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Recent Progress in Solar-Pumped Lasers at the NOVA University of Lisbon

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Abstract

The urgency of climate change mitigation has driven scientific research and technological advancements in the pursuit of sustainable energy solutions, positioning solar energy as one of the most promising renewable resources to help reduce dependence on fossil fuels. Solar-pumped lasers are specifically designed to directly harness and convert a portion of the Sun's incoherent radiation into coherent laser light, paving the way for the advancement of environmentally friendly laser technology. Nearly two decades ago, our research team at the NOVA University of Lisbon embarked on this topic with the goal of significantly enhancing the performance of solar-pumped lasers, whose endeavors positioned us at the forefront of this field. This article highlights the latest advancements of this renewable technology accomplished by our research team through pioneering experiments with Ce:Nd:YAG as a novel active medium for solar lasers and the exploration of innovative schemes for simultaneous pumping of multiple media. Notable progress included the establishment of new records in solar laser efficiency for both multimode and fundamental mode regimes and attaining the lowest threshold pump power for solar laser emission. Significant improvements were also achieved in thermal management and solar tracking error compensation capacity, which have resulted in enhanced laser output power stability. These developments are critical for the practical application of solar-pumped lasers.

Keywords: Solar-pumped Laser; Ce:Nd:YAG; Multirod; Conversion Efficiency; Low-threshold; Solar Tracking Error Compensation

Introduction

Solar-pumped lasers possess the unique ability to directly convert sunlight into laser light, eliminating the need for artificial pumping sources and reducing electrical energy consumption. Therefore, this special kind of laser is particularly well-suited for space-based applications, such as free-space optical communication [1], space-to-space [2] or space-to-Earth [3] wireless power transmission, beam-powered propulsion [4], and asteroid deflection [5]. Solar-pumped lasers have also a promising role to play in sustainable laser-based material processing [6] and fossil-fuel-free energy cycles [7]. Besides, they could be instrumental in advancing efficient hydrogen production [8] and enabling wireless charging for electric vehicles [9]. This renewable technology has undergone significant advancements over its 60-year history [10], with remarkable progress in the last four years, mainly driven by the efforts of our research team. Key contributions include the successful application of neodymium-doped yttrium aluminum garnet

(Nd^{3+}: YAG) doped with cerium (Ce^{3+}) ions as an active medium for solar-pumped lasers [11-16], further supported by the progress in multirod solar pumping techniques [15-21]. A comprehensive overview of these advancements will be presented in the subsequent sections.

Harnessing Solar Energy with Ce:Nd:YAG Media

Nd^{3+}:YAG has been the most widely used laser medium in solar-pumped lasers since their earliest reports [10], due to the advantageous combination of the YAG host material's thermal and mechanical properties with the spectroscopic features of the Nd^{3+} active ion [22]. However, the limited overlap between the Nd^{3+} absorption bands and the solar spectrum hinders the solar-to-laser energy conversion. Ce^{3+} ions serve as a sensitizer for Nd^{3+} ion emission in the YAG host, possessing two prominent and wide absorption bands in the ultraviolet and visible region that overlap well with the higher intensity region of the solar spectrum, as shown in Figure 1. Additionally, Ce^{3+} exhibits a wide fluorescence band centered around 530 nm, spanning from 500 nm to over 600 nm, effectively overlapping with key absorption lines of the Nd^{3+} ion. When Ce:Nd:YAG is pumped with solar radiation, efficient energy transfer occurs from Ce^{3+} to Nd^{3+} ions through both radiative and non-radiative pathways [23]. This process significantly increases the population of excited Nd^{3+} ions, thereby enhancing the solar laser efficiency [12-16,24].

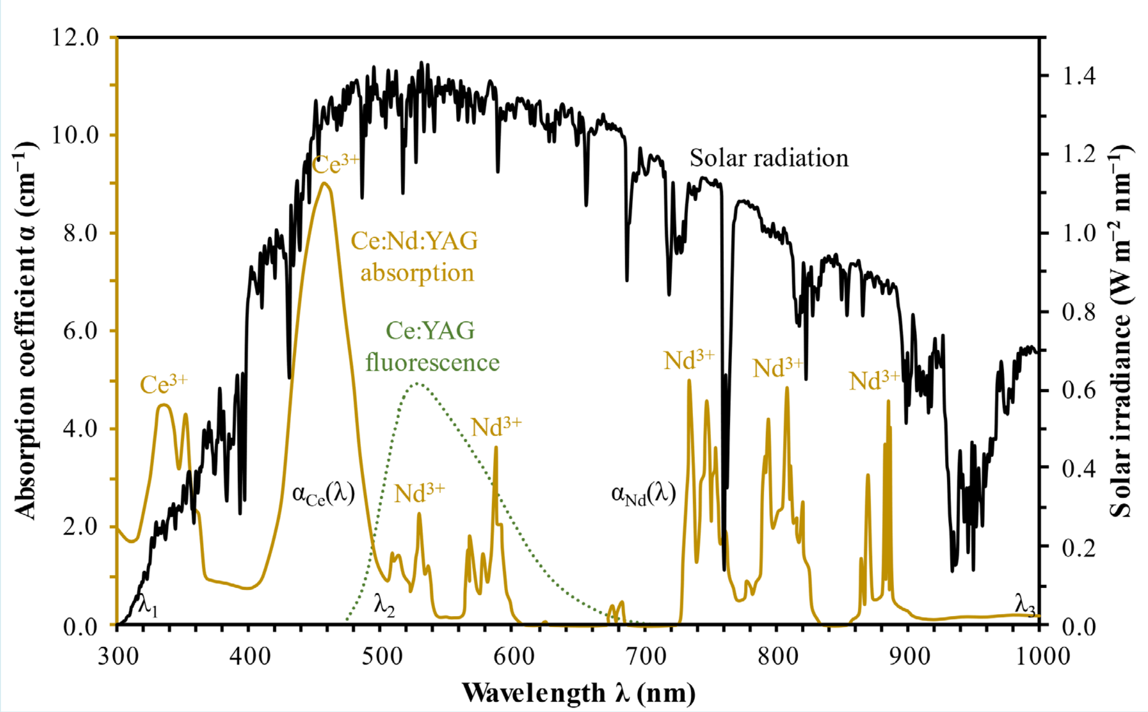

Figure 1: AM1.5 direct solar spectrum (black line); Ce^{3+} fluorescence (green line); and Ce^{3+}, Nd^{3+} absorption spectra (golden line) [20].

Ce:Nd:YAG Side-Pumped Solar Laser

In 2020, we reported the first emission of a Ce:Nd:YAG solar-pumped laser using an end-side-pumping configuration [11]. While the most efficient solar laser systems have employed this type of optical pumping [14,15,24], side-pumping is more suitable for scaling laser power, as it provides a more uniform light distribution along the rod axis, thus mitigating thermal loading issues. As a result, in 2021, we evaluated the output performance of the Ce:Nd:YAG solar laser with a side-pumping configuration, represented in Figure 2 [12]. The solar laser head was composed of a double-stage semispherical lens and a trapezoidal-shaped pumping cavity, which coupled and redistributed the concentrated solar radiation from the focal zone of the NOVA parabolic mirror into a Ce:Nd:YAG single-rod with 4.0 mm diameter, 35 mm length. The output performance of Ce:Nd:YAG solar laser was compared to that of Nd:YAG solar laser under the same pumping conditions (Figure 2d). The side-pumping of the Ce:Nd:YAG laser rod at the NOVA solar facility led to 1.6 times increase in solar-to-laser conversion and collection efficiencies [12]. This work demonstrated the great potential of the Ce:Nd:YAG laser material as a gain medium for solar-pumped lasers.

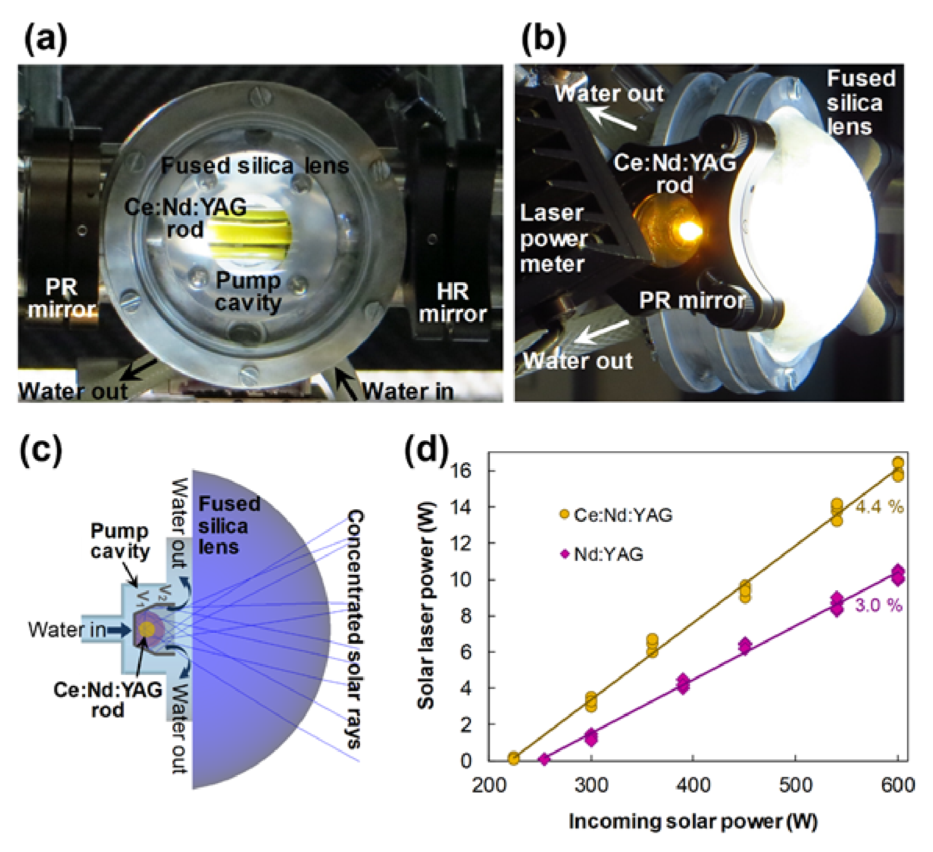

Figure 2: (a) Front-view and (b) side-view of the Ce:NdYAG side-pumped laser prototype. PR, partial reflection; HR, high reflection. (c) Design of the solar laser head. (d) Solar laser output power as a function of incoming solar power for the Ce:Nd:YAG and the Nd:YAG laser rods. Adapted from [12].

Lowest-Threshold Solar-Pumped Laser with single-rod Ce:Nd:YAG medium

Efficiency is widely recognized as a primary criterion for evaluating laser performance. However, primary concentrators with high concentration ratios are usually required to harvest sunlight for efficient pumping of the active medium, which can limit the practical applications of solar lasers. Therefore, in addition to the critical effort to enhance solar laser efficiency, there is also an urgent need to lower the threshold solar power required for laser operation. In 2023, we reported the first solar laser emission at low threshold of 54.9 W under cloudy sky conditions [13]. This achievement was accomplished by end-side-pumping a single thin Ce:Nd:YAG rod, measuring 2.5 mm in diameter and 25 mm in length, positioned at the focal point of a parabolic mirror with small collection area of 0.293 m^2. The cloud-filtered infrared solar radiation was beneficial for lessening the thermal lensing effects, enabling also a three-fold increase in solar-to-laser conversion efficiency compared to that under clear sky conditions [13]. Most recently, a lightweight and compact Fresnel lens with smaller collection area of 0.0615 m^2 was utilized as the primary solar concentrator to focus the incoming solar radiation via the NOVA two-axis solar heliostat onto a 2 mm diameter, 30 mm length Ce:Nd:YAG rod, as shown in Figure 3 [14]. This setup achieved the lowest threshold solar power of 16.5 W under clear sky condition, marking a 3.37-fold reduction compared to the previous record [13]. In addition, the highest solar-to-laser conversion efficiency of 2.06% in the fundamental mode regime was attained, setting a new benchmark for TEM_{00}-mode solar laser collection efficiency at 16.5 W/m^2 [14]. This innovative combination of a compact Fresnel lens and a thin Ce:Nd:YAG rod offers a highly cost-effective approach for generating efficient TEM_{00}-mode renewable laser emission at 1064 nm, making it readily accessible for a wide range of potential applications.

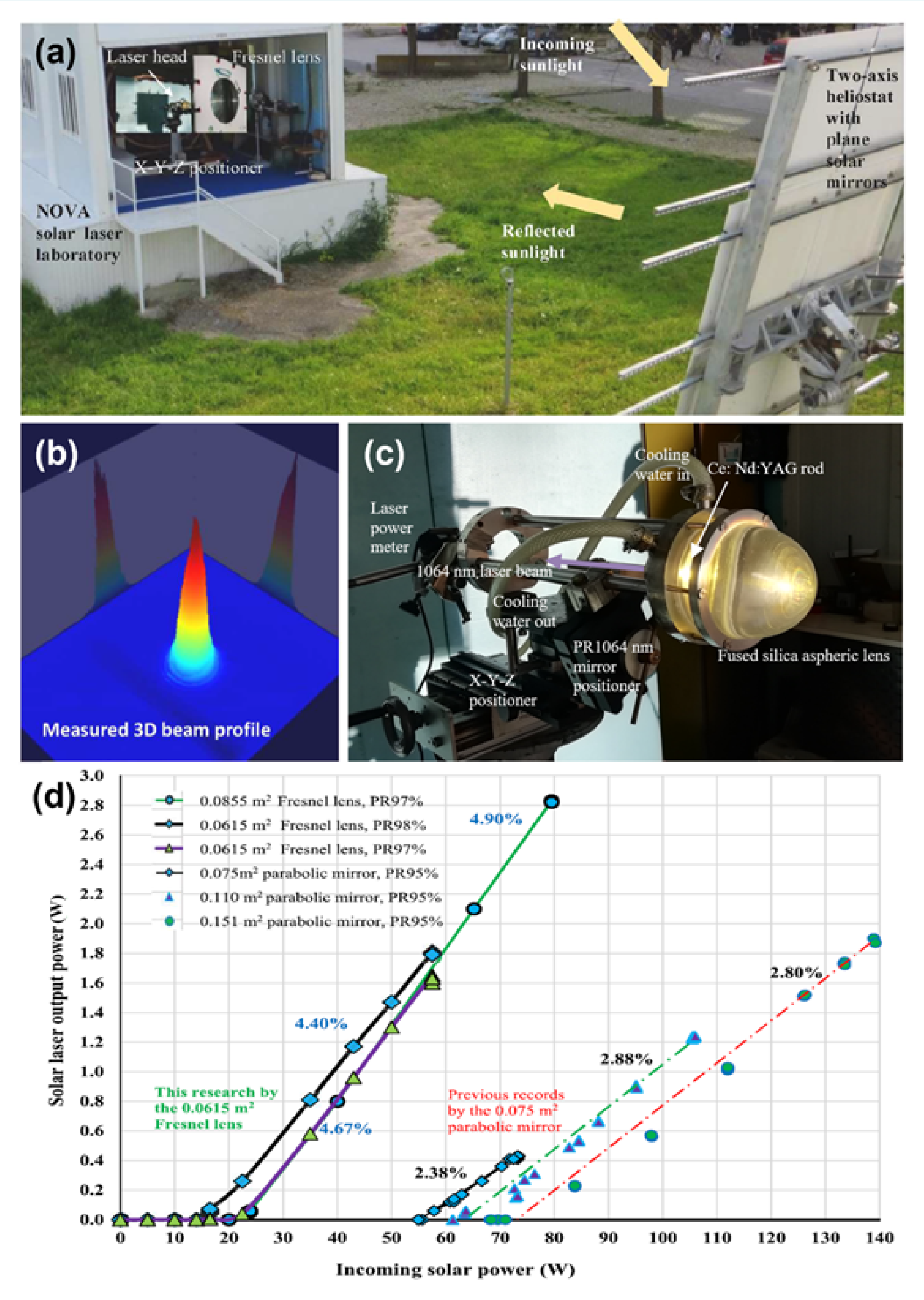

Figure 3: (a) NOVA solar laser laboratory. (b) Measured TEM_{00}-mode output laser beam. (c) Photograph of the solar laser head at the focus of the Fresnel lens. (d) Solar laser power versus incoming solar power. Adapted from [14].

Most Efficient Simultaneous Solar Laser Emissions from Three Ce:Nd:YAG Rods

Our research team has also played a pioneering role in advancing solar laser prototypes through the simultaneous pumping of multiple laser media [15-19]. By adopting this configuration, each laser rod absorbs only a fraction of the highly concentrated solar radiation, thereby reducing thermally induced effects and enhancing the scalability and stability of the laser power. The first simultaneous emissions of three 1064 nm continuous-wave solar laser beams was reported in 2020 by end-side-pumping three

Nd:YAG rods, each with 3 mm diameter and 25 mm, within a single conical pump cavity at the focus of the NOVA heliostat-parabolic system [17]. The concept of pumping multiple laser rods within a single pump cavity holds significant importance, as it enables the sharing of pump energy among the rods, potentially boosting solar laser efficiency while simultaneously reducing system complexity. Currently, the highest reported values for collection, slope, and solar-to-laser conversion efficiencies are 41.3 W/m^2, 7.64%, and 4.64%, respectively [15]. These milestones were achieved in 2022 through the simultaneous end-side-pumping of three Ce:Nd:YAG laser rods, each with a diameter of 2.5 mm and a length of 25 mm, within a single pump cavity, as depicted in Figure 4. These solar laser systems also proved to be crucial in addressing the thermal load issues typically associated with solid-state lasers [15,17], providing the capability to tailor the solar laser energy to the specific needs of material processing applications [6].

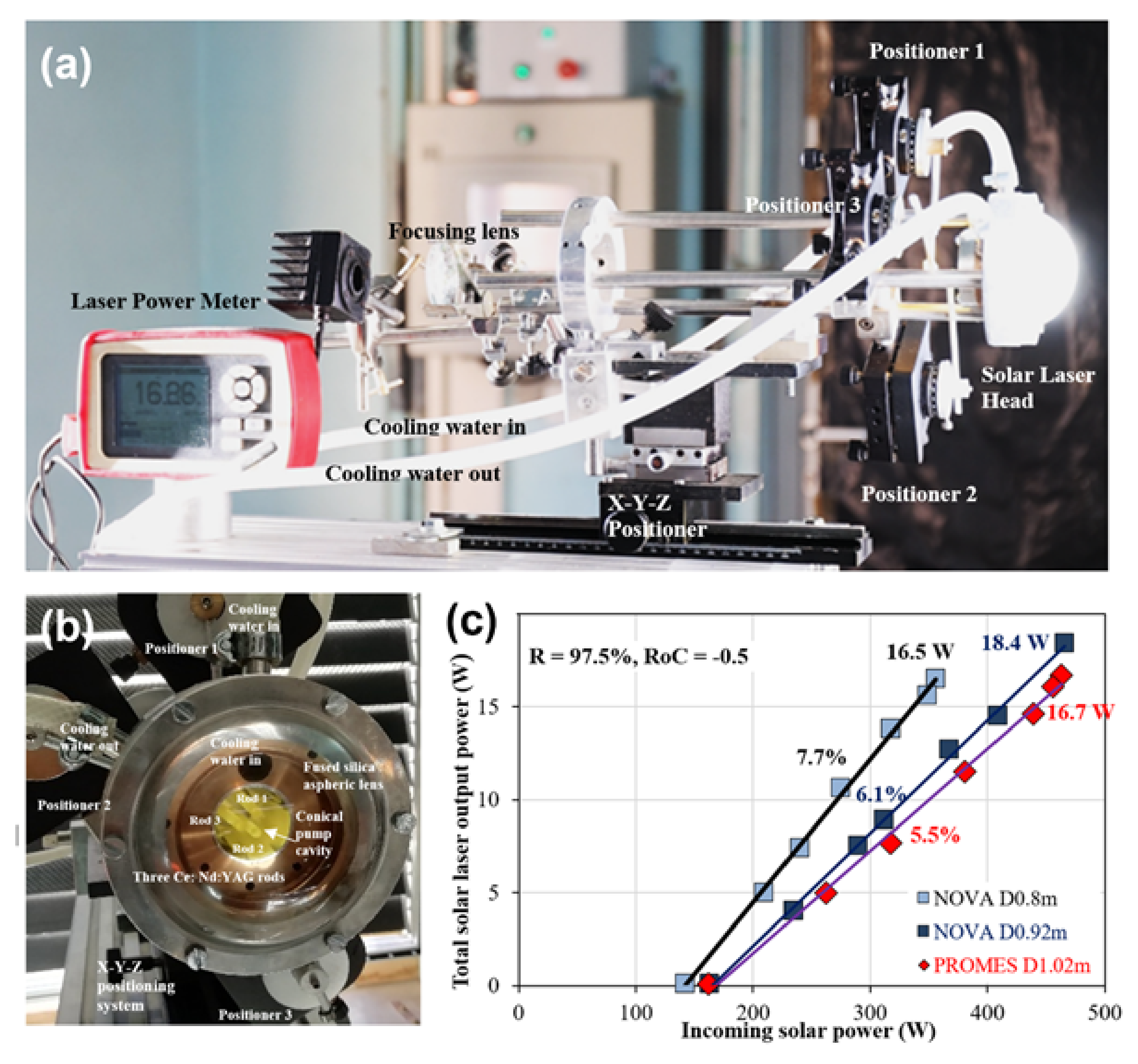

Figure 4: (a) Three-rod Ce:Nd:YAG solar laser in action. (b) Photograph of the solar laser head. (c) Solar laser output power as a function of incoming solar power from the three Ce:Nd:YAG rods. Adapted from [15].

Multirod Solar-Pumped Laser with High Solar Tracking Error Compensation Capacity

Multirod solar-pumping systems have also demonstrated significant potential for compensating high solar tracking errors, offering an economic advantage by reducing reliance on costly high-precision trackers [16,18,19]. In 2022, Tibúrcio, et al. reported the first experimental results in solar laser tracking error compensation capacity by using a side-pumped dual-rod solar laser head at the focus of the NOVA solar energy collection and concentration system, as outlined in Figures 5a & b [18]. Maximum tracking error compensation width at 10% laser power loss ($TEW_{10\%}$) of 1.4° was calculated. In the subsequent year, the capacity for compensating large tracking errors was improved by over four times using a dual-rod Ce:Nd:YAG laser head with a wide side-pumping cavity, represented in Figures 5c & d [16]. Furthermore, this prototype enabled the measurement of a maximum continuous-wave total solar laser power of 58 W, the highest recorded for a Ce:Nd:YAG solar laser.

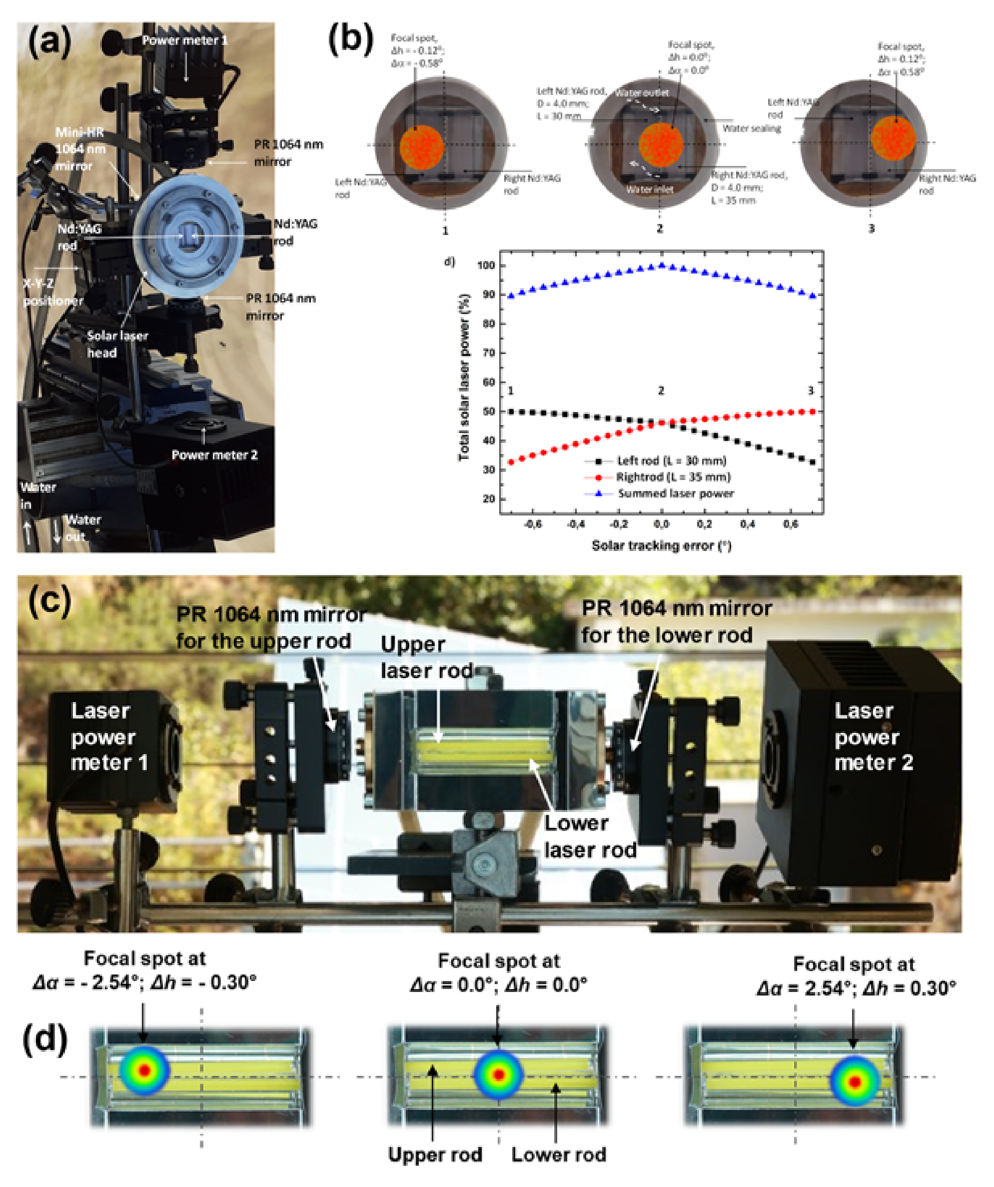

Figure 5: (a),(c) Photographs of the dual-rod solar laser heads with Nd:YAG [18] and Ce:Nd:YAG [16] active media, respectively. (b) and (d) represent the corresponding outcomes used to assess the tracking error compensation capacity. Δα, azimuth; Δh, altitude. Adapted from [16,18].

Conclusion

Our research efforts have contributed to meaningful progress in solar-pumped laser technology through the pioneering use of Ce:Nd:YAG as a laser gain medium and innovative multirod/multibeam pumping schemes. Key milestones, such as record-breaking solar-to-laser conversion efficiencies, low solar power thresholds, enhanced scalability and stability of laser power, and improved tracking error compensation have been reached. These advancements position solar-pumped lasers as a promising renewable laser technology with diverse applications on Earth and in Space.

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Conflicts of Interest

The authors declare no conflicts of interest.

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