YAG laser material is $\lambda_L = 1064$ nm for solar-pumped Nd:YAG laser and $\lambda_p = 660$ nm [67], quantum defect efficiency η_s is 0.62. Typically, upper state efficiencies of a Nd:YAG medium show a variation of $\eta_U(\lambda)$ from 0.58 to 0.60, revealing its slight dependence on laser rod diameter. Consequently, upper state efficiency of $\eta_U(\lambda) = 0.59$ can be considered.

2.4.5 Beam Overlap Efficiency

Beam Overlap Efficiency η_B expresses the spatial overlap between the laser resonator modes and the pumped region of the laser medium, which can be given by an overlap integral [67].

$$\eta_B = \frac{(\iiint \varepsilon(x,y,z) \omega(x,y,z) dV)^2}{\iiint \varepsilon(x,y,z)^2 \omega(x,y,z) dV} \quad (2.33)$$

$$\varepsilon(x,y,z) = \frac{\rho(x,y,z)}{\rho_0} \quad (2.34)$$

$$\iiint \omega(x,y,z) dV = 1 \quad (2.35)$$

$$\omega(x,y,z) = \frac{W_p(x,y,z)}{W_{p0}} \quad (2.36)$$

Where $\rho(x,y,z)$ is the cavity mode energy density, ρ_0 is the total value of the energy density, $W_p(x,y,z)$ denotes the pump rate per unit volume and W_{p0} is the total number of absorbed photons.

Choice of laser geometry can have a profound effect on overlap efficiency and average power capability. Historically, laser geometries were often in the form of cylinders. They can also be

useful for end pumping of laser materials with low absorption coefficients. Laser rods pose a hard aperture making extraction of the population inversion near the periphery of the laser rod more difficult. If laser operation is restricted to TEM₀₀ modes, the beam *radius* is often set at about 0.6 of the laser rod *radius*. This restricts the overlap efficiency to roughly 0.36 [68]. In addition, cooling was usually achieved by flowing coolant over the lateral surface of the laser rod. This leads to radial thermal gradients and thermal lensing that degrade beam quality and limits average power. Consequently, analytical calculation of the beam overlap efficiency of a solid-state laser is rather complex, since it is strongly dependent on the resonator parameters such as *radius* of curvature of cavity mirrors, cavity length, rod diameter and, more importantly, also on solar pumping conditions such as tracking errors of either a heliostat or a solar tracker in the case of solar-pumped lasers. Therefore, it is very important to note that laser output power from a resonant cavity with a certain length L presents usually a considerably reduced laser output power level due to the influence of the beam overlap efficiency of less than unity ($\eta_B < 1$), as compared to that of a closely coupled laser resonant cavity with $\eta_B = 1$, corresponding to a laser cavity with high reflection (HR) and partially reflection (PR) mirrors closely positioned near the laser rod, allowing the maximum extraction of laser power from that rod.

2.4.6 Extraction Efficiency

Photon loss rate through an output mirror with reflectivity R_2 is defined as laser power extraction efficiency, η_E , and is determined by:

$$\eta_E = \frac{c}{2L'} \ln \frac{1}{R_2} \quad (2.37)$$

L' is the effective cavity length and is given as

$$L' = L_C + (n - 1)l \quad (2.38)$$

Where L_C is the length between the two cavity mirrors, n is the refractive index of the laser host material, and l is the length of the laser material.

2.4.7 Solar-to-laser power efficiency

Solar power to laser power conversion efficiency η_c can be simply calculated:

$$\eta_c = \frac{P_{out}}{P_{in}} \quad (2.39)$$

Where P_{out} is the solar laser power produced and P_{in} is the input solar power.

2.5 Solar laser output power calculation

2.5.1 Solar laser output power

The laser output power P_{out} of a continuous-wave laser is calculated from the following relation:

$$P_{out} = \rho V \eta_E E \quad (2.40)$$

- ρ is the photon density calculated from:

$$\rho = \frac{1}{\sigma c} \left[\left(\frac{N_t \sigma l}{\gamma} - 1 \right) W_p - \frac{1}{\tau_e} \right] \quad (2.41)$$

Where N_t is the total number density of the active atoms in the laser rod (for 1.0 at.% $Nd^{3+}YAG$ medium, $N_t = 1.38 \times 10^{20} cm^{-3}$) and τ_e is the effective lifetime of the upper laser level.

- V represents the lasing volume in the resonant cavity and can be defined as:

$$V = A L' \quad (2.42)$$

Where A is the laser beam cross section, and L' is the effective cavity length.

- η_E is defined as laser power extraction efficiency is determined by:

$$\eta_E = \frac{c}{2L'} \ln \frac{1}{R_2} \quad (2.37)$$

- E is the photon energy calculated from:

$$E = h\nu \quad (2.1)$$

Since normally, $\frac{N_t \sigma l}{\gamma} \gg 1$, we can reach a simplified equation for P_{out} :

$$P_{out} = A h\nu \left(\frac{N_t l}{\gamma} \right) \frac{1}{2} \ln \frac{1}{R_2} \left[W_p - \frac{\gamma}{\sigma \tau_e N_t l} \right] \quad (2.43)$$

2.5.2 Slope efficiency

A simplified presentation for laser output power is presented:

$$P_{out} = \eta_{slope} (W_p - W_{pth}) \quad (2.44)$$

Where η_{slope} is defined as laser slope efficiency:

$$\eta_{slope} = A h\nu \left(\frac{N_t l}{\gamma} \right) \frac{1}{2} \ln \frac{1}{R_2} \quad (2.45)$$

And W_{pth} is defined as threshold pump rate:

$$W_{pth} = \frac{\gamma}{\sigma \tau_e N_t l} \quad (2.46)$$

It is important to note that W_{pth} is directly proportional to resonant cavity loss γ , and inversely proportional to the product of four important laser gain parameters, e.g. stimulated emission cross section σ , upper level lifetime τ_e , active ion number N_t and laser rod length l . Consequently, threshold pump rate can be either reduced by diminishing γ or by increasing σ, τ_e, N_t, l values.

Maximum pump power to threshold pump power ratio is defined:

$$\frac{P_{in}}{P_{th}} = \frac{W_p}{W_{th}} = x \quad (2.47)$$

Solar laser slope efficiency can also be calculated:

$$\eta_{slope} = \frac{P_{out}}{P_{in} - P_{th}} = \frac{P_{out}}{P_{in}} \frac{1}{1 - \frac{P_{th}}{P_{in}}} = \frac{P_{out}}{P_{in}} \frac{1}{1 - \frac{W_{th}}{W_p}} = \eta_c \frac{x}{x-1} \quad (2.48)$$

TOOLS FOR ND:YAG LASER MODELLING AND NUMERICAL ANALYSIS

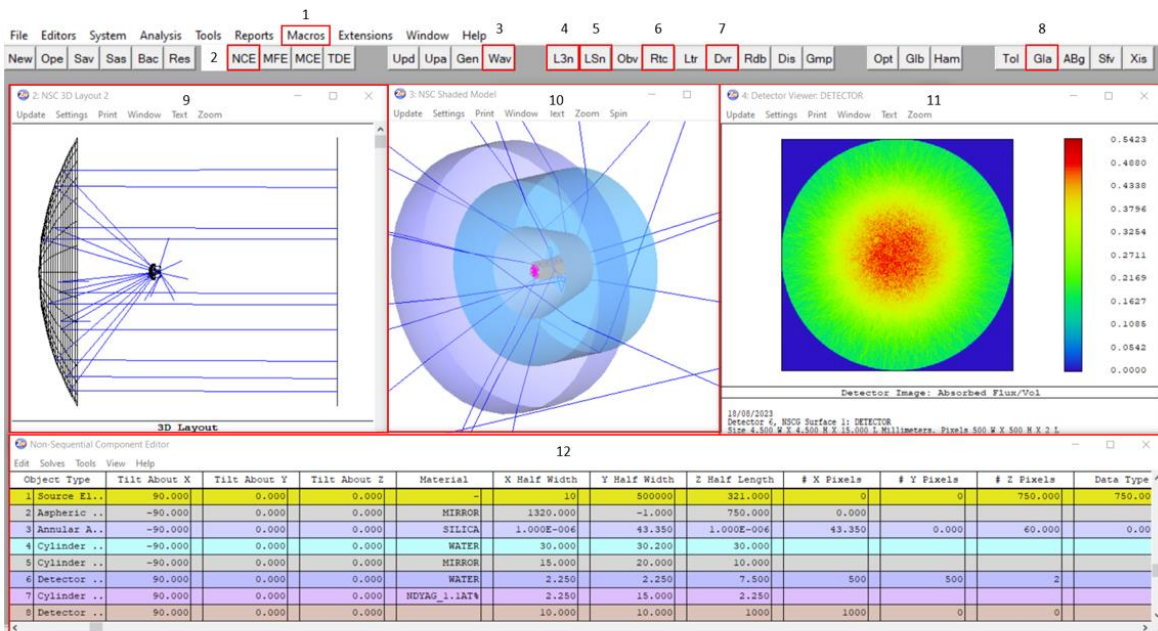
In this chapter, the tools for design and optimization of the laser system will be introduced. The design parameters of all the solar pumping systems were firstly optimized through ZEMAX[®] non-sequential ray-tracing software. Laser resonator parameters were then modelled by Laser Cavity Analysis and Design (LASCAD[™]) codes to optimize the laser output power and beam quality.

3.1 Zemax[®] software

In the realm of optical engineering, the importance of accurate and efficient design tools cannot be overstated. Zemax[®], a commercially available software program, emerges as a prominent solution catering to the intricate needs of optical system modelling, analysis, and optimization, empowering users to transform their envisioned optical systems into reality. The software's ray tracing capabilities simulate the behaviour of light rays as they interact with optical components, aiding in the visualization of light paths and enabling the prediction of system performance. Advanced optimization algorithms allow users to fine-tune system parameters for desired outcomes, be it maximizing efficiency, minimizing aberrations, or meeting specific design criteria. Furthermore, the software offers tolerance analysis, enabling engineers to account for real-world manufacturing variations and environmental conditions, ensuring the robustness of the designed systems.

3.1.1 Main window

For solar-pumped laser modelling, the Zemax® software operates in the non-Sequential mode. Depending on the properties of the struck object, the ray will refract, reflect, or be absorbed, after which it continues along a new trajectory. This non-sequential ray tracing approach allows rays to interact with groups of objects in any order, or they may repeatedly strike the same object, contingent on the objects' geometry and properties. The typical main window display in the non-sequential mode of Zemax® software for the design of an Nd:YAG solar laser is presented in Fig. 3.1. The primary functionalities employed to manipulate the non-sequential components (NSC) involved in solar-pumped laser modelling are highlighted in red.



- | | | |
|--------------------------|----------------------------------|----------------------------|
| 1 Run/edit ZPL macros | 2 Open the non-sequential editor | 3 Open the wavelength data |
| 4 Open the NSC 3D layout | 5 Open the NSC shaded model | 6 Open ray trace control |
| 7 Open detector viewers | 8 Open glass catalog | 9 NSC 3D layout |
| 10 NSC shaded model | 11 Detector viewer | 12 NSC editor |

Figure 3-1. Zemax® software main window. The primary functionalities employed to manipulate the non-sequential components (NSC) involved in solar-pumped laser modelling are highlighted in red.

Macros written in Zemax® programming language (ZPL) can be used to perform optimizations, automate analysis or produce complex geometries. These macros can directly affect the Zemax non-sequential components editor, the 3D layout windows or even the detector viewers settings.

The local optimization feature provided by Zemax[®] can improve lens designs given a starting point and a set of variable parameters. Variables can be curvatures, thicknesses, glasses, conics, parameter data, extra data, and any of the numeric multi-configuration data. The algorithms are capable of optimizing a merit function composed of weighted target values. It must be at least one variable for the optimization algorithm to be able to make any progress. The design that yields the lowest possible value of the merit function is called the "global" optimum and is, by definition, the best possible design. However, there is no known optimization algorithm that can universally find the global optimum for an arbitrary design problem. The art of optical design with computer assistance has two basic components. First, the designer must be able to determine a suitable starting design, and second, to play the role of supervisor during the optimization process. Unfortunately, this often requires considerable experience, and even more often, excessive tedium. An experienced designer uses a combination of intuition, analysis, and luck in searching for new, better, design forms. Zemax[®] automated capability for performing this global optimum search was not used during this work.

3.1.2 Source

Sources are the objects utilized to emit the rays of the simulation, thus representing the pumping sources. The source wavelength is configurable in Wavelength Data window, shown in Fig. 3.2. A total of 24 wavelength entries can be accepted at a time. Each wavelength has its respective unitless weight. Each tick box activates and deactivates the selected wavelengths or to sort, save and load the wavelength data. A minimum and maximum computational wavelength can be set for the system. The wavelength measured in micrometers and referenced to the system's air temperature and pressure. The default system temperature is set at 20 °C, and the default air pressure is at 1.0 atm. In the case of a solar-pumped Nd:YAG laser system modeling, for Nd:YAG laser medium, 22 absorption peaks are defined in Zemax[®] numerical data. The central wavelengths of these peaks are 527, 531, 568, 578, 586, 592, 732, 736, 743, 746, 753, 758, 790, 793, 803, 805, 808, 811, 815, 820, 865, and 880 nm. Spectral irradiance ($\text{W/m}^2/\text{nm}$) values corresponding to the above mentioned 22 peak absorption wavelengths could be consulted from the standard solar spectrum for 1.5 air mass (AM1.5)[69].

Wavelength Data

Use	Wavelength (μm)	Weight	Use	Wavelength (μm)	Weight
☒ 1	0.527	65	☒ 13	0.79	67
☒ 2	0.531	70	☒ 14	0.793	66
☒ 3	0.568	82	☒ 15	0.803	65
☒ 4	0.578	87	☒ 16	0.805	64
☒ 5	0.586	88	☒ 17	0.808	63
☒ 6	0.592	88	☒ 18	0.811	62
☒ 7	0.732	81	☒ 19	0.815	61
☒ 8	0.736	80	☒ 20	0.82	60
☒ 9	0.743	80	☒ 21	0.865	49
☒ 10	0.746	78	☒ 22	0.88	46
☒ 11	0.753	77	☐ 23	0.55	1
☒ 12	0.758	76	☐ 24	0.55	1

Select-> F. d. C (Visible) Primary: 1

Gaussian Quadrature -> Steps: 4

Minimum Wave: 0.527 Maximum Wave: 0.88

OK Cancel Sort

Help Save Load

Figure 3-2. Wavelength Data window. 22 solar wavelengths with their respective weights selected from the solar spectrum overlapped with the absorption bands of Nd:YAG.

There are parameters common to all the three types of objects (Sources, geometric optical elements and detectors) such as the position (X, Y, Z position) and direction (Tilt about X, Y, Z), and there are parameters specific of each object.

Object type

There exist several types of source objects in Zemax®; however, only the "Source Ellipse" is utilized for defining the solar pumping source.

Tilt About X/Y

These parameters can be utilized to simulate misalignments in the solar radiation with the solar laser system. Typically, these systems are optimized assuming perfect alignment, where their values are set to 0.

Layout / Analysis Rays

The layout rays indicate the number of rays displayed in the NSC 3D layout and shaded model windows and do not influence the simulations. The number of analysis rays is a crucial parameter in Zemax® simulations. Increasing the number of rays results in highly accurate simulations; however, it also increases simulation time. This parameter must be defined for each optical system, considering the required precision and available time.

Power

Indicates the total power of the source in watts. Considering the NOVA heliostat-parabolic mirror system in Lisbon, the terrestrial solar irradiance in Lisbon area, in Summer can reach about 950 W/m^2 , and the parabolic mirror has 1.5 m diameter. For the modelling of a solar laser system, the effective pump power of the light source has also to take into account the overlap between the absorption spectrum of the active medium and the solar emission spectrum, which is considered as 16% for the Nd:YAG [28]. Thus, for the modelling of the Nd:YAG solar laser system, the source power is calculated by the product of the source area ($\pi \times (0.75 \text{ m})^2 = 1.77 \text{ m}^2$) with the terrestrial irradiance, and the overlap between the Nd:YAG absorption spectrum and absorption spectrum ($1.77 \text{ m}^2 \times 950 \text{ W/m}^2 \times 0.16 \approx 268 \text{ W}$).

Y/X Half Width

Express the dimensions of the source, which is a flat elliptical surface, in millimeters (mm). The radiation collected correlates with the collection area of the primary concentrator, a circular parabolic mirror with a diameter of 1.5 m. As a result, the width of the solar pumping source is the same as of the primary concentrator.

Gauss G_x/ G_y

The rays launched lie on the surface of the ellipse with a Gaussian distribution that follows a from the following Eq. 3.1[66]:

$$I(l, m) \approx I_0 e^{-(G_x l^2 + G_y m^2)} \quad (3.1)$$

Where l and m are the direction cosine of the rays in the X and Y axis direction and G_x and G_y are constants. This form defines a far-field pattern that is different in the X or Y directions. The larger G_x and G_y are, the narrower the distribution. If both G_x and G_y are zero, then all rays will emit from a virtual point source as collimated light. The apparent half angle of $\pm 0.27^\circ$ subtended by the Sun must be considered in the analysis of our solar laser system, which is defined by $G_x = G_y = 40000$ [66]. This value was calculated by Zemax® analysis.

3.1.3 Primary concentrator

The Nd:YAG solar laser systems here designed during this PhD project used a parabolic mirror as the primary concentrator. Fig. 3.3 presents the NSC shaded model for both the NOVA parabolic mirror and the PROMES-CNRS medium size solar furnace (MSSF) parabolic mirror.

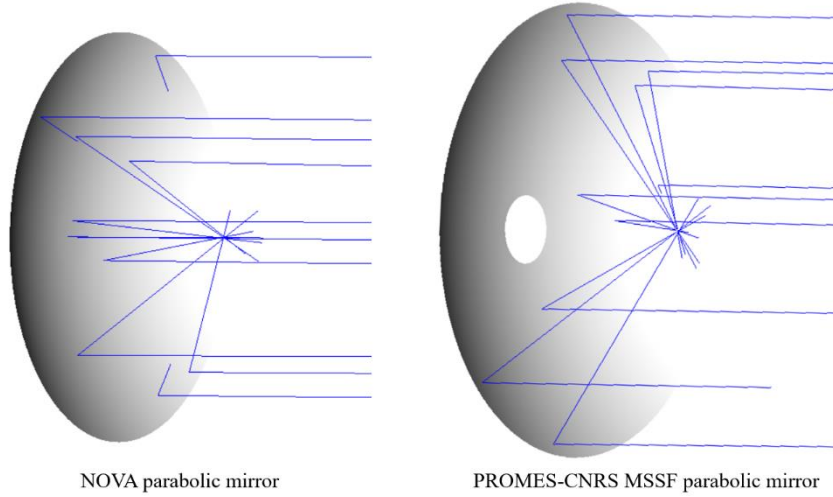


Figure 3-3. NSC shaded model of both the NOVA parabolic mirror and the PROMES-CNRS MSSF parabolic mirror.

A parabola focuses rays parallel to its axis into a focal point. However, due to the superior diameter of the Sun relative to Earth, Sun rays are not parallel, making an apparent half-angle $\pm 0.27^\circ$ in relation to Earth. In this case, the focal point becomes a spot. To effectively represent the parabolic mirrors, the chosen object type was the Aspheric Surface. The material MIRROR was chosen with distinct reflectivity programmed for each specific case. An aspheric surface is defined by the following sag equation:

$$z = \frac{cr^2}{1 + \sqrt{1 - (1+k)c^2r^2}} + \sum_{i=1}^N \alpha_i r^i \quad (3.2)$$

Where c is the curvature of the surface, k is the conic constant, r is the radial coordinate, and the terms α are aspheric coefficients. This object type supports specification of both a minimum and a maximum radial aperture; so annular surfaces may be defined, as in the case of the PROMES-CNRS MSSF parabolic mirror.

3.1.4 Secondary concentrator

The solar laser head is usually composed of a second-stage concentrator similar to those presented in Fig. 3.4. The conical or aspherical shaped lenses coupled efficiently the concentrated solar radiation from the focal spot of the parabolic mirror into the active media. For the conical lens, the object type Cone was used, whereas for the aspheric lens the object type used was the Annular Aspheric Lens. The curved surface of the aspheric lens follows the sag Equation (3.2). Fused silica was the optical material chosen for the aspheric lens due to its transparency over the Nd:YAG absorption spectrum, low coefficient of thermal expansion, and resistance to thermal shock. Besides, since the refractive index of fused silica ($n_{\text{silica}} \approx 1.46$) is higher than that of water ($n_{\text{water}} \approx 1.33$), the direct contact of the aspheric lens output end with water ensures the efficient light coupling into the water flooded pump cavity. The absorption spectrum and the wavelength-dependent refractive indices of fused silica material for the secondary concentrator were included in the glass catalog data of Zemax[®].

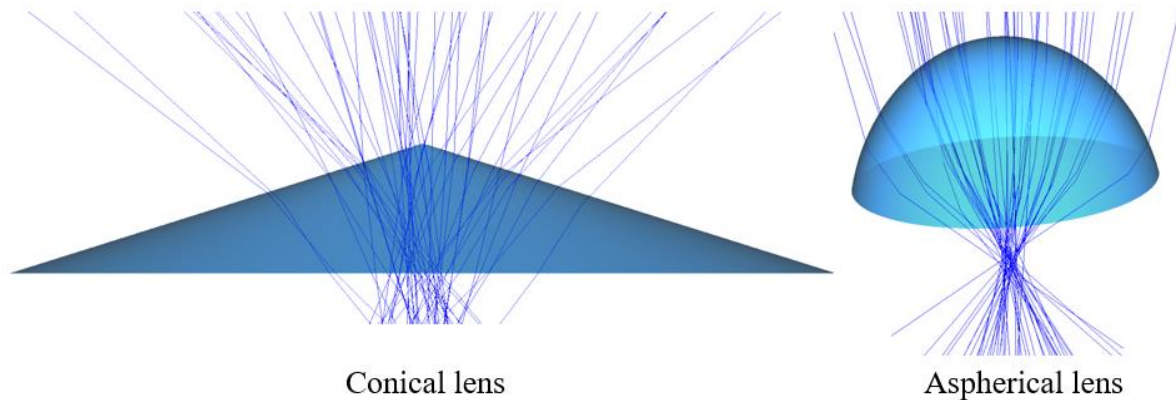


Figure 3-4. NSC shaded model of both a conical lens and an aspherical lens.

3.1.5 Pump cavity

Pump cavities are designed to efficiently transfer energy from the pump source to the gain medium. The pump cavity helps ensure that the maximum amount of energy is absorbed by the gain medium, minimizing losses and maximizing the efficiency of the laser system. Fig 3.5 presents the different pump cavities optimized by me during the PhD project for lamp-pumped (Fig. 3.5 a)) and solar-pumped (Fig. 3.5 b-d)) laser systems using Zemax[®] software [60,62,63,70].

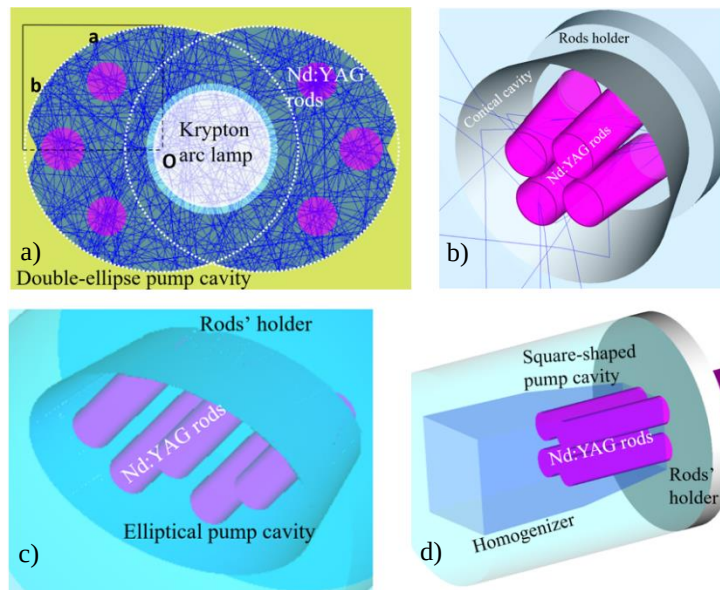


Figure 3-5. NSC shaded model of different pump cavities geometries. a) A double-ellipse pump cavity explored in lamp-pumped lasers [70]. b) A conical pump cavity commonly used in solar-pumped laser systems [60]. c) An elliptical pump cavity designed to address the solar tracking error issues associated with solar lasers [63]. d) A square-shaped pump cavity for uniformly pump four Nd:YAG rods [62].

The geometry of these optical components varies for each application. By using the object type Boolean, is it possible to design complex geometries that originate from subtracting and adding other object types previously included in Zemax[®]. As presented in Fig. 3.5a, a double-ellipse pump cavity, working at imaging principle, was used to pump six Nd:YAG rods around a lamp source [70]. In solar-pumped laser systems, conical pump cavities are commonly used. This geometry can be easily achieved in Zemax[®] software by using the object type Cylinder Pipe, as shown in Fig. 3.5b. An elliptical pump cavity can also be useful when leading with solar tracking errors; however, modelling this geometry in Zemax[®] is slightly more complex. In this case (Fig. 3.5c), two object were created: a Cylinder Volume and an Elliptical Volume. The first was designed with the material MIRROR and the latter with WATER. The water volume was dimensioned with the desired geometry for the pump cavity and positioned inside the larger mirror volume. By correctly order the objects in the NSC editor (the mirror volume first, followed by the water volume), it was possible to model the elliptical pump cavity. A simpler pump cavity is presented in Fig. 3.5d, where a Rectangular Pipe object was used to uniformly pump four Nd:YAG rods. The reflectivity of all the above mentioned MIRROR objects was programmed in the object properties, as presented in the Fig. 3.6. I.06 indicates 94% reflectivity.

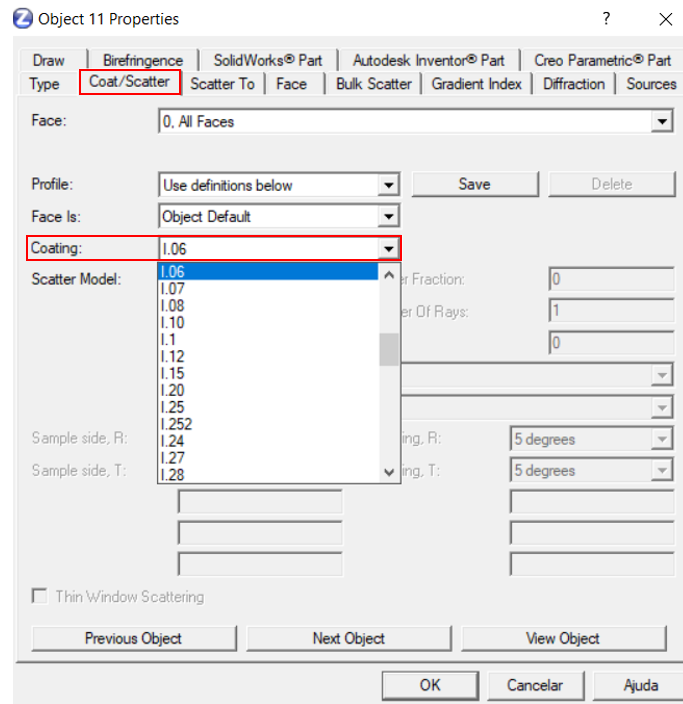


Figure 3-6. Object properties window for coat/scattering settings.

3.1.6 Nd:YAG laser rod

Laser rods are usually adopted in solar-pumped laser systems. This geometry is simple to model in Zemax[®] software using the object type Cylinder Volume. However, in the case of a refractor material, such as the laser rod, all the characteristics must be defined through the *Glass Catalog* menu, within which it is possible to update the values or create new materials, depending on the specific need of each case. One of the parameters that can be changed is the absorption / transmission spectrum of the material, which depends on the wavelength, doping material, absorption coefficient, temperature and distance traveled by the radiation inside the material. The transmission spectrum of 1.0 at.% Nd:YAG laser material, at a temperature of 300 K, is shown in FIG. 3.7. The refractive index of the glass material is also highlighted in red. When programming the NSC editor, the name for the material needs to correspond to the name presented in the Glass Catalog.

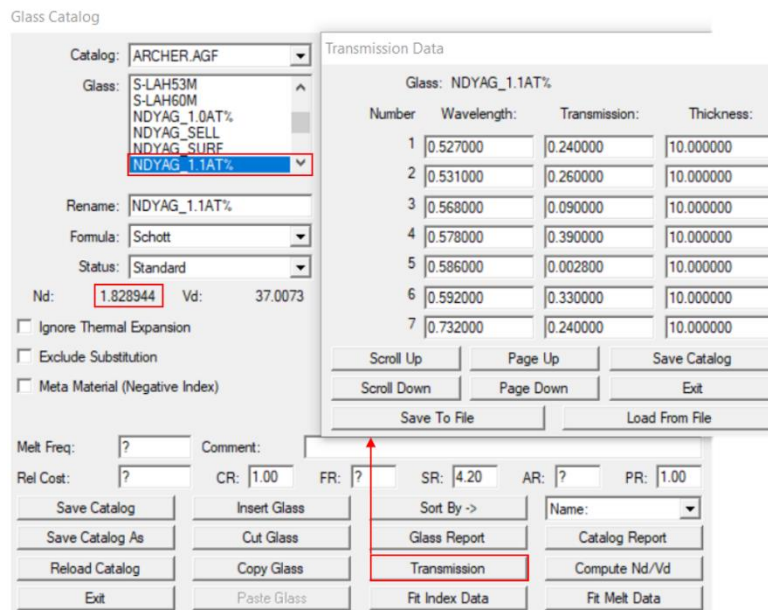


Figure 3-7. Transmission data of the Nd:YAG laser material.

3.1.7 Detector

To provide the information of the incident or absorbed pump power it is necessary to use the detector objects in ZEMAX®. For example, to detect the numerical information at the focus of the primary concentrator, illustrated in Fig. 3.3, a *detector rect* is usually utilized. The rectangular detector allows to record more amount of data, such as the incident power and angle, the bidimensional power distribution and the profile of incident/absorbed power in the area defined by the detector. This type of detector can be placed either inside or outside of an object and have the function of absorbing, reflecting, or not have any effect on the incident radiation. The shape of the detector is however limited to a rectangular surface defined by the user. The image resolution can be adjusted by parameterizing the number of pixels of the detector, taking into account the influence on the total time required for each simulation. For the analysis of the incident or absorbed pump power within the laser material, as well as the pump profile in Fig. 3.8, a *detector volume* is used in this case. Similar to the rectangular detector, the detector volume is limited to the shape of a rectangle. However, with this detector it is possible to add a new dimension to obtain the power information, since it has a parallelepiped shape, whose dimensions are defined by the user, as well as the number of voxels. The resolution of the volume detector has also a great influence on the calculation time of each simulation. For example, in ZEMAX® non-sequential ray-tracing, the *detector volume* of the laser rod is divided into a total of several voxels. The pump flux distributions along five transversal cross-sections of a Nd:YAG rods are given in Fig. 3.8.

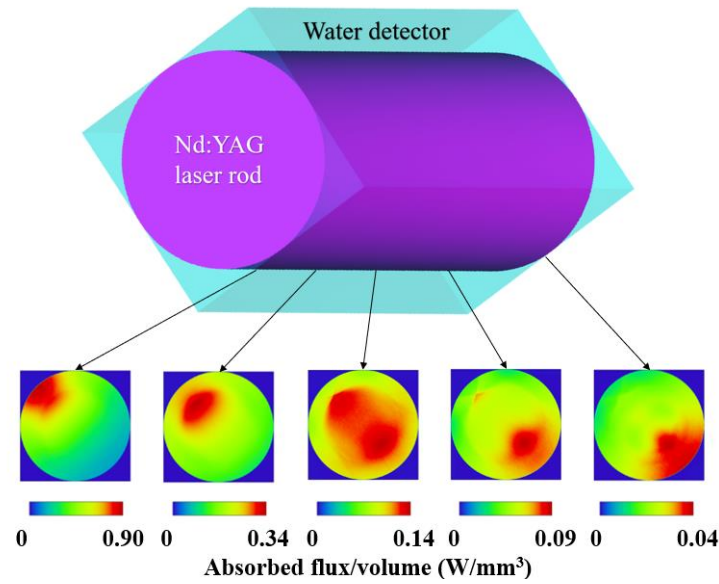


Figure 3-8. Absorbed pump-flux distributions along five transversal cross-sections of a Nd:YAG rod. Adapted from [60].

The absorbed pump flux data from the ZEMAX® analysis is then processed by LASCAD® software to study the laser beam parameters and quantify the thermal effects applied in the active medium.

3.2 LASCAD® software

LASCAD™ software, a dominant package in the laser industry, facilitates a sophisticated, multi-physics system interaction analysis known as thermal lensing solid-state optics. This powerful tool integrates simulation algorithms—such as thermal and structural Finite Element Analysis (FEA), the ABCD Gaussian Beam Propagation Code, and the Beam Propagation Method (BPM) for non-Gaussian beams—to optimize laser resonator design comprehensively. The software excels in modelling resonant cavities, meticulously analyzing thermal lensing effects and their impact on light quality, device stability, and light efficiency. Essential parameters, including reflectivity, *radius* of curvature, distances between cavity components, diffraction losses, gain saturation, and more, are considered for a thorough analysis and optimization of laser resonators.

3.2.1 Finite element analysis

LASCAD™ uses FEA to compute the temperature distribution, deformation, and stress of a thermally loaded crystal, taking into account the laser material parameters, pump configuration and cooling geometry. LASCAD™ provides some pre-defined models of typical configurations, as shown in Fig. 3.9a. Nevertheless, each pumping scheme may exhibit distinctive characteristics not encompassed by the predefined models of LASCAD™, especially in scenarios such as solar-pumped lasers. In order to accurately model solar laser systems, the software allows for the seamless import of files from ZEMAX® ray-tracing software, as illustrated in Fig. 3.9b. These files encapsulate the three-dimensional distribution of absorbed pump power by the active medium as defined in ZEMAX®.

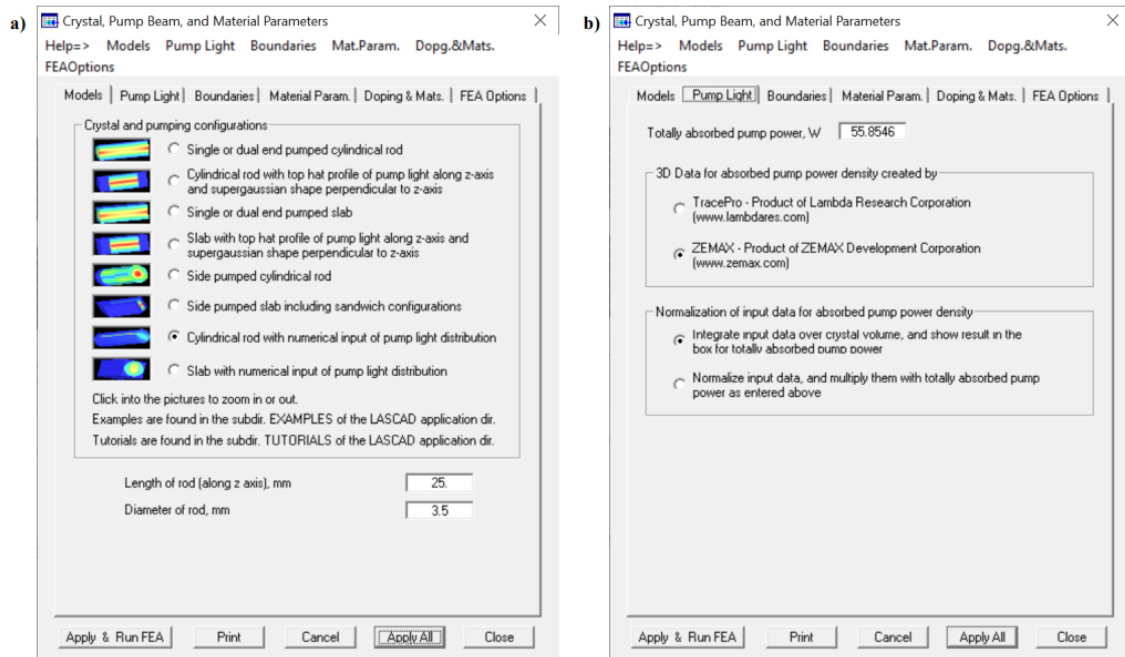


Figure 3-9. LASCAD™ FEA window presenting (a) active medium and pump configuration models of LASCAD™ and (b) the settings to import data files from ZEMAX®.

Parameters related to the active medium and material properties can also be defined, as depicted in Fig. 3.10. The material data of 1.0 at.% Nd:YAG crystal with a stimulated emission cross-section of $2.8 \times 10^{-19} \text{ cm}^2$, a fluorescence lifetime of 230 μs [9] and an absorption/scattering loss of 0.002 cm^{-1} was set in LASCAD™.

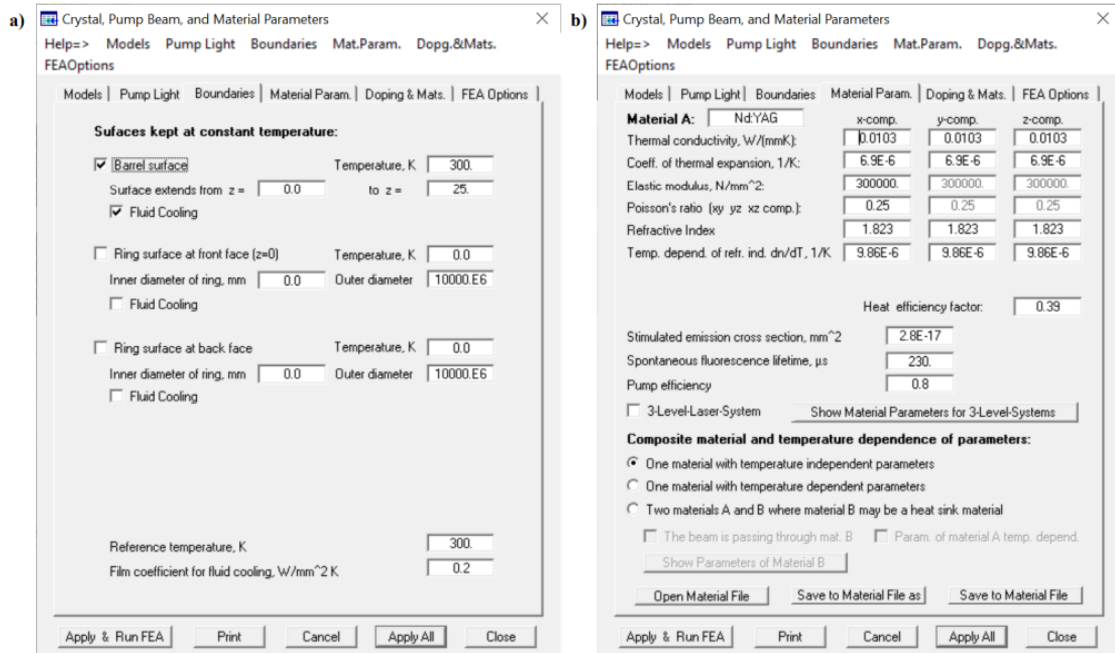


Figure 3-10. LASCAD™ FEA window presenting (a) the cooling parameters of a side-pumping scheme solar laser and (b) Nd:YAG laser material parameters.

The simulation conditions, such as the resolution and the number of iterations are defined in Tab FEA options. After defining all the parameters related to pumping, active medium and cooling, the thermal and structural analysis by FEA can be started. The thermal analysis is carried out through the determination of the heat load distribution, the 3D differential equations of the heat conduction and the differential equation of structural deformation. To solve the differential equations, the LASCAD™ FEA code discretizes the laser crystal into a tri-dimensional grid, whose resolution is defined by the user, and produces the iterations through a number of times. The accuracy of the results depends directly on the grid resolution, as well as on the simulation time. Running the FEA generates the data used for simulating thermal lensing within the laser cavity. It also produces three dimensional representations of the crystal heat load, temperature and stress, relying on the equations which describe heat conduction, structural deformation and absorption. The remaining results of the algorithms within LASCAD™ depend on the results from the FEA.

The thermal performance of the laser material under solar pumping is of paramount importance in solar-pumped lasers. For example, it is possible to study the thermal performance of different solar pumped laser configurations and predict which is less likely to result in fracturing the active media. The thermal parameters, such as heat load, temperature and stress

intensity, were calculated for a single-rod scheme, and for a four-rod scheme, both arranged in an end-side-pumping configuration [60]. The results are summarized in Fig. 3.11, showing a significant reduction of the prejudicial thermal induced effects in the four-rod scheme.

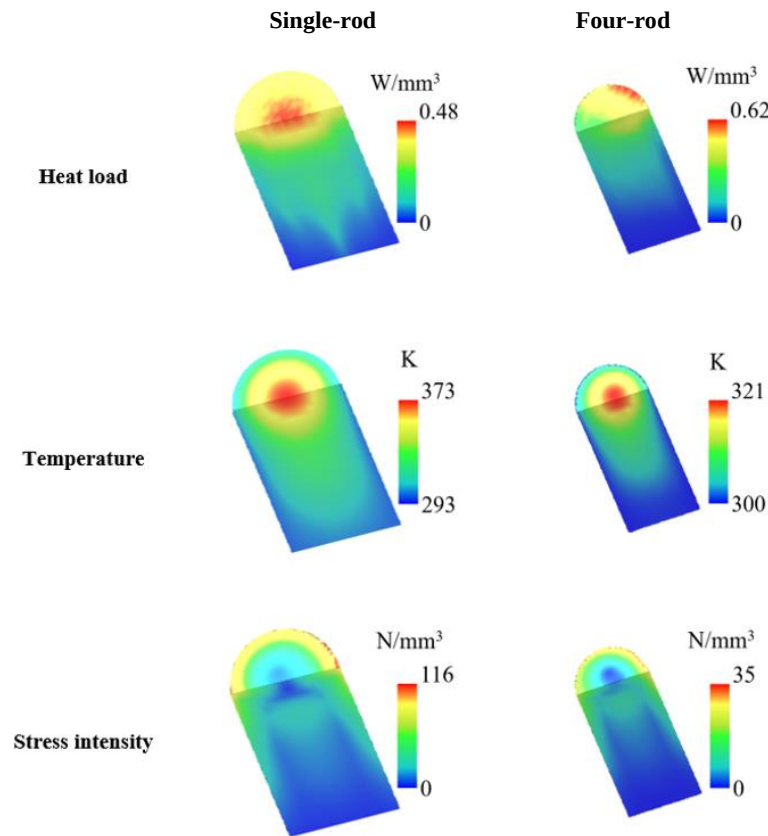


Figure 3-11. Numerically calculated heat load, temperature and stress intensity distributions of the 5.50 mm diameter, 25 mm length Nd:YAG rod from a single-rod scheme, and one of the four 4.55 mm diameter, 15 mm length Nd:YAG rods from a four-rod scheme. Adapted from [60].

For an end-side pump scheme, the uneven light flux distribution along the crystal is a serious thermal issue, particularly at the upper-end side of the rod. The 5.5 mm diameter, 25 mm length rod of the single-rod scheme has a more severe stress intensity, reaching a maximum value of 116 N/mm^2 , while by using a four rod-scheme, each rod with 4.55 mm diameter, 15 mm length, the maximum stress intensity was significantly reduced to 35 N/mm^2 . Note that for both schemes the maximum stress intensity was lower than the stress fracture limit of 200 N/mm^2 for Nd:YAG medium [60].

3.2.2 Gaussian ABCD matrix approach

By using the FEA mesh results, the thermal lensing element can be defined by parabolic approximation. In the same way, a fit of the deformed end faces of the crystal is accomplished. With the obtained parabolic coefficients, it is possible to model the resonant cavity through the Gaussian beam propagation matrix algorithm (ABCD code).

Fig. 3.12 presents the LASCADTM representation of two distinct resonant cavities usually studied in solar pumped laser systems [71]. An asymmetric resonator (Fig. 3.12a) significantly enhances the pump and laser mode matching, providing high quality laser beams [72]. L_1 represents the distance from the HR mirror to the left end face of the laser rod, and L_2 the distance from the right end face of the laser rod to the PR output coupler, with both being particularly important parameters in order to obtain optimum mode overlap. L_2 was fixed at 10.0 mm and L_1 was optimized by LASCAD[®] software in order to achieve the highest pump and laser mode matching. The laser rod length is represented by L_R . The *radius* of curvature of both HR end mirror (RoC₁) and PR output coupler (RoC₂) were also optimized. For the 5.5 mm diameter, 35 mm length rod, optimum laser design parameter was found at $L_1 = 260.0$ mm.

Still, the HR resonator is difficult to implement in an end-side-pumping solar laser configuration, since one of the rods faces is subjected to intense solar pumping [60]. As represented in Fig. 3.12b, for this case, the resonator is comprised of two opposing mirrors: the HR 1064 nm 99.98% coating on the upper end face of the Nd:YAG rod and the PR 1064 nm output mirror, with reflectivity varying between 90% and 99% in the present design. L represents the separation length between the output end face of the Nd:YAG rod with AR coating at 1064 nm and the PR 1064 nm output mirror. For multimode operation, a plane-concave laser resonator with a relatively small L was adopted to ensure that the energy of higher-order modes was not wasted by diffraction losses.

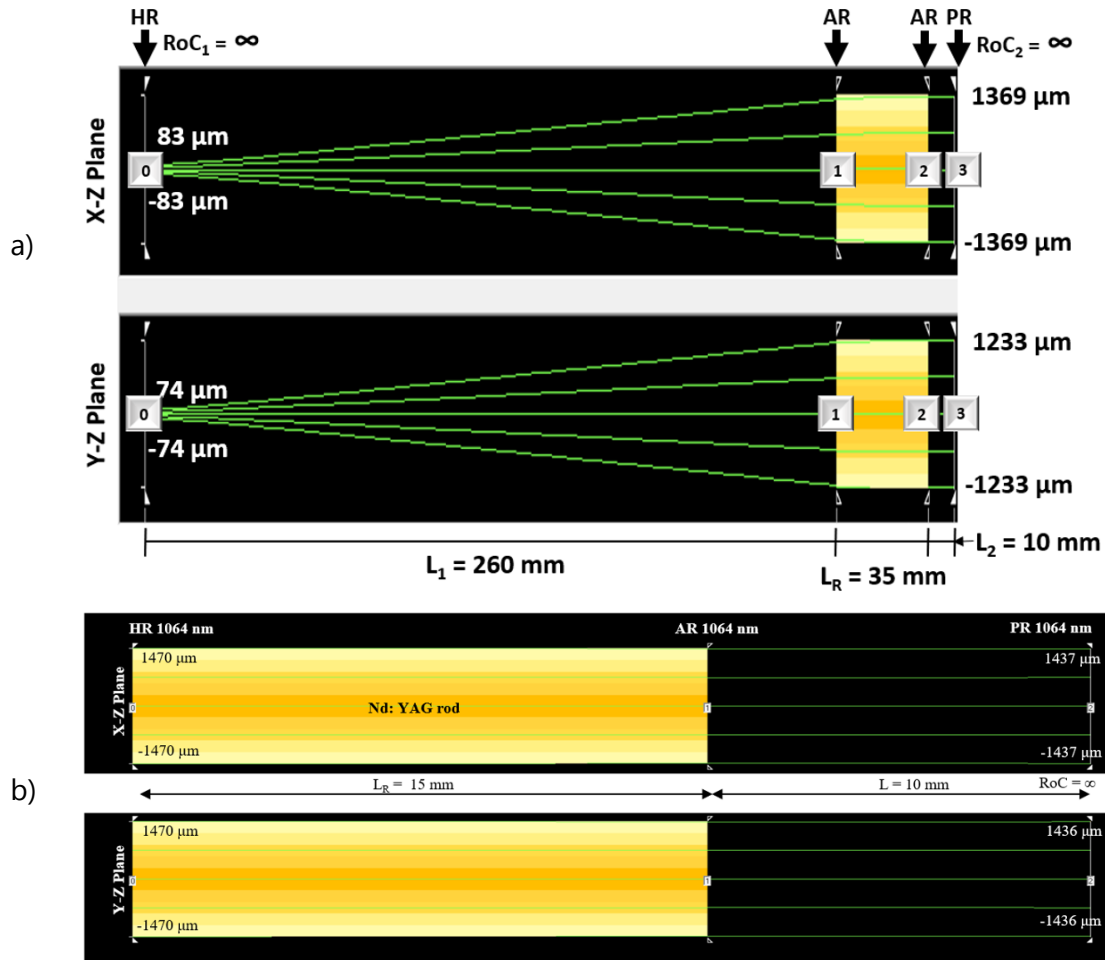


Figure 3-12. LASCAD™ representation of (a) an asymmetric laser cavity for efficient laser power extraction from a 5.5 mm diameter rod in a side-pumping scheme [71] and (b) from a 3.2 mm diameter rod in an end-side-pumping scheme [60].

With the Gaussian modes distribution and absorbed pump power distribution we can calculate the multimode or TEM₀₀ mode laser power in CW or pulsed operation mode using the Laser Rate Equations [66]. The laser emission curve as a function of either the power absorbed or the reflectivity of the output coupler can be displayed, as shown in Fig. 3.13a and Fig. 3.13b, respectively. In addition, it is possible to optimize the laser resonator by changing its length, angle between the various components, applying mirrors or lenses and changing the focal length of the components.

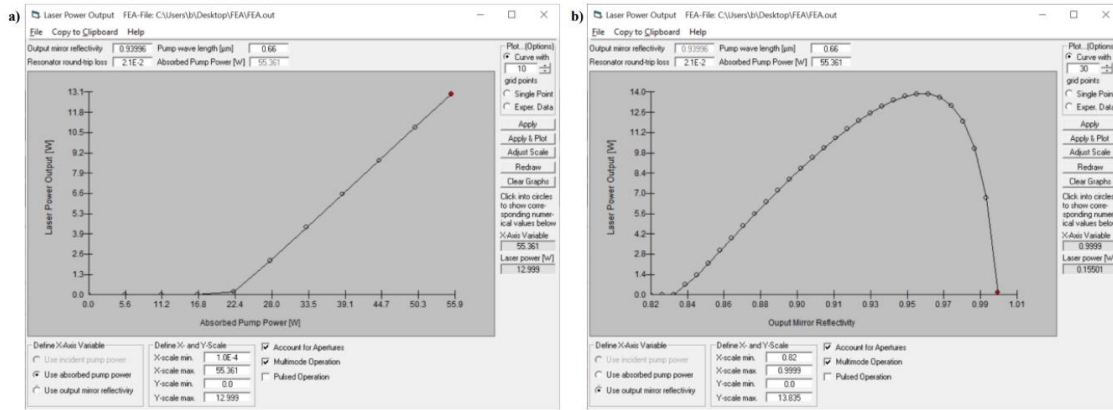


Figure 3-13. Calculated laser output power as a function of (a) the absorbed pump power and (b) the reflectivity of the output coupler used.

The mean absorbed and intensity-weighted solar pump wavelength of 660 nm was included in the analysis [66]. The sum of absorption, scattering, and diffraction losses for the 1064 nm laser emission wavelength within the active medium constituted the most important part of round-trip resonant cavity losses. Imperfect HR and AR coating losses of resonator cavity mirrors and the laser media are also an important portion of the round-trip losses. Diffraction losses depend heavily on the rod diameter, the resonator length and the curvature of the PR output mirror. For multimode calculation, relatively small resonators are used, and the diffraction losses can be dismissed. Still, for longer resonators, the diffraction loss is calculated by the BPM analysis of LASCADTM software.

3.2.3 Beam Propagation Method

FEA results can be used as input for a Fast Fourier Transform (FFT) split-step Beam Propagation Method. This code is able to give a full 3D simulation of the interaction of the wave-front propagating through the thermally deformed laser crystal. The BPM code also takes into account the gain dynamics and diffraction effects, due to the finite extension of apertures and mirrors. Based on the principle of Fox and Li, a series of roundtrips through the resonator is computed, which finally converges to the fundamental mode, or to a superposition of higher-order transverse modes [66]. As presented in Fig. 3.14, the $1/e^2$ width beam waist value stabilizes during the computation. The intensity profile at the output mirror, as it is computed with the increasing number of iterations, is also shown as the computation is running. The final intensity profile for two different solar-pumped laser resonators is shown in Fig. 3.15 [71].

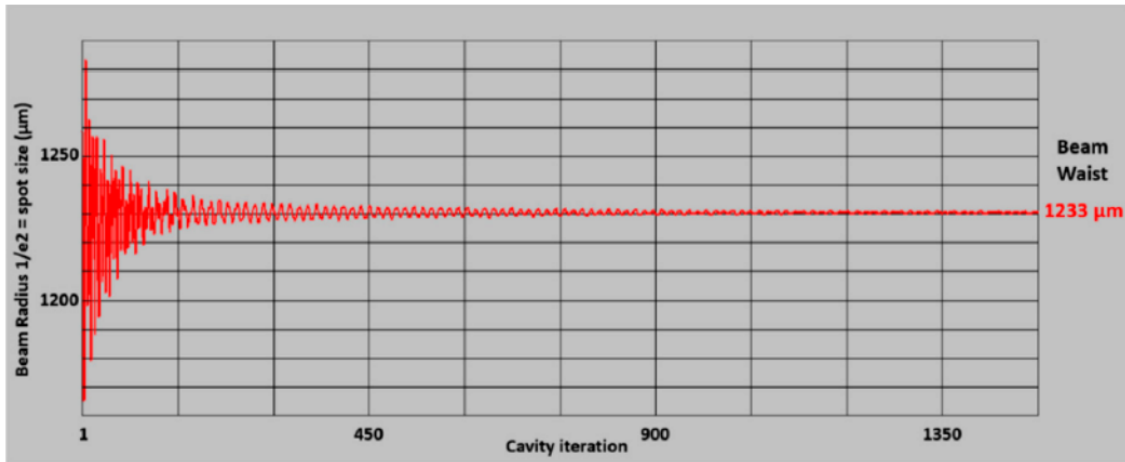


Figure 3-14. Laser beam waist at the output mirror calculation by BPM cavity iterations function of LAS-CAD™ software [71].

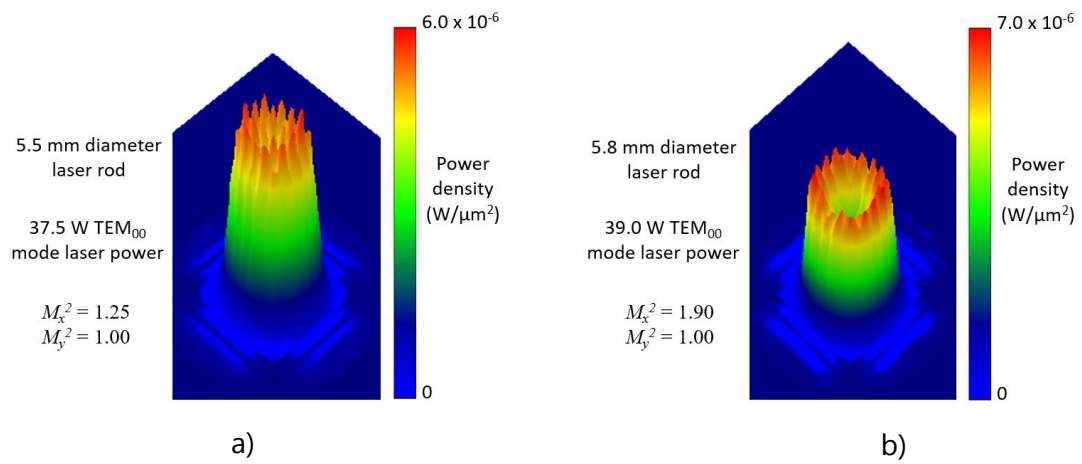


Figure 3-15. Numerically simulated 3D laser beam profile with (a) a top-hat profile and (b) a doughnut-shaped profile [71].

ND:YAG LASER MODELLING AND NUMERICAL ANALYSIS

Chapter 4 focuses on the modelling and numerical analysis of ND:YAG lasers, beginning with the modelling of lamp-pumped laser systems. It explores both single lamp/multi-rod and multi-lamp/multi-rod schemes. Additionally, the chapter investigates beam merging techniques, examining both lamp-pumped and solar-pumped laser beam merging processes. Numerical analyses are also conducted to understand doughnut-shaped and top hat profile beams within the context of solar-pumped lasers. The chapter also addresses the stability of Nd:YAG solar lasers, exploring various factors such as heliostat-parabolic mirror systems, multibeam end-side-pumped approaches, and considerations regarding the Sun-Earth relationship. Moreover, it delves into azimuth solar tracking error compensation capacities, multibeam uniformity, and the stable emission of TEM₀₀ mode multibeam lasers.

4.1 Lamp-pumped laser

The first laser, the ruby laser built by Maiman [23] and the first Nd:YAG laser, reported by Geusic et al. [73], were all pumped with arc lamps. Continuous-wave lamp or flash lamp provides the lifeblood for the majority of industrial solid-state lasers [74–76], but it is rarely afforded the importance it deserves. While the spotlight of attention has fallen on diode-pumped lasers, lamp-pumped lasers have been quietly competing with diode-pumped systems year after year. Even though diode-pumped lasers have become very common due to a number of advantages, lamp-pumped lasers will continue to be used for a long time [77–81]. The main advantages of lamp-pumped lasers are: 1. stability, even with voltage and current spikes [9]; 2. very high energy densities can be generated [82]; 3. reliability under harsh conditions; 4. thermal endurance; 5. lower price per watt, compared with diode-pumped lasers.

There are many commercial lamp-pumped Nd:YAG laser products on the market. Here, for example, a state-of-the-art of commercially available Spectron SL series CW lamp-pumped laser: for 4 kW electrical input power, 65 W multimode, 16 W TEM₀₀ mode 1064 nm CW laser power were generated by SL902 Model, resulting in 1.63% lamp input-to-multimode laser output conversion efficiency, 0.4% lamp input-to-TEM₀₀ mode laser output conversion efficiency and 24.6% TEM₀₀ mode power/multimode power ratio [83]. Besides, high-power lamp-pumped solid-state lasers usually exhibit notorious beam quality M² factor varying from several dozens to more than one hundred, essentially because strong thermal effects in the laser crystal lead to beam distortions [74].

As solar pumped lasers, lamp-pumped systems use optical pump to achieve laser emission. In order to gain experience in using Zemax[®] and Lascad[™] software, lamp-pumped laser systems were modelled [70,84]. Low lamp input-to-TEM₀₀ mode laser output conversion efficiency and strong thermal lensing effects are the bottleneck issues in commercially available single-rod/single-beam lamp-pumped lasers [83]. So, a multi-rod pumping concept was proposed to substantially increase electrical power to TEM₀₀ mode laser power conversion efficiency.

4.1.1 Single lamp/multi-rod scheme

For 4 kW electrical lamp input power, Spectron SL902 TEM₀₀ mode Nd:YAG laser uses a 4 mm bore diameter, 100 mm arc length krypton lamp to pump a 4 mm diameter, 105 mm length 1.0 at. % Nd:YAG rod within a single-ellipse pump cavity. The krypton arc lamp radiate about 45% of the input electrical power [85]. Special attention was paid to the calculation of the spectral overlap between the krypton arc lamp emission and the Nd:YAG medium absorption. The krypton arc lamp has 6 strong emission wavelengths (758 nm, weight 21.9%; 793 nm, weight 4.4%; 808 nm, weight 30.7%; 820 nm, weight 17.5%; 865 nm, weight 15.8%; 890 nm, weight 9.7%) [85], which were defined as Zemax[®] source wavelength data. The respective absorption coefficients at these peak emission wavelengths were programmed in Zemax[®] glass catalogue for 1.0 at. % Nd:YAG medium, so as to calculate its absorbed pump power. The absorption spectrum and the wavelength-dependent refractive indexes of arc lamp quartz body wall and cooling water were also programmed in Zemax[®] glass catalogue data.

As shown in Fig. 4.1, six Nd:YAG rods, all with 73.5 mm length, were pumped by the single custom-made krypton arc lamp of 5.7 mm bore diameter, 63.5 mm arc length sealed by a 0.5

mm thickness quartz body wall [70]. It was positioned at the central line O of the 63.5 mm length modified double-ellipse cavity with 95% reflectivity. This two-ellipse pump cavity was formed theoretically by the intersection of two identical 63.5 mm length tubular reflectors with $a = 6.85$ mm, $b = 6.3$ mm elliptical cross sections, centered along the two lines O_1 and O_2 (parallel to the central line O and positioned at distances of $OO_1 = OO_2 = 2.7$ mm). The elliptical cavity, widely explored in solid-state lasers, is based on the geometrical theorem that rays originating from one focal line of an elliptical cylinder are reflected to the other focal line. As a consequence of the preservation of angles, the portion of the elliptical reflector nearer the rod forms a reduced image of the pump source [86]. When a large diameter arc lamp is used, the image forming properties of the elliptical cylinder result in an enlarged pump light distribution zone around its focal line, enabling therefore the simultaneous pumping of several thin laser rods. By comparing with the performance of a 2D–compound parabolic concentrator (CPC)–CPC cavity, significant improvements in both absorption efficiency and absorption distribution were achieved by a 2D–CPC–elliptical cavity [87]. Elliptical pump cavities, working at imaging principle, contribute to a better absorbed light concentration within the rod, and hence a better TEM_{00} mode laser efficiency [88]. However, with a classical double-ellipse cavity, it was very difficult to achieve an optimal pump power distribution for TEM_{00} mode laser production at rod 2 and 5 in Zemax® analysis, so a modified double-ellipse cavity was put forward. Along the external waistline of the two elliptical cavity, two ledges with triangular cross-section (with $W = 2.20$ mm width and $\beta = 75.7^\circ$ inclination angle) were symmetrically added. These ledges were numerically optimized to allow an enhanced pump power distribution mainly within rod 2 and 5. The distances l_1 or l_2 from each rod to the center, as well as the angle α in relation to the central horizontal axis of the cavity, were optimized to achieve maximum absorbed power for TEM_{00} mode laser production, while allowing the passage of the coolant and the correct mechanical assembling of all components. Four rods (rod 1, 3, 4 and 6, all with 2 mm diameter) were positioned at a distance of $l_1 = 9.2$ mm from the central line O, with symmetric inclination angles of $\alpha = \pm 54.2^\circ$. Rod 2 and 5, with 2.2 mm diameter, were positioned at a distance of $l_2 = 10.4$ mm away from the center O. Water was used to cool the arc lamp, the Nd:YAG rods and the modified pump cavity efficiently. By optimizing all the design parameters of six-beam fundamental mode lamp-pumped laser, the maximum absorbed pump power and profiles by the six thin Nd:YAG rods within the modified pump cavity around the 4 kW arc lamp were numerically calculated by Zemax® software. The absorbed pump flux distributions along six central transversal cross-sections of each 1.0 at% Nd:YAG laser rod are shown in Fig. 4.1. Red color means near maximum pump absorption, whereas blue means little or no absorption. As

expected, the rod 1, 3, 4 and 6 showed a nearly identical absorbed pump profile with rotationally symmetry around the arc lamp. The rods 2 and 5 showed also nearly identical mirrored absorbed pump profiles. Therefore, identical absorbed pump power for rod 1, 3, 4, 6 and for rods 2 and 5 were calculated.

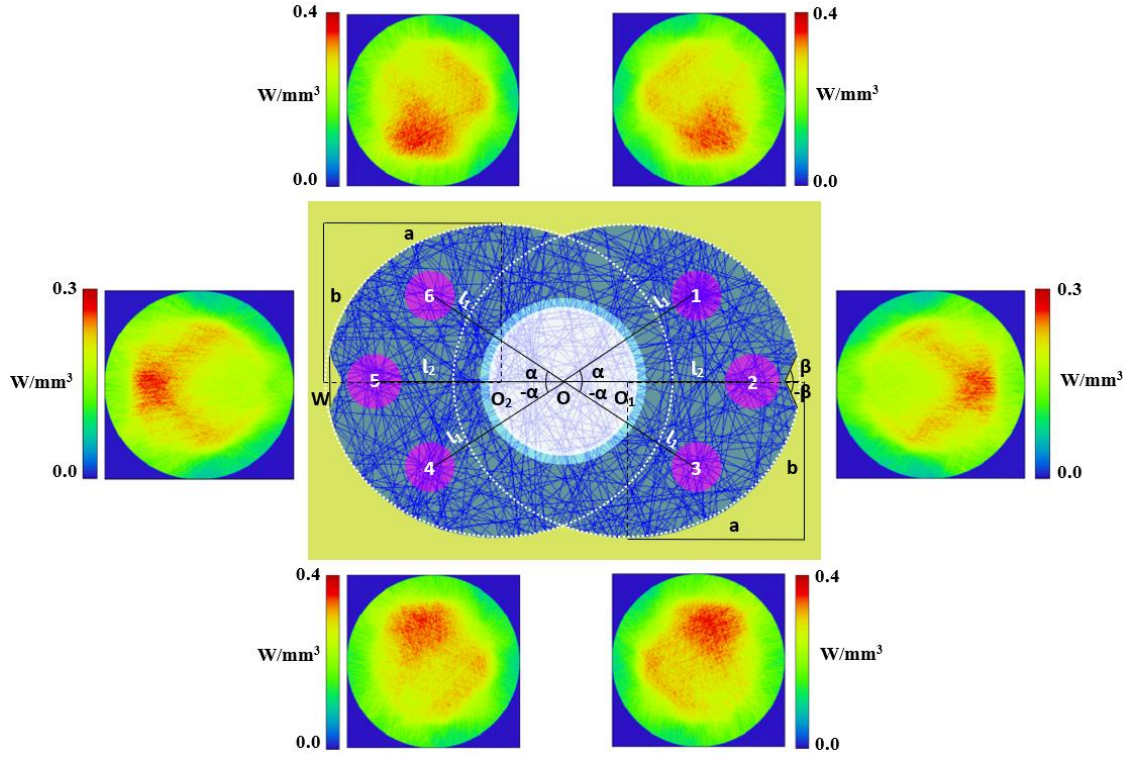


Figure 4-1. 2D view of the six Nd:YAG rods pumped by the thick krypton arc lamp, inside the modified double-ellipse cavity. The absorbed power distribution along the central transversal cross-sections of the rods obtained with Zemax® numerical simulation are shown [70].

The laser resonator for each Nd:YAG rod was formed by two opposing mirrors, the end mirror with 1064 nm HR coated (99.98%), and the output coupler with 1064 nm PR coated (between 80% and 99%, according to different laser rods diameters for CW operation), as indicated in Fig. 4.2. Both end faces of each rod were 1064 nm AR coated. By aligning six mini 1064 nm HR mirrors with different *radius* of curvature (RoC) and reflectance near the thermal focal zone of each rod, maximum extraction of fundamental mode 1064 nm laser beams with Gaussian profiles was numerically achieved (inset Fig. 4.2a and inset Fig. 4.2b). Since the six rods absorbed differently pumping power with the modified double-ellipse pump cavity, different thermal focal lengths were calculated by LASCAD™ numerical simulation. The adoption of an asymmetric resonator has shown to provide a large spatial overlap between the fundamental mode volume and the pump volume in solid-state solar lasers, contributing largely to high laser beam quality [33,37,89,90].

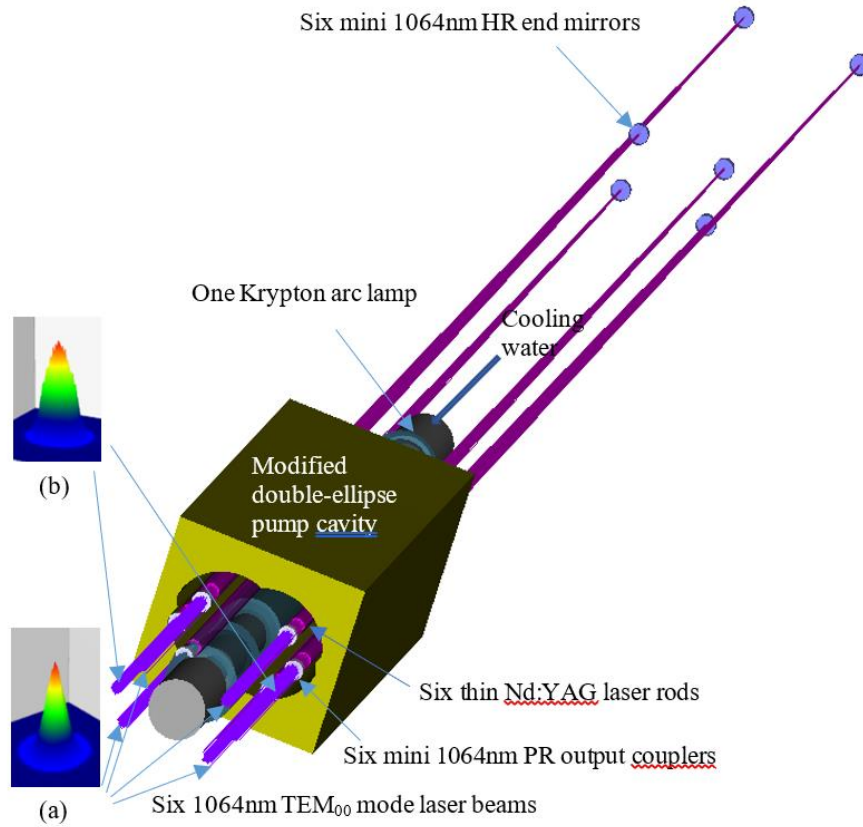
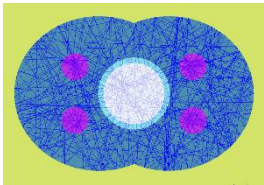
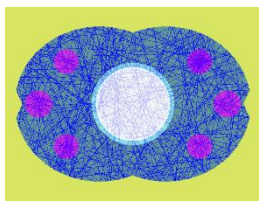
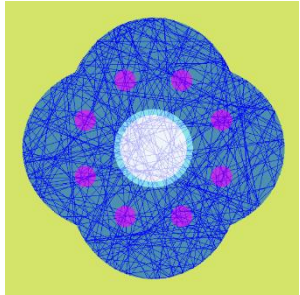
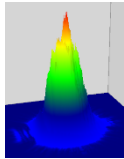
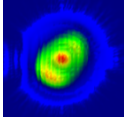
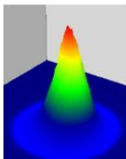
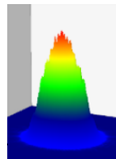
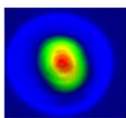
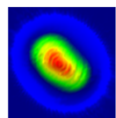
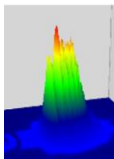
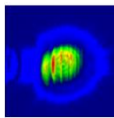


Figure 4-2. 3D view of the six thin Nd:YAG rods pumped by the thick arc lamp inside the modified double-ellipse cavity. Each of the six asymmetric resonant cavities was composed of the thin Nd:YAG rod, the 1064 nm HR mini end mirror and the 1064 nm PR mini output coupler. TEM₀₀ mode laser beam profiles from both the 2 mm and the 2.2 mm rods are shown by insets a) and b), respectively [70].

By numerically optimizing six mini 1064nm HR end mirrors and six mini 1064nm PR output mirrors with different RoCs and reflectivity near the thermal focal zone of each rod, the maximum fundamental mode laser power with different beam quality factors were calculated, ranging from 4.81 W with $M_x^2 = 1.62$, $M_y^2 = 1.00$ to 6.30 W with $M_x^2 = 1.03$, $M_y^2 = 1.00$ for the 2.2 mm and the 2.0 mm diameter rods, respectively. The total TEM₀₀ mode solar laser power of 34.82 W was consequently calculated, corresponding to average 0.87% lamp electrical power-to-TEM₀₀ mode laser power conversion efficiency and 2.18 times improvement over that of the state-of-the-art lamp-pumped laser. TEM₀₀ mode power-to-multimode power ratio of 59.0% was obtained, representing 2.40 times more than that of the most efficient single-rod TEM₀₀ mode lamp-pumped laser [70].

Table 1 compares the optimized laser output performances from four, six and eight Nd:YAG rods. Cavity geometry, rods dimensions and positions were manually optimized with Zemax[®] and LASCAD[®] software to achieve enhanced TEM₀₀ mode laser power and beam quality.

Table 4-1. TEM mode laser performance from four-rod, six-rod and eight-rod configurations [70].

Spectron SL902 model	4-rod scheme	6-rod scheme	8-rod scheme
 16 W TEM₀₀ mode laser power $M^2 < 1.5$			
Pump cavity	Double-ellipse	Double-ellipse	Quadruple-ellipse
Number of Nd:YAG rods (diameter)	4 (2.5 mm)	4 (2.0 mm) 2 (2.2 mm)	8 (1.8 mm)
TEM ₀₀ mode laser power	$4 \times 8.5 \text{ W} = 34.0 \text{ W}$	$4 \times 6.3 \text{ W} + 2 \times 4.8 \text{ W} = 34.8 \text{ W}$	$8 \times 1.5 \text{ W} = 12.0 \text{ W}$
Beam quality factors	$M_x^2 = 1.00$ $M_y^2 = 1.09$	$M_x^2 = 1.03$ $M_y^2 = 1.00$ $M_x^2 = 1.62$ $M_y^2 = 1.00$	$M_x^2 = 2.26$ $M_y^2 = 1.00$
TEM ₀₀ mode laser beam profile	3D  2D 	   	 
Brightness figure of merit	$\frac{8.5 \text{ W}}{1.00 \times 1.09} = 7.80 \text{ W}$	$\frac{6.3 \text{ W}}{1.00 \times 1.03} = 6.12 \text{ W}$ $\frac{4.8 \text{ W}}{1.00 \times 1.62} = 2.96 \text{ W}$	$\frac{1.5 \text{ W}}{2.26 \times 1.00} = 0.66 \text{ W}$

For practical application	Four laser beams	Six laser beams	Eight laser beams
	High brightness	Good brightness	Low brightness
	Simple assembly	Intermediate assembly complexity	Complex assembly

Both four-rod and six-rod configurations reached the total TEM₀₀ mode laser power of 34.0 W and 34.8 W, respectively. Satisfactory M² beam quality factors of $M_x^2 = 1.00$, $M_y^2 = 1.09$ (2.5mm diameter) for the four-rod scheme and $M_x^2 = 1.03$, $M_y^2 = 1.00$ (2.0 mm diameter), $M_x^2 = 1.62$, $M_y^2 = 1.00$ (2.2 mm diameter) for the six-rod scheme were numerically calculated. Laser beam brightness figure of merit – defined as the ratio between TEM₀₀ mode laser power and the product of M_x^2 and M_y^2 [90]– of 7.8 W, 6.12 W and 2.96 W were calculated respectively. The four-rod scheme is simple to assemble. However, the six-rod configuration can provide two extra laser beams. The eight-rod scheme is more complex. A quadruple-ellipse pump cavity with eight thin rods constitutes a mechanical fixing challenge, moreover, low pump power absorbed by each rod resulted in large thermal focal length and, consequently, big diffraction losses. Low total TEM₀₀ mode laser power of only 12 W was therefore calculated. Poor beam quality factors of $M_x^2 = 2.26$, $M_y^2 = 1.00$ were also calculated.

4.1.2 Multi-lamp/multi-rod scheme

Although single-lamp schemes show the best efficiency results [83], they have strong limitations to deliver a high energy pump and to obtain a well-distributed energy density on the crystal surface. One solution is to pump the active medium with multiple lamps, being able to deliver more energy around the entire rod surface. These conditions, in addition to the usage of thin rods, are suitable for TEM₀₀ mode high-laser power production [84]. For comparison with the SL902 model, the total 4.0 kW electrical lamp input power was evenly divided by four lamps. Since long and thin rods are preferable for TEM₀₀ mode laser production [91], the lamp bore diameter was reduced to the minimum commercially available value of 3.0 mm [92]. The arc lamp length was defined attending to the maximum loading that a 3.0 mm bore diameter Krypton arc lamp allows for each centimeter length. As shown in Fig. 4.3, four Nd:YAG rods with 2.3 mm diameter and 45.0 mm length were pumped by four Krypton arc lamps of 3.0 mm bore diameter and 35.0 mm arc length, sealed by a 0.5 mm thickness quartz body wall. The

four rods were positioned at a distance of $l_e = 4.8$ mm from the center O, as indicated in Fig. 4.3, with symmetric inclination angles of $\alpha = \pm 45.0^\circ$. The 40.0 mm length quadruple-ellipse cavity with 95% reflectivity was formed by the intersection of four identical 40.0 mm length tubular reflectors with $a = 6.00$ mm, $b = 4.55$ mm elliptical cross sections, with its center positioned at distances of $OO_1 = OO_2 = 3.91$ mm. Each arc lamp was positioned at one focus of each elliptical section, distancing $L_k = 7.82$ mm from the center O. The distances l_e and l_k , as well as the angle α in relation to the central horizontal axis of the cavity, were optimized to achieve maximum absorbed power for TEM₀₀ mode laser production, while allowing the passage of coolant and the mechanical assembling of all components. Water was used to cool the arc lamp, the Nd:YAG rods and the pump cavity efficiently. By optimizing the maximum absorbed pump power and profiles of the four thin Nd:YAG rods within the pump cavity, all the design parameters were numerically calculated by Zemax[®] software. The absorbed pump flux distributions along the central transversal cross section of each 1.0 at.% Nd:YAG laser rod are shown in Fig. 4.3. Red means near maximum pump absorption, whereas blue means little or no absorption. As expected, the four rods showed a nearly identical absorbed pump profile with rotation symmetry around the center. Therefore, identical absorbed pump powers were calculated. The absorbed pump flux data from the Zemax[®] analysis was then processed by LASCAD[®] software.

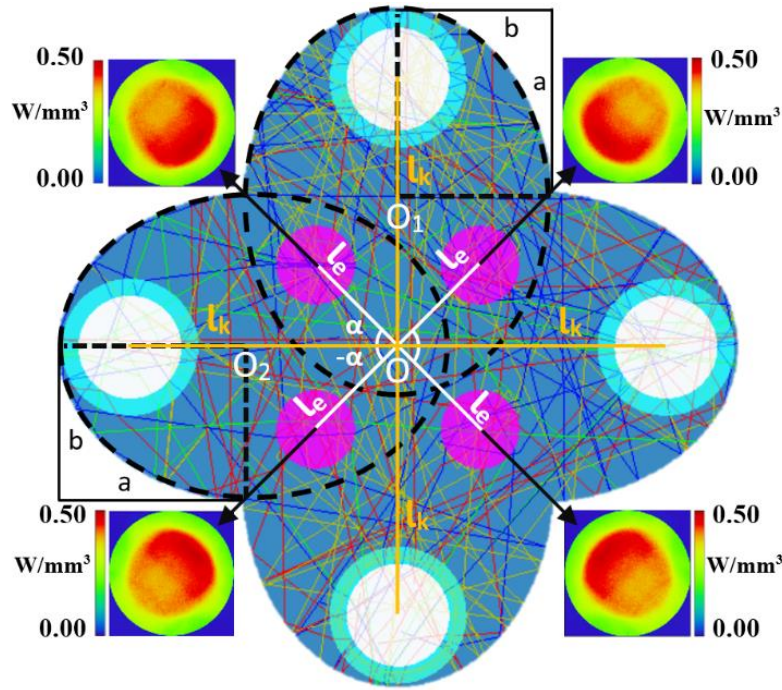


Figure 4-3. 2D side view of the four Nd:YAG rods pumped by the four Krypton arc lamps, inside the quadruple-ellipse pump cavity. The absorbed power distribution along the central transversal cross sections of the rods obtained with Zemax® numerical simulation are shown. The colored rays inside the cavity are emitted from the four arc lamps, with each color corresponding to a lamp source [84].

Four 1064 nm HR mirrors were aligned near the thermal focal zone of each rod to achieve maximum extraction of fundamental mode 1064 nm laser power with Gaussian profiles. As indicated in Fig. 4.4, L_R represents the laser rod length, L_1 the separation between the HR1064 nm mirror and the left AR1064 nm end face of the laser rod and L_2 the separation between the right AR1064 nm end face of the laser rod and the PR1064 nm output mirror. L_1 and L_2 are the key parameters for achieving the highest fundamental mode power. L_2 was fixed at 60.0 mm and L_1 was optimized by LASCAD® software in order to achieve the best overlap between the pump volume and the fundamental mode volume.

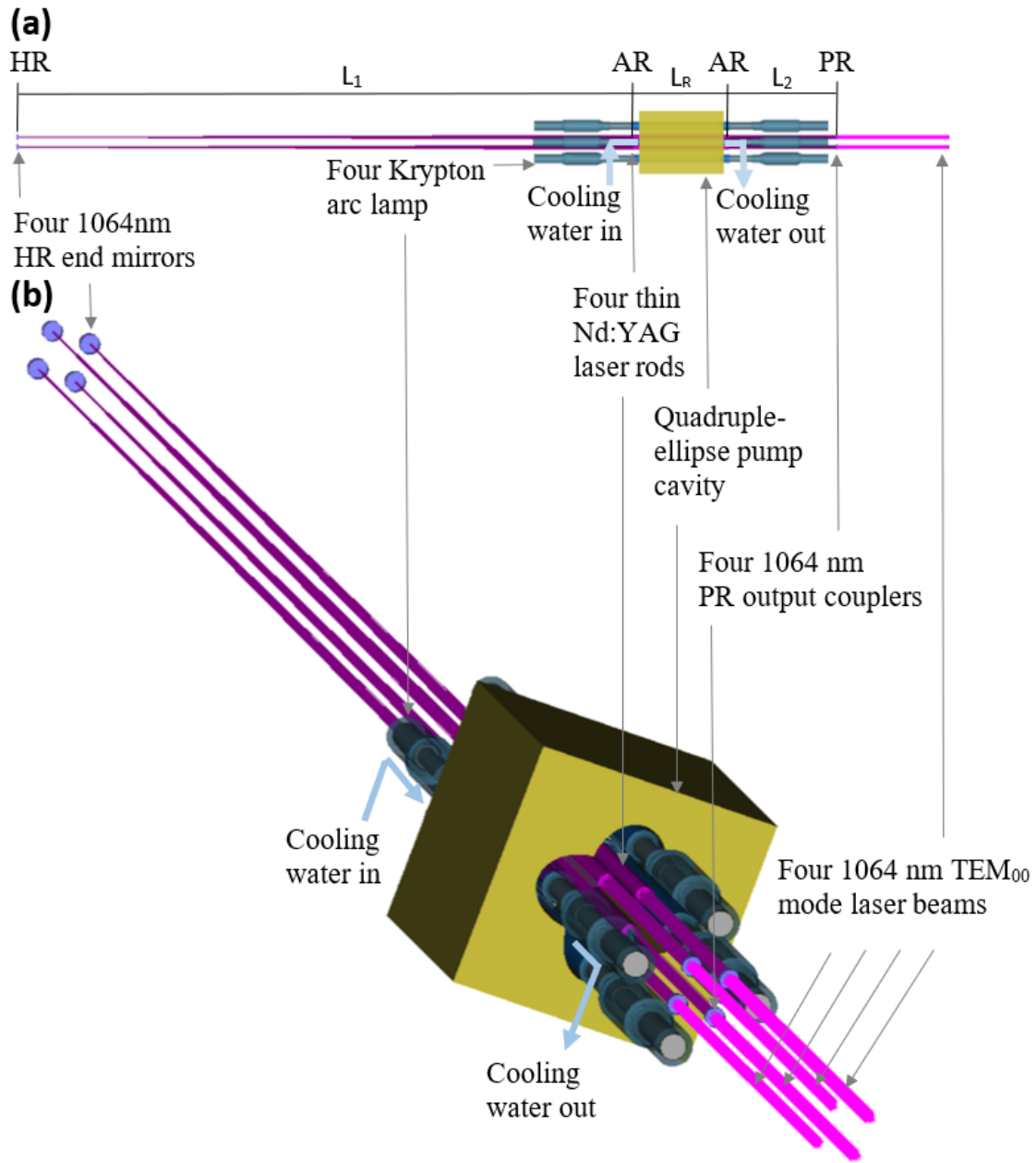


Figure 4-4. (a) 2D top view and (b) 3D view of the four thin Nd:YAG rods pumped by the four Krypton arc lamp within the quadruple-ellipse cavity. Each of the four asymmetric resonant cavities was composed of the thin Nd:YAG rod with both end faces 1064 nm antireflection coated (AR), the 1064 nm high-reflection (HR) end mirror and the 1064 nm partial-reflection (PR) output coupler. TEM₀₀ mode laser beam profile from the 2.3 mm laser rod is presented in inset figure [84].

35.80 W total output TEM₀₀ mode laser power was numerically attained, corresponding to the electrical input power to TEM₀₀ mode laser power conversion efficiency of 0.90%, leading to 2.25 times improvement as compared to that of the state-of-the-art lamp-pumped laser. Moreover, the TEM₀₀ mode power-to-multimode laser power ratio also reached 65%, corresponding to 2.6 times enhancement relative to that of the state-of-the-art lamp-pumped laser. The

significant increase in electrical input power to TEM₀₀ mode laser power conversion efficiency may enhance productivity, constituting hopefully an effective innovation to the development of lamp-pumped lasers [84].

4.2 Beam merging technique

The efficient extraction of one single laser beam from the multiple rods may constitute an interesting solution for obtaining high TEM₀₀ mode laser power and high beam quality simultaneously and, consequently, high beam brightness.

4.2.1 Lamp-pumped laser beam merging

This technique was numerically studied to TEM₀₀-mode lamp-pumped laser systems, a type of laser that has been widely applied in research and industry [70,84]. A multi-rod concept is proposed to substantially enhance lamp input-to-TEM₀₀ mode laser output conversion efficiency. Two multi-rod schemes were studied: a 4-kW-single-thick arc lamp was used to efficiently pump six thin Nd:YAG rods simultaneously within a modified two-ellipse pump cavity; and four thin Nd:YAG rods were pumped by four 1.0 kW input power Krypton CW arc lamps within a quadruple-ellipse pump cavity. All the design parameters were numerically optimized by Zemax[®] and LASCAD[™] software. Asymmetrical laser resonators were adopted to enable a large mode-matching between the lamp pump mode and the fundamental laser mode within each rod. For the extraction of a single TEM₀₀ mode laser beam, a laser resonant cavity with folding mirrors was proposed. The resonator configuration for the six-rod and the four-rod concepts are presented in Figs. 4.5 and 4.6, respectively.

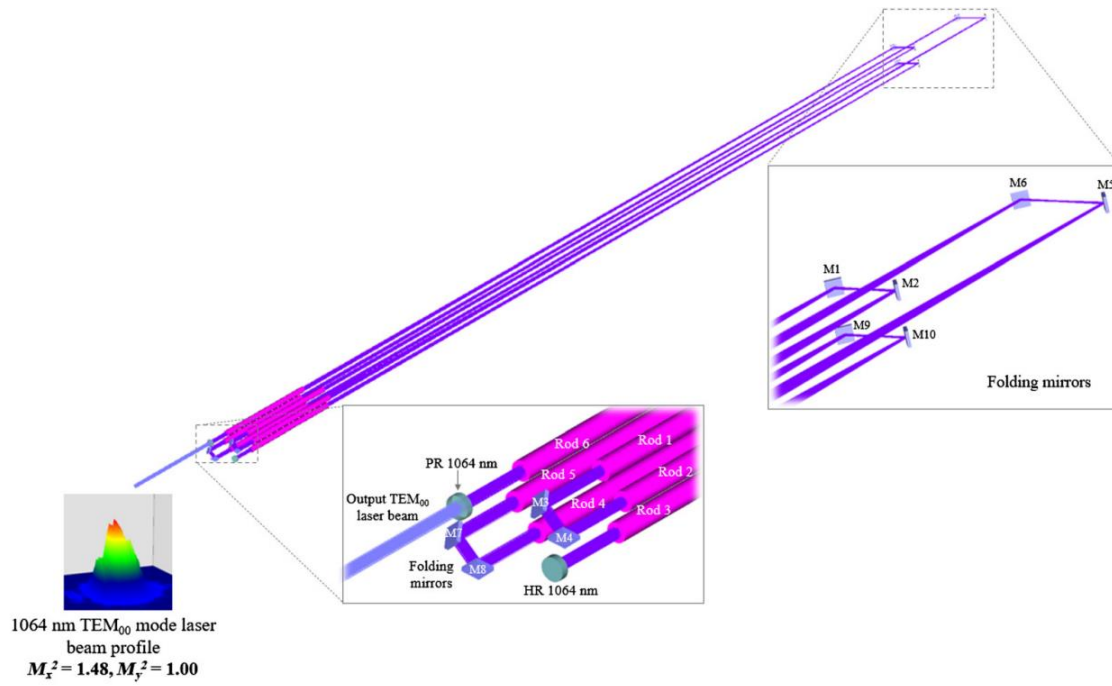


Figure 4-5. Six TEM₀₀ mode laser beam merging by a resonant cavity composed of a PR 1064 nm output mirror, six thin laser rods, five sets of two-folding-mirrors, and an HR 1064 nm end mirror [70].

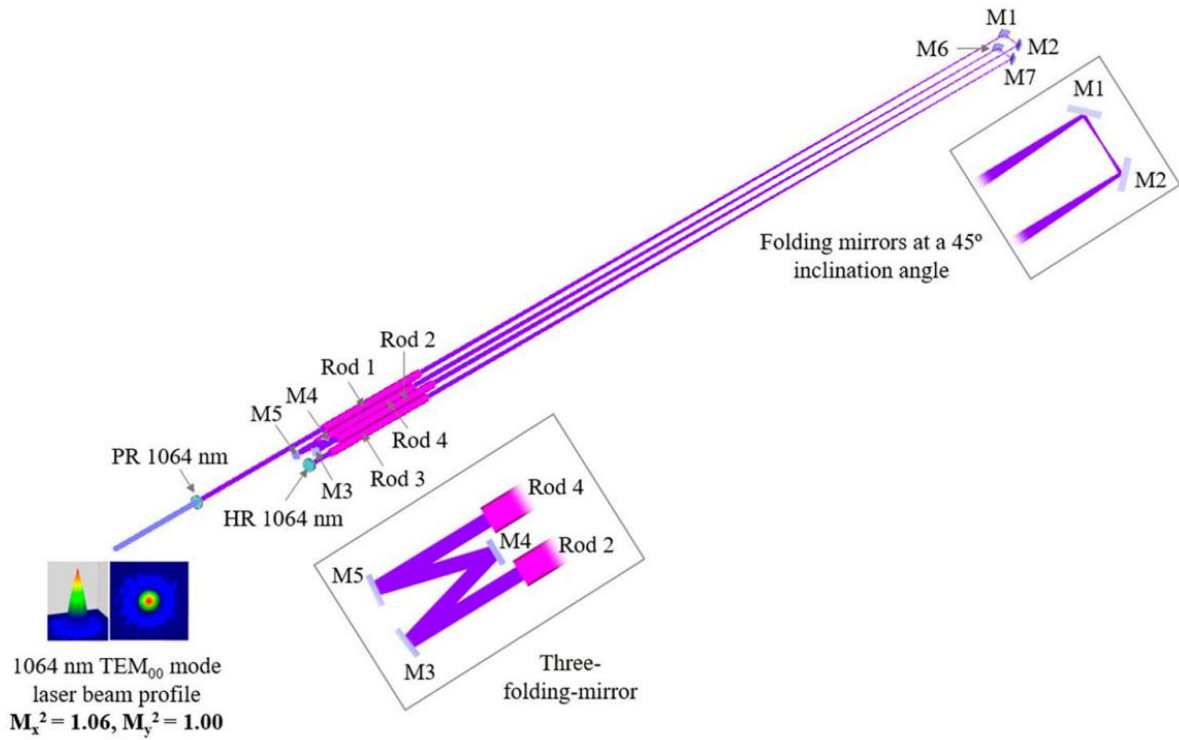


Figure 4-6. Four TEM₀₀ mode laser beam merging by a novel resonant cavity composed of a PR 1064 nm output mirror, the four thin laser rods, two sets of two-folding-mirror, one set of three-folding-mirror and an HR 1064 nm end mirror [84].

Figs. 4.7 and 4.8 present the comparison between the TEM₀₀ mode laser profile extracted individually from each laser rod and considering the beam merging technique, for the six-rod and four-rod schemes, respectively. For both cases the beam quality significantly increased. For the extraction of a single TEM₀₀ mode laser beam, 15.34 W laser beam brightness figure of merit was numerically calculated, corresponding to a 13-fold increase over that from each of the six TEM₀₀ mode laser beams. For the four-rod scheme, the single TEM₀₀ mode laser beam presented 25.94 W laser beam brightness figure of merit – output power divided by the product of the beam quality M_x^2 and M_y^2 factors – corresponding to a 4-fold increase over that from each of the four TEM₀₀ mode laser beams [70]. The extraction of one single TEM₀₀ mode laser beam from the multiple Nd:YAG rods and, more importantly, the increase in laser beam figure of merit may constitute an interesting solution to present-day lamp-pumped lasers characterized by their relatively poor beam quality and brightness.

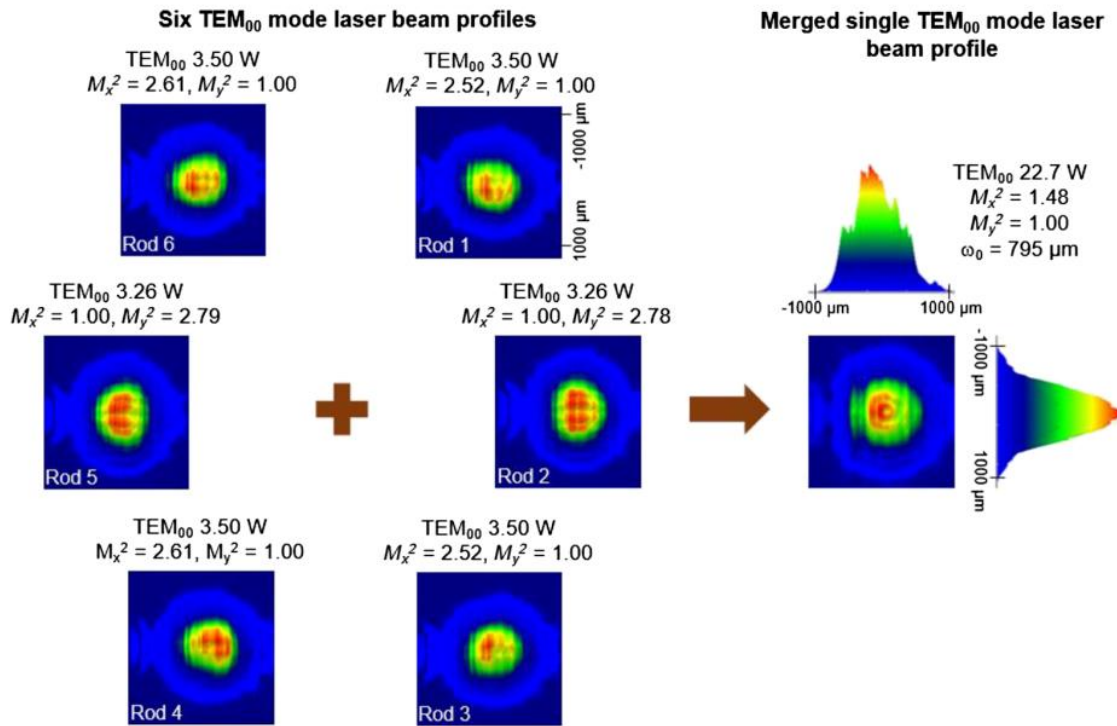


Figure 4-7. Comparison of the TEM₀₀ mode laser beam profile from each of the six Nd:YAG rods, and the merged single TEM₀₀ mode laser beam profile [70].

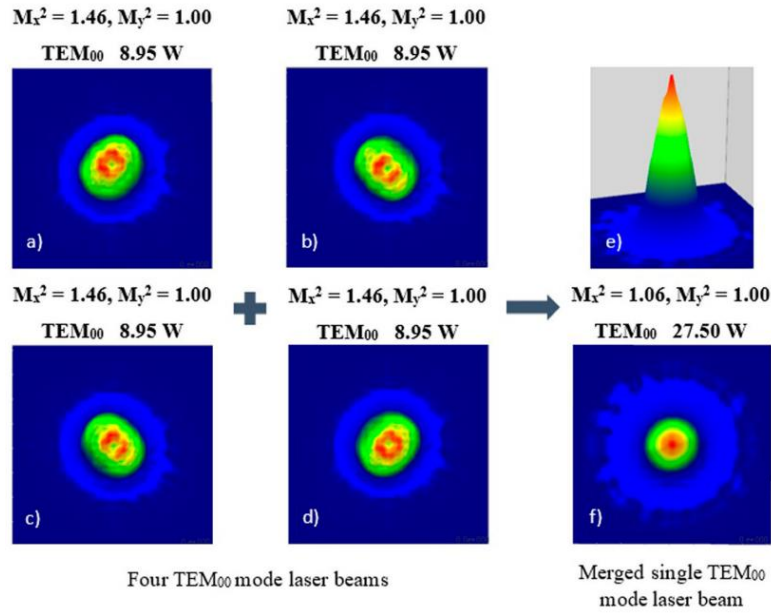


Figure 4-8. Comparison between the TEM₀₀ mode laser beam profile from each of the four Nd:YAG rods, and the merged single TEM₀₀ mode laser beam profile. (a)(d) represents the 2D top view of the TEM₀₀ mode laser beam profile. (e) and (f) represent the 3D view and 2D top view of the merged single TEM₀₀ mode laser beam profile, respectively [84].

4.2.2 Solar-pumped laser beam merging

The same beam merging technique has been also studied for solar pumped lasers. Tibúrcio et al. end-side pumped two thin laser rods simultaneously by using a fused silica aspheric lens and a 2D-semicylindrical pump cavity, within which the crystal rods were placed, allowing an efficient pumping of the laser rods [93]. In order to extract one single laser beam from the two laser crystals, a single folding laser resonant cavity can be set, such as in diode-pumped lasers [94], as shown in Fig. 4.9. The solution of a single laser beam is interesting, since it can improve the M² factors and consequently the brightness figure of merit of solar-pumped lasers. A three-folding-mirror laser beam merging technique was implemented to attain a single laser beam from the dual-rod with enhanced laser beam quality. For an easier understanding, each laser rod of the dual-rod configuration was divided into two zones, one representing the section with higher pump flux absorption (A and B for the right and the left rods, respectively) and the other representing the section with lower pump flux absorption (A' and B' for the right and the left rods, respectively). Analogously, the representation of the laser beam, passing back and forth through those sections of the laser rod, between the HR 1064 nm and the PR 1064 nm mirrors, was also divided into two sections in order to represent the contribution in those

pumped zones and, consequently, on the merged solar laser emission. An improvement of the laser beam profile was obtained with an arrangement of three HR 1064 nm folding mirrors M_1 , M_2 , and M_3 . The part of the laser beam passing through the region of the right laser rod with higher pump flux absorption (A) is folded into the region of the left laser rod with lower pump flux absorption (B'); while the part of the laser beam passing through the zone of the left laser rod with higher pump flux absorption (B) is folded towards the zone of the right laser rod with lower pump flux absorption (A'). In this way, the non-uniformity of the pump flux absorption by the laser rods was balanced, resulting in an enhanced beam profile for this dual-rod single laser beam.

The dual-rod scheme achieved 16.1 W/m^2 TEM₀₀ mode collection efficiency, 1.70% solar-to-laser power conversion efficiency [93], 25 W brightness figure-of-merit, being 1.46, 1.30 and 1.75, respectively, more than the previous numerical records with a dual-rod configuration [95]. The numerical results of the present work in its single laser beam configuration, regarding collection efficiency, solar-to-laser power conversion efficiency and brightness figure-of-merit were also 2.04, 1.60 and 3.87, respectively, more than the experimental demonstrations of the most efficient solar laser with single-rod [96].

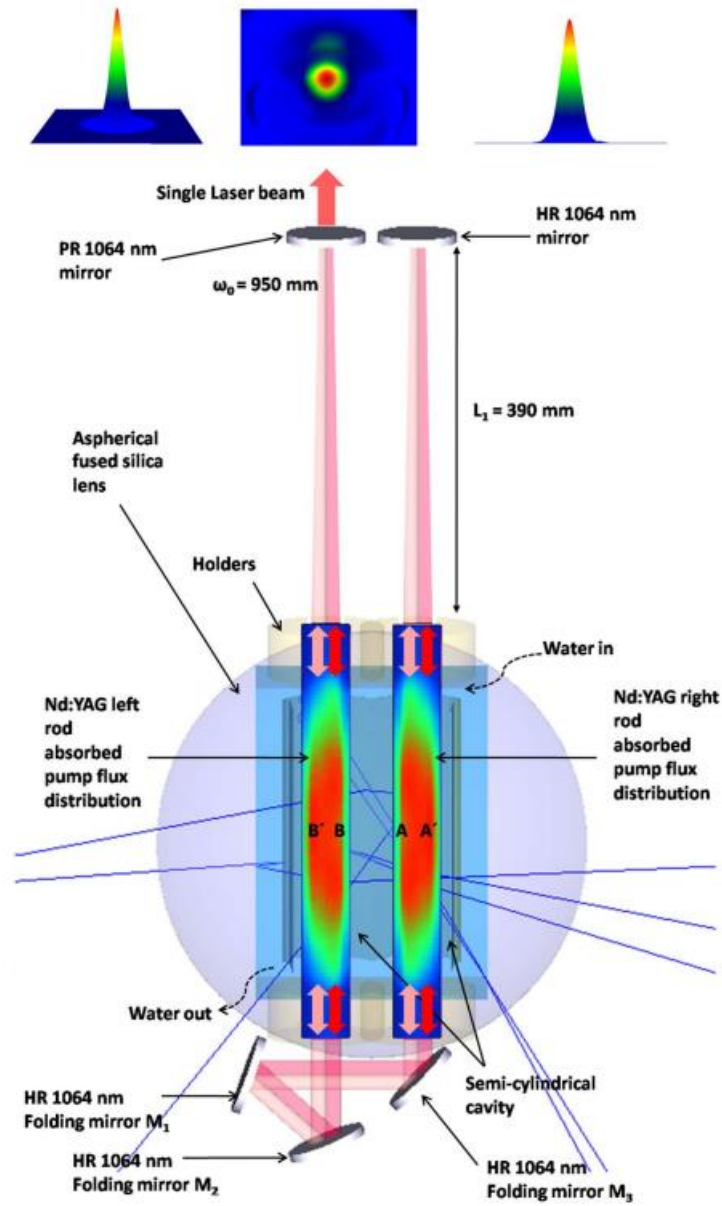


Figure 4-9. Schematics of the dual-rod single laser beam from the two Nd:YAG crystals. A compensation of the laser beam profile was achieved, by using the arrangement of three HR 1064 nm folding mirrors (M_1 , M_2 , and M_3) to compose the folding resonant cavity, along with the mirrors of the laser cavities [93].

Costa et al. also employed the beam merging technique on numerical work with an alternative multi-rod solar laser end-side-pumping concept, based on the megawatt solar furnace in France [97]. A solar flux homogenizer was used to deliver nearly the same pump power to multiple core-doped Nd:YAG laser rods within a water-cooled pump cavity through a fused silica window.

The proposed beam merging technique is presented in Fig. 4.10. For the numerical analysis of the merged laser beam performance, the following steps were taken:

1. In Zemax[®], a long detector volume was added for each of the N Nd:YAG cores of the array. Its length (LDET) was $N \times \text{LROD}$, with LROD being the rod length. The number of pixels in the z-axis was $N \times \text{PZ}$, with PZ being the number of pixels from the previous case of laser beam extraction from each rod. Each Nd:YAG core occupied a different portion of the corresponding detector.

2. After running the Zemax[®] simulation, N text files were exported, with the absorbed pump flux/volume data from each detector volume.

3. Tables with information about each z-plane and voxel are crucial for the LASCAD[™] analysis. Therefore, the lines with z-plane and voxel data from the different N text files were copied to replace the empty ones in the text file from one of the detectors. In Figure 4.10, the data from the detectors of rods 2 to 11 were used to replace the corresponding lines in the text file from rod 1 detector, since it already contained the absorbed pump flux/volume data of the Nd:YAG core in the detector volume's first portion. This helped in maintaining the same structure of a typical file directly exported from a detector volume in Zemax[®]. This single text file, with all the information of the core-doped Nd:YAG rods, was then imported into LASCAD[™]

By mounting 399 rods at a 30° angle of inclination and employing the beam merging technique, the TEM₀₀-mode power improved by three times, to 5.2 kW, from 37 merged laser beams [97]. The highest solar laser beam brightness figure of merit achieved was 148 W, corresponding to an improvement of 23 times in relation to the previous experimental record. [38]. The extraction of several high-power Gaussian TEM₀₀-mode solar laser beams of good quality and thus high brightness could greatly decrease the production costs with high power lasers, paving the way for the future application of this renewable energy system in the industrial sector, as well as its expansion worldwide.

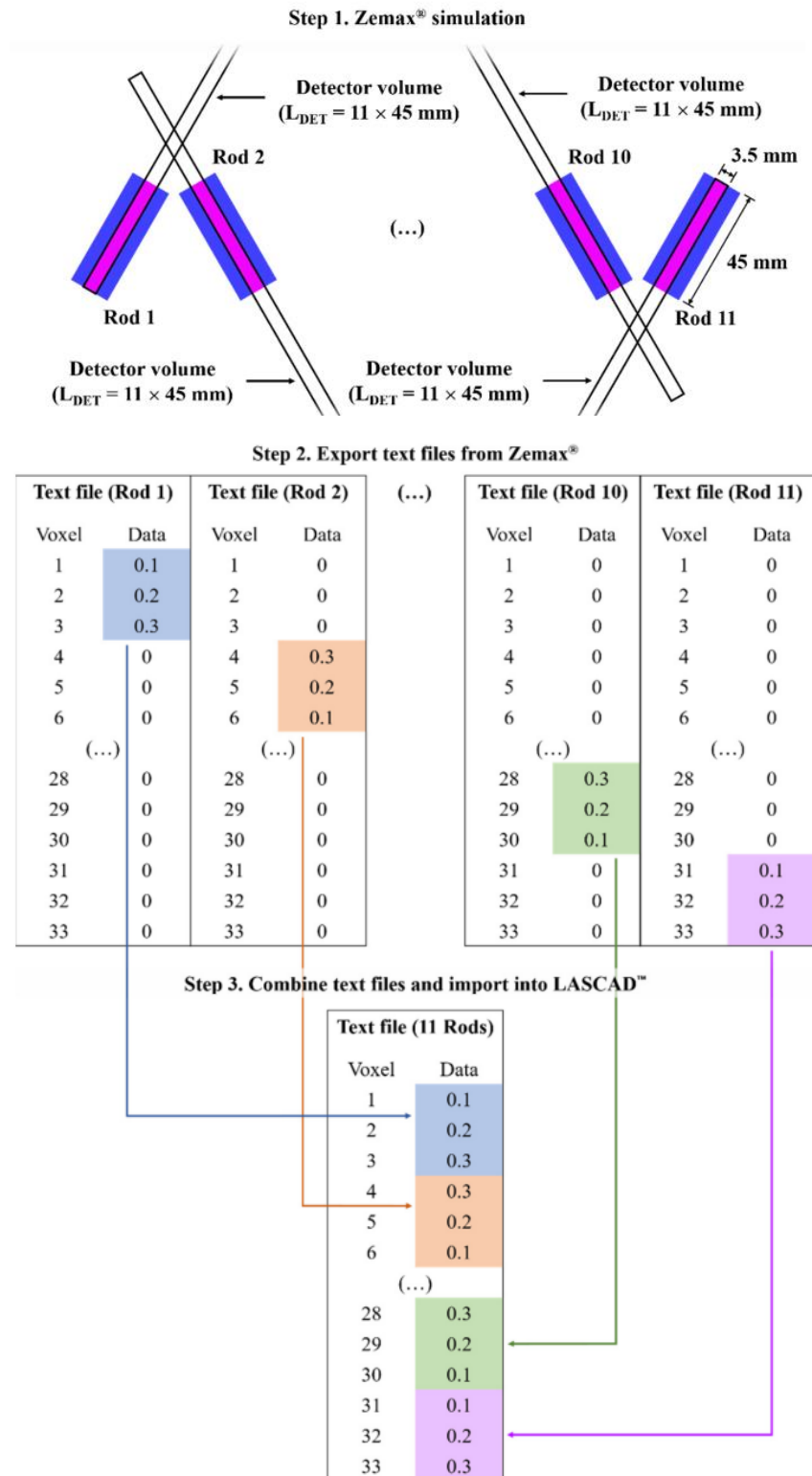


Figure 4-10. Simplified diagram of the process of combination of text files exported from Zemax® for LASCAD™ analysis of the extraction of a merged laser beam from an array with 11 rods. In this configuration, the HR and PR 1064 nm mirrors are closer to rod 1 and 11, respectively. The data presented in this diagram are for illustrative purposes only [97].

4.3 Doughnut-shaped and top hat profile numerical analysis

Aside from the industry-standard Gaussian intensity profile, top hat and non-conventional laser beam shapes, such as doughnut-shaped profile, are ever more required [98]. The top hat laser beam profile is well-known for uniformly irradiate the target material, significantly reducing the heat affected zones, typical of Gaussian laser irradiation [99–104], whereas the doughnut-shaped laser beam has attracted much interest for its use in trapping particles at nanoscale and improving mechanical performance during laser-based 3D metal printing [105,106]. Doughnut-shaped solar laser emission was already achieved, and several experimental studies were conducted to better understand the phenomenon [107–109]. As far as we know, the first numerical simulation of doughnut-shaped and top hat solar laser beam profiles is reported here, significantly contributing to the understanding of the formation of such beam profiles [71]

4.3.1 Solar energy collection and concentration system with Fresnel lenses

The proposed side-pumping solar laser approach (Fig. 4.11) was composed of six circular Fresnel lenses ($F_1 - F_6$), for collection and concentration of the incoming solar radiation, aligned with six plane folding mirrors ($M_1 - M_6$), which redirected the concentrated solar radiation from the Fresnel lenses onto the laser head. Each Fresnel lens was centered at a distance $d = 950$ mm from their common optical center point C , which was placed at a height $h = 551$ mm above the center of the laser head, as indicated in Fig 4.11. The plane folding mirrors had an inclination angle of 45° in relation to their common optical axis and were located below their respective Fresnel lenses. In ZEMAX[®] non-sequential analysis, the *radius* parameter defines the radius of curvature of the Fresnel lens. For this system, an optimum *radius* of curvature of 700 mm was used, corresponding to a focal length of approximately 1.5 m. The Fresnel lenses were made of polymethyl methacrylate, which has high transmission efficiency for both visible and near infrared wavelengths between 350 and 900 nm. Each one of the 3 mm thick Fresnel lenses had a *radius* of 461 mm, summing a total collection area of 4 m². For the whole solar spectrum, an averaged transmission efficiency of 84% was numerically attained for the Fresnel lenses. For 950 W/m² terrestrial solar irradiance and 95% reflectivity plane folding mirrors, a total of 3032 W solar power was assumed to reach the laser head [71].

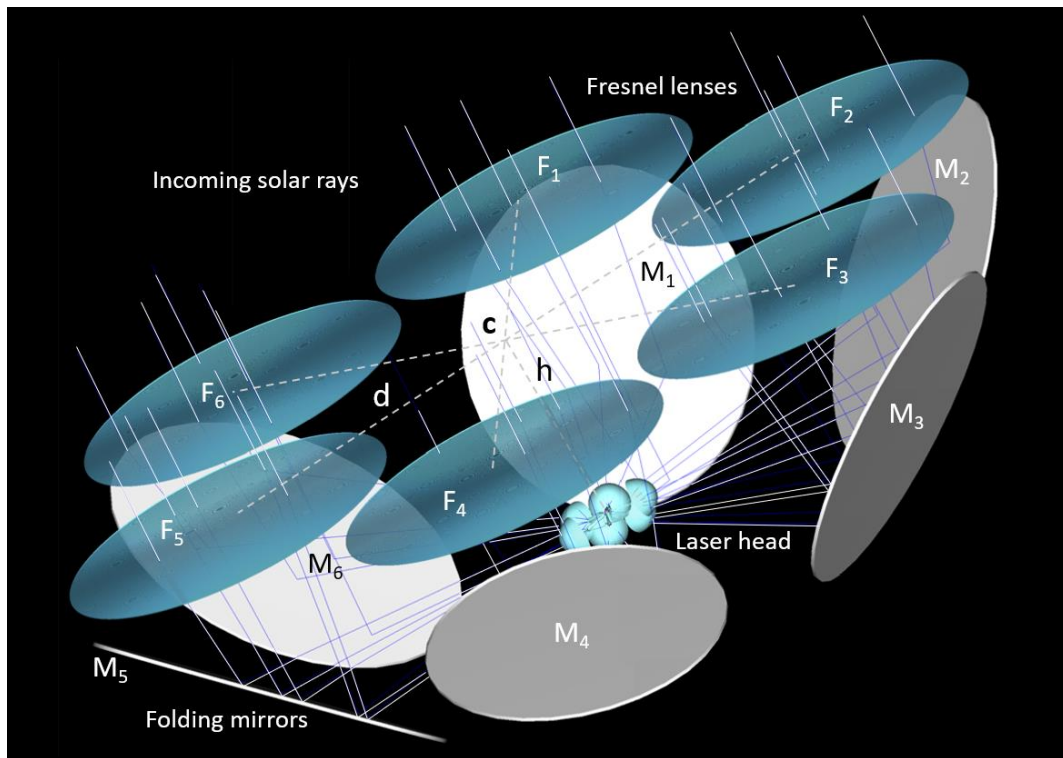


Figure 4-11. Six Fresnel lens solar laser side-pumping concept with 4.0 m^2 total collection area. $F_1 - F_6$ and $M_1 - M_6$ indicates the six Fresnel lenses and the six folding mirrors, respectively. Each Fresnel lens was symmetrically positioned at a distance $d = 950 \text{ mm}$ from their common optical center point C, and at a height $h = 551 \text{ mm}$ from the center of the laser head [71].

4.3.2 Solar laser head

For a high focusing and redistribution of the solar radiation into the Nd:YAG laser rod, six fused silica aspheric concentrators and six twisted fused silica light guides were designed, as presented in Fig 4.12. The six aspheric lenses were all equally designed to efficiently couple the concentrated solar radiation from the focal zone of each Fresnel lens onto the input face of each twisted light guide. Each optimized aspheric concentrator had 112 mm diameter, 53 mm height, -53 mm rear *radius*, and -0.150 rear conic value, and all were symmetrically positioned 96.5 mm away from the center of the laser head. An averaged transmission efficiency of 87% was numerically determined for the fused silica aspheric lenses, each one focusing 440 W solar power [71].

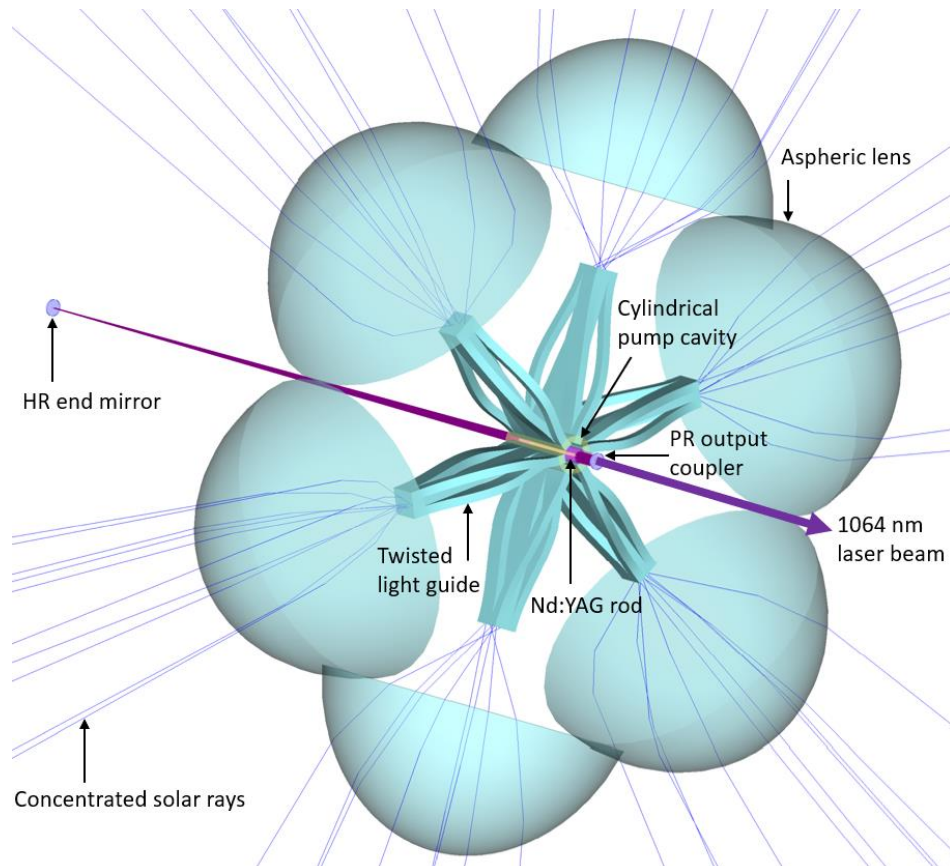


Figure 4-12. 3D view of the six secondary aspheric lenses, the six twisted light guides, the cylindrical pump cavity and the Nd:YAG rod, and the high reflection (HR) end mirror and the partial reflection (PR) output coupler, which compose the resonant cavity [71].

The concentrated solar radiation was then transmitted through six twisted fused silica light guides with 10.00 mm × 10.00 mm input face, 62.50 mm length and 3.33 mm × 30.00 mm output end, experiencing the principles of refraction and total internal reflection, as demonstrated in Figs. 4.13. The six twisted light guides were designed with AutoCAD software and evenly redistributed at 4 mm from the center of the laser head in order to deliver efficiently the concentrated solar radiation from each aspheric lens. Each one of the twisted light guides was composed of five sections: the 3.33 mm × 10.00 mm central section, two 3.33 mm × 6.67 mm sections, and two 3.33 mm × 3.33 mm sections. At the guide's input face, the five sections were arranged in a 10.0 mm × 10.0 mm square cross-section and at its output end they became a single column with 3.33 mm × 30.00 mm rectangular cross-section. Fig. 4.13 gives the pump light distribution at several cross-sections for one twisted light guide. Maximum transmission is indicated with red color, whereas blue means almost none or zero pump light transmission. An averaged transmission efficiency of 90% was computed for the twisted light guides, each one delivering 396 W solar power into the cylindrical cavity ($396 \text{ W} \times 6 = 2376 \text{ W}$ total solar

power). The contribution of the water layer was also included in the simulations, with the laser rod receiving at its surface a total of 1995 W concentrated solar power [71].

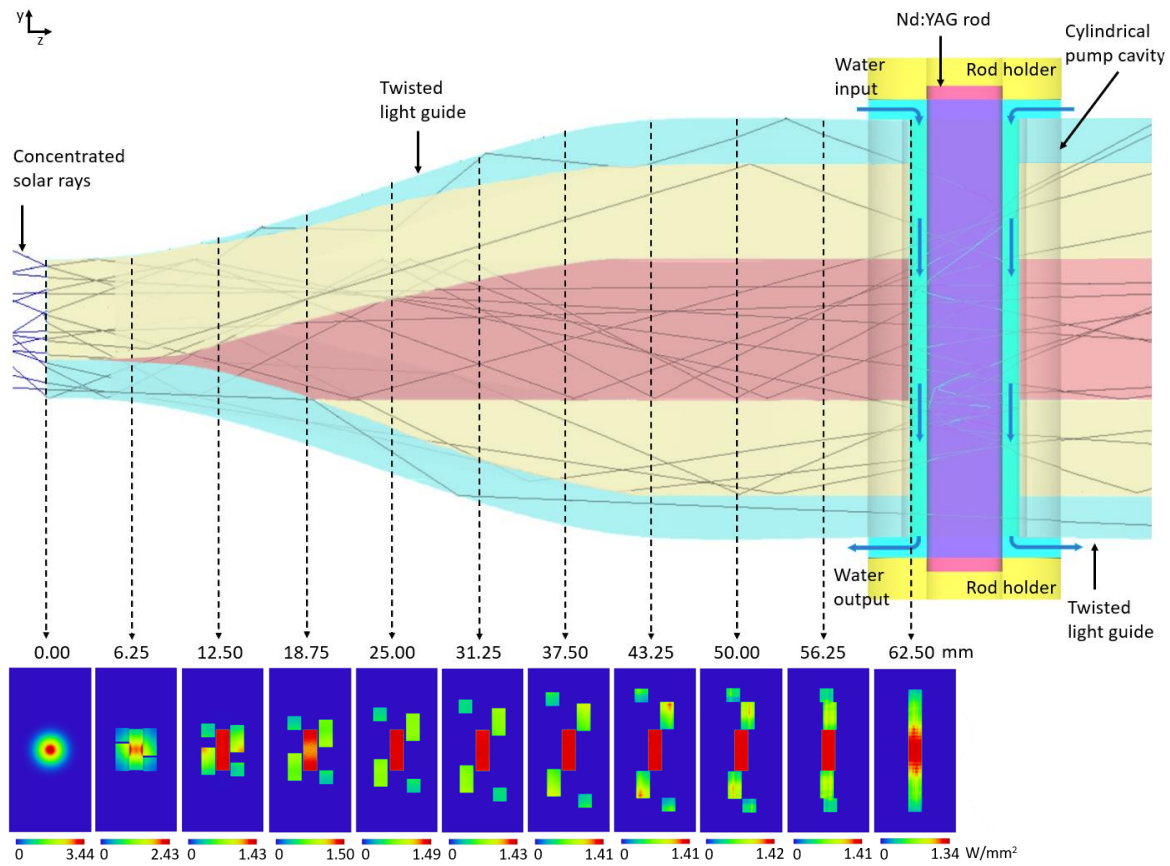


Figure 4-13. Pump light transmission through the twisted light guides. Only one twisted light guide is entirely shown to indicate how the solar rays were delivered into the laser rod, inside the cylindrical pump cavity with cooling water. Pump light distribution at several cross-sections along one twisted light guide is also presented [71].

As shown in Figs. 4.13, a single 5.5 mm diameter, 35.0 mm length Nd:YAG rod was placed at the center of a cylindrical pump cavity (95% reflectivity inner surface) with 9 mm internal diameter and 30.0 mm height. The Nd:YAG rod was cooled with water flowing inside the pump cavity along 32.5 mm of its longitudinal surface and was mechanically fixed on each side by two holders. 1064 nm antireflection (AR) coating was considered for both Nd:YAG rod end faces. The 1064 nm HR mirror and the PR output coupler formed the laser resonator, as previously indicated in Fig. 4.12.

4.3.3 Solar laser beam profiles

Based on the previously described parameters, multimode solar laser power, TEM₀₀ mode laser power and M² beam quality factors at the x and y-axis were calculated with the LASCAD[®] software. The numerical calculated TEM₀₀ mode laser power corresponded to the fundamental mode within the obtained beam profile. The above-described laser resonant cavity was optimized for several laser rod diameters. Both the HR end mirror and the PR output coupler remained plane (RoC₁ = RoC₂ = ∞), the L₂ resonant cavity parameter was fixed at 10 mm, and L₁ was optimized in order to achieve the best overlap between the pump and the laser mode volumes for each case. Fig. 4.14 shows the strong influence of the Nd:YAG laser rod diameter on the laser beam profile calculated through LASCAD[®] analysis. The laser beam profile revealed a top hat shape for the 5.2 mm laser rod diameter. As the rod diameter increased, the laser beam profile showed lower energy in its center, and a doughnut-shaped laser beam profile emerged from the 5.8 mm Nd:YAG laser rod diameter. The L₁ resonant cavity parameter, the 1/e² width beam waist value ω , the laser beam divergence half-angles at the X-Z and Y-Z planes (θ_x and θ_y , respectively), the multimode and TEM₀₀ mode laser power, the laser beam quality factors M_x² and M_y² and the 2D and 3D view of the laser beam profile are also presented in Fig. 4.14 as a function of the laser rod diameter [71].

As far as we know, the top hat solar laser beam profile was never reported in experimental essays. A doughnut-shaped laser beam was also numerically attained, from the 5.8 mm diameter laser rod, with 9.8 W/m² TEM₀₀ mode laser power collection and 1.03% solar-to-TEM₀₀ mode power conversion efficiencies, corresponding to an increase of 2.2 and 1.9 times, respectively, compared to the experimental result for doughnut-shaped solar laser power achieved by Vistas et al. [108].

Rod diameter (mm)	L_1 resonant cavity parameter (mm)	$1/e^2$ width beam waist ω (μm)	Divergence half-angle Θ_x and Θ_y ($^\circ$)	Multimode laser power (W)	TEM ₀₀ mode laser power (W)	Beam quality factors M_x^2 and M_y^2	Beam profile	
							2D	3D
5.2	248	1150	$\Theta_x = 0.016^\circ$ $\Theta_y = 0.011^\circ$	83.6	36.1	$M_x^2 = 1.88$ $M_y^2 = 1.00$		
5.3	252	1188	$\Theta_x = 0.019^\circ$ $\Theta_y = 0.012^\circ$	82.6	37.5	$M_x^2 = 2.30$ $M_y^2 = 1.00$		
5.4	257	1245	$\Theta_x = 0.018^\circ$ $\Theta_y = 0.010^\circ$	86.1	37.2	$M_x^2 = 2.83$ $M_y^2 = 1.00$		
5.5	260	1233	$\Theta_x = 0.011^\circ$ $\Theta_y = 0.010^\circ$	87.2	37.5	$M_x^2 = 1.25$ $M_y^2 = 1.00$		
5.6	264	1215	$\Theta_x = 0.011^\circ$ $\Theta_y = 0.011^\circ$	85.8	36.5	$M_x^2 = 1.00$ $M_y^2 = 1.05$		
5.7	269	1245	$\Theta_x = 0.010^\circ$ $\Theta_y = 0.016^\circ$	89.3	34.6	$M_x^2 = 1.00$ $M_y^2 = 2.23$		
5.8	274	1375	$\Theta_x = 0.012^\circ$ $\Theta_y = 0.008^\circ$	90.2	39.0	$M_x^2 = 1.90$ $M_y^2 = 1.00$		

Figure 4-14. Summary of the laser beam profiles obtained as function of the Nd:YAG laser rod diameter through LASCAD™ analysis [71].

4.4 Nd:YAG solar laser stability numerical analysis

The solar tracking error compensation capacity of multi-rod solar laser systems has been evaluated based on the solar tracking error width at 10% laser power loss ($TEW_{10\%}$). In 2020, Tibúrcio et al. proposed a dual-rod side-pumping solar laser concept that numerically demonstrated a promising stability under solar tracking error condition on the azimuthal direction, presenting $0.70^\circ TEW_{10\%}$ [51]. Then, in 2022, a dual-rod side-pumping prototype was experimentally studied, achieving up to $1.40^\circ TEW_{10\%}$. [54]. Despite Tibúrcio et al. work achieved high tracking error tolerance, the efficiency was limited by its side-pumping configuration [54]. In fact, the current record in Nd:YAG solar laser collection efficiency with a side-pumping configuration is only 17.6 W/m^2 [59]. Single-rod end-side-pumping configurations attained far superior efficiency [41]; however, the concentrated solar power is directly focused onto the end face of the laser rod, and any slight solar tracking error in either azimuth or altitude axis can prevent its stable emission, causing a significant reduction or even the extinction of solar laser output. By end-side-pumping an arrangement of multiple Nd:YAG rods closely coupled within a single pump cavity, it is possible to enhance the total multimode laser power while maintaining high tracking error tolerance [54,56]. Therefore, a four-rod/four-beam single solar laser head was proposed to improve the solar laser efficiency and solar tracking error compensation capacity with end-side-pumping configuration, while significantly reducing the thermal lensing and thermal stress problems that have affected single-rod solar lasers [60].

4.4.1 NOVA heliostat-parabolic mirror system

The previous solar laser experiments on tracking error compensation capacity were performed with the NOVA heliostat-parabolic mirror system. The same collection and concentration system was considered in the following numerical works [60,62,63]. The NOVA heliostat-parabolic mirror system is presented in Fig. 4.15. The annual Sun's path in Lisbon, Portugal (Latitude 38.66° , Longitude -9.21°) is also represented for 25th December 2022 (Fig. 4.15a) and 19th May 2023 (Fig. 4.15b). The system uses a dual-axis heliostat equipped with a set of large plane mirrors (93.5% reflectivity) to track the Sun's apparent path in both azimuthal and altitude directions and redirect the incoming solar radiation towards a stationary back-surface silver coated parabolic mirror (80% reflectivity) with 1.5 m diameter, 60° rim angle and 660 mm focal length, as illustrated in Fig. 4.15c. The total combined reflectance of both the heliostat and the parabolic mirror was considered as 74.8%. For a typical solar irradiance of 950 W/m^2

in Lisbon and 1.767 m² full collection area, about 1250 W solar power can be focused into a concentrated pump light spot with near-Gaussian distribution of 8 mm full width at half maximum [66].

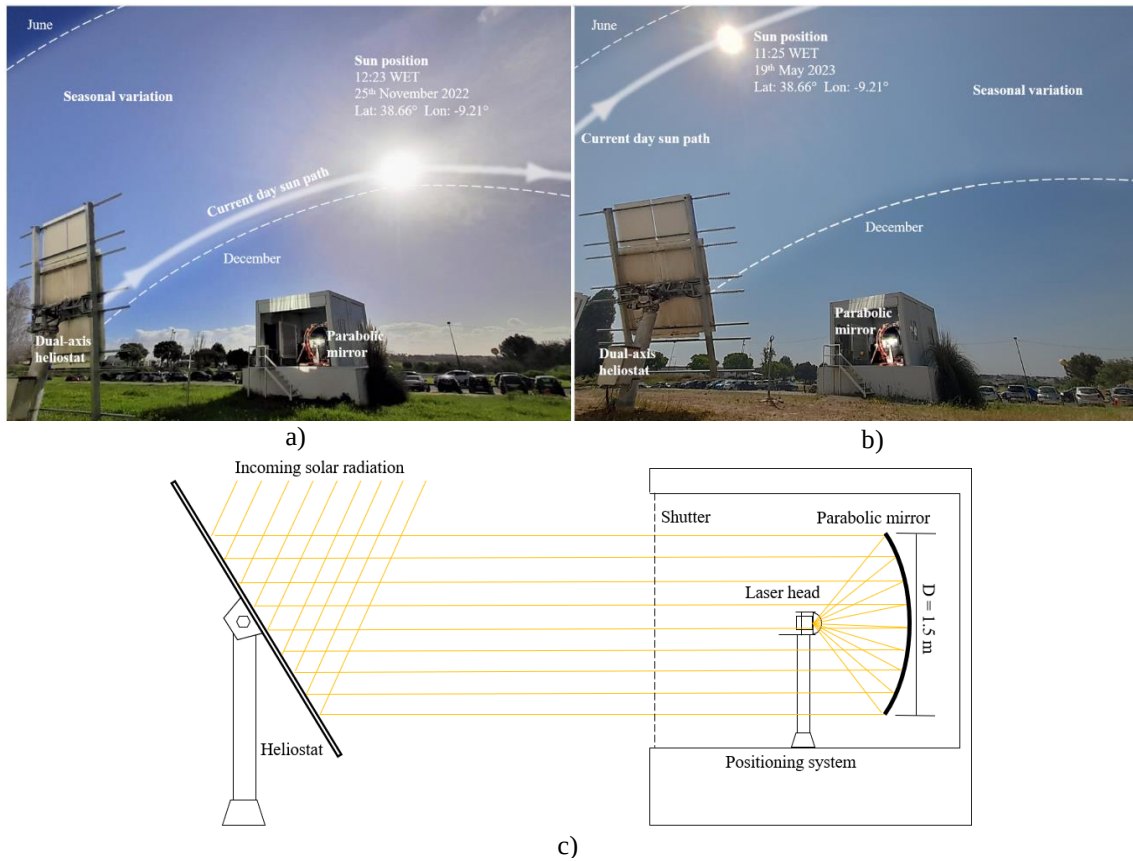


Figure 4-15. NOVA heliostat-parabolic mirror system. Photograph of the system operating on (a) 25th November 2022 at 12:23 Western European Time (WET), and on 19th May 2023 at 11:25 WET. (b) Illustration of the system redirecting and concentrating the solar radiation towards a solar laser head. Adapted from [63].

4.4.2 Multibeam end-side-pumped approach

As illustrated in Fig. 4.16, a fused silica conical lens further concentrated the solar radiation onto four Nd:YAG rods, within a single conical pump cavity actively cooled by circulating water. The four Nd:YAG laser rods were evenly mounted on the rod holder in rotational symmetry, tilted 5° in relation to the central axis, so as to create enough fixing spaces between the neighboring rods. Each optical resonator was comprised of two opposing mirrors: HR 1064 nm coating on the upper end face of each Nd:YAG rod and the PR 1064 nm output mirror. L represents the separation length between the output end face AR 1064 nm coatings of each Nd:YAG rod and the respective PR 1064 nm output mirror.

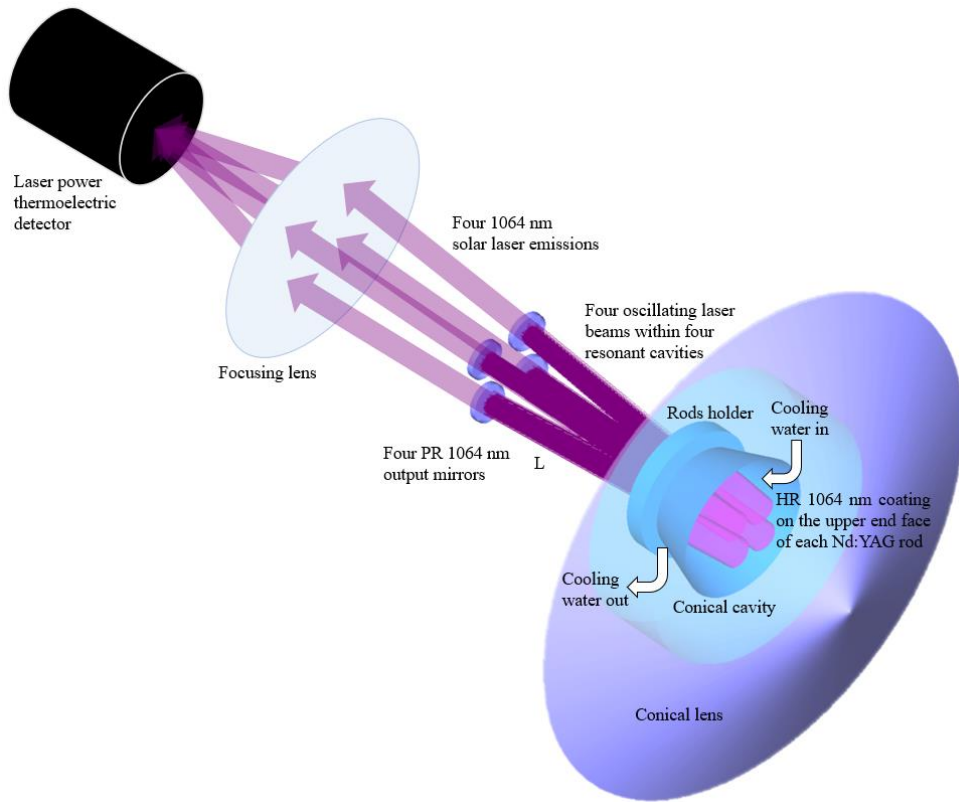


Figure 4-16. Solar-power-to-four-laser-beam conversion approach. Four PR 1064 nm laser output couplers were positioned near of their respective four Nd:YAG rods for the efficient extraction of four output laser beams [60].

Substantial improvement in multimode solar laser performance was numerically achieved with this concept. 51.2 W maximum total multimode solar laser power was calculated from the four 3.00 mm diameter, 20 mm length rods, leading to 29.0 W/m² collection efficiency and 3.1% solar-to-laser power conversion efficiency. Fig. 4.17 show the 3D of the total multimode solar laser powers from a single-rod scheme and the four-rod scheme as a function of the altitude and azimuthal solar tracking errors, ranging from 0.0° to 0.5°. D_R and L_R represent the diameter and length of the Nd:YAG rods, respectively [60]. Both the single-rod and the four-rod schemes were pumped within a similar pump cavity, as previously presented in Fig. 4.16.

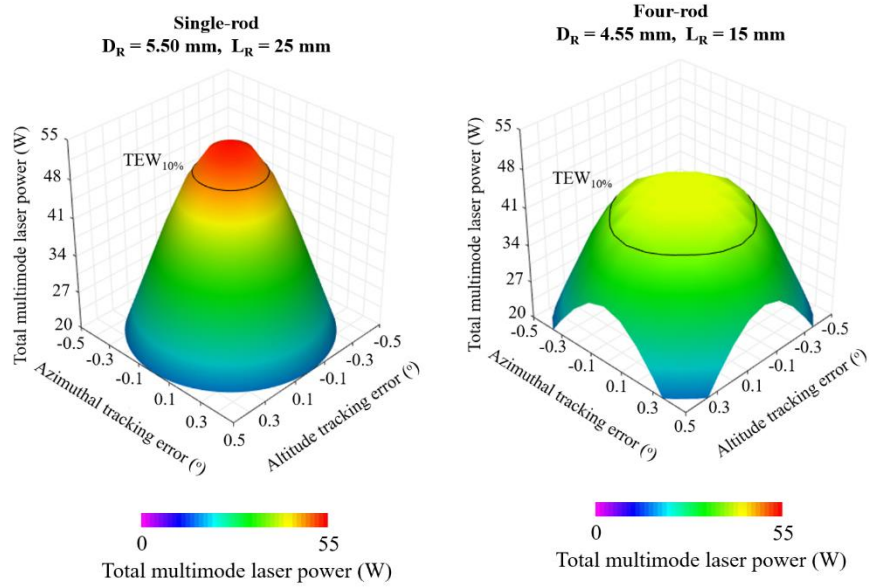


Figure 4-17. Total multimode solar laser power as a function of the simultaneous the tracking error in altitude and azimuthal directions, ranging from the optimal alignment (0.0°) to 0.5° , for the single-rod scheme with $D_R = 5.50$ mm and $L_R = 25$ mm and the four-rod scheme with $D_R = 4.55$ mm and $L_R = 15$ mm [60].

In the optimal alignment (0.0° solar tracking error in both directions), the single-rod scheme numerically attained the highest multimode solar laser power; however, any slight solar tracking error in either azimuth or altitude axis causes a significant reduction of solar laser output. By using the four-rod scheme the concentrated solar power was focused onto the enlarged area comprised by the end faces of the four laser rods, reducing the output laser emission sensitivity to the solar tracking error. This effect was significant, particularly for the four-rod scheme with $D_R = 4.55$ mm, $L_R = 15$ mm. The four larger diameter laser rods substantially improved tracking error compensation capacity, enabling the most stable multimode solar power emission in terms of solar tracking error compensation capacity, leading to 0.76° $TEW_{10\%}$ [60].

4.4.3 Sun-Earth relationship

The conceptualization of the apparent movement of the Sun is pivotal to the development of solar energy systems. The relative motions of the Sun and Earth are not simple, but they are systematic and thus predictable. As illustrated in Fig. 4.18, the rotation axis of the earth is always inclined at an angle of 23.45° [110].

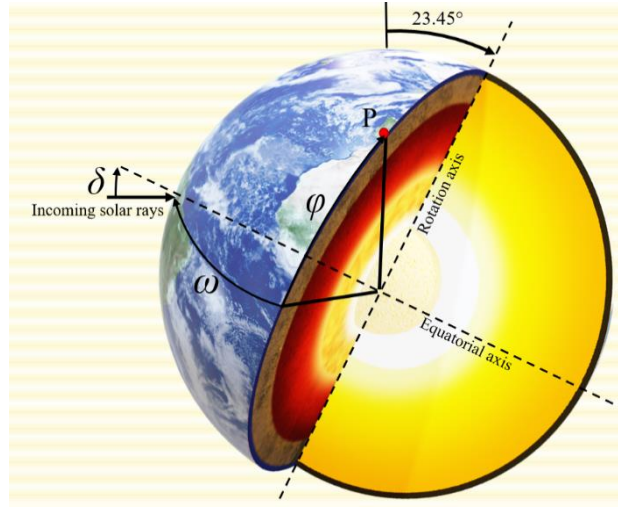


Figure 4-18. Representative illustration of solar declination (δ), hour angle (ω) and latitude (φ), for an observer P [63].

The solar declination (δ) is the angle between the line joining the centers of the Sun and the Earth and its projection on the equatorial plane. It can be approximately calculated for any day of the year (D) by the following equation [110]:

$$\delta = 23.45^\circ \sin \left[\frac{360}{365} (284 + D) \right] \quad (4.1)$$

The concept of hour angle (ω) is used to describe the Earth's rotation about its polar axis, corresponding to the angle between the meridian passing through the Sun and the meridian of the observer P, as shown in Fig. 4.18. It is given by [110]:

$$\omega = \pm 0.25^\circ \times t \quad (4.2)$$

where t is the time in minutes from local solar noon.

These two Earth-Sun angles are fundamental to calculate the two angles that characterize the apparent motion of the Sun: the solar altitude angle and the solar azimuth angle. The solar altitude angle (h) is the angle of the Sun's rays relative to the Earth's horizontal plane, and it is related to both the declination angle and the hour angle by the following expression [110]:

$$\sin(h) = \cos(\omega) \cos(\varphi) \cos(\delta) + \sin(\varphi) \sin(\delta) \quad (4.3)$$

where φ is the local latitude of the observer P, as illustrated in Fig. 4.18.

The azimuth angle (α) is the horizontal angle of the Sun's rays, and is given by the following equation [110]:

$$\sin(\alpha) = \frac{\sin(\omega) \cos(\delta)}{\cos(h)} \quad (4.4)$$

By using the equations 4.1, 4.2, 4.3 and 4.4, both the altitude and azimuth angles were studied for the local latitude of Lisbon ($\varphi = 38^\circ\text{N}$). Fig. 4.19 presents the variation of the altitude angle (Δh) as a function of the variation of the azimuth angle ($\Delta\alpha$), both starting at $t = 0$ minutes deviation from local solar noon [62].

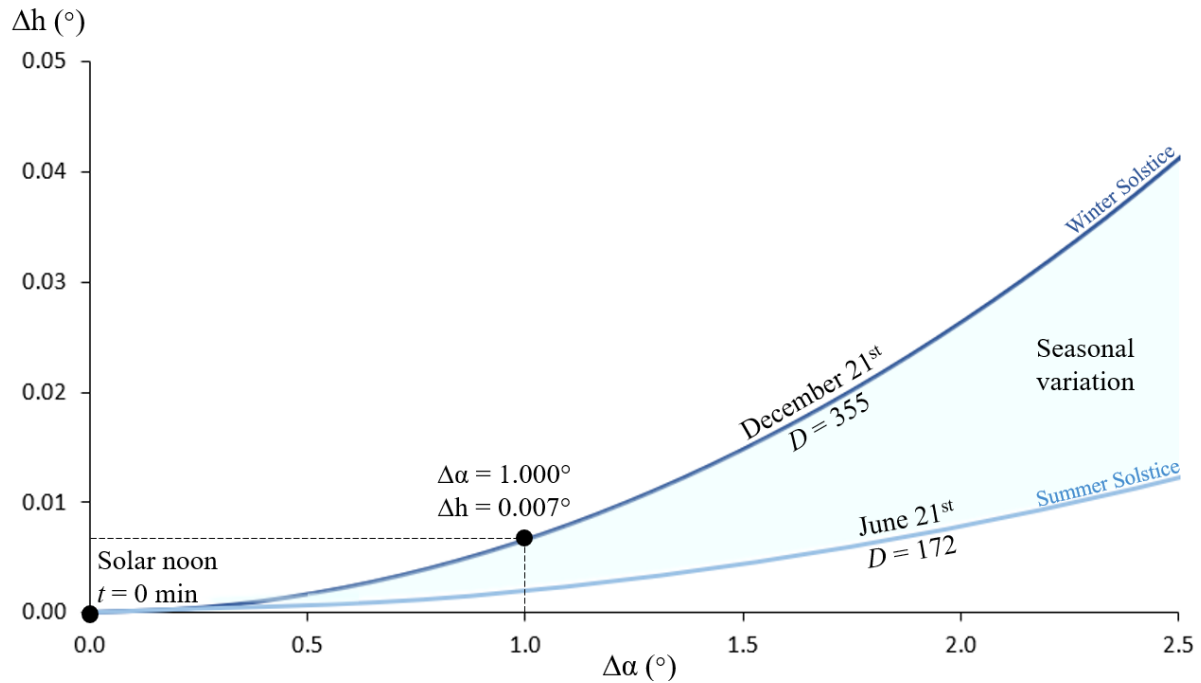


Figure 4-19. Variation of the altitude angle (Δh) as a function of the variation of the azimuth angle ($\Delta\alpha$), both starting at $t = 0$ minutes deviation from local solar noon, for the local latitude of Lisbon ($\varphi = 38^\circ\text{N}$) [63].

As observed in Fig. 4.19, the solar altitude and azimuth angles are not constant; they depend on the location, date and time of the observation. The major discrepancy between altitude and azimuth angles occurs in the Winter Solstice (December 21st). Still, for an azimuthal variation of 1.00° , the altitude angle variation was less than 0.01° , considering $\Delta h = \Delta\alpha = 0.0^\circ$ at local solar noon ($t = 0$) [62].

4.4.4 Azimuth solar tracking error compensation capacity

By end-side-pumping an arrangement of multiple Nd:YAG rods closely coupled within a single pump cavity, it is possible to enhance the total multimode laser power while maintaining high tracking error tolerance, as numerically demonstrated by Catela et al. with a four-rod solar laser concept (0.76° TEW_{10%}) [60], and further explored with a seven-rod solar laser numerically studied by Costa et al. (0.99° TEW_{10%}) [61]. Both solar laser systems evidenced symmetric tracking error compensation capacity for the altitude and azimuthal directions. Still, in practice, the variation of the two solar angles that describe the Sun's apparent movement in the sky (altitude and azimuth angles) is not symmetric, being much more stable on the altitude angle for a couple of hours around the solar noon, depending on the location and date of the observation. A five-rod solar laser pumping approach was proposed to enhance the solar laser stability under non-continuous solar tracking conditions. As presented in Fig. 4.20, a fused silica aspheric lens further concentrated the solar rays towards five Nd:YAG rods, while an elliptical-shaped pump cavity ensured a more complete pump absorption. Five PR 1064 nm laser output couplers were positioned near of their respective five Nd:YAG rods for the efficient extraction of five output laser beams [63].

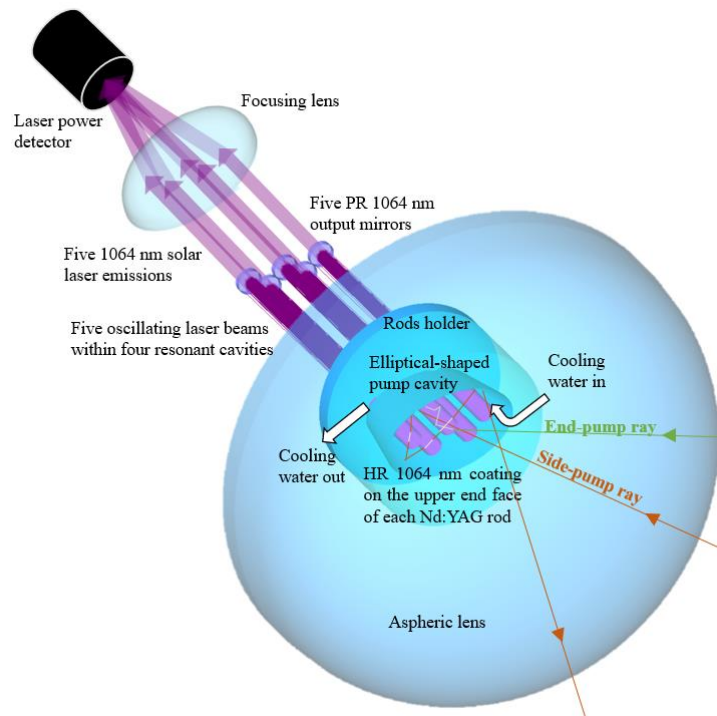


Figure 4-20. Design of the solar laser head, composed of the fused silica aspheric lens, the elliptical-shaped pump cavity and the five Nd:YAG rods, cooled by water. The solar laser resonant cavities are also represented [63].

In Zemax[®] and LASCAD[™] software numerical analysis, the solar laser head was optimized considering the position of the Sun at solar noon, when the irradiance is maximum. As the Sun apparently moves in the sky, the variation of both altitude (Δh) and azimuth ($\Delta \alpha$) angles can be described as altitude and azimuth solar tracking errors. In section 4.4.3, it was demonstrated that the variation of the altitude angle can be considered approximately zero around solar noon at the latitude of Lisbon. Therefore, arranging the position of the five rods in line inside an elliptical cavity, as illustrated in Fig 4.21A, seems to be an obvious option under larger azimuth tracking error condition. However, as the focal spot moved along the top end faces of the five laser rods, the total multimode solar laser power decreased. By changing the positions of the five Nd:YAG rods as shown in Fig. 4.21B both high TEW_{10%} on the azimuthal direction and good power stability on that tracking error range were achieved. This arrangement presented vertical symmetry within the elliptical-shaped pump cavity. The geometry of the pump cavity, namely its input/output apertures, was also optimized to enhance the total absorbed pump power and, thus, the calculated multimode solar laser power. The optimized elliptical-shaped pump cavity led to higher total multimode solar laser power than that with a typical conical pump cavity, as presented in Fig. 4.21C [63].

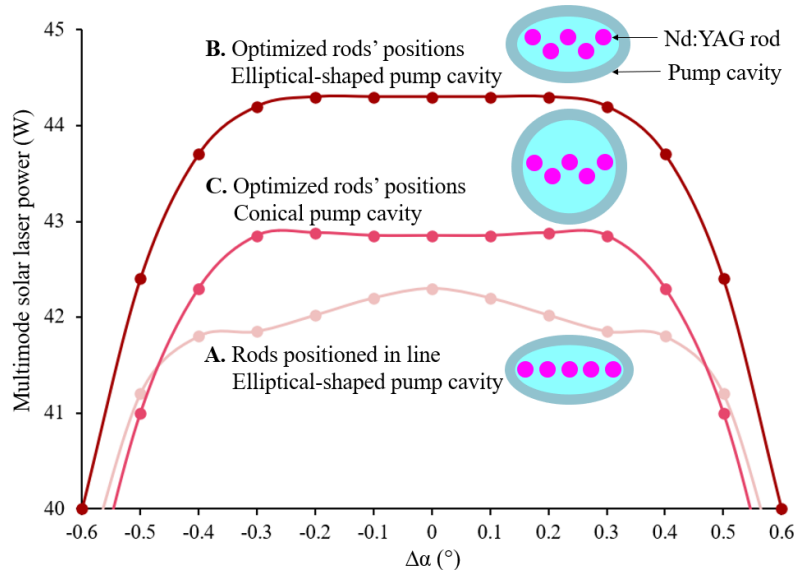


Figure 4-21. Total multimode solar laser power for the five-rod scheme as a function of the azimuthal solar tracking error ($\Delta\alpha$), ranging from the optimal alignment (0.0°) to $\pm 0.6^\circ$, for the 3.0 mm diameter 15 mm length rods positioned in line (A) and at the optimized positions within an elliptical-shaped pump cavity (B) and a conical pump cavity (C) [63].

The total multimode laser power from the five rods was numerically studied as a function of the azimuthal solar tracking error, as represented in Fig. 4.22. The key design parameters of the elliptical-shaped pump cavity and the relative position of the five Nd:YAG rods were optimized for D_R of 2.5 mm, 3.0 mm, 3.5 mm, 4.0 mm, 4.5 mm, 5.0 mm, 5.5 mm, 6.0 mm and 6.5 mm. The optimization focused on attaining total multimode solar laser power stability for the widest azimuthal solar tracking error range. Typical azimuthal solar tracking errors up to $\pm 1.1^\circ$ were considered in the analysis. The total multimode laser power at the optimum alignment ($P_{0.0^\circ}$) and the $TEW_{10\%}$ are also indicated in Fig 4.22 [63].

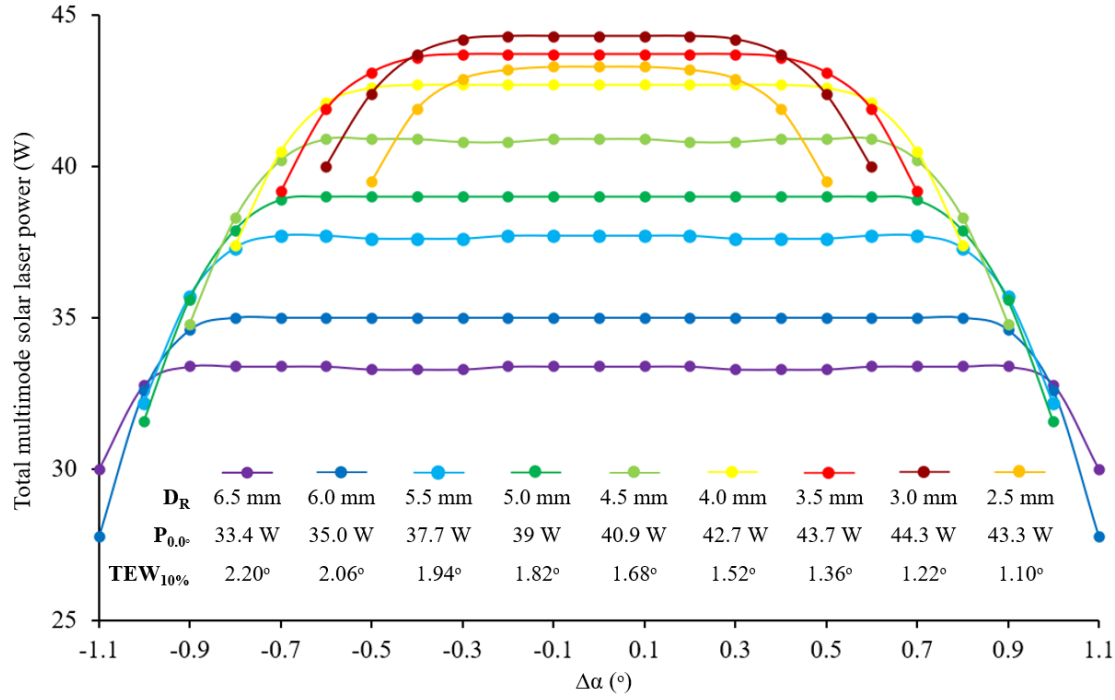
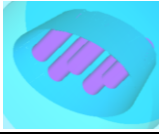
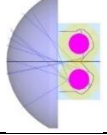
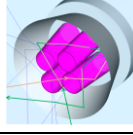


Figure 4-22. Total multimode solar laser power for the five-rod scheme as a function of the azimuthal solar tracking error ($\Delta\alpha$), ranging from the optimal alignment (0.0°) to $\pm 1.1^\circ$, for different D_R . [63].

Table 3.1 presents the recent progress on solar laser systems regarding solar tracking error compensation capacity. Solar laser power collection and conversion efficiencies and $TEW_{10\%}$, as a measure of the solar tracking error compensation capacity, were used to compare the different systems. In 2020, Tibúrcio et al. proposed a dual-rod side-pumping solar laser concept for studying its potential on solar tracking error compensation capacity [51]. Numerical simulations revealed a promising solar tracking error compensation capacity on the azimuthal direction, presenting 0.70° $TEW_{10\%}$. End-side-pumping configurations lead to higher efficiencies [41]. Therefore, in the same year, Catela et al. studied a four-rod end-side-pumping solar laser concept [60]. Numerical analysis proved the high efficiency characteristic of end-side-pumping configurations, while maintaining high solar tracking error compensation capacity of 0.76° $TEW_{10\%}$. Costa et al. further improved this concept by widening the input aperture of the conical pump cavity and filling it with more laser rods [61]. The seven-rod end-side-pumping concept achieved 0.99° $TEW_{10\%}$. 2.20° maximum $TEW_{10\%}$ was calculated for the five-rod solar laser approach with 6.5 mm diameter and 15 mm length designed to compensate for the azimuth solar tracking error [63].

Table 4-2. Recent progress on solar laser systems regarding solar tracking error compensation capacity.

Parameters	Catela et al. 2023 [63]		Tiburicio et al. 2020 [51]	Catela et al. 2022 [60]	Costa et al. 2022 [61]
					
Effective collection area	1.767 m ²		1.560 m ²	1.767 m ²	1.767 m ²
Number of rods	5		2	4	7
Pumping configuration	End-side-pumping		Side-pump-ing	End-side-pumping	End-side-pumping
Rods diameter	6.50 mm	3.00 mm	4.00 mm	4.55 mm	4.00 mm
Rods length	15 mm	15 mm	25 mm	15 mm	13 mm
Total multimode laser power	33.4 W	44.3 W	37.7 W	43.7 W	41.2 W
Multimode solar laser collection efficiency	18.9 W/m ²	25.1 W/m ²	24.2 W/m ²	24.7 W/m ²	23.3 W/m ²
Multimode solar-to-laser conversion efficiency	2.0%	2.6%	2.9%	2.6%	2.5%
TEW_{10%}	2.20°	1.22°	0.70°	0.76°	0.99°

4.4.5 Multibeam uniformity

The above-mentioned works achieved good solar tracking error compensation capacity by exploring multi-rod solar laser configurations. Still, the solar laser power extracted from the laser rods was not well-distributed, with some rods contributing more than others, specially under tracking error condition. The incorporation of a solar flux homogenizer was numerically studied to achieve uniform and stable multimode solar laser emissions. As presented in Fig. 4.23, in this solar pumping approach, the solar radiation was secondarily concentrated by an aspheric lens into a solar flux homogenizer that ensured even energy distribution among four Nd:YAG rods while filtering the solar spectrum from undesired infrared wavelengths. The four laser rods were positioned within a square-shaped pump cavity, parallel to each other and with rotational symmetry. Through Zemax[®] and LASCAD[™] software numerical analysis, the four-rod solar laser head was optimized to emit simultaneously four 1064 nm solar laser beams with similar multimode solar laser power even under solar tracking error condition [62].

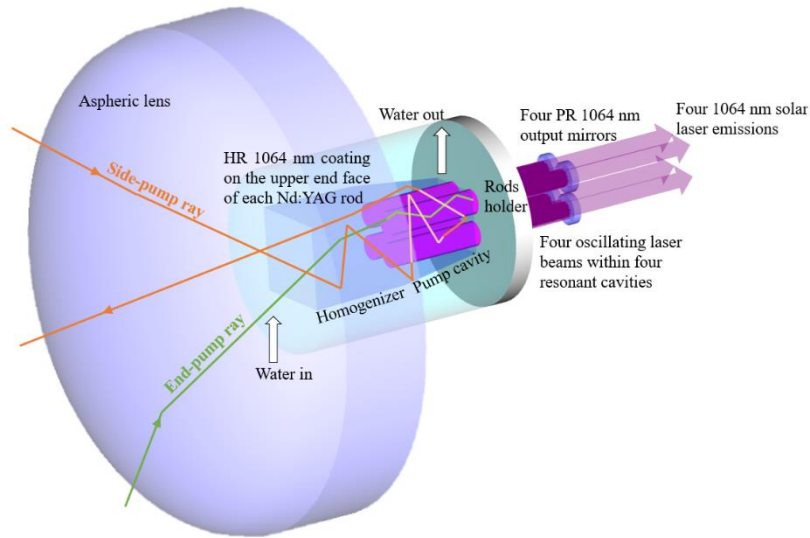


Figure 4-23. Design of the solar laser head, composed of the fused silica aspheric lens, the solar flux homogenizer, the square-shaped pump cavity and the four Nd:YAG rods, cooled by water. The solar laser resonant cavities are also represented, as well as four simultaneous and stable solar laser emissions [62].

The homogenizer was essential to evenly distribute the pump power among the four laser rods. The coefficient of variation (CV) was considered to provide a standardized way of comparing the variation on the multimode solar laser power extracted from the four laser rods. Fig. 4.24 presents the CV as function of the homogenizer length L_H for the optimum alignment ($\Delta\alpha = 0.0^\circ$) and under a solar tracking error variation on the azimuthal direction of $\Delta\alpha = 0.1^\circ$ and 0.2° , giving a visual representation of how increasing L_H led to a significant reduction on the variation of the multimode solar laser power extracted from each rod. By analyzing the relationship between the CV and L_H , the optimal length of the homogenizer was found for $L_H = 13$ mm. The variation on the multimode solar laser power obtained from each of the four laser rods was reduced from 32.38% and 55.52% to 0.00% and 0.21% for $\Delta\alpha = 0.1^\circ$ and 0.2° , respectively [62].

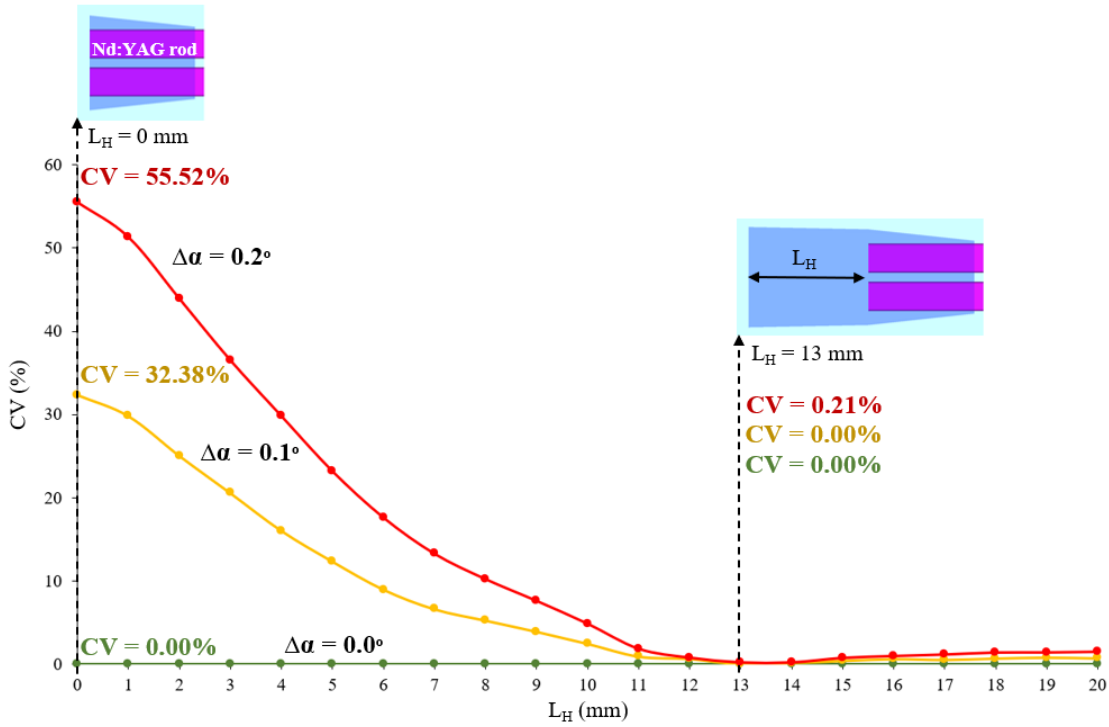


Figure 4-24. Coefficient of variation (CV) of the multimode solar laser power obtained from the four Nd:YAG rods as a function length of the homogenizer (L_H), ranging from $L_H = 0$ mm (no homogenizer) to $L_H = 20$ mm, for the optimum alignment ($\Delta\alpha = 0.0^\circ$) and for $\Delta\alpha = 0.1^\circ$ and 0.2° [62].

At the optimum alignment, the maximum total multimode solar laser power of 41.36 W (4×10.34 W) was calculated for the four Nd:YAG rods with $D_R = 3.2$ mm and $L_R = 15$ mm, corresponding to 23.4 W/m^2 collection efficiency and 2.5% solar-to-laser conversion efficiency. $0.44^\circ \text{ TEW}_{10\%}$ was verified [62].

4.4.6 TEM₀₀ mode multibeam emission.

The TEM₀₀ mode, known as the fundamental mode or single mode, is typically the most stable mode in a laser resonator, as it experiences minimal mode competition and exhibits a well-defined Gaussian shaped intensity profile over time. These laser systems present also superior beam quality (M_x^2 , M_y^2), high spatial and the lowest beam divergence. Additionally, the industry has shown significant interest in TEM₀₀ mode multibeam laser systems due to their potential for reducing processing time. Therefore, the performance of the solar laser head presented in section 4.4.5 was also evaluated to produce TEM₀₀ mode solar laser power under solar tracking error condition with LASCADTM numerical analysis software. Fig. 4.25 presents the TEM₀₀ mode solar laser beam profile calculated for each Nd:YAG rod for the optimal alignment ($\Delta\alpha = 0.0^\circ$) and under typical solar tracking error condition of $\Delta\alpha = 0.1^\circ$ and 0.2° . Despite the TEM₀₀ mode solar laser power and beam quality factors obtained from the four laser rods had been affected

under solar tracking error condition, the four TEM₀₀ mode solar laser emissions were not extinguished even considering $\Delta\alpha = 0.2^\circ$. The homogenizer distributed the pump energy evenly among the four laser rods, being essential in the maintenance of simultaneous TEM₀₀ mode solar laser operation even under solar tracking error condition [62].

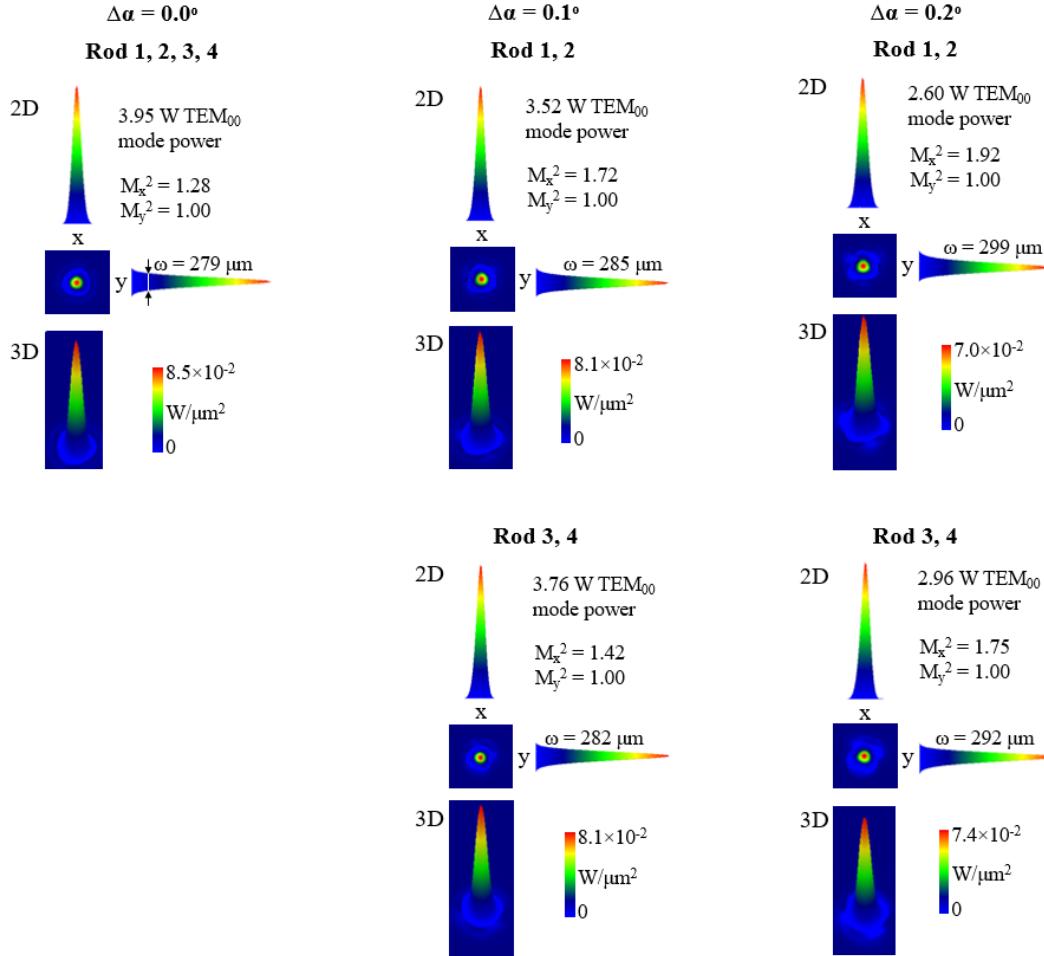


Figure 4-25. 2D and 3D view of the four TEM₀₀ mode solar laser beam profiles extracted from the four Nd:YAG rods with $D_R = 3.2$ mm and $L_R = 15$ mm for the optimum alignment ($\Delta\alpha = 0.0^\circ$) and under a solar tracking error variation on the azimuthal direction of $\Delta\alpha = 0.1^\circ$ and 0.2° . The TEM₀₀ mode solar laser power extracted from each laser rod is also presented, as well as the beam quality factors (M_x^2 , M_y^2) for each case [62].

In order to further study the ability of end-side pumped multi-rod configurations in produce stable and uniform TEM₀₀ multibeam emissions, a solar laser head similar to that of [62] was designed. The system required a longer homogenizer. Moreover, long resonators were chosen so that only the TEM₀₀ mode could oscillate, improving the beam quality factors (M_x^2 , M_y^2), as represented in Fig. 4.26. As in the above-mentioned works, L represents the separation length

between the output end face of each Nd:YAG rod with AR 1064 nm coatings and the respective PR 1064 nm output mirror and plays a crucial role in the extraction of the TEM₀₀ mode laser beam. The optimization of the position and RoC of the output mirror in LASCAD™ software ensured sufficient stability of the laser resonator to maintain single mode emission even under solar tracking errors.

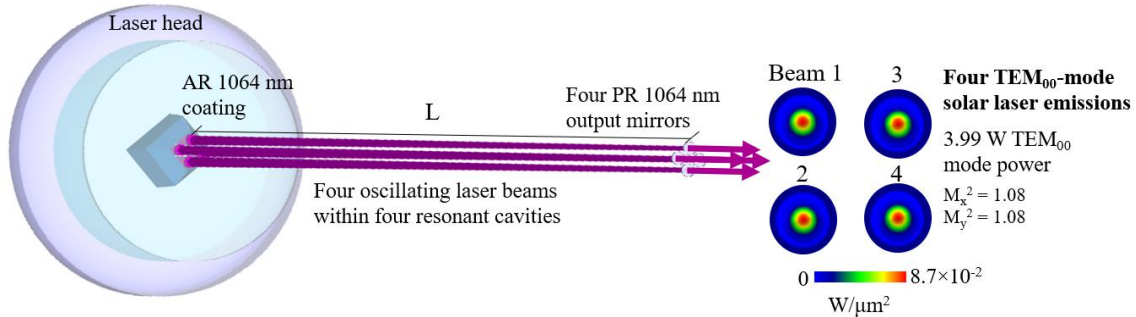


Figure 4-26. Laser cavities for TEM₀₀ mode extraction. Four PR 1064 nm laser output couplers were positioned at a distance L from the AR end face of their respective Nd:YAG rod for the efficient extraction of four TEM₀₀-mode laser beams (1-4), here presented for $L = 430$ mm and RoC = -2000 mm at the optimum alignment.

The performance of the solar laser head in producing TEM₀₀ mode solar laser power was evaluated with LASCAD™ numerical analysis software for typical azimuthal solar tracking errors up to $\pm 0.3^\circ$, considering the apertures that limit the spatial extent of the beam, such as the rod and the PR mirror diameters, as presented in Fig. 4.27. The maximum TEM₀₀ mode solar laser power of 3.99 W was found for RoC = -2000 mm, maintaining the single mode oscillation at $\Delta\alpha = \pm 0.1^\circ$. However, by flattening the PR mirror to RoC = -6000 mm, it was possible to maintain single mode oscillation even with $\Delta\alpha = \pm 0.2^\circ$. Successful generation of four uniform and stable 1064 nm continuous-wave solar laser emissions was numerically demonstrated, exhibiting similar TEM₀₀ power levels and beam quality factors. The system showed resilience against solar tracking errors, tolerating deviations of up to $\pm 0.20^\circ$.

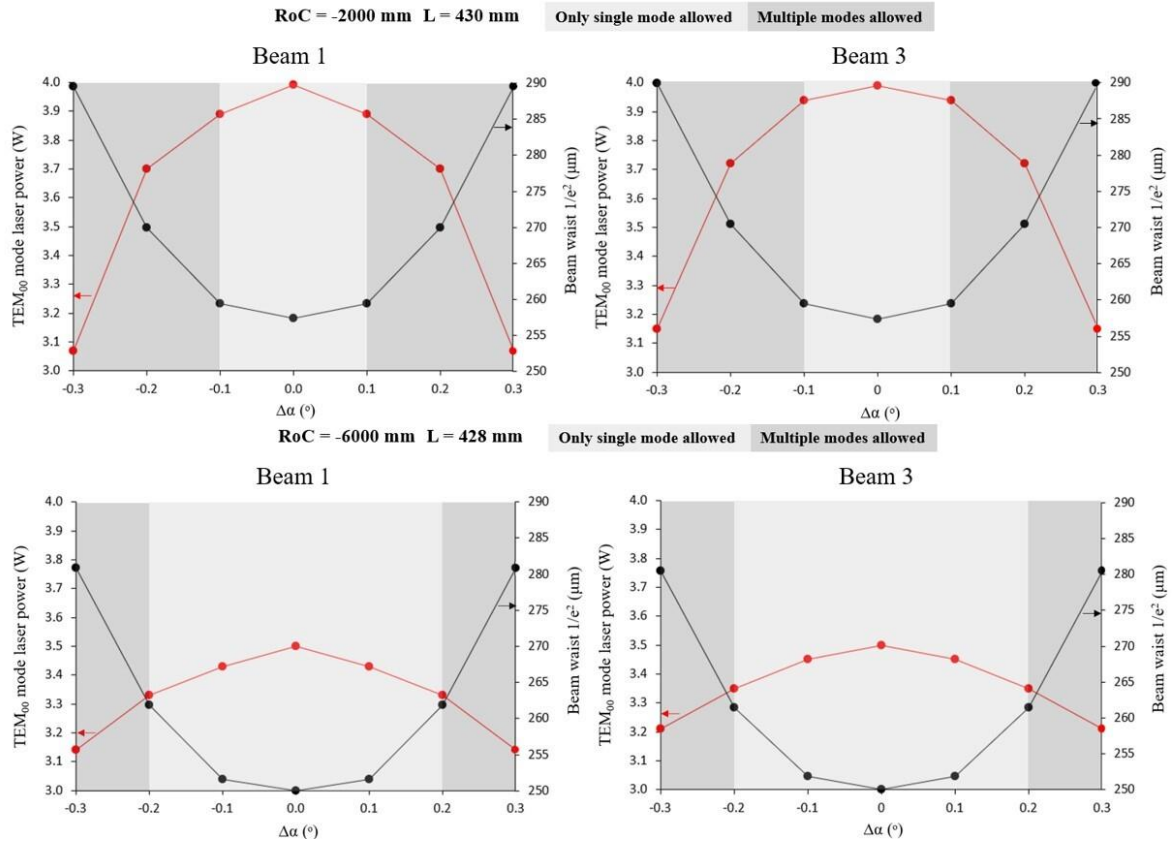


Figure 4-27. TEM₀₀ mode solar laser power versus azimuthal solar tracking error ($\Delta\alpha$) for beam 1 and 3. The $1/e^2$ beam waist is also presented for each case.

ND:YAG SOLAR LASER EXPERIMENTS

This chapter describes an end-side-pumped four-rod solar laser head approach. Leveraging the numerical analysis outlined in section 4, a solar laser head was fabricated and its solar laser power multimode stability was tested under solar tracking error condition. The complete fabrication process is meticulously detailed, accompanied by a comprehensive presentation of the experimental work conducted at PROMES-CNRS, France.

5.1 End-side-pumped four-rod solar laser head approach.

The numerical models mentioned in section 4 gave a very important contribution for building and preparing the experimental tests. End-side-pumping schemes lead to higher efficiencies; however, focusing the concentrated solar radiation onto the end face of a single laser rod requires a highly accurate solar tracking system (STS). Therefore, multi-rod end-side-pumping solar laser designs were numerically studied, attaining high solar tracking error compensation capacity. A large aspheric lens was essential to focus the solar radiation even with under solar tracking error, while the incorporation of a homogenizer component promised stable and uniform multibeam emission. The project of the solar laser head was designed using ZEMAX®, LASCAD™ and CAD software. As shown in Fig. 5.1, the four-rod end-side pumping scheme was composed of an aspheric lens, a rectangular-shaped pump cavity and four Nd:YAG rods, symmetrically positioned around a reflective cone and cooled by water. Four partially reflective mirrors were precisely aligned to extract continuous-wave 1064 nm solar laser power from each laser rod [64].

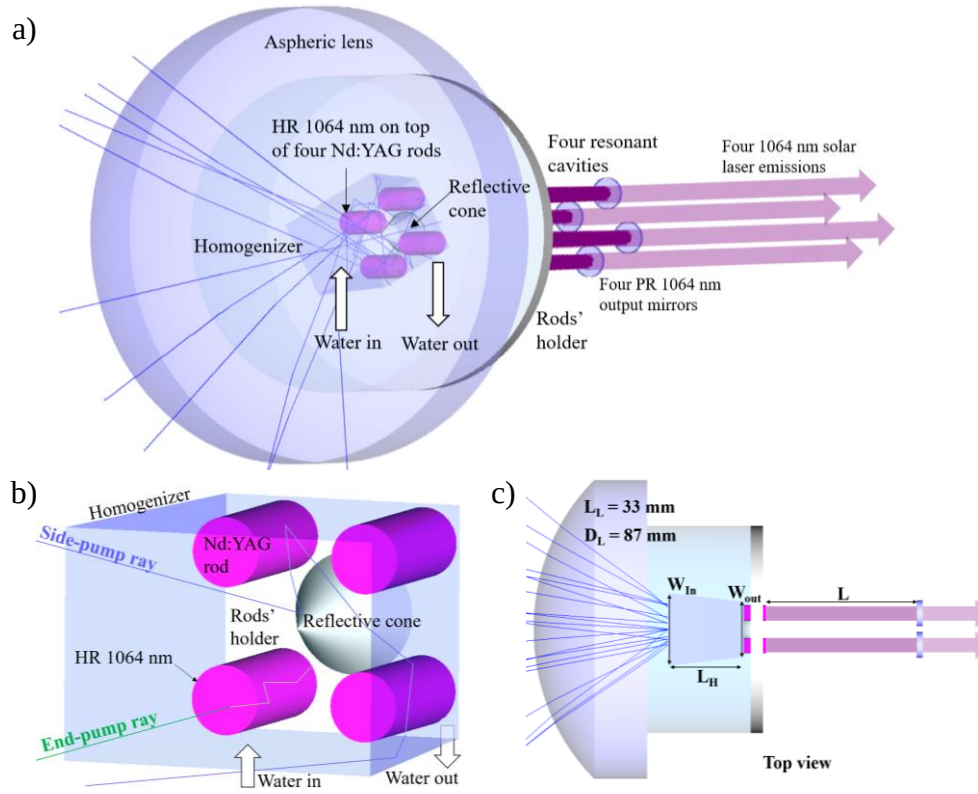


Figure 5-1. Design of the solar laser head. a) 3D view of the solar laser system composed of the fused silica aspheric lens, the flux homogenizer, the reflective cone and the four Nd:YAG rods. The solar laser resonant cavities are also represented. b) The interior of the flux homogenizer, where the laser rods were end-side-pumped and water cooled. c) Top view of the solar laser system and its key dimensions [64].

The aspheric lens further concentrated the solar radiation towards the entrance of the homogenizer (Fig. 5.1a). The front surface of the lens (z) followed the sag equation (Eq. 3.2), with an aspheric coefficient α_2 of -0.0005 , a radial distance r from the optical axis of 43.5 mm, an input face with *radius* of curvature c of 60 mm and a conic constant k of 0. The 33 mm thickness (L_L), 87 mm diameter (D_L) aspheric lens had a plane output surface. A 6 mm gap between the lens flat surface and the input aperture of the homogenizer provided more than enough spacing for the passage of the cooling water. The concentrated solar radiation was then transmitted through the rectangular-shaped homogenizer with an input aperture width W_{in} of 21 mm, an output aperture width W_{out} of 16 mm, and a constant height of 15 mm along its length L_H of 22 mm. As illustrated in Fig. 5.1b, for side-pumping (blue line), the solar rays zigzagged on the homogenizer wall and the reflective cone, entering the active media through the lateral surface of each rod. For end-pumping (green line), the solar rays were focused onto the active media through the top end face of each Nd:YAG rod, where the HR 1064 nm (99.95% @ 1064 nm) coating is deposited. The four optical resonators were composed of the HR 1064 nm coatings and the four mini PR 1064 nm output mirrors, positioned at a distance L from the AR 1064 nm

coating on the back end face of each Nd:YAG rod. A laser resonator with $L = 70$ mm was adopted to provide sufficient spacing for fixing and calibrating the complex opto-mechanical assembly required for the simultaneous extraction of four laser beams. The solar laser parameters mentioned above are illustrated in Fig. 5.1c [64].

5.2 Solar head fabrication

5.2.1 Aspheric lens

Aspheric lenses are commonly used as secondary concentrators for solar laser prototypes. Fused silica is an ideal optical material for Nd:YAG laser pumping since it is transparent over the visible spectrum. Moreover, it has a low coefficient of thermal expansion, and it is resistant to scratching and thermal shock. For manufacture of aspheric lenses, 99.995% optical purity fused silica rods can be supplied by Beijing Kinglass Quartz Co., Ltd. Solar laser pumping necessitates precision optical components, particularly aspheric lenses with a unique curved front face and a flat back face. Achieving the desired front face curvature can be both challenging and time-consuming. The optimal designed achieved with Zemax[®] software was firstly exported into CAD software. A PMMA mold was meticulously crafted, featuring the inverse curvature of the designed lens, using a laser cutting system available at FCT Fab lab. That mold was finally used as reference to validate the lens front face curvature during its machining at the workshop of Physics Department. The front face of the aspheric lens was machined to precisely fit the curvature of the mold. A meticulous polishing process was applied to enhance the transparency of both surfaces of the aspheric lens, thereby optimizing its optical properties. The fused silica aspheric lens used for these experimentations was already available in the laboratory, as presented in Fig. 5.2.



Figure 5-2. Fused silica aspheric lens used in the experimental essays.

5.2.2 Pump cavity

The pump cavity was made of brass, known for its low-density yet durable properties, provided structural stability to the pump cavity. Its resilience against mechanical stress and vibrations helps maintaining the integrity of the cavity's components, preventing misalignment that could affect laser performance. Brass's moderate thermal conductivity aided in distributing and dissipating excess heat generated during laser operation, ensuring stable and prolonged functionality. Brass's optical properties, including low light absorption and scattering, make it conducive for maintaining a clean optical environment within the pumping cavity. This is crucial to minimize energy losses and ensure optimal light amplification. The ease of machining and shaping brass simplifies the fabrication process, allowing the manufacturing of the cavity's components with precision. Brass offers a cost-effective solution for the pump cavity without

compromising its performance. The CAD drawing showed in Fig. 5.3a was sent to an outsourcing company and the pump cavity was produced as presented in Fig. 5.3b.

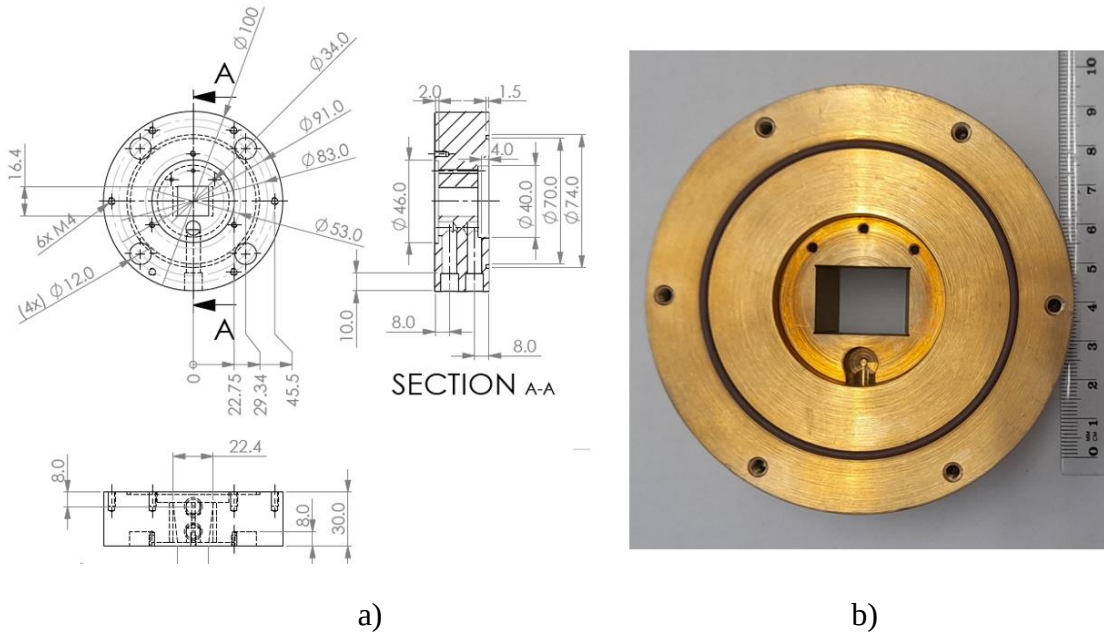


Figure 5-3. Pump cavity. a) CAD drawings; b) Photograph of the front view.

5.2.3 Rods' holder

Similarly to the pump cavity, the rods' holder was machined by the same outsourcing company. The material chosen was also brass for the above-mentioned reasons. The CAD drawing is presented in Fig. 5.4a. The laser crystals presented in Fig. 5.4b were acquired from Beijing Jiepu Trend Technology Co., Ltd. (Beijing, China). Each one of the four 4.5 mm diameter, 15 mm length Nd:YAG rods had an HR 1064 nm (99.95% @ 1064 nm) coating and an AR coating (<0.2% @ 1064 nm) deposited on the front and back end face, respectively. These coatings played a crucial role in the laser emission process, allowing the passage of solar radiation while selectively reflecting photons at a wavelength of 1064 nm. Fig. 5.4c presents the rods holder machined by the outsourcing company. The diameter of each of central holes was dimensioned in order to allow the fixation of the four laser rods, while restricting the flow of water to the confines of the pump cavity [64].

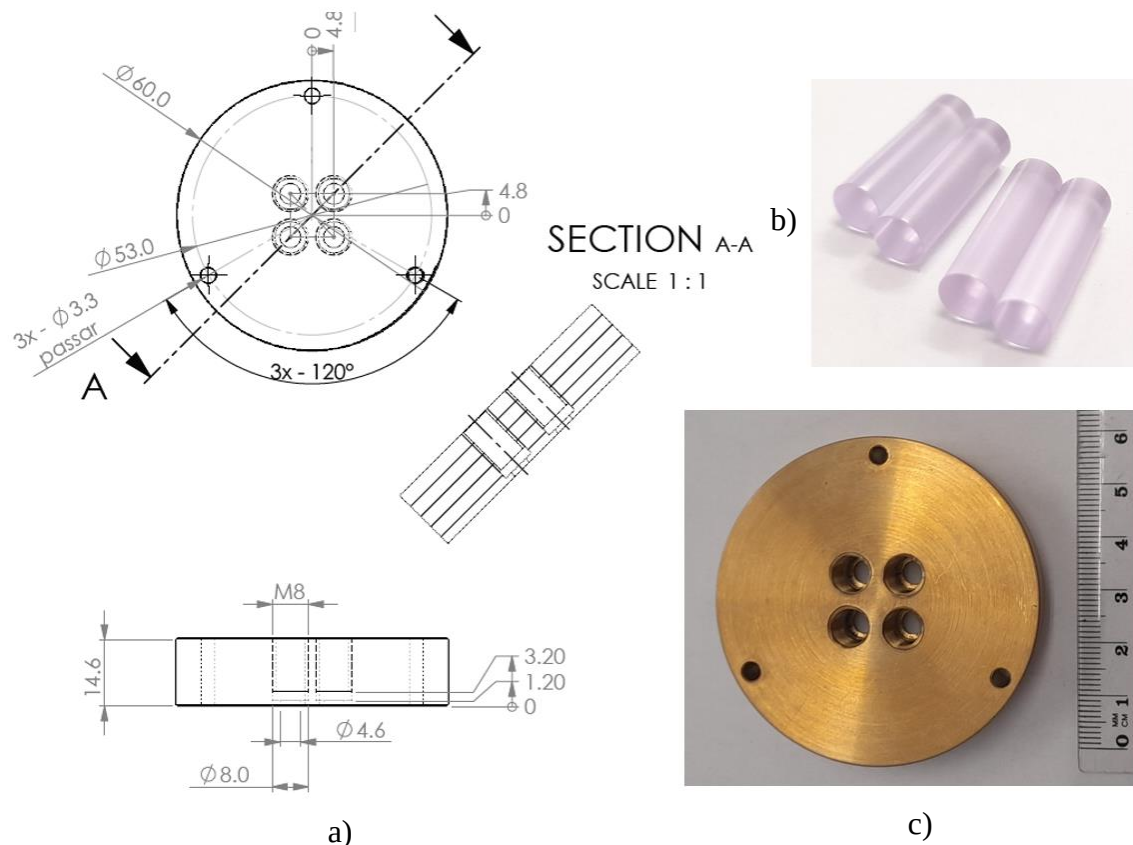


Figure 5-4. Rods' holder. a) CAD drawings; b) Nd:YAG laser rods; c) Photograph of the holder back view

5.3 Solar laser head assembly

5.3.1 Water test

Water was used to remove the heat in the laser rods associated with the intense optical pumping, due to its low viscosity, easy availability and high specific heat and thermal conductivity. Furthermore, water can absorb the infrared component of the solar spectrum, not useful for Nd:YAG solar pumping, making it an ideal candidate for filtering the pump radiation in Nd:YAG solar laser systems. Still, water leakages can compromise the solar laser emission and even lead to the destruction of the prototype. Therefore, the solar laser head was assembled, and the water leakage tests were performed in the laboratory, as presented in Fig. 5.5.

For the entry and exit of the cooling water, two inox tubes were inserted into two holes previously drilled on the lateral surface of the pump cavity. A polyurethane tube was then attached to each of the inox tubes. In order to minimize the risk of damaging the Nd:YAG laser rods,

four brass rods were produced with the same dimensions of the four Nd:YAG rods. These “dummy” rods were then fixed into the rods’ holder. Different O-rings were tested in order to fix the four “dummies” while avoiding water leakages; however, using Teflon tape around their tips was the most effective method. For the water sealing mechanism, an O-ring was inserted into the sealing channel of the pump cavity (Fig. 5.5a). The rods’ holder was then fixed to the back of the pump cavity with three M3 screws, as presented in Fig. 5.5b. The four custom made screws used to fix the four “dummies” rods are also visible.

The solar laser head was not complete without assembling the aspheric lens (Fig. 5.5c). Thus, an aluminium ring was used to fix the fused silica concentrator to the top of the pump cavity with six M4 screws. For the water sealing mechanism, an O-ring was also inserted between the lens and the pump cavity. Fig. 5.5d and 5.5e presents the solar laser head front view and lateral view, respectively, being flooded with water at 6 l/min flow rate with no leaks.

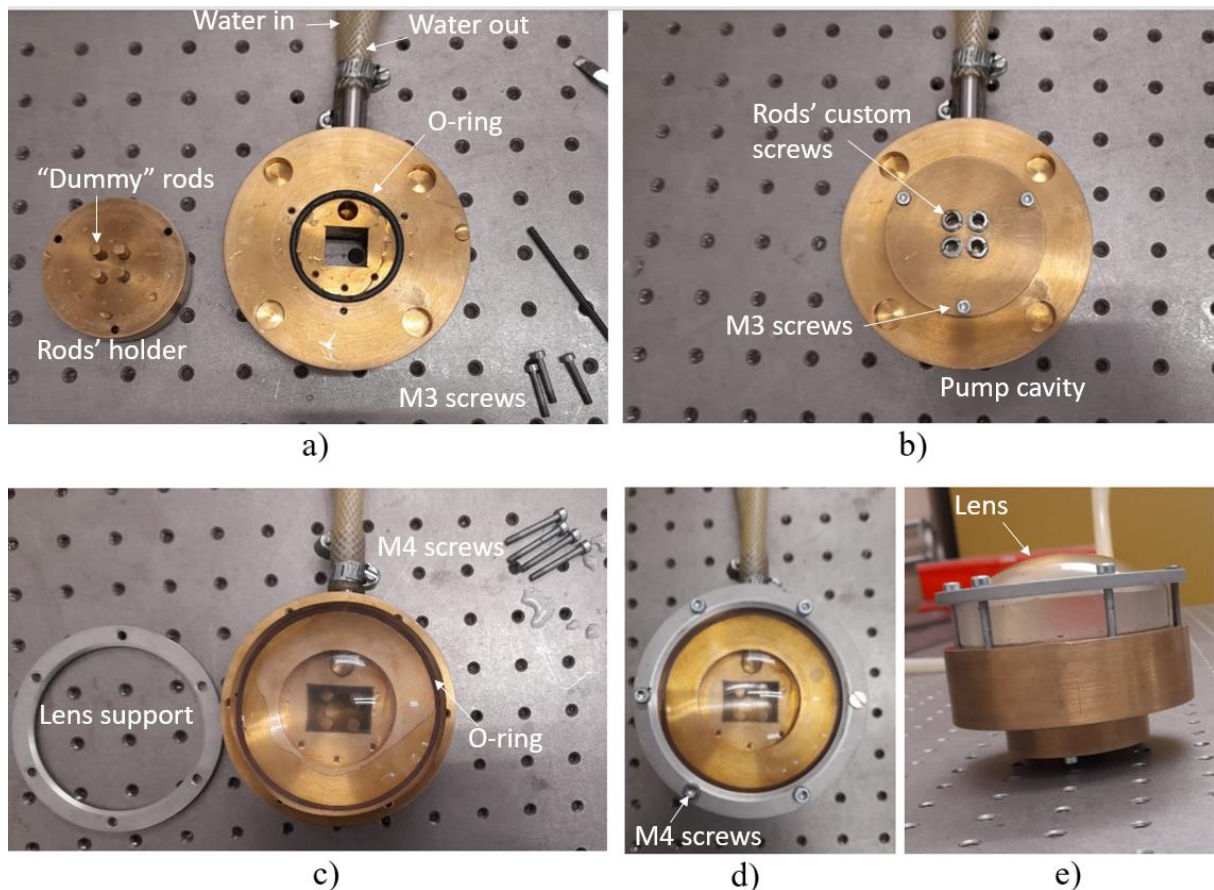


Figure 5-5. Water test. a) Rods’ holder with four bass rods and pump cavity with the water tube assembled. b) back view of the solar laser head. c) Assembling of the aspheric lens. d) Front view. e) Lateral view.

5.3.2 Pump cavity applications

The pump cavity was designed to effectively transfer the concentrated solar radiation into the four Nd:YAG rods. Thus, a silver-coated aluminum foil of 94% reflectivity was applied to each one of the four inner walls of the homogenizer, as presented in Fig 5.6a. Each one these foils was cut and polish to precisely cover the interior of the pump cavity. A thin layer of glue was applied between the back surface of each foil and the interior of the pump cavity. Controlled pressure was exerted using a purpose-produced Teflon tool. In precise optical systems, such as solar-pumped lasers, structural stability is crucial to achieve and maintain the precise alignment of the resonant cavity, as well as to fix the necessary measurement equipment. Therefore, four inox long rods were inserted into the back of the pump cavity mechanics, as presented in Fig. 5.6b. A brass ring helped to maintain the rods parallel, while serving as a support base for the solar laser system.

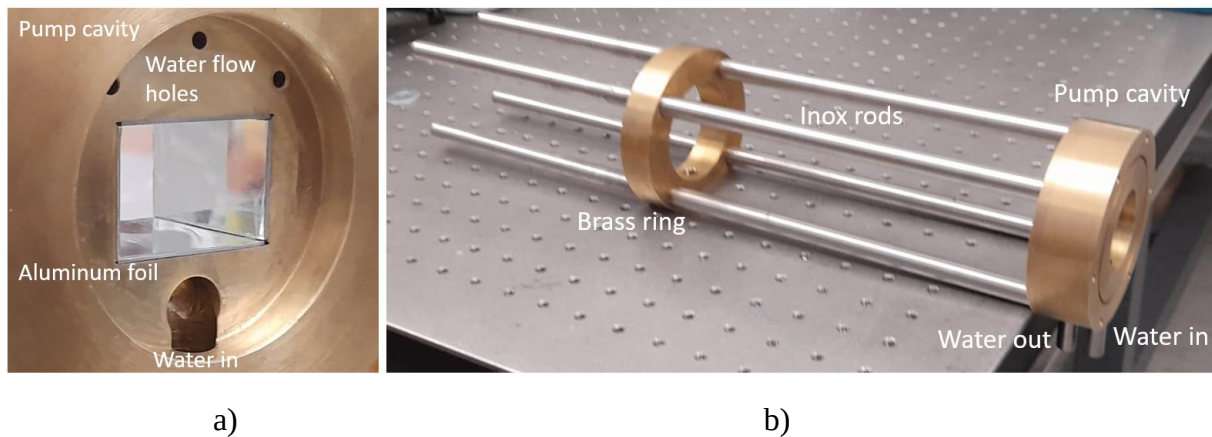


Figure 5-6. Pump cavity applications. a) Reflective foils were applied to the interior of the pump cavity. b) Inox rods were inserted into the back face of the pump cavity.

5.3.3 Nd:YAG rods assembly

Nd:YAG crystal stands as a well-established laser medium characterized by robust mechanical strength. Still, it is a brittle material, similar to glass, and can break relatively easily when subject to mechanical stress or improper handling. Therefore, caution is necessary when working with Nd:YAG crystals to avoid damaging them.

As mentioned in section 4.3.1, four brass “dummy” rods were used to practice the attachment of the laser rods onto the rods’ holder. After several days of practice, the Nd:YAG rods were prepared. They were carefully cleaned with isopropanol and the HR end face was identified.

Teflon tape was rolled closer to the AR end face. Each one of the Nd:YAG rods were inserted through the back of the rods' holder. A brass tube was used to help positioning each Nd:YAG rod inside the rods' holder by making contact only with the Teflon tape on the back face of the rods. Four M8 screws were used to fix the Nd:YAG rods. The screws exerted pressure on the brass tube, compressing the Teflon tape and ensuring a tight junction between the Nd:YAG rods and the rods' holder. Fig. 5.7 presents the different stages of assembly of the Nd:YAG rods onto the rods' holder. The above-described process was repeated for each rod (Fig. 5.7a), until the four rods were tightly fixed onto the rods' holder, presenting a similar exposed length and an inclination close to zero (Fig. 5.7b). Note that the screws used to fix the laser crystals were drilled to ensure that the back face of each Nd:YAG rod remains exposed for laser extraction (Fig. 5.7c).

An aluminium reflective cone was produced and glued on the center of the front face of the rods' holder, as presented in Fig. 5.7d, to redirect some pump rays onto the laser rods with the aim of enhancing the absorption efficiency. The flux homogenizer and the reflective cone were crucial to ensure uniform pump power distribution among the four Nd:YAG rods, considering shadowing effects and solar tracking error conditions.

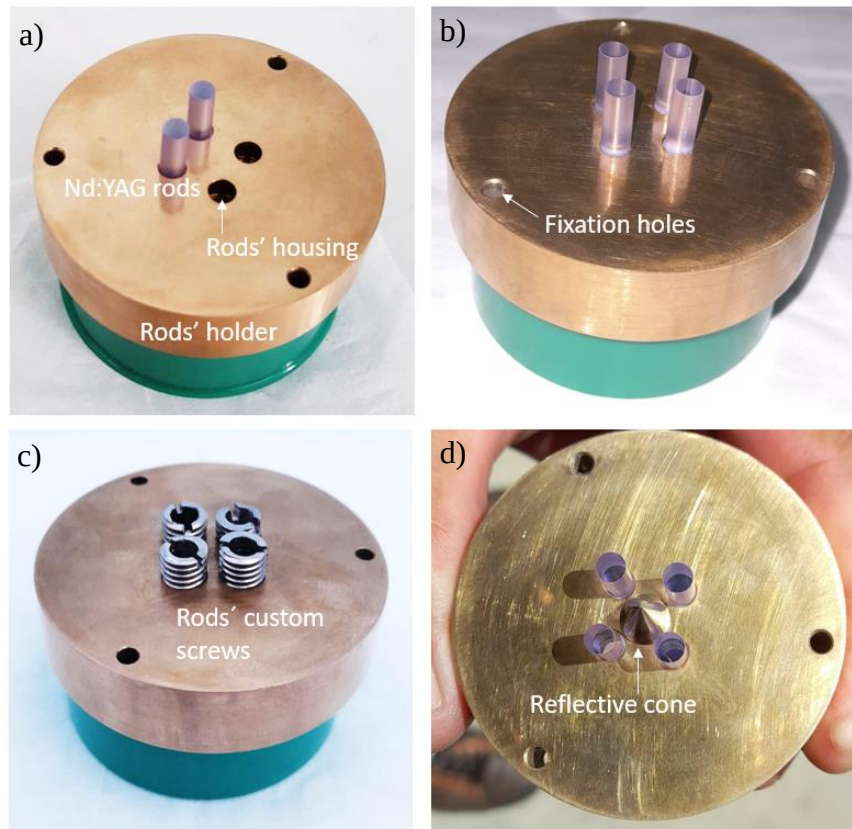


Figure 5-7. Nd:YAG rods assembly. a) The laser crystals were fixed one by one until b) all presented the same exposed length and an inclination close to zero. c) back face of the rods' holder with the four custom screws used to fix the laser rods. d) front view with the four Nd:YAG rods and the reflective cone at the center.

5.3.4 Solar laser head prototype

As previously described in section 5.3.1, the rods' holder was fixed into the pump cavity with three M3 screws. Fig. 5.8a presents the front view of the solar laser head without the aspheric lens. The four Nd:YAG rods, as well as the reflective cone were positioned inside the pump cavity. It is also possible to view the reflective walls of the pump cavity. The aspheric lens was then fixed into the front face of the pump cavity, as presented in Fig. 5.8b. The water test was again performed. The solar laser head showed no water leakages.

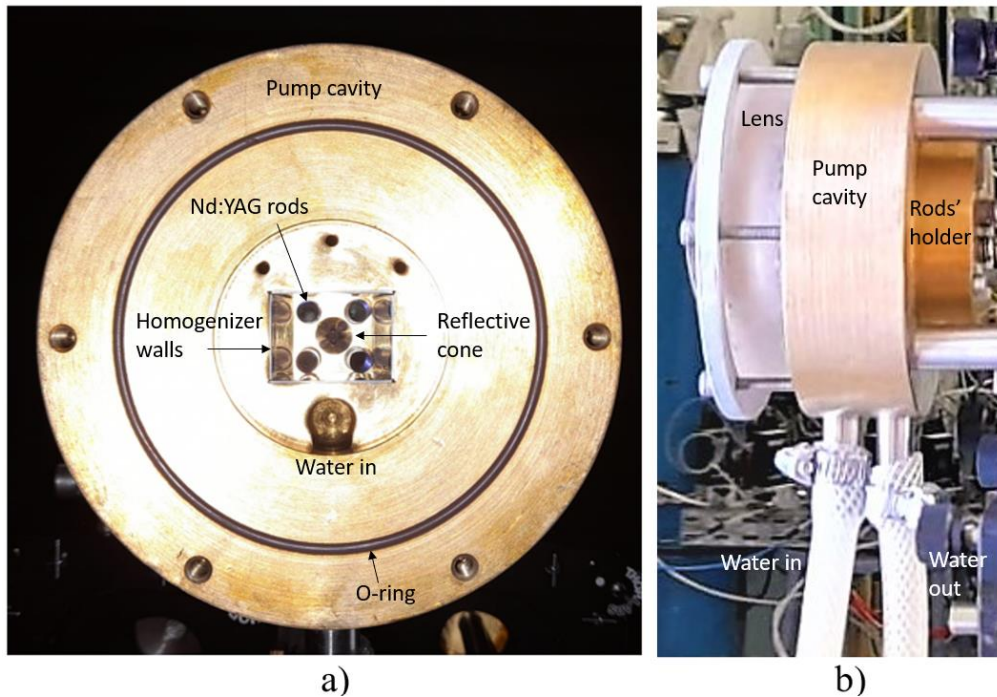


Figure 5-8. Solar laser head assembly. a) Front view without the aspheric lens. b) water test with the solar laser head fully assembled.

5.4 Resonant cavity

5.4.1 Output mirrors fixation

As previously described in section 3.2, the resonant cavity typically comprises two opposing mirrors: the HR 1064 nm mirror and the PR 1064 nm mirror, from which the laser beam is extracted. While the HR 1064 nm consists of a coating on the top end face of each laser rod, the PR 1064 nm is a standard commercial output mirror positioned in front of each Nd:YAG rod. Due to the dimensions of the solar laser head and its accessories, as for example the distance between the four rods, which hamper the installation of a standard commercial output mirror, several mini mirrors were built to act as the PR 1064 nm output couplers. They were manufactured by cutting a commercial output coupler with 98% reflectivity and $RoC = -10$, as shown in Fig. 5.9a). Four laser mirror positioners were modified to precisely optimize the position of each PR mirror (Fig. 5.9b)).

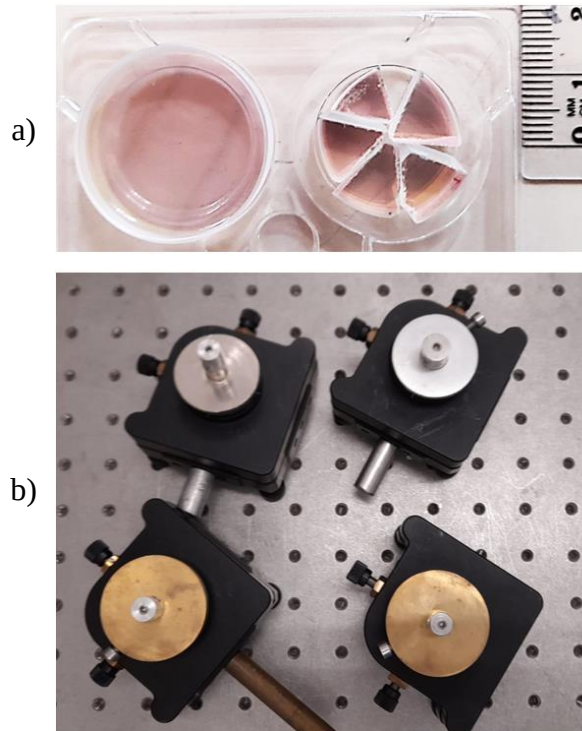


Figure 5-9. PR mirror fixation. a) A standard commercial output mirror (left) and five mini mirrors cut from other standard commercial output mirror (right). b) Four positioners used to fix and align the four PR mirrors.

5.4.2 Resonant cavity alignment

The PR mirrors had their lateral surfaces polished and one of the surfaces of each mirror was glued to an aluminum rod in order to be fixed into each positioner. The four positioners were assembled onto the solar laser head, as presented in Fig. 5.10.

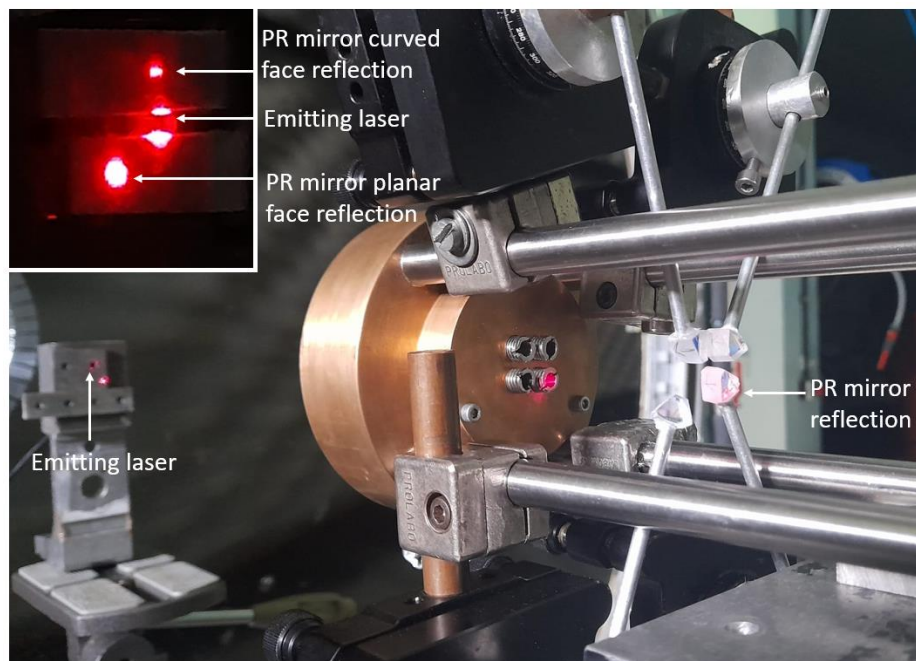


Figure 5-10. Optical alignment process. A red laser was used to ensure precise alignment of the four resonant cavities.

In order to extract solar laser power from each laser rod, each resonant cavity needs to be precisely aligned. A red laser emitting source was used in the alignment. Firstly, the aspheric lens was removed, and the cavity was dry to minimize errors. Secondly, a red laser was aligned with a Nd:YAG laser rod. The laser enters the top end face of the rod and exits through its back face, reflecting some laser light, that is used to check for the alignment which happens when the emitted laser light and the reflected laser light interfere. Then the PR mirror is introduced in the cavity. Two different reflections appear: one smaller, representing the reflection on the PR mirror curved face, and the other, representing the reflection on the PR mirror planar face (Fig. 5.10). Finally, the smaller reflection should be over the laser emitting source for the laser cavity to be precisely aligned. This process was repeated for the four resonant cavities.

5.5 Experiments on solar tracking error stability

The PROMES-CNRS solar facilities in Odeillo, France, offers different solar furnaces, capable of producing very high temperatures (over 3000°C). They are equipped with a wide variety of reactors and modular equipment, designed and developed in the laboratory, to carry out, in the best conditions, high level research in a very wide scientific field. In addition, an extensive set of in-situ diagnostic tools and advanced means of analysis and characterization of materials

complete these facilities. These solar installations are adapted to both fundamental research with high risk stakes, and more applied research that can go as far as the industrial pilot. For solar furnaces, the availability of high fluxes and/or high temperatures without contamination, and the ability to control the atmosphere (pressure, vacuum, composition), make them unique instruments for the study of materials synthesis, solar chemical processes, solar energy chemical storage cycles, thermo-physical behavior of materials under extreme conditions, and the fundamental physics of high flux.

The laboratory's solar facilities include :

- the 1 megawatt solar furnace (MWSF) and its environment
- the 11 medium size solar furnaces (MSSFs) and their environment
- a parabolic trough pilot plant and its environment

5.5.1 Medium Size Solar Furnace

The medium size solar furnaces (MSSFs) consist of 11 concentrators ranging from 1.5 to 6 kW. Nine are located on the 6th floor of the main building, operating along a vertical axis, and lit by 3 heliostats located on the south side of the building. A set of two 2 kW concentrators with horizontal axis is located in an annex building. The MSSFs are equipped with shutters or flow controllers, vacuum or controlled atmosphere chambers, temperature measurement devices and diagnostic instruments.

In this work it was considered one of the two 2 kW concentrators located in the annex' building. Its horizontal axis is more convenient for solar laser operations since the focal spot of the parabolic mirror as an easier and safer access, allowing frequent adjustments required to precisely align the resonant cavities.

Fig. 5.12 presents the set of two heliostats used to redirect solar radiation towards the two horizontal axis parabolic mirrors (Fig. 5.12a). Each heliostat had mounted 36 flat square-shaped mirrors, each one with 0.25 m^2 collection area. The system uses a two sensor system (Fig. 5.12b) to detect variations on the vertical and horizontal directions. Corrections can be done by the dual-axis system that controls both heliostats as a single set (Fig. 5.12c). The heliostats are capable of rotation in two axes, enabling compensation for solar tracking errors in both azimuth and altitude directions [64].

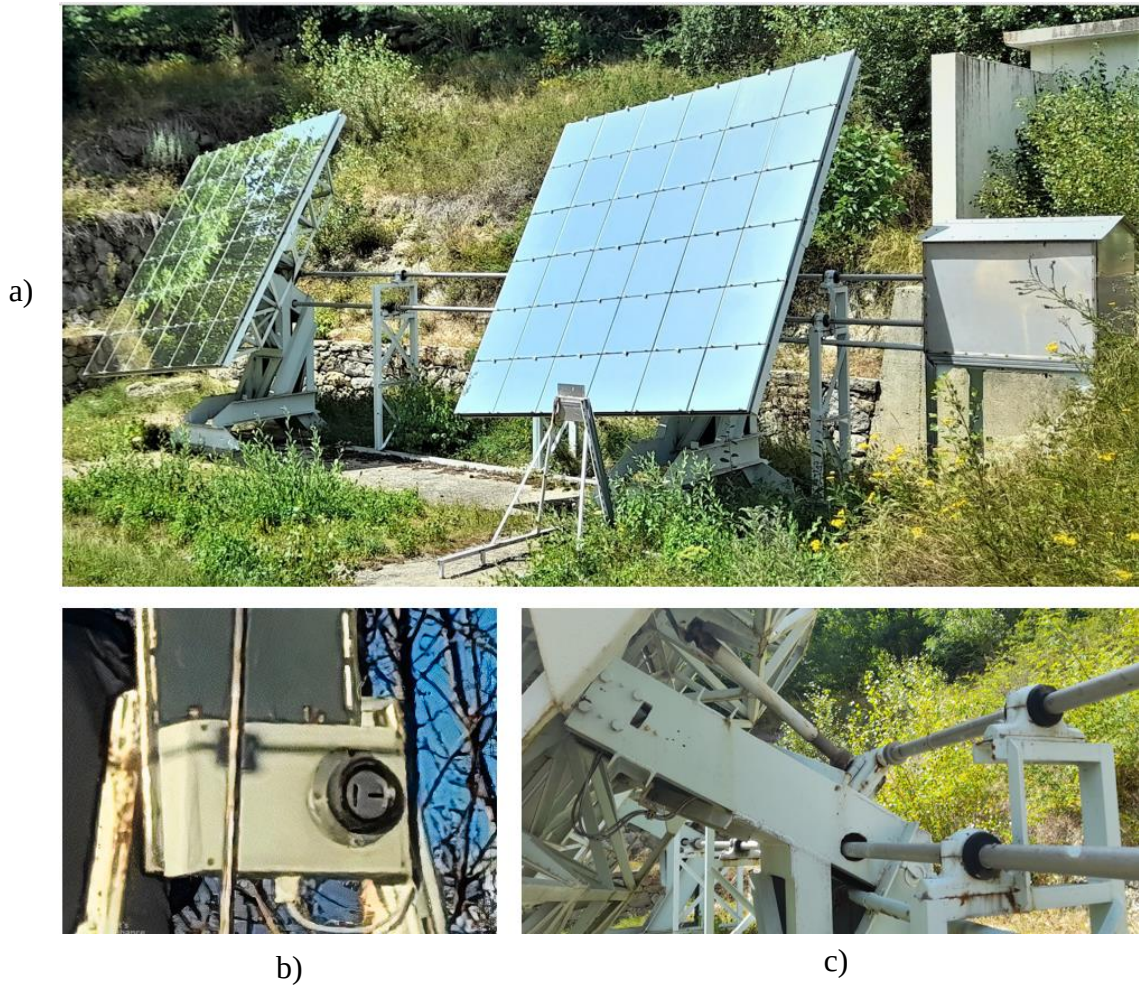


Figure 5-11. Dual-axis heliostat system. a) A set of two heliostat mirrors, with (b) two sensors detecting variation on horizontal and vertical directions and (c) a dual-axis system that corrects the inclination of the heliostat set as a whole.

A shutter controls the energy entering the interior of the annex building where the parabolic mirrors are installed, as presented in Fig. 5.13a. The parabolic mirror used in this work is shown in Fig. 5.13b. It has a diameter of 2 m and a central hole with a diameter of 0.3 m, Both the heliostat mirrors and the parabolic mirror are back-surface silver coated, presenting a measured total combined reflectance of only 59% [64].

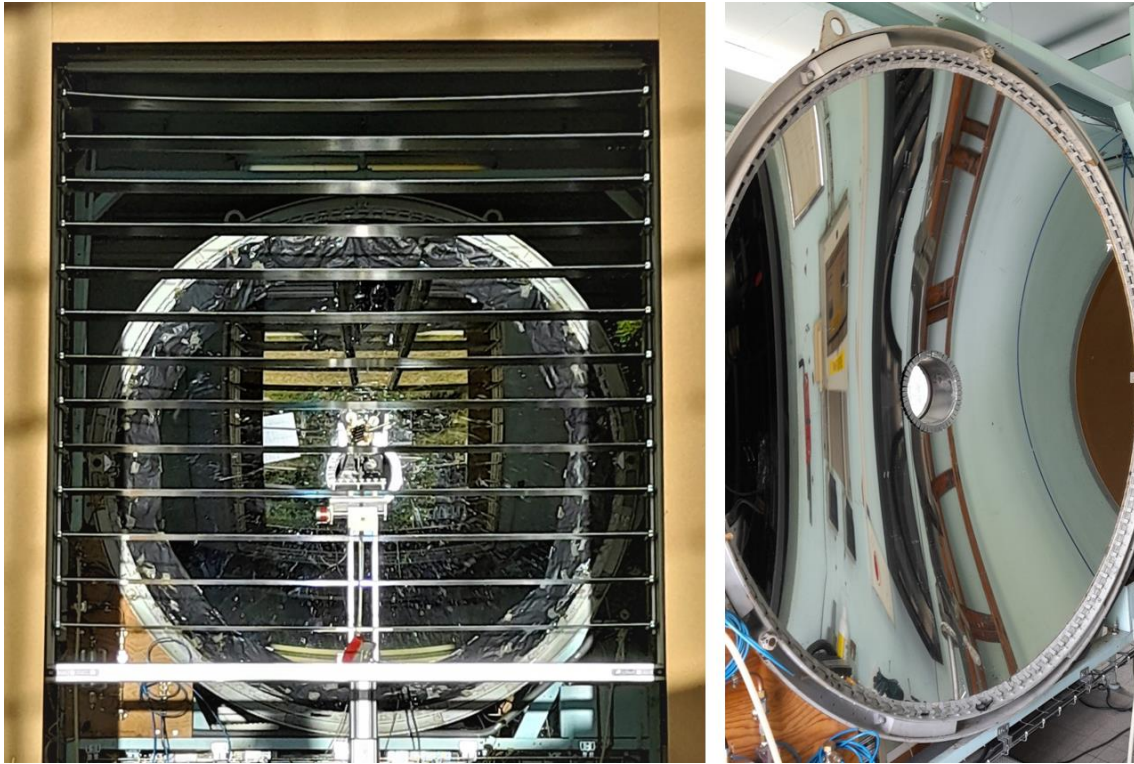


Figure 5-12. Parabolic mirror. a) A shutter controls the energy entering the annex laboratory where (b) the 2 m diameter parabolic mirror is installed.

5.5.2 Experimental set-up

In order to harvest the necessary input power to stimulate laser emission, the MSSF heliostat-parabolic mirror system previously described was considered, as shown in Fig. 5.14.a. The annual Sun's path in Odeillo, France (Latitude 42.49° , Longitude 2.03°) is also represented. Fig. 5.14b presents an illustration of the MSSF used in the experiments [64].

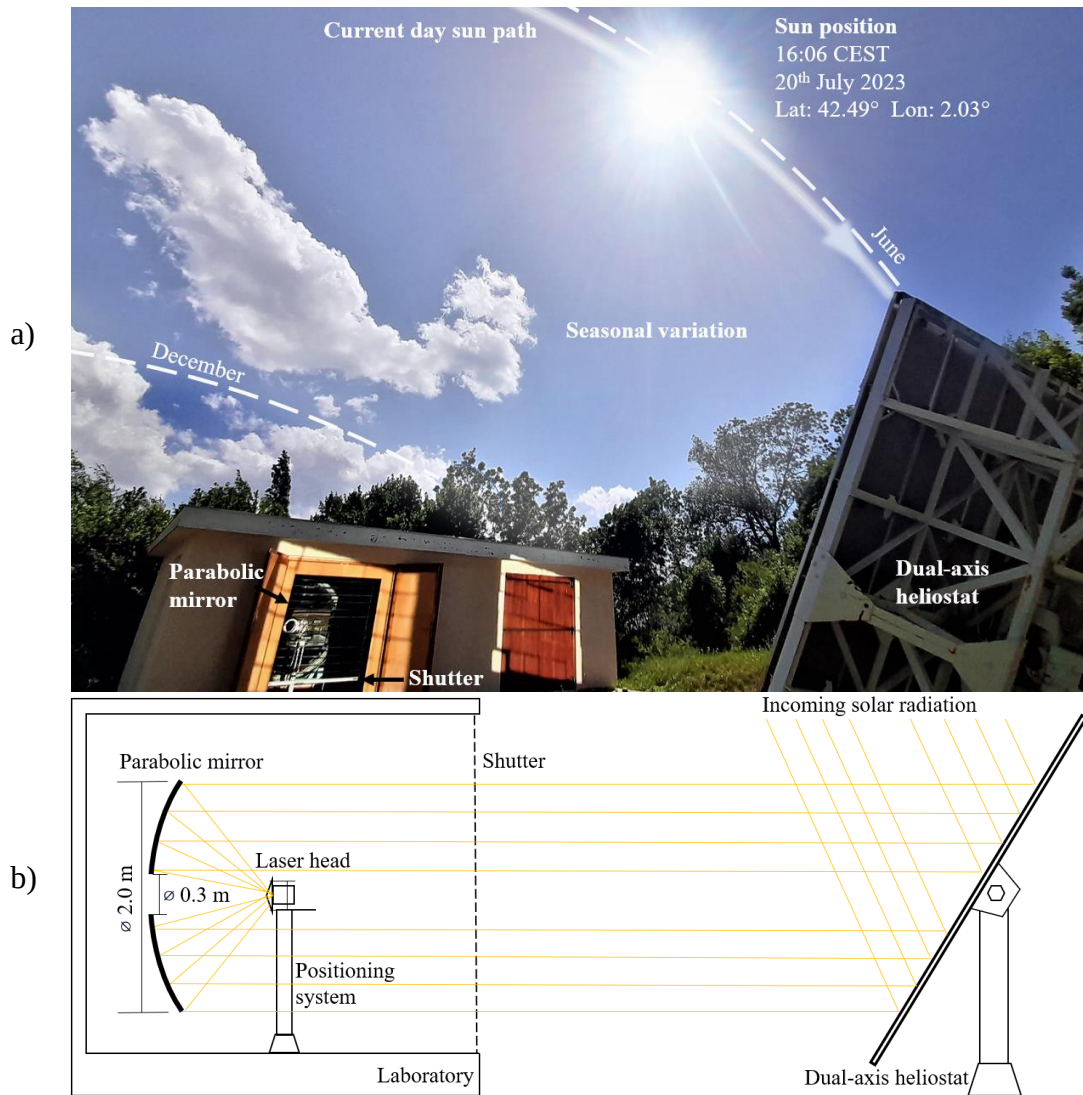


Figure 5-13. PROMES-CNRS MSSF heliostat-parabolic mirror system. (a) Photograph of the system operating on 20th July 2023 at 16:06 CEST. (b) Illustration of the system redirecting and concentrating the solar radiation towards a solar laser head mounted on top of a positioning system. A shutter controlled the solar radiation that entered the laboratory [64].

Figs. 5.15a and 5.15b present the front view of the solar laser head composed of the fused silica aspheric lens, the rectangular-shaped flux homogenizer within which the four Nd:YAG rods were water cooled, and the reflective cone positioned at the center of a rods' holder. Fig 5.15.c shows the four small PR 1064 nm output mirrors used to extract continuous-wave 1064 nm solar laser power from the four 4.5 mm diameter, 15 mm length Nd:YAG rods. The solar laser head was mounted on top of an X-Y-Z positioner, allowing precise adjustments in the three directions. Cooling water provided by the local plumbing system with 4.5 bar at room temperature was used, as shown in Fig. 5.16 [64].

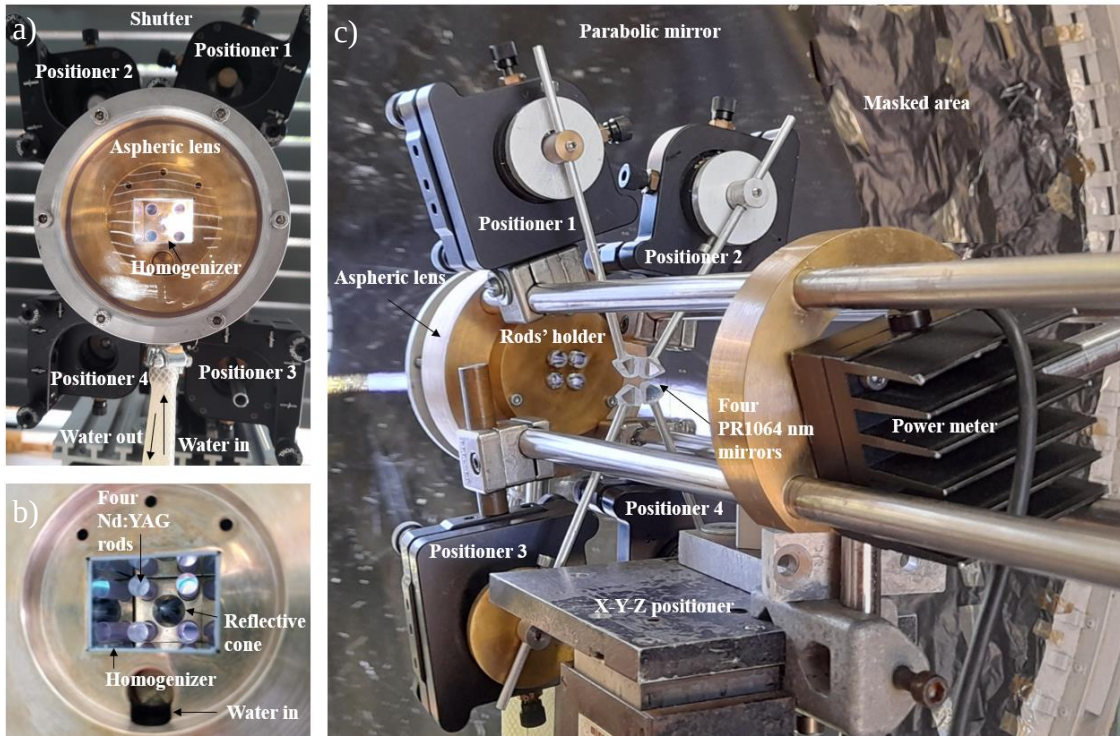


Figure 5-14. Photograph of the solar laser head and the four laser resonators. a) Front view showing the aspheric lens and the flux homogenizer within which (b) four Nd:YAG rods were water cooled. The reflective cone positioned at the center of the rods' holder is also shown. c) Back view of the solar laser head with four small output couplers accurately aligned to their respective rods [64].



Figure 5-15. Cooling water provided by the local plumbing system with 4.5 bar at room temperature.

The experiments were conducted on 20 July 2023 with high diffusivity and an average direct solar irradiance of 800 W/m^2 , measured locally by a Kipp and Zonen CH1 pyrliometer, on a Kipp and Zonen 2AP solar tracker, from Kipp and Zonen, Delft, The Netherlands. The external annular area of the MSSF parabolic mirror was masked so that only 1.48 m diameter central circular area was used. Note that the MSSF parabolic mirror had a central circular opening with

a diameter of 0.30 m, as previously illustrated in Figs. 5.13b and 5.14b. The effective collection area of 1.12 m² was considered by discounting the shadow area caused by the solar laser head, the X-Y-Z positioner, the blades of the shutter, and the gap between the heliostat mirrors. The input solar radiation was controlled by the rotation angle of the shutter. A Thorlabs PM100D power meter measured the total output power extracted from the solar-pumped laser [64].

5.5.3 Solar laser multimode power

Initially (12:30 CEST, 20 July 2023), the total output power was registered with the STS turned on and accurately following the apparent motion of the Sun. Fig. 5.17a presents the total output power as a function of the solar power at focus with the direct solar irradiance of 790 W/m². The four-rod solar laser head started emitting laser with the shutter open at 73% of its maximum capacity, corresponding to an input solar power at the focus of 365 W. Upon fully opening of the shutter, 3.40 W total output power was measured. Then, the STS was turned off and the total the output power extracted from the solar-pumped laser was registered after 60 s of solar laser operation without STS assistance, as shown in Fig. 5.17b. For 800 W/m² direct solar irradiance, the solar laser head started emitting laser with the shutter open at 72% of its maximum capacity, corresponding to an input solar power at the focus of 370 W. Upon fully opening of the shutter, 3.52 W total output power was measured. As demonstrated, the performance of the solar laser system remained unaffected, even with the STS turned off for 60 s. Considering the time and date of the experiment (12:30 CEST, 20 July 2023) and its geographical position (Latitude 42.49°, Longitude 2.03°), it is possible to determine the variation on both the azimuth ($\Delta\alpha$) and altitude (Δh) solar angles during the time that the STS was turned off [18]. For 60 s, that corresponded to $\Delta\alpha = 0.5^\circ$ and $\Delta h = 0.1^\circ$ [64].

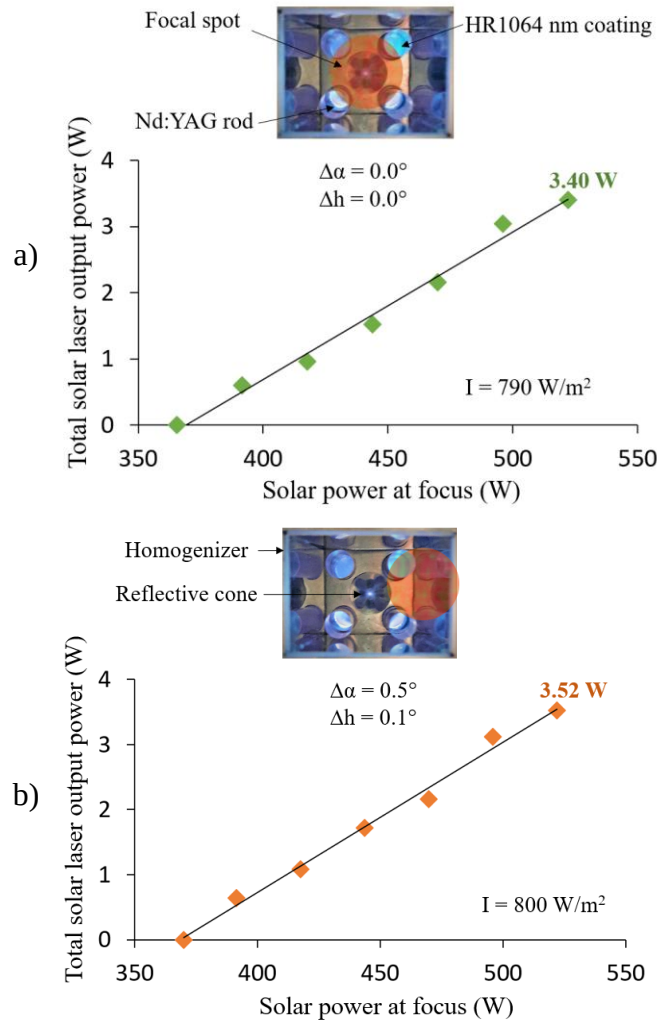


Figure 5-16. Total output power as a function of the solar power at the focus of the MSSF parabolic mirror. The measurements were taken (a) with the STS turned on and (b) after 60 s of solar laser operation without STS assistance [64].

5.5.4 Multibeam solar laser stability

In order to study the performance of the four-rod solar laser prototype in terms of power stability, the normalized total output power extracted from the solar-pumped laser was continuously measured for a time $t = 60 \text{ s}$ with the STS turned on, as presented in Fig. 5.18a. Upon fully opening of the shutter, the solar laser emission was immediately detected, the total output power peaked in the initial seconds and stabilized after 15 s, maintaining the same laser output power values throughout the recorded 60 s. This initial variation was attributed to the water temperature reaching thermal equilibrium, affecting the emission cross-section of the Nd^{3+} dopant due to its strong dependence on temperature. In Fig. 5.18b, the STS was turned off at the same time the shutter was fully opened, yet the total output power remained consistent,

demonstrating stability even without the STS working. It is worth noting that after 60 s, the STS computer displayed a complete misalignment of the Sun's position [64].

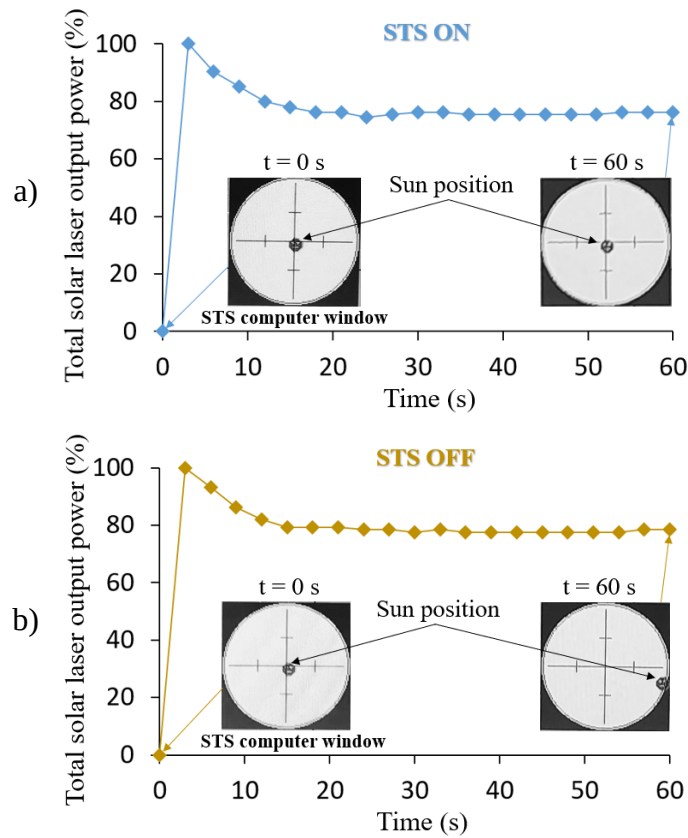


Figure 5-17. Normalized total output power during 60 s (a) with the STS turned on, and b) with the STS turned off at $t = 0$ s. In the latter, the STS computer window displayed a complete misalignment with the Sun's position at $t = 60$ s [64].

As the Sun apparently moves in the sky along the day, the variations of both azimuth and altitude angles can be considered as azimuth and altitude solar tracking errors, respectively, when the STS is deactivated. For a couple of hours around solar noon, the variation on the solar angles is relatively more significant in the azimuthal direction [18]. Fig. 5.19 presents the normalized total solar laser power produced from the four-rod solar laser prototype as a function of the azimuth solar tracking error, since these results were obtained around local solar noon at 13:00 CEST. Firstly, the shutter was fully open, and the four-rod solar laser prototype worked with the STS turned on until the water inside the laser head reached thermal equilibrium. Then, the STS was stopped ($t = 0$ s), and the total output power extracted from the solar-pumped laser was measured without Sun tracking for 2 min. The Sun apparently kept moving and, consequently, the focal spot changed its position (1 – 3) as shown in Fig. 5.19 [64]. During the first minute without solar tracking, the total output power remained stable. The experiment continued for 1 minute, with the total output power decreasing by approximately 8%.

Considering the time and date of the experiment (13:00 CEST, 20 July 2023) and its geographical position (Latitude 42.49°, Longitude 2.03°), it is possible to determine the variation on both the azimuth and altitude solar angles during the time that the STS was turned off [18]. For 2 minutes that corresponded to $\Delta\alpha = 1.0^\circ$ and $\Delta h = 0.2^\circ$.

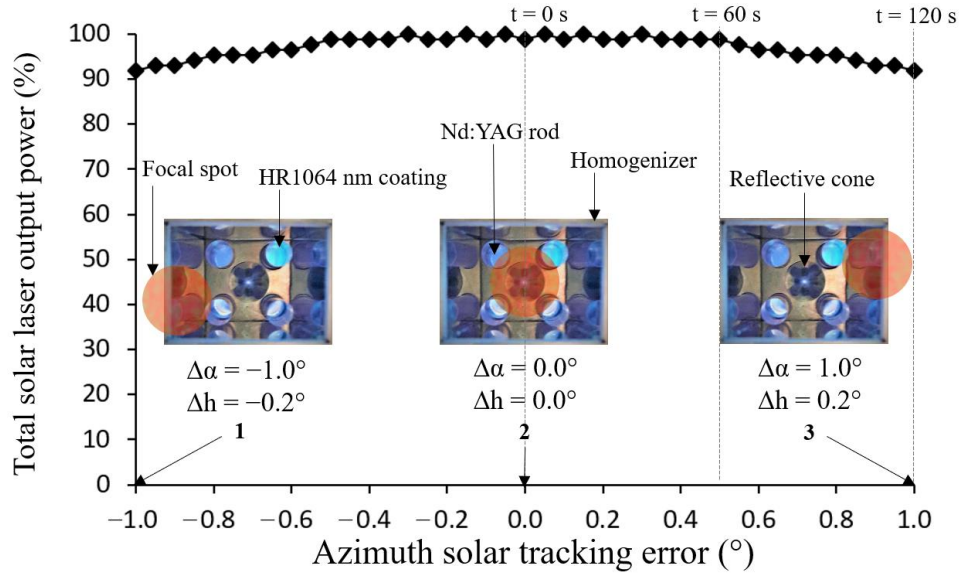


Figure 5-18. Normalized total output power as a function of the azimuth solar tracking error ($\Delta\alpha$), ranging from $\Delta\alpha = 0.0^\circ$ (position 2) to $\Delta\alpha = \pm 1.0^\circ$ (position 1 and 3). These results were obtained around local solar noon at 13:00 CEST and the variation on altitude solar tracking error (Δh) was relatively smaller [64].

5.5.5 Discussion

The end-side-pumped four-rod solar laser head was able to produce a maximum multimode solar laser power of 3.52 W by using 1.12 m² collection area, resulting in a collection efficiency of 3.14 W/m² [64]. Considering the direct solar irradiance of 800 W/m², the solar-to-laser conversion efficiency was only 0.4%. The performance in terms of efficiency fell significantly below the state-of-the-art solar laser efficiency due to a combination of the following issues:

- Collection and concentration system: The end-side pumped four-rod solar laser head was tested at PROMES-CNRS MSSF facility, that presents a combined reflectance of only 59%. Still, the accurate dual-axis STS was crucial to demonstrate the stability of the total output power extracted from the solar laser prototype.
- Active media: Recent progress in solar-pumped laser efficiency have been possible by exploiting the superior absorption efficiency of the Ce:Nd:YAG laser medium [111]. However, the thermal issues also increases, which can lead to the fracture of the active medium when subjected to intense solar pumping levels [56]. In contrast, the Nd:YAG crystal, while exhibiting a relatively lower absorption efficiency, stands as a well-

established laser medium characterized by robust mechanical strength and good thermal conductivity. This makes it a prominent choice within the solid-state laser industry and solar laser research.

- Resonator length: The output mirrors are usually mounted relatively close (10 – 20 mm) from the AR 1064 nm coating to ensure that the energy of higher-order modes is not wasted by diffraction losses [56]. In this experiment, the primary focus was not on achieving the highest efficiency, so each mini output mirror was positioned 70 mm away from the AR 1064 nm coating. This spacing allowed for the proper installation and alignment of the complex opto-mechanics required to fix and calibrate the four separate mini output mirrors.

To the best of our knowledge, this end-side-pumped four-rod solar laser head achieved the first successful demonstration of stable multibeam solar laser operation without solar tracking. In previous solar tracking error experiments conducted by Tibúrcio et al., the side-pumped dual-rod solar laser head lost over 10% of the initial total output power extracted from the solar-pumped laser after 1 minute of operation without solar tracking [54]. In this experiment, the total output power extracted from the solar-pumped laser remained stable for 1 minute with the STS turned off. After 2 minutes, the total output power only dropped by approximately 8%.

In Fig. 5.20, the normalized total output power is presented as a function of the azimuth solar tracking error, ranging from the optimal alignment (0.0°) to $\pm 1.0^\circ$ azimuth angle, in order to compare this study with the work of Tibúrcio et al. [54]. The variation in output power (ΔP) is also represented for azimuth solar tracking errors of 0.5° and 1.0° . Table 4.1 summarizes the progress achieved by this study in solar laser operation under solar tracking error conditions.

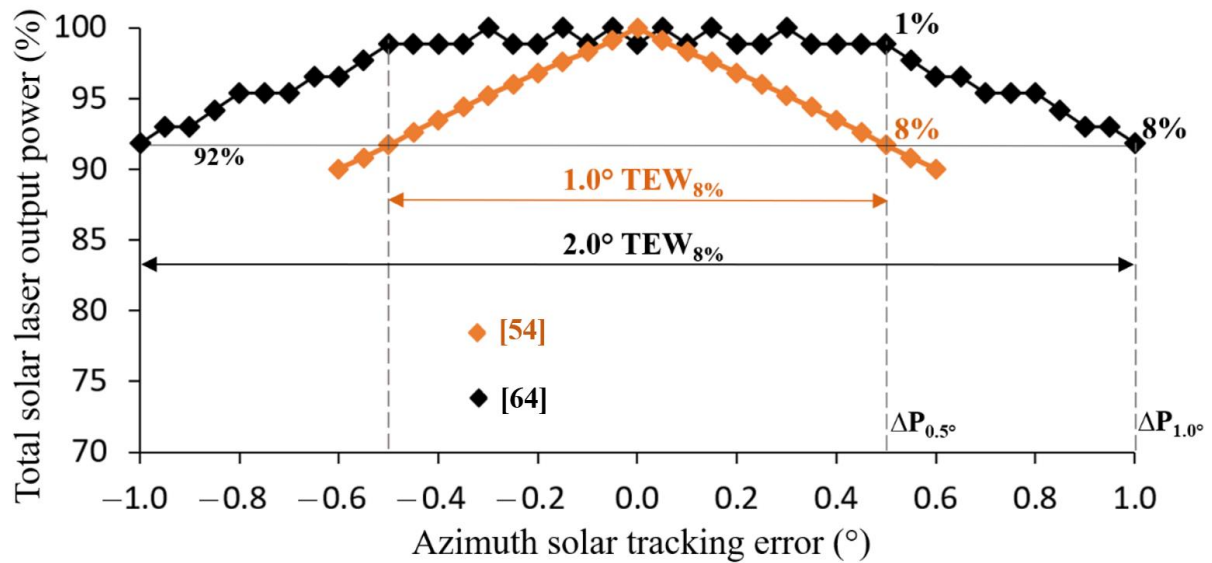


Figure 5-19. Normalized total output power as a function of the azimuth solar tracking error, ranging from the optimal alignment (0.0°) to $\pm 1.0^\circ$, for this study and for the work of Tibúrcio et al. [54]. The variation in solar laser output power is also represented in Apercentage for azimuth solar tracking errors of 0.5° and 1.0° ($\Delta P_{0.5^\circ}$ and $\Delta P_{1.0^\circ}$, respectively).

Table 5-1. Progress on solar laser power stability under solar tracking error conditions [63].

	Tibúrcio et al. (2022) [54]	This work [64]	Improvement
$\Delta P_{\pm 0.5^\circ}$	8%	1%	8.0 times
$\Delta P_{\pm 1.0^\circ}$	-	8%	-
TEW _{8%}	1.0°	2.0°	2.0 times

For typical solar tracking errors up to $\pm 0.5^\circ$, the four-rod solar laser head achieved a variation in the total solar laser power produced $\Delta P_{\pm 0.5^\circ}$ of about 1%, representing an 8.0 times improvement over the Tibúrcio et al.'s work [54]. It was not possible to calculate the TEW_{10%} for this study, as the total output power only dropped 8% during the recorded 2 minutes. Instead, the TEW_{8%} was considered. This study attained a TEW_{8%} of 2.0°, which is 2.0 times higher than that verified by Tibúrcio et al. [54].

5.6 Improving Nd:YAG solar laser efficiency

The Nd:YAG crystal is the most used active medium in solid-state laser industry, not only due to its relatively low price and availability in the market, but more due to its high quantum efficiency, exceptionally good thermal conductivity, and robust mechanical strength [66]. However, the absorption efficiency of the Nd^{3+} ions in YAG is rather low when pumped by either flash lamps or sunlight.

5.6.1 Ce:Nd:YAG laser material

The study of Ce^{3+} ion doped in Nd:YAG under broadband pumping has been a topic of research for decades, starting in 1969 by Holloway et al. [112]. In 1987, Mares et al. studied the energy transfer mechanism between Ce^{3+} and Nd^{3+} in YAG at low temperatures [113]. Later in 2015, Tai et al. explored the mechanism of energy transfer of Ce^{3+} to Nd^{3+} in YAG with quantum cutting Near-infrared quantum cutting of Ce^{3+} - Nd^{3+} co-doped $\text{Y}_3\text{Al}_5\text{O}_{12}$ crystal for crystalline silicon solar cells [114]. The direct solar spectrum, the Ce:Nd:YAG absorption spectrum, the Ce^{3+} and Nd^{3+} ions' emission bands in YAG are presented in Fig. 5.20. The broad absorption bands of the Ce^{3+} ion are located at the most energetic region of the electromagnetic spectrum, between 315 nm and 510 nm, corresponding to the excited energy level of $5d_2$ (centered at 339 nm) and $5d_1$ (centered at 460 nm) [114]. While the Nd^{3+} absorption bands are in between 510 nm and 888 nm, with five prominent absorbing bands, $^4\text{G}_{7/2} + ^2\text{G}_{9/2} + ^2\text{K}_{13/2}$ (centered at 530 nm), $^2\text{G}_{7/2} + ^4\text{G}_{5/2}$ (centered at 580 nm), $^4\text{S}_{3/2} + ^4\text{F}_{7/2}$ (centered at 770 nm), $^2\text{H}_{9/2} + ^4\text{F}_{5/2}$ (centered at 805 nm), and $^4\text{F}_{3/2}$ (centered at 878 nm) [66]. The strong UV and blue photons excite the Ce^{3+} 4f level (the $^2\text{F}_{5/2}$ ground state), toward the 5d sublevels of $5d_1$ and $5d_2$, as shown in Fig. 5.21 [115]. The consequent energy relaxation from $5d_1$ to both ground states $^2\text{F}_{7/2}$ and $^2\text{F}_{5/2}$ forms a yellow/green broad emission spectrum, overlapping with the excitation peaks of the Nd^{3+} ion at the $^4\text{G}_{7/2} + ^2\text{G}_{9/2} + ^2\text{K}_{13/2}$ energy levels between 510 nm and 540 nm and the $^2\text{G}_{7/2} + ^4\text{G}_{5/2}$ energies levels between 566 nm and 595 nm [116]. The radiative transfer mechanism by the transition $5d \rightarrow 4f$ of the Ce^{3+} ion and the transitions $^4\text{I}_{9/2} \rightarrow ^4\text{G}_{7/2} + ^2\text{G}_{9/2} + ^2\text{K}_{13/2}$ and $^4\text{I}_{9/2} \rightarrow ^2\text{G}_{7/2} + ^4\text{G}_{5/2}$ through cross-relaxation process are indicated by pathway (1) in Figure 5.21 [28]. The pathway (2) represents the energy transfer from the Ce^{3+} excited state at $5d_1$ to the two Nd^{3+} ions at $^4\text{F}_{3/2}$ level through quantum cutting down-conversion process.

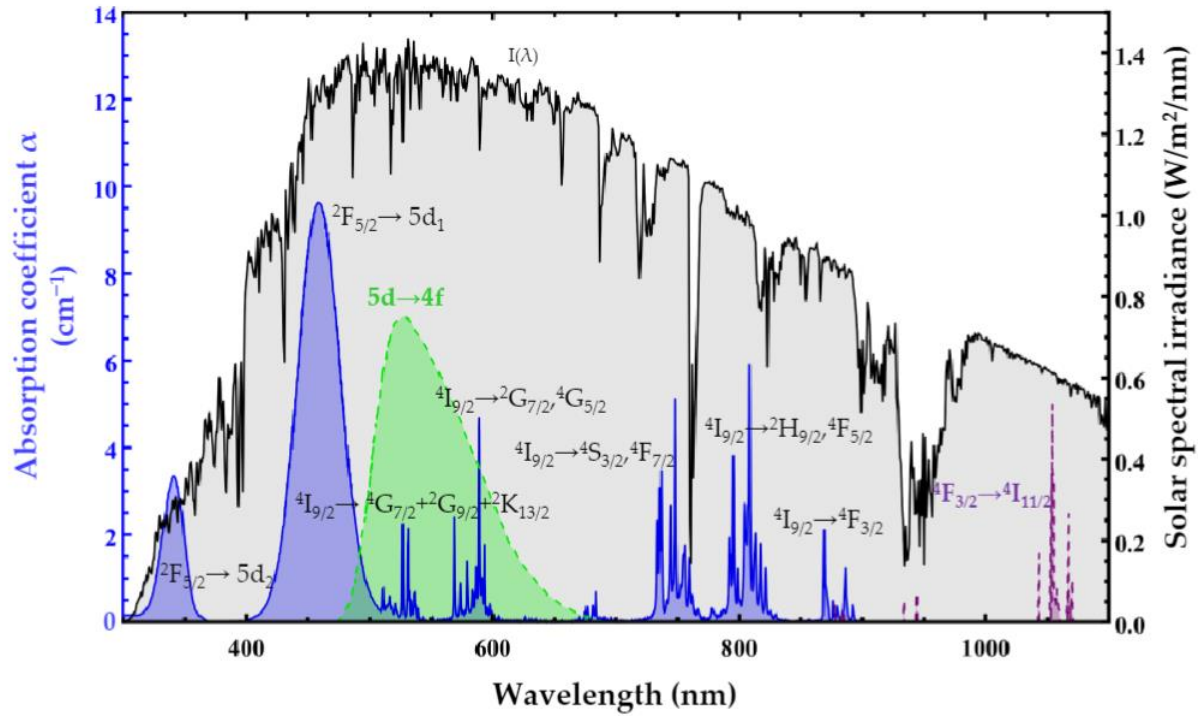


Figure 5-20. AM1.5 direct solar spectrum (black), adapted from [30]. Ce (0.1 at%):Nd (1.1 at%):YAG absorption spectrum (blue), Ce^{3+} (green) and Nd^{3+} (purple) emission spectra in YAG, adapted from [66].

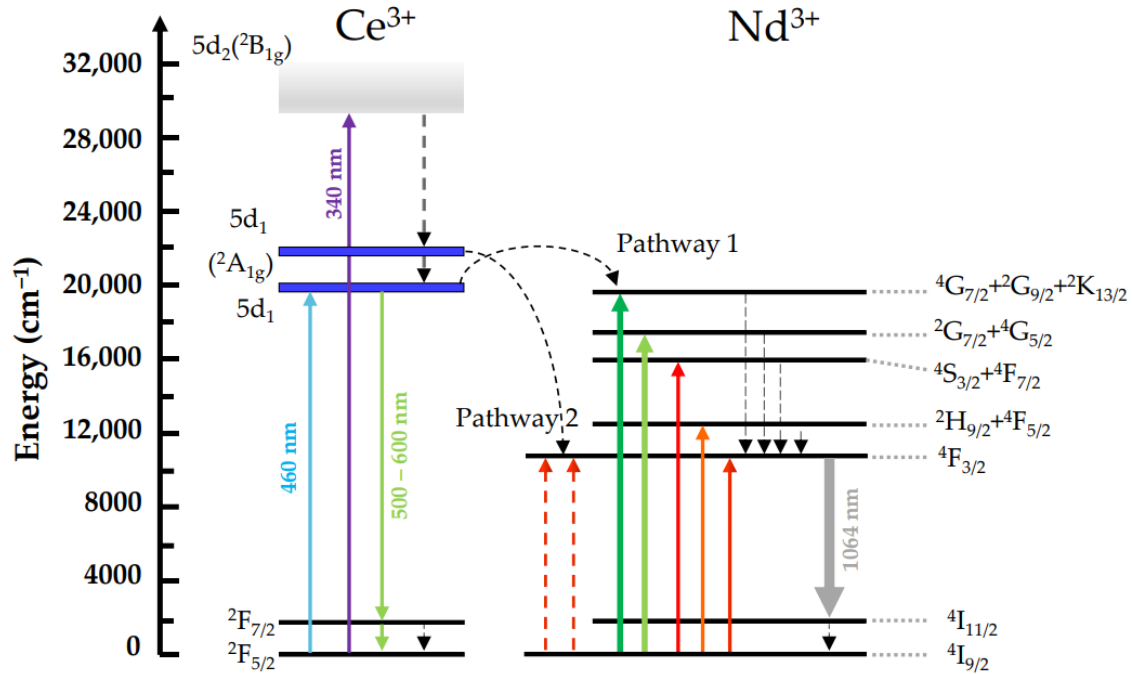


Figure 5-21. Absorption and emission energy level of Ce^{3+} and Nd^{3+} ions. (1) The energy transfer by cross relaxation of Ce^{3+} to Nd^{3+} ion, and (2) the quantum cutting down conversion of Ce^{3+} ion from $5d_1$ energy level into two Nd^{3+} ions at $4F_{3/2}$ energy level. Adapted from [66].

Because of the strong Ce^{3+} absorption in UV and visible spectral region at broadband light pumping and efficient energy transfer from Ce^{3+} to Nd^{3+} ions, Ce:Nd:YAG medium have shown to improve diode/ lamp-pumped laser efficiency, compared with the Nd:YAG crystal [116]. Motivated by the advantages of potential high laser efficiency, low threshold and anti-violet radiation capacity, research on Ce:Nd:YAG solar laser has gained enhanced momentum in recent years [117,118]. Payziyev et al. [119] demonstrated, by a simulation model, that the output laser power and the slope efficiency of a Ce:Nd:YAG solar laser could be doubled in relation to that with Nd:YAG medium.

5.6.2 Ce:Nd:YAG solar laser experiments

The first Ce:Nd:YAG solar laser emission was reported in 2020 [117], producing 6.0 W cw solar laser power and was followed by the Ce:Nd:YAG rod fracture at higher solar power level in end-side-pumping configuration. Side-pumping of a 4 mm diameter, 35 mm length Ce:Nd:YAG laser rod was more successful [118]. With 600 W incoming solar power, 16.5 W cw solar laser power was measured, corresponding to 23.6 W/m² collection efficiency and 2.8% solar-to-laser conversion efficiency. In 2022, Garcia et al. adopted a parabolic mirror with small collection area of only 0.293 m² to pump a single thin Ce:Nd:YAG rod with 2.5 mm diameter and 25 mm length [41]. High collection efficiency of 38.22 W/m² and high solar-to-laser conversion of 4.5% were respectively attained (Fig. 5.23). In the same year, Liang et al. used a three-rod configuration to simultaneously end side-pump three thin Ce:Nd:YAG rods within a single cavity, ensuring an equal redistribution and sharing of the solar pump light by the Ce:Nd:YAG media while substantially improving the solar laser collection and solar-to-laser conversion efficiencies to 41.25 W/m² and 4.64%, respectively [56] (Fig. 5.24).

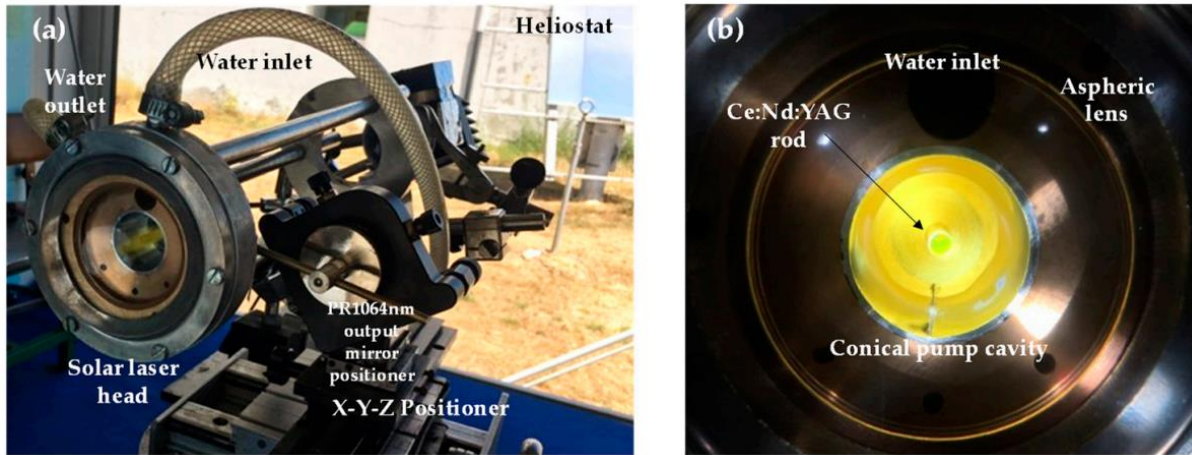


Figure 5-22. Photograph of (a) the Ce (0.1 at%):Nd (1.1 at%):YAG solar laser head at the focus of the parabolic mirror, and (b) the front view of the laser head [41].

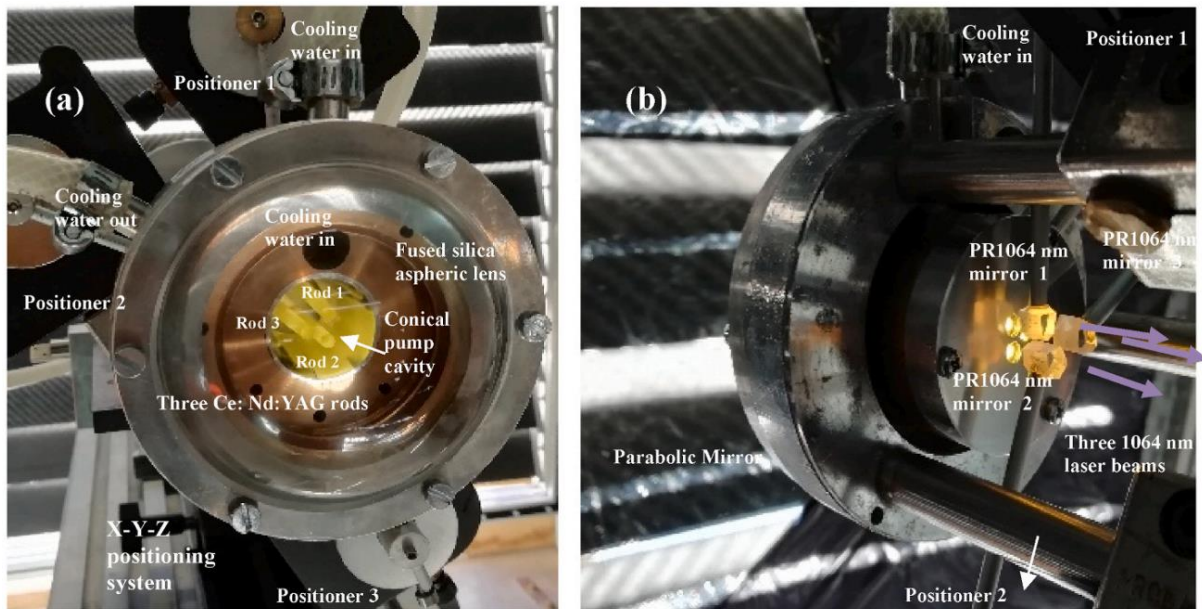


Figure 5-23. (a) Front image showing the three-Ce:Nd:YAG rod solar laser head cooled by water. (b) Back image of the solar laser head with three small output couplers accurately aligned to their respective rods [56].

CONCLUSIONS AND FUTURE PERSPECTIVES

Solar-pumped lasers can directly convert incoherent, low-brightness solar radiation into coherent, high-brightness laser radiation without the requirement of artificial pump light sources such as arc lamps or laser diode stacks. A significant shortcoming of semiconductor laser arrays is their limited lifetime and performance degradation over time, that seems to scale with the level of average output power. Entirely avoiding semiconductor laser arrays by direct solar pumping of solid-state lasers exhibits potential to overcome the current limitations of artificial pump sources, enabling reliable space borne laser operation over a multitude of years. Solar lasers are required in locations where sunlight is highly abundant and other forms of energy sources are limited, ensuring therefore promising space applications [1,2]. The direct production of free laser power from natural sunlight may also offer cost-effective solutions to coherent optical radiation generation for terrestrial applications [20,21].

This dissertation explored solar-pumped lasers, looking at different methods and strategies to develop and adapt this technology for scientific and industrial challenges:

1. Lamp-pump lasers are widely used in industry specially where high powers are needed [77–81]. These laser systems operate on optical pumping principles, akin to solar lasers. Solar laser technology was studied to enhance lamp-pump laser efficiency and brightness, while reducing thermal issues. By exploring elliptical-shaped pump cavities and multi-rod configurations, the TEM_{00} mode efficiency was improved 2.25 times over that of the state-of-the-art lamp-pumped laser [70,84].
2. Aside from the industry-standard Gaussian intensity profile, top hat and non-conventional laser beam shapes, such as doughnut-shaped profile, are ever more required [98]. The top hat laser beam profile is well-known for uniformly irradiate the target material, significantly reducing the heat affected zones, typical of Gaussian laser irradiation [99–104], whereas the doughnut-shaped laser beam has attracted much interest for its use in trapping particles at nanoscale and improving mechanical performance

during laser-based 3D metal printing, material processing and biomedical imaging [105,106]. It has been demonstrated that, through solar pumping, it is possible to generate and replicate solar laser beams with a doughnut shape by designing a long optical resonant cavity with Nd:YAG as the active medium [107–109]. As far as we know, the first numerical simulation of doughnut-shaped and top hat solar laser beam profiles is reported in this dissertation, significantly contributing to the understanding of the formation of such beam profiles [71].

3. One of the limitations of solar-pumped laser technology is the need for costly and highly accurate solar tracking systems, imposing a substantial financial barrier on solar laser research and applications. Therefore, it is economically beneficial to develop solar laser systems that can maintain their performance during a couple of minutes using low-cost STS's. By exploring the superior efficiency of end-side pump configurations and the thermal advantage of multi-rod schemes, a four-rod solar laser design was numerically studied [60]. The apparent movement of the Sun was also leveraged to achieve a maximum solar tracking error compensation capacity of 2.20° TEW_{10%} [63]. Still, the solar laser power extracted from the laser rods was not well-distributed, with some rods contribute more than others, specially under tracking error condition. The incorporation of a solar flux homogenizer was numerically studied to achieve uniform and stable multi-mode solar laser emissions. The solar laser flux allowed four 1064 nm continuous-wave multimode emission with similar power levels even with azimuthal solar tracking errors up to $\pm 0.5^\circ$. More importantly, simultaneous and stable TEM₀₀ mode solar laser emissions from the four rods were also numerically attained under solar tracking error condition [62]. An end-side-pumped four-rod solar laser head was designed and built for testing at PROMES-CNRS solar facility in Odeillo, France [64]. In the experiment, the four-rod solar laser prototype demonstrated a stable multibeam solar laser operation with the STS turned on. Even when the STS was turned off, the total output power extracted from the solar-pumped laser remained stable for 1 min. After 2 min, the total output power only dropped by approximately 8%. For typical solar tracking errors of up to $\pm 0.5^\circ$, the variation in the total solar laser power produced by the four-rod solar laser head was only about 1%, representing an 8.0-fold improvement over the state-of-the-art solar laser operation under tracking error conditions [54]. By significantly reducing the solar laser head's sensitivity to variations in solar angles, the STS's stepper motor does not need to be continuously running, thus reducing the power consumption and extending the lifetime of the system. Moreover, the end-side-pumped four-rod solar laser approach offers a cost-effective solution to build a stable solar laser system with a cheap, low-accuracy STS.

Innovations in Nd:YAG solar lasers were also addressed in this thesis, promising a future with more efficient and affordable systems. Regarding the primary concentrator, Fresnel lenses are a cost-effective solution [52,53], while more complex designs such as ring array concentrators or sag-shaped Fresnel lenses promise higher efficiencies [120–122]. The adoption of dopants, namely the Ce^{3+} , has led to groundbreaking solar lasers efficiencies, with Ce:Nd:YAG solar lasers being the state-of-the-art laser material for solar laser efficiency [41,56].

Solar laser technology is advancing towards practical applications. Various solar laser beam profiles have been demonstrated, including the industry-standard single-mode [59], as well as the promising doughnut-shaped [109]. Notably, solar laser emission has been achieved even under cloudy sky condition, with clouds acting as heat filters to enhance efficiency. Additionally, significant progress has been made in ensuring stability under solar tracking error condition [64]. Thanks to the adoption of the side-pumping configuration with a wide pumping cavity, continuous solar laser operation with no solar tracking assistance was possible for 280 s [123]. These breakthroughs with Ce:Nd:YAG gain media proved that, with an appropriate pumping configuration, it is possible to develop simpler and less expensive solar laser systems of high efficiency and stability, which may help to extend the applicability of this renewable technology. So, the next step involves implementing Ce:Nd:YAG rods in the end-side pumping four-rod prototype, which has the potential to enhance system efficiency. Additionally, integrating Fresnel lenses is recommended as they are cheap and effective primary concentrators.

The major barrier to the application of this technology is related with the unreliability of solar radiation at Earth's surface. Despite this challenge, solar lasers offer significant advantages, particularly in space applications. A significant shortcoming of semiconductor laser arrays is their limited lifetime and performance degradation over time, that seems to scale with the level of average output power. Entirely avoiding semiconductor laser arrays by direct solar pumping of solid-state lasers exhibits potential to overcome the current limitations of artificial pump sources, enabling reliable space borne laser operation over a multitude of years [124].

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First author

- I. M. Catela, D. Liang, C. R. Vistas, D. Garcia, B. D. Tibúrcio, H. Costa, and J. Almeida, "Six-rod/six-beam concept for revitalizing TEM00 mode lamp-pumped lasers," *Opt. Eng.* 59(12), (2020).
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Highlights

- I. Cover page of Journal of Photonics for Energy, July-September 2020 J. Almeida, D. Liang, H. Costa, D. Garcia, B. D. Tibúrcio, M. Catela, C. R. Vistas Seven-rod pumping concept for simultaneous emission of seven TEM₀₀-mode solar laser beams <https://www.spiedigitallibrary.org/journals/journal-of-photonics-for-energy?SSO=1>
- II. Cover page of Journal of Photonics for Energy, Volume 12. Issue 4, 2022 H. Costa, J. Almeida, D. Liang, D. Garcia, M. Catela, B. D. Tibúrcio, C. R. Vistas Multirod approach to enhance solar-to-laser conversion efficiency in the Odeillo solar furnace <https://www.spiedigitallibrary.org/journals/journal-of-photonics-for-energy>
- III. Featured Article of Photonics, November, 2023 VII. M. Catela, D. Liang, J. Almeida, H. Costa, D. Garcia, B. D. Tibúrcio, E. Guillot, and C. R. Vistas Stable Emissions from a Four-Rod Nd:YAG Solar Laser with $\pm 0.5^\circ$ Tracking Error Compensation Capacity <https://www.df.fct.unl.pt/noticias/2023/11/trabalho-desenvolvido-pelo-grupo-de-tecnologia-laser-do-cefitec-departamento-de-fisica-da-fct-nova-d>

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