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Numerical study of a ring-array-concentrator for Nd:YAG solar laser pumping

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Abstract. In this paper, we report a numerical study of a Nd:YAG solar laser side-pumped by a ring-array concentrator (RAC) system. We used the ZEMAX© and LASCAD© software to optimize a 1.5-m diameter RAC system, a 3V-shaped pump cavity within which a Nd:YAG single-crystal laser rod (4-mm diameter, 30-mm length) is mounted, and the laser resonator parameters. The multimode solar laser output power was numerically calculated to be 34.8 W in a continuous-wave mode, corresponding to a solar laser collection efficiency of 19.69 W/m^2, a slope efficiency of 3.07%, and 2.3% solar-to-laser conversion efficiency, indicating an improvement of 2.05, 1.31, and 1.5 times, respectively, relative to that of the previous results for a side-pumped Nd:YAG solar laser. Moreover, this study is the first numerical analysis of a Nd:YAG solar laser side-pumped by a RAC concentrator.

Keywords: Side-pumped solar laser, ring-array concentrator, Nd:YAG, fused silica light guide, ZEMAX© and LASCAD© simulation.

1. Introduction

The idea of pumping a laser by solar energy has existed since the invention of the laser. The first report of 1-W sun-pumped continuous-wave (cw) laser was published in 1966 [1]. Today, solar lasers can be used for many applications, such as spatial communication, high-temperature material processing, electrical power generation, marking and cutting, hydrogen and magnesium production [2-5].

During the last decade, numerous experimental and theoretical studies of solar lasers have been carried out to improve the laser efficiency and beam quality. Usually, high solar laser collection efficiencies and output powers have been achieved through end-side-pumping approaches. In 2018, 33.1-W cw multimode solar laser power was measured by pumping a large composite Nd:YAG rod through a 1.03-m^2 effective solar radiation collection area of a Fresnel lens, reaching a slope efficiency of 10.8% and a 32.1-W/m^2 solar laser collection efficiency [6]. In the same year, 32.5-W cw multimode output power was registered using a monolithic fused silica liquid light guide by pumping of a Cr:Nd:YAG ceramic laser rod through a heliostat-parabolic mirror system, corresponding to a 6.7% slope efficiency and a 32.5-W/m^2 collection efficiency [7]. Also in 2018, 67.3-W cw multimode solar laser power was numerically calculated for end-side-pumped Nd:YAG laser rod through a 1.5-m diameter ring-array concentrator, corresponding to a 38.2-W/m² collection efficiency and a 4.0% solar-to-laser conversion efficiency [8].

The side-pumping solar laser approach is also an attractive configuration due to its higher beam brightness, stability and quality [9-14]. This configuration may provide a uniform absorption along the rod axis, hence reducing the thermal effects in the laser rod and increasing the solar laser efficiency. Moreover, the side-pumping approach has an excellent solar tracking error compensation capacity as compared to that of the end-side-pumped configuration. In 2012, 27.7-W cw solar laser power was achieved in multimode operation by pumping a 4-mm diameter, 30-mm length Nd:YAG rod through a 2.88-m^2 effective collection area of a parabolic mirror, corresponding to a 9.62-W/m² solar laser collection efficiency, a 2.2% slope efficiency and a 1.38% solar-to-laser conversion efficiency [9]. One year later, 8.1-W cw multimode laser power was produced by pumping a 3-mm diameter, 30-mm length Nd:YAG laser rod with a 1-m diameter Fresnel lens, corresponding to a 8.8-W/m² solar laser collection efficiency, a 2.35% slope efficiency and a 1.13% solar-to-laser conversion efficiency [10].

In this paper, we report a numerical study of a side-pumped Nd:YAG solar laser through a 1.5-m diameter ring-array concentrator in order to improve the final solar laser efficiency. The study consists in optimizing the ring-array-concentrator (RAC) system, the laser head and the optical resonator parameters by using the ZEMAX© and LASCAD© software. The cw multimode solar laser power was numerically calculated to be 34.8 W, corresponding to a 19.69-W/m^2 collection efficiency, a 3.07% slope efficiency and a 2.3% solar-to-laser conversion efficiency, thus indicating an improvement of 2.05, 1.31, and 1.5 times, respectively, compared to the previous results for a side-pumped Nd:YAG solar laser [9, 10]. Moreover, this study can be considered as the first numerical analysis of side-pumped Nd:YAG solar laser with an RAC concentrator system.

The first concept of an RAC system was introduced in 2002 by Vasylyev et al. [15]. This design allows one to eliminate the shadow area between the incoming solar rays and the focal zone, as compared with the heliostat-parabolic mirror system. Consequently, a more efficient solar concentration can be achieved into the focal spot. Using an RAC can also avoid the dispersion of the solar radiation spectrum along its focal zone, providing a higher solar collection efficiency in comparison to Fresnel lenses [8].

2. Solar energy collection and concentration RAC system

Figure 1 shows the design of a Nd:YAG solar laser side-pumped by a ring-array concentrator optimized by ZEMAX© software. The 1.5-m diameter RAC system consists of several rings with different diameters and radius of curvature. An off-axis parabolic profile and a 95% reflectivity were assumed for all rings. In order to fill the entire collection area, a small Fresnel lens was fixed in the central region of the RAC.

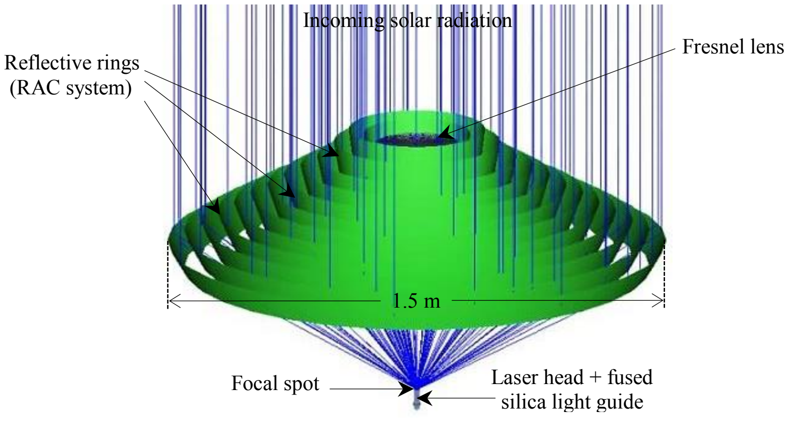

Figure 1. Simplified scheme of a side-pumped Nd:YAG solar laser with a ring-array concentrator.

For this RAC design, the focal length was chosen to be 405 mm with an effective solar radiation collection area of 1.76 m^2, as illustrated in figure 2. Further, we assume an average solar irradiance of 1000 W/m² for clear sunny days in Algeria. Therefore, 1760 W of solar power can be measured at the RAC focus. The light spot has a near Gaussian distribution profile with an 8-mm diameter (FWHM) and a 400-W/cm^2 peak flux. As a result, the RAC system presented proves to be able to focus the sunlight to the theoretical limits, allowing us to choose the appropriate dimensions of the light guide, the laser rod and the pump cavity.

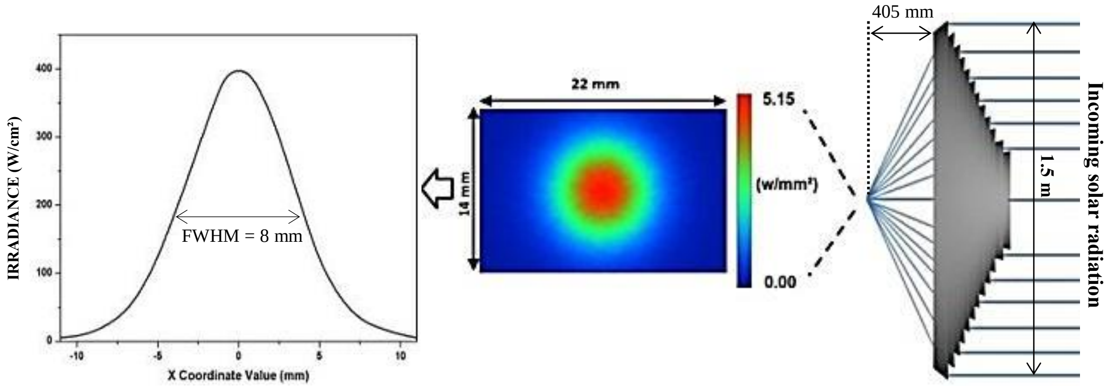

Figure 2. Solar irradiance of a near Gaussian spatial profile at the RAC focus.

3. Laser head

Figure 3 presents the laser head design, which consist of a hollow 3V-shaped pump cavity, a rectangular fused-silica light guide and a 1.0-at.% Nd:YAG single-crystal rod with a 4-mm diameter and a length of 30 mm.

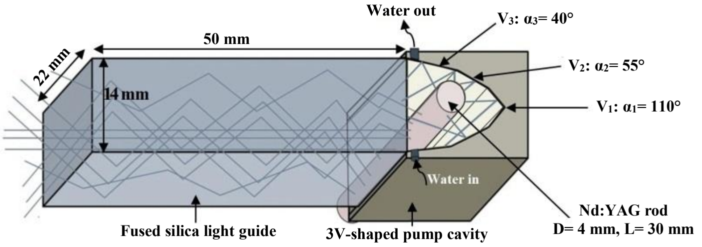

Figure 3. 3D design of the 3V-shaped pump cavity, the rectangular-shaped fused silica light guide and the Nd:YAG laser rod.

The solar radiation concentrated by the RAC system at its focus is then collected by the rectangular fused-silica light guide and transmitted to the laser cavity for coupling to the laser rod. The choice of the fused silica material is due to its good optical and thermal properties; it has a high-energy damage threshold [16] and a high light transmission efficiency [14]. Furthermore, the heliostat tracking errors move the center of the absorption distribution along the laser rod, resulting in less output power and a lower beam quality. The use of a light guide is essential in overcoming this problem [14]. In the present study, a light guide (L) with a 14×22-mm^2 cross-section and a 50-mm length was optimized by the ZEMAX$^©$ software, resulting in a transfer efficiency as high as 89%.

For coupling the pump rays exiting the light guide to the laser rod, an efficient 3V-shaped pump cavity was also optimized that concentrates the solar radiation on the Nd:YAG laser rod. As shown in figure 3, the entrance aperture is 14×22 mm² with a depth of 9 mm and angles V_1 ($\alpha_1 = 40°$), V_2

($\alpha_2 = 55°$) and V$_3$ ($\alpha_3 = 110°$). A cavity reflectivity of 94% and water cooling of the laser rod were also assumed in the simulation.

4. ZEMAX© and LASCAD© simulations

A non-sequential ray-tracing ZEMAX© method was used to optimize the design parameters of the entire solar laser system. The 22 absorption peak wavelengths of the 1.0 at.% Nd:YAG single-crystal rod and their absorption coefficient values were introduced into the ZEMAX© numerical data [17]. The absorption spectrum and the refractive indexes of fused silica and water were also included. A pump power conversion efficiency of 16% was assumed.

Figure 4 shows the solar light distribution in the rectangular fused silica light guide optimized by the ZEMAX© software. It is seen that the light guide serves as a beam homogenizer by transforming the near-Gaussian profile at the concentrated light spot at its input end into a uniform pump light distribution at its output end.

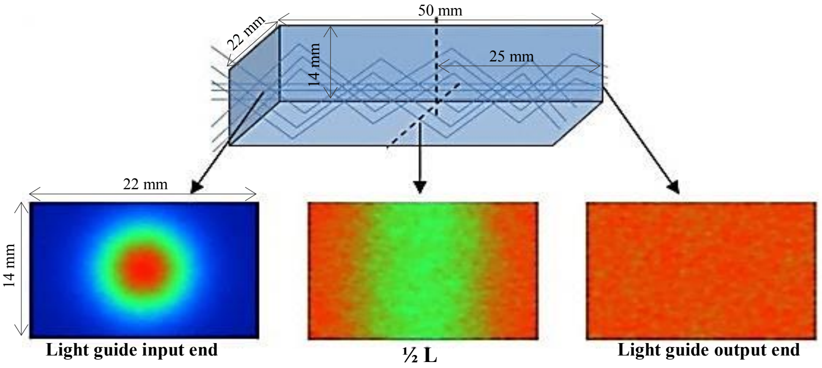

Figure 4. Solar flux distribution in the rectangular light guide.

To calculate the absorbed pump power within the Nd:YAG laser rod, the latter is divided into a total of 18 000 zones. The total absorbed pump power can be calculated by summing up the absorbed pump power of all zones, taking into account 3% extra losses due to the thickness of the rings and their structures [8]. Figure 5 shows the absorbed pump flux distribution calculated by ZEMAX© software along the transversal central cross section (figure 5 (a)) and the longitudinal central cross section (figure 5 (b)), respectively, of a 4-mm diameter and 30-mm length Nd:YAG rod.

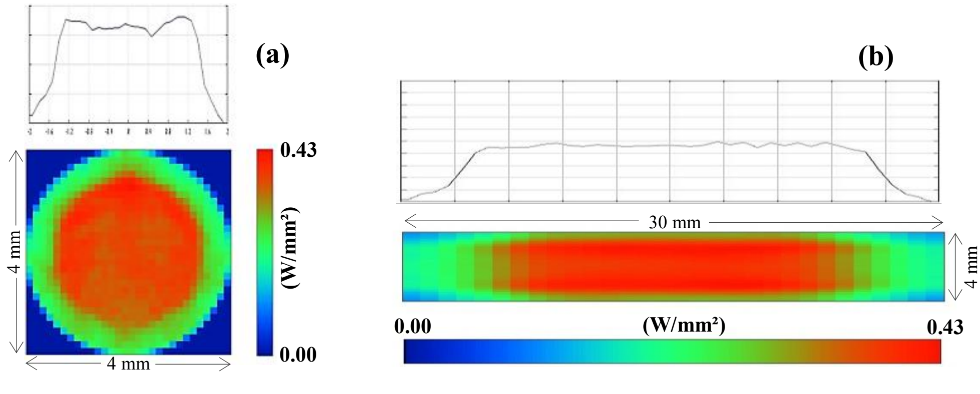

Figure 5. Absorbed pump power distribution into a 4-mm diameter, 30-mm length Nd:YAG rod.

A uniform absorbed pump profile along the rod is seen; this profile is essential to achieving a high laser power and a high beam quality by reducing the thermal effects into the laser rod, such as thermal lensing, high-order aberrations, strain and stress. The absorbed pump flux data is then integrated in LASCAD© software. The following parameters of the 1.0 at.% Nd:YAG medium were adopted for the LASCAD© analysis: stimulated emission cross section of 2.8×10^{-19} cm^2, fluorescence lifetime of 230 μs, a typical absorption and scattering loss of 0.003 cm^{-1}, as well as an averaged solar pump wavelength of 660 nm. The optical resonator parameters were also included.

As shown in figure 6, a symmetric optical resonator is considered in order to obtain a maximum laser output power in multimode operation. It consists of two mirrors of a -1 m radius of curvature, a rear mirror with high reflectivity (R = 99.98%) and an output coupler. The separation length between the two mirrors is set at 270 mm. Different output coupler reflectivities were also tested in the LASCAD© analysis in order to maximize the solar laser output power.

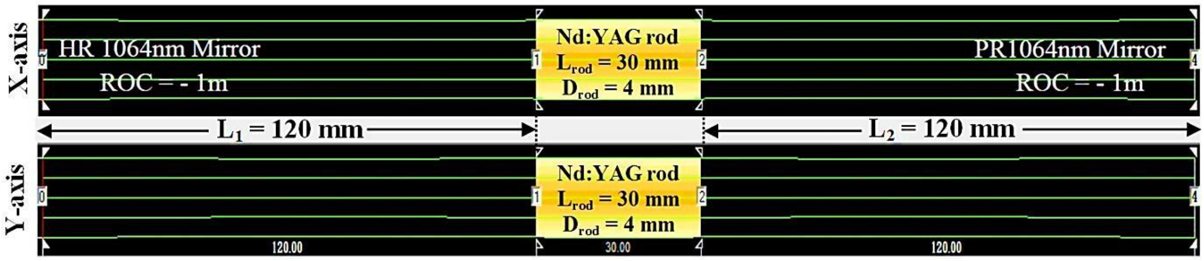

Figure 6.

A symmetric Nd:YAG laser resonator for multimode solar laser operation.

Figure 7 presents the LASCAD© simulation results for the side-pumped Nd:YAG solar laser in multimode operation. The laser output power as a function of the output mirror reflectivity is shown in figure 7 (a), while figure 7 (b) illustrates the corresponding laser beam spatial profile. Solar laser output power of 34.8 W cw was calculated for a 94% output mirror reflectivity, corresponding to a 19.69-W/m^2 collection efficiency. This value is 2.05 times higher than the best previous collection efficiency in a side-pumping configuration of a Nd:YAG solar laser [9].

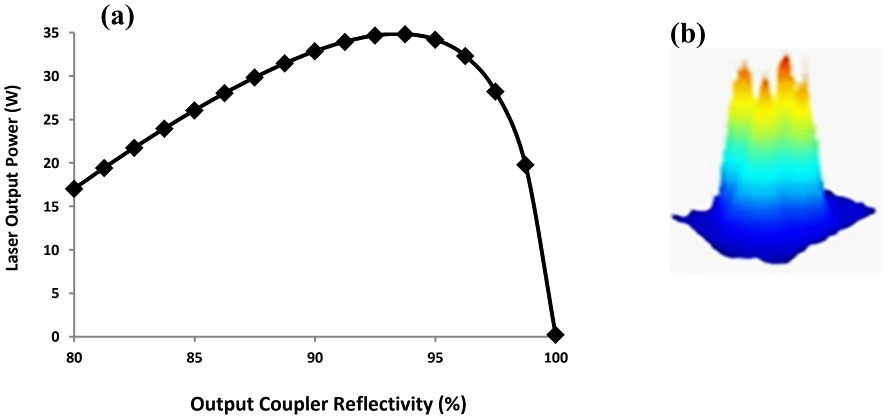

Figure 7. (a): Multimode solar laser output power variation as a function of the output coupler reflectivity, (b): The corresponding laser beam spatial profile.

The solar laser output power evolution as a function of both the absorbed pump power within the laser rod and the incoming solar power are given in figures 8 (a) and 8 (b), respectively. It is seen that the laser oscillation threshold can be reached for an absorbed pump power of around 40 W. A 3.07% slope efficiency and a 2.3% solar-to-laser conversion efficiency were also numerically calculated, being 1.31 and 1.5 times, respectively, more than the previous results for aside-pumped Nd:YAG solar laser [9, 10].

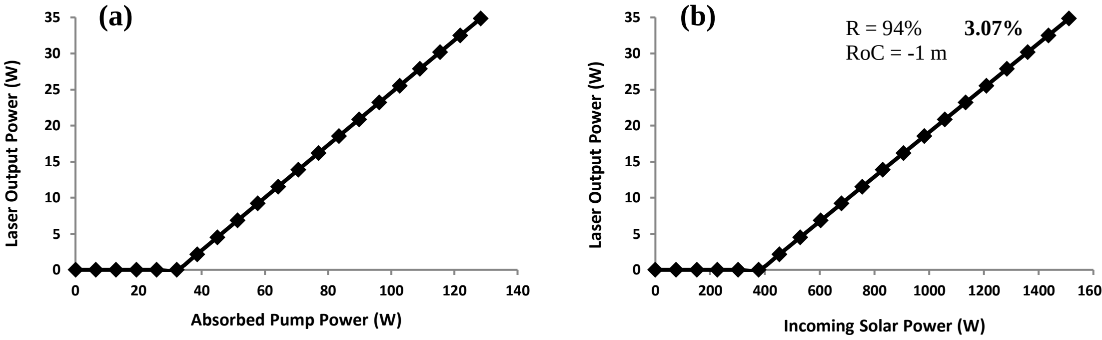

Figure 8. Solar laser output power variation as a function of: (a) the pump power absorbed into the Nd:YAG laser rod, (b) the incoming solar power.

5. Conclusion

By using both ZEMAX© and LASCAD© software, a Nd:YAG solar laser side-pumped by an efficient RAC concentrator system was numerically studied. A 3V-shaped laser pump cavity was optimized to obtain a more efficient light coupling to the laser rod. By employing a rectangular fused-silica light guide, a uniform pumping profile and a higher tracking error compensation capacity were also obtained.

A multimode solar laser power of 34.8 W was calculated in a cw mode, corresponding to 19.69 W/m^2 solar collection efficiency, 3.07% slope efficiency and 2.3% solar-to-laser conversion efficiency, indicating an enhancement of 2.05, 1.31, and 1.5 times, respectively, over that of the previous similar schemes. Moreover, the present study can be considered as the first numerical analysis of a Nd:YAG solar laser pumped by an RAC concentrator system in a side-pumping configuration.

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