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Efficient Production of Doughnut-Shaped Ce:Nd:YAG Solar Laser Beam

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Abstract: Laser beams with a doughnut-shaped profile have garnered much attention for their contribution to trapping nanoparticles and improving the scanning speed during laser-based 3D metal printing. For this reason, the production of a doughnut-shaped solar laser beam by end-side pumping a Ce:Nd:YAG rod with a small reflective parabolic collector was investigated. The resultant beam profile shape depended on the absorbed solar power, displaying a TEM00-mode profile at elevated input power. This phenomenon was primarily attributed to the role of distributing energy around the central region of the crystal. In contrast, at lower input power, a doughnut-shaped beam emerged, characterized by minimal energy distribution at the center. Through experiments conducted with a collection area of 0.226 m² and a nominal solar irradiance from 970 W/m² to 1000 W/m², it was demonstrated that sufficient energy was available to generate a doughnut-shaped beam with a solar laser collection efficiency of 5.96 W/m², surpassing previous measurements by 1.32 times. Further research with a larger collection area of 0.332 m² and a diverse solar irradiance range of 650 W/m² to 800 W/m² revealed that the presence of a thin layer of cloud caused a transition from a doughnut-shaped to a TEM10-mode and, eventually, a TEM00-mode as the absorbed input solar power increased. Notably, under heavier cloud cover, the laser beam exhibited deformation at low input power instead of maintaining a doughnut-shaped profile. This research significantly enhances our comprehension of doughnut-shaped solar laser beams and their reliance on solar energy. By harnessing the plentiful and readily accessible energy from the Sun, the incorporation of solar energy into the realm of solar-pumped lasers holds immense promise for promoting sustainability. This transformative utilization can progressively diminish the industry’s carbon footprint, yielding long-term environmental benefits.

Keywords: solar-pumped laser; Ce:Nd:YAG; doughnut-shaped laser beam; solar energy

1. Introduction

Solar-pumped lasers are a class of lasers that utilize solar radiation as the pump source to generate coherent laser beams. This technology holds immense potential for various space applications, including deep-space communications, laser power beaming, space-to-Earth wireless power transmission, and asteroid deflection [1–3], offering significant advantages over electrically pumped lasers at a lower cost and reduced environmental impact. However, on Earth, solar-pumped laser applications are limited by factors such as the Earth’s rotation and revolution, atmospheric phenomena, and cloud cover. Despite these limitations, solar laser technology may lead to a green and sustainable industry [4,5]. The development of high-quality solar-pumped laser technology has been the subject of extensive research, with numerous studies focusing on improving laser efficiency, power output, and stability. The use of advanced optical elements, such as aspheric lenses, anti-reflective coatings, and partial-reflective output couplers, and the adoption of Ce:Nd:YAG...
instead of the commonly used Nd:YAG have significantly improved the performance of solar-pumped lasers, increasing interest in various industrial and scientific applications [6].

Optical pumping methods for solar-pumped lasers have been studied for several decades. The 1960s marked the beginning of this research field [7,8], and since then, researchers have reported several notable advances [6,9–12]. The design of optical pumping systems involves using primary, secondary, and tertiary concentrators to achieve the required pumping intensity for lasing threshold. Primary concentrators, such as parabolic mirrors and Fresnel lenses, collect and concentrate solar radiation to a focal zone where a solar laser head is placed. Secondary concentrators, such as aspheric lenses and light guides, concentrate and distribute solar light rays from the primary concentrator’s focal zone to the laser-active medium. Tertiary concentrators, such as 2D and 3D compound parabolic concentrators and V-shaped pump cavities, compress or wrap the concentrated solar radiation from their input aperture to the laser-active medium.

Two commonly used methods for solar pumping are side-pumping [12–14] and end-side-pumping [6,11,15,16]. Side-pumping offers the advantage of distributing the absorbed power more evenly along the axis of the laser rod, thereby mitigating thermal lensing concerns. However, it requires a more robust resonant cavity setup. On the other hand, end-side pumping achieves higher laser efficiency but comes with the drawback of non-uniform light distribution along the laser rod, which can result in thermal loading issues. Significant progress has been made in solar laser efficiency and beam quality using both pumping methods.

The Ce:Nd:YAG medium has been evaluated for use in solar lasers in both end-side-pumping [17–19] and side-pumping [13,14] setups. In 2022, Garcia et al. employed a parabolic mirror with a small collection area of 0.293 m² to pump a thin Ce:Nd:YAG rod with a 2.5 mm diameter and 25 mm length, achieving a high collection efficiency of 38.22 W/m², along with solar-to-laser power conversion and slope efficiencies of 6.02% and 9.9%, respectively, at the primary concentrator’s focus [17]. Cai et al. later used a Fresnel solar collector and a grooved bonded crystal rod with a 6 mm diameter and 95 mm length to obtain an incoming threshold solar power of 200 W, 38.8 W/m² collection efficiency, 3.88% solar-to-laser power conversion efficiency, and 3.3% slope efficiency [20]. The first solar-pumped laser operation under a cloudy sky was achieved using this system [18]. With the clouds filtering out the infrared sunlight, a notable improvement in solar laser performance was verified due to the reduction of the thermal lensing effects in the laser medium. This led to a further reduction of the threshold pump power from 32.4 W to 29.2 W, and a maximum solar laser output of 14 W was recorded. The focal slope efficiency almost doubled from 4.03% during clear weather to 7.71% under a cloudy sky. Moreover, the solar-to-laser power conversion efficiency nearly tripled, from 2.32% on a clear day to 6.32% under a cloudy sky, while the solar laser collection efficiency increased from 12.62 W/m² to 21.47 W/m². These results suggest that a cloudy environment could be beneficial for solar laser research [18]. The end-side pumping of three Ce:Nd:YAG rods has been shown to improve the efficiency of solar laser emission. This method resulted in the generation of a continuous-wave multimode laser with a total power output of 16.5 W at an incoming solar power of 35 W, corresponding to record solar-to-laser power conversion, collection, and slope efficiencies of 4.64% (6.19% effective), 41.25 W/m², and 7.64% (10.19% effective), respectively [19].

The doughnut-shaped laser beam, also referred to as a ring-shaped beam or a hollow beam, exhibits enhanced energy intensity at the boundary of the laser spot while being weakened at its center compared to a traditional Gaussian beam [21–35]. This distinctive laser output shape is highly desirable and finds applications in diverse fields, including optical trapping [21], material processing [22,23], and biomedical imaging [24–26]. However, attaining this specific beam shape is complex, requiring careful configuration and optimization. One method to obtain this shape is by altering the laser cavity design to introduce additional phase elements, such as a helical phase plate or an annular aperture, that modify the laser beam profile [22,27]. This modification to the laser cavity leads to
some power losses, which can decrease the effective laser output power. Another method reproduces ring-shaped beams from the scattered Laguerre-Gaussian and Bessel-Gaussian beams. A rotating ground glass plate is used as a scattering medium, and a plano-convex lens collects the scattered light to generate ring-shaped beams at the Fourier plane [32]. 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 [6]. It is crucial to configure the resonant cavity close to the edge of the optical stable region to achieve a doughnut-shaped beam profile by precisely adjusting the resonant cavity parameters for the specified active medium size and pumping intensity.

This study focuses on the experimental setup and results of an end-side-pumped solar laser, aiming to generate specific beam modes, including doughnut-shaped solar laser beams and TEM$_{00}$-mode solar laser beams. The investigation explores the relationship between the amount of solar energy absorbed into the crystal and the resulting beam characteristics. Two different setups were utilized, with one being a small parabolic collector with an area of 0.226 m$^2$, subject to solar irradiance ranging from 970 W/m$^2$ to 1000 W/m$^2$. This setup achieved a notable solar laser collection efficiency of 5.96 W/mm$^2$, surpassing previous measurements by 1.32 times [6]. Furthermore, a larger collector with an area of 0.332 m$^2$ was employed, which experienced a solar irradiance ranging from 650 W/m$^2$ to 800 W/m$^2$, incorporating a thin layer of cloud cover. This setup yielded the most distinct results, with a pronounced contrast observed between the doughnut-shaped beam with the lowest depletion depth at lower input power and the TEM$_{00}$-mode laser beam at the highest input power. In addition, the study examined solar irradiance ranging from 500 W/m$^2$ to 800 W/m$^2$ under heavier passing clouds. These conditions led to the deformation of the doughnut-shaped beam at lower input power and the formation of a TEM$_{00}$-mode beam at higher input power. Overall, the findings of this study contribute to our understanding of the sustainable production of doughnut-shaped solar laser beams and provide valuable insights that can drive further advancements in this field.

2. Materials and Methods

2.1. Solar Energy Collection and Concentration: MSSF Heliostat-Parabolic System

Figure 1 shows a medium-sized solar furnace (MSSF) parabolic mirror installed in the laboratory. This mirror had a 2 m diameter, 850 mm focal length, and 80% reflectivity. The incoming solar radiation was redirected towards the parabolic mirror by a two-axis heliostat made of 36 small flat back-surface silver-coated mirrors (each measuring 0.5 m × 0.5 m) with a reflectivity of less than 80%. Thus, only 59% of the effective incoming solar radiation was used to pump the laser head.

![Figure 1. Schematics of the MSSF solar energy collection and concentration system.](image-url)
shutter blades, X-Y-Z mechanical positioner, and the laser head was then deducted to determine the total effective collection area. The experiment was conducted with two collection areas of 0.226 m² and 0.332 m². Direct solar irradiances were measured in Odeillo, France, during September 2022, using the Kipp and Zonen CH1 pyrheliometer mounted on a Kipp and Zonen 2AP solar tracker from Delft, The Netherlands.

2.2. End-Side Pumped Solar Laser Head

The laser head used in this experiment, as shown in Figure 2, was previously employed at the NOVA [17] and PROMES-CNRS facilities [18]. It consisted of a large aspheric lens made of 99.995% pure fused silica that focused the concentrated solar radiation onto a 2.5 mm diameter, 25 mm long crystal rod enclosed by the laser head’s lid. The aspheric lens had an 82 mm diameter and a 37 mm thickness, a radial aperture (r) of 41 mm, a parabolic constant of $k = 0$, a radius of curvature ($c$) of $-43$ mm, and an aspheric coefficient $\beta_1 = -0.004$, designed by the sag ($z$) Equation (1).

$$z = \frac{c \times r^2}{1 + \sqrt{1 - (1 + k)c^2r^2}} + \beta_1 r^2,$$

![Figure 2](image_url)

Figure 2. (a) Design and (b) photograph of the laser head in an end-side pumping configuration with the key components: the fused silica aspheric lens, the conical pump cavity, and the Ce:Nd:YAG laser rod that is actively cooled by water.

The Ce(0.1 at%):Nd(1.1 at%):YAG crystal, provided by Chengdu, Dongjun Laser Co., Ltd. (Dongguan, China), had a high-reflection (HR) coating on one end-face, providing 99.9% reflectivity at the laser emission wavelength of 1064 nm. The other end face was coated with an anti-reflection (AR) coating, which had a reflectivity of less than 0.2% at 1064 nm. The rod was positioned at the center of a conical pump cavity of 19.5 mm in length with input and output aperture diameters of 18 mm and 9 mm, respectively. Its surface was covered with 94% reflective silver-coated aluminum foil. The conical surface allowed the reabsorption of crisscrossing solar rays by the laser rod, improving energy distribution and absorption throughout the active medium. A cooling system that utilized water from the local plumbing system, with a pressure of 4.5 bar at room temperature, was used to remove the heat generated by the concentrated solar energy.

The configuration and positioning of the laser head and the partial reflection (PR) output coupler were numerically optimized in Zemax® Version 13 and LASCAD™ Version 3.6.5 software.

2.3. Resonant Cavity and Beam Profile Setup

Proper alignment of all optical elements was crucial for the successful emission of a solar-pumped laser. In the experimental setup, a PR output coupler with a radius of curvature of $-0.5$ m and 95% reflectivity for the 1064 nm laser emission was positioned...
490 mm away from the AR-coated end face of the laser rod. Laser power measurements were performed using a Thorlabs PM100D power meter console and a S310C thermal power sensor head. Additionally, the laser beam quality, assessed by the $M^2$ factors following ISO 11146-1 guidelines, was continuously tracked throughout the experiment using a CINOYG UV-NIR beam profiler—CinCam CMOS. For safeguarding the CMOS camera, a prism attenuator and a 1064 nm PR-coated flat lens were employed. In this configuration, only 15% of the solar laser power was employed for profiling, while the remaining 85% was redirected to the power meter. The precise alignment of optical elements and the monitoring of laser power and beam quality ensured accurate measurements and reliable performance of the solar-pumped laser system.

The solar laser resonant cavity was designed to operate at the limit of the optical stable zone for low-order laser mode generation at an average solar irradiation of 950 W/m$^2$ and pumped by a 0.322 m$^2$ collector. This resonant cavity was composed of a PR mirror of 95% reflectivity with a radius of curvature of $-0.5$ m positioned 490 mm away from the laser rod and the beam profiler positioned 430 mm away from the PR output coupler, as illustrated in Figure 3.

Figure 3. Photograph of the experimental setup.

The amount of solar input power was determined by the size of the collector and the solar irradiance measured at the time of measurement. It can also be regulated by adjusting the degree of openness of the shutter. Considering all the shading effects in the primary concentrator (the X-Y-Z axis positioning system, the laser resonant cavity, its mechanical fixation, and the water cooling tubes), the effective collection areas were determined. The calculation of the input solar energy at the focus accounted for the combined reflection efficiency of 59% from both the heliostat and the parabolic mirror and the 81% reflected sunlight from the heliostat mirrors (accounting for the gap losses) that passed through the shutter blades after obstruction.

3. Measurements and Results

3.1. Ce:Nd:YAG End-Side-Pumped Solar Laser Experiment during the Cloudless Sky Period

The collection area of 0.226 m$^2$ was used in the experiments under a clear sky with an average solar irradiance between 970 W/m$^2$ and 1000 W/m$^2$. The solar laser output power as a function of the solar power at the focus for the parabolic collector is shown in Figure 4. The solar laser increased from 1.12 W to 1.34 W, with the power varying from 115.4 W to 124.0 W.
Figure 4. Solar laser power as a function of the solar power at the focus and the solar laser beam shape during the cleared sky period with a 0.226 m² collector area.

3.2. Ce:Nd:YAG End-Side-Pumped Solar Laser Experiment during a Thin Layer of Clouds

Figure 5 shows the relationship between the solar laser output power and the changing input power. The solar laser was tested with a parabolic collector size of 0.332 m², with solar power at the focus varying from 127 W to 150 W, derived from solar irradiance ranging from 650 W/m² to 800 W/m² due to a thin layer of Altostratus-type cloud, while the aperture of the shutter was adjusted. At 127 W of focal power, a doughnut-shaped solar laser with a power output of 1.26 W was observed. As the focal power increased, the beam size and shape underwent transformations. At 132 W, the beam changed into a TEM₀₀-mode beam profile with two beams closely positioned next to each other, deforming the doughnut-shaped beam. When reaching 142 W, the solar laser beam exhibited a top-hat pattern. Finally, at a focal power of 149 W, a TEM₀₀-mode beam was achieved with a solar laser power of 1.14 W.

Figure 5. Solar laser power as a function of the solar power at the focus and the solar laser beam shape during the thin cloud-layered sky period with a 0.332 m² collector area.

3.3. Solar Laser Beam in Cloudy Sky Conditions

The formation of a TEM₀₀-mode beam shape from the Ce:Nd:YAG solar-pumped laser during cloudy weather was observed and is illustrated in Figure 6. The initial solar laser emission occurred under 490 W/m² solar irradiance during thicker cloud passage. With each subsequent increase in solar irradiance, the solar laser power consistently increased. Eventually, at a maximum solar irradiance of 800 W/m², the solar laser achieved a power output of 1.56 W.
power consistently underwent transformations. At 132 W, the solar laser beam demonstrated a transition of a laser beam with a doughnut shape to one with a TEM00 mode beam shape from the Ce:Nd:YAG end-side-pumped solar laser. The maximum laser power of 1.34 W was observed. As the focal power increased, the beam changed into a TEM00 mode beam shape.

Figure 5 shows the relationship between the solar laser output power and the change in beam profile shape during the thin cloud layer period with high cloud density, while the solar laser achieved a power output of 1.26 W. Eventually, at a maximum solar irradiance of 800 W/m², the solar laser achieved a power output of 1.14 W. During cloudy weather, a power output of 1.56 W was observed. As the focal power increased, the beam changed into a TEM00 mode. However, due to limitations imposed by the size of the parabolic mirror and a maximum solar irradiance of 1000 W/m², it was not possible to observe this transition. Moreover, the solar laser power of 1.34 W at 123.8 W focal power was equivalent to 1.08% solar-to-laser power conversion efficiency and 5.93 W/m² collection efficiency, which was 1.32 times larger than the 4.5 W/m² measured by Vistas et al. [6].

4. Discussions


Generating a high-efficiency and high-quality solar laser beam requires careful consideration of the laser’s operational parameters. The optically stable region refers to a range of parameters, such as the resonant cavity length and the pump beam’s diameter, where the laser operates without experiencing any mode instabilities. To achieve high-efficiency and high-quality solar laser beams, it is necessary to operate the laser near the edge of the optically stable region, which can be achieved with a long resonant cavity [36,37]. This ensures that the laser is operating at a point where there is a significant spatial overlap between the lower-order mode volume and the pump mode volume. This overlap is essential for efficient energy transfer from the pump beam to the laser medium. With a long cavity length, there is a greater distance for the light to travel between the resonator mirrors. Table 1 presents a summary of the solar-pumped laser output performances.

Table 1. Summary of the Ce:Nd:YAG end-side-pumped solar laser performance at different collection areas and sky conditions.

<table>
<thead>
<tr>
<th>Sky Status</th>
<th>Clear</th>
<th>Thin-Layer Cloud</th>
<th>Cloudy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collection area</td>
<td>0.226 m²</td>
<td>0.332 m²</td>
<td>0.332 m²</td>
</tr>
<tr>
<td>Beam profile shape</td>
<td>Doughnut</td>
<td>Doughnut</td>
<td>TEM00-mode</td>
</tr>
<tr>
<td>Maximum laser power</td>
<td>1.34 W</td>
<td>1.26 W</td>
<td>1.14 W</td>
</tr>
<tr>
<td>Solar power at the focus</td>
<td>123.8 W</td>
<td>127.2 W</td>
<td>149.1 W</td>
</tr>
<tr>
<td>Solar-to-laser power conversion efficiency</td>
<td>1.08%</td>
<td>0.99%</td>
<td>0.77%</td>
</tr>
<tr>
<td>Collection efficiency</td>
<td>5.93 W/m²</td>
<td>3.80 W/m²</td>
<td>3.43 W/m²</td>
</tr>
</tbody>
</table>

The experiment performed with a collection area of 0.226 m² under clear sky conditions demonstrated a consistent output of a doughnut-shaped solar laser beam. The maximum power of the beam reached 1.34 W. It is worth noting that as the focal solar power increased, the doughnut-shaped beam tended to converge towards a TEM00-mode. However, due to limitations imposed by the size of the parabolic mirror and a maximum solar irradiance of 1000 W/m², it was not possible to observe this transition. Moreover, the solar laser power of 1.34 W at 123.8 W focal power was equivalent to 1.08% solar-to-laser power conversion efficiency and 5.93 W/m² collection efficiency, which was 1.32 times larger than the 4.5 W/m² measured by Vistas et al. [6].

The experiment conducted with a collection area of 0.332 m² under a semi-clear sky demonstrated a transition of a laser beam with a doughnut shape to one with a TEM00-mode shape through the increase of solar power at the focus, from 127 W to 149 W, as...
shown in Figure 5 and Table 1. The doughnut-shaped and TEM$_{00}$-mode solar laser beams exhibited laser powers of 1.26 W and 1.14 W, respectively. These powers correspond to solar-to-laser power conversion efficiencies of 0.99% and 0.77% and collection efficiencies of 3.80 W/m$^2$ and 3.43 W/m$^2$. It is important to reemphasize that the resonance cavity was optimally configured for solar irradiance larger than 950 W/m$^2$ at a collection area of about 0.3 m$^2$.

In contrast to the prevailing content in the literature [21–35], our study deviates from the customary method of modifying a Gaussian laser beam using various optical elements to produce a doughnut-shaped laser beam. It is also worth noting that in those prior studies, the Gaussian laser beam originated from a laser crystal that received a consistent and uniform light source. Our study offers a distinct viewpoint by linking the formation of this exceptional beam profile to the implementation of an end-side pumping technique. This method leads to an uneven energy distribution within the laser crystal, leading to a profound alteration in the shape of the laser output beam with the variation of input power.

The solar laser system was originally designed to ideally generate a TEM$_{00}$-mode solar laser beam using the resonant cavity depicted in Figure 3, operating on cloudless days with a consistent solar irradiation of 950 W/m$^2$ and a collection area of 0.300 m$^2$. Nevertheless, in practice, the solar irradiation varied from over 800 W/m$^2$ to 650 W/m$^2$ due to the presence of thin clouds during the 0.322 m$^2$ collection area measurement and 950 W/m$^2$ during the 0.226 m$^2$ collection area. A notable change in the shape of the solar laser beam was observed under different input solar power conditions. The sudden reduction in input power altered the energy required for achieving the necessary thermal shift in the refractive index of the Ce: Nd: YAG rod for efficient extraction of TEM$_{00}$-mode solar lasers. This caused a shift in the positioning of the solar laser beam from the TEM$_{00}$-mode to a higher-order laser mode at the measurement location, as depicted in Figure 7.

![Figure 7. Absorbed energy distribution along the Ce:Nd:YAG crystal in Zemax® and laser beam profiling for: (a) TEM$_{00}$-mode pumped by 800 W/m$^2$ with a 0.322 m$^2$ collector; (b) doughnut-shaped beam pumped by 950 W/m$^2$ with a 0.226 m$^2$; and (c) doughnut-shaped beam pumped by 600 W/m$^2$ with a 0.226 m$^2$.](image-url)

Figure 7a displays the TEM$_{00}$-mode solar laser beam with a power output of 1.14 W, generated from the collection area of 0.322 m$^2$. This beam was produced under solar radiation of 800 W/m$^2$. In Figure 7b, the doughnut-shaped solar laser beam with a power output of 1.34 W is shown, generated through the 0.226 m$^2$ collection area and pumped by solar radiation of 950 W/m$^2$. Figure 7c presents the doughnut-shaped solar laser beam...
with a power output of 1.26 W, produced through the 0.322 m² collection area under the solar radiation of 600 W/m².

The generation of the TEM₀₀-mode solar laser was intricately linked to the energy distribution within the crystal. In typical lamp-pumped lasers, energy is usually evenly distributed. In our case, as depicted in Figure 7a, there was a non-uniform energy distribution, particularly with a dense energy concentration in the central left region of the crystal and a ring-shaped energy distribution on the right side. This combined absorbed power profile was responsible for producing the TEM₀₀-mode laser.

However, in Figure 7b, the lower energy intensities on the left side and center-right part of the crystal contributed to the generation of the doughnut-shaped beam. This energy was not sufficient to effectively build the center part of the Gaussian beam, causing the laser beam intensity at the center to be only a part of its peak value and, consequently, the formation of a doughnut-shaped beam.

Even though the amount of input solar energy in Figure 7c matched that of (b), the energy distribution within the crystal was widely spread due to the significant reduction of the solar irradiance with the appearance of thin clouds. This contributed to the spreading of the solar radiation at the focus and, consequently, across the crystal, thereby reducing the energy accumulation at the crystal’s center and facilitating the production of a higher-quality (high-contrast) doughnut-shaped laser. The reduction in pumping energy prevented the emission of laser light from the center, resulting in a deeper depletion of laser power at the center of the doughnut-shaped beam as compared to that generated by the crystal with more tightly focused pumping.

As observed in both Figure 6 and Table 1, under a passing cloudy sky, an enhancement in the output power of the Ce:Nd:YAG TEM₀₀-mode solar laser was observed, reaching 1.56 W at a solar focal power of 145.7 W. This improvement was accompanied by an increase in the solar-to-laser power conversion efficiency by 1.07% and a collection efficiency of 4.70 W/m². Additionally, a lower threshold solar power of 81 W was measured.

A layer of cloud can scatter the sunlight due to Snell’s law, which may contribute to the dispersion of the concentrated solar radiation along the active medium and pump cavity. This, in turn, can lead to the reduction of the heat load in the laser medium and the consequent increase of the thermal focal length, which will affect the laser output power. This suggests that low-density clouds may have a positive impact on the performance of solar laser systems. Andrews et al. [38] and Bird et al. [39] studied the effect of cloud thickness on solar spectral intensity. They found that there is a slight loss in solar intensity from the UV to the middle of the visible light range (0.1 µm to 0.5 µm). However, from 0.5 µm to 1.4 µm, there is a significant decrease of up to half of the solar intensity, while the IR waveband is often blocked by clouds. The removal of the IR waveband is highly beneficial for reducing the heat load in the laser head and minimizing the thermal lensing effect in the active medium, which ultimately leads to improved laser output performance [18]. These findings highlight the importance of understanding the impact of clouds on solar systems, including solar-pumped lasers.

4.2. Rotational Symmetry and Depletion Depth of the Doughnut-Shape Beam

Figure 8 shows the doughnut-shaped laser beam profiles for the two different collection areas. In Figure 8a, the doughnut-shaped beam with an output power of 1.26 W at the focus of the 0.332 m² parabolic mirror is presented. It has a maximum diameter of 2.5 mm and 4% of the maximum intensity at the center, which is 4.5 times smaller than the 18% value reported in the previous doughnut-shaped solar laser [6]. Figure 8b displays the doughnut-shaped beam with the highest collection efficiency of 5.93 W/m², generated by a 1.34 W laser beam at a 0.226 m² collector. It has a 2.5 mm diameter and a 41% maximum intensity at the center.
Figure 8. Doughnut-shaped solar laser beam profiles at the focus of (a) the 0.332 m² collector and (b) the 0.226 m² collector.

The distribution of energy along the boundaries of the doughnut-shaped laser beam plays a crucial role in numerous laser-based applications [40]. The shape of the laser beam influences the temperature distribution of the molten pool, leading to variations in cooling rate, microstructure, and residual stress distributions [25,27,40]. Furthermore, the size and intensity distributions of the doughnut-shaped beam have a significant impact on the thermal behavior when in contact with the material surface, while its rotational symmetry governs the homogeneous distribution of the transformed material. Achieving a well-distributed energy profile within the boundaries of the doughnut-shaped laser beam is therefore essential for controlling these thermal effects and ensuring optimal results in laser processing applications.

Figure 9 provides a comparison of the energy distribution of the doughnut-shaped solar laser beam with a higher depletion depth from the current work with that from the previous one [6]. In Figure 9a,c, the energy distribution within the doughnut-shaped beam is represented by distinct concentric lines marked as red (1), brown (2), green (3), blue (4), orange (5), and black (6). Figure 9b,d displays the energy intensity of each concentric line, with the outer ring (6) exhibiting the lowest energy intensity, while the central red line (1) displays the low energy intensity at the center of the doughnut-shaped beam.

The doughnut-shaped beam represented in Figure 9a has 1.26 W solar of laser power, driven by 127 W of input power from a 0.332 m² collector. The concentric lines sizes, in increasing order, are approximately 0.20 mm, 0.70 mm, 1.12 mm, 1.48 mm, 1.86 mm, and 2.60 mm. As shown in Figures 8a and 9b, the concentric line at the center (1) has 4% of the maximum energy intensity. The green concentric line (3) exhibits on average 80% of the total energy intensity, and the transitional boundaries between the brown ring (2) and the blue ring (4) surpass 60%, representing a thickness of approximately 0.39 mm for the energy ring-wall.
Figure 9. (a,b) Represents the energy intensity distribution of the doughnut-shaped laser beam of 1.26 W power with a higher depletion depth produced with a solar focal power of 127.1 W at the 0.332 m² collector. (c,d) depict the energy intensity distribution of the doughnut-shaped solar laser beam reported by Vistas et al. at 4.2 W power with a higher depletion depth achieved with a solar focal power of 636 W using a collector area of 1.0 m² [6].

Figure 9b illustrates the doughnut-shaped beam reported by Vistas et al. [6] with a solar laser power of 4.2 W obtained from a focal power of 636 W using a collector area of 1 m². The concentric lines sizes, arranged in ascending order, are approximately 0.10 mm, 0.44 mm, 0.70 mm, 1.04 mm, 1.30 mm, and 1.62 mm. The presence of energy intensity fluctuations in the orange (5), blue (4), and green (3) concentric lines suggests the formation of the doughnut-shaped beam through the merging of two TEM₁₀⁻mode beams, resulting in the absence of rotational asymmetry. The central part of the beam contributes to about 20% of the maximum intensity, which increases to 60% at the brown ring (2). The thickness measured between the brown (2) and blue (4) rings is approximately 0.30 mm.

Table 2 provides a summary of the doughnut-shaped solar laser beams comparison between the current work and the study conducted by Vistas et al. [6]. This work demonstrated the production of a doughnut-shaped solar laser beam with a higher depletion depth, presenting 4% of maximum energy intensity at the center compared to 18% of the previous doughnut-shaped solar beam [6]. Additionally, the thickness of the beam is 1.3 times larger at 60% of the energy intensity, compared to that of Vistas et al. [6], despite having a beam size that is 1.56 times larger. The solar laser collection efficiency is similar for both systems. Nevertheless, the present doughnut-shaped beam was achieved with a collector size that is 3 times smaller and requires 0.19 times less energy.
Table 2. Comparison of the doughnut-shaped solar laser beam performance in terms of contrast from the current work with that reported by Vistas et al. [27].

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Vistas et al., 2019 [6]</th>
<th>This Work</th>
<th>Improvements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sky status</td>
<td>Clear</td>
<td>Semi-clear</td>
<td></td>
</tr>
<tr>
<td>Primary concentrator</td>
<td>Parabolic mirror (NOVA)</td>
<td>Parabolic mirror (PROMES-CNRS)</td>
<td></td>
</tr>
<tr>
<td>Total reflectivity of the collection system</td>
<td>75%</td>
<td>59%</td>
<td></td>
</tr>
<tr>
<td>Tracking method</td>
<td>Via heliostat</td>
<td>Via heliostat</td>
<td></td>
</tr>
<tr>
<td>Active medium</td>
<td>Nd:YAG</td>
<td>Ce:Nd:YAG</td>
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<tr>
<td>Pumping method</td>
<td>End-side-pump</td>
<td>End-side-pump</td>
<td></td>
</tr>
<tr>
<td>Laser rod dimensions</td>
<td>Ø 4.0 mm × 35 mm</td>
<td>Ø 2.5 mm × 25 mm</td>
<td></td>
</tr>
<tr>
<td>Solar irradiance</td>
<td>~850 W/m²</td>
<td>~950 W/m²</td>
<td></td>
</tr>
<tr>
<td>Effective collection area</td>
<td>1.000 m²</td>
<td>0.332 m²</td>
<td>×0.32</td>
</tr>
<tr>
<td>Maximum solar power at the focus</td>
<td>636.0 W</td>
<td>127.1 W</td>
<td>×0.19</td>
</tr>
<tr>
<td>Maximum laser power</td>
<td>4.20 W</td>
<td>1.26 W</td>
<td>×0.30</td>
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<tr>
<td>Solar collection efficiency</td>
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<td>3.80 W/m²</td>
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<td>Solar-to-laser conversion efficiency at the focus</td>
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<td>0.99%</td>
<td>×1.41</td>
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<tr>
<td>Maximum intensity at the center</td>
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<td>4%</td>
<td>×0.22</td>
</tr>
<tr>
<td>Beam size (diameter)</td>
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<td>2.5 mm</td>
<td>×1.56</td>
</tr>
<tr>
<td>Energy wall thickness (60% at maximum energy intensity)</td>
<td>0.30 mm</td>
<td>0.39 mm</td>
<td>×1.30</td>
</tr>
</tbody>
</table>

Figure 10 provides a comparison of the energy distribution of the doughnut-shaped solar laser beam with higher depletion depth from the current work with that from the previously reported doughnut-shaped solar laser beam with higher depletion depth [6]. In Figure 10a,c, the energy distribution within the doughnut-shaped beam is represented by distinct concentric lines marked as red (1), brown (2), green (3), blue (4), orange (5), and black (6). Figure 10b,d displays the energy intensity of the concentric line, with the outer ring (6) exhibiting the lowest energy intensity, while the central red line (1) displays the low energy intensity at the center of the doughnut-shaped beam.

The doughnut-shaped beam represented in Figure 10a has 1.34 W of solar laser power, driven by 123.8 W of input power from a 0.226 m² collector. The concentric lines sizes, in increasing order, are approximately 0.20 mm, 0.50 mm, 1.00 mm, 1.54 mm, and 2.50 mm. As shown in Figures 8b and 10b, the concentric line at the center (1) has 41% of the maximum energy intensity. The green concentric line (3) exhibits on average 80% of the total energy intensity, and the transitional boundaries between the brown ring (2) and the blue ring (4) surpass 60%, representing a thickness of approximately 0.39 mm for the energy ring wall.

Figure 10b illustrates the doughnut-shaped beam reported by Vistas et al. [6] with a solar laser power of 4.6 W obtained from a focal power of 636 W using a collector area of 1.0 m². The concentric lines sizes, arranged in ascending order, are approximately 0.10 mm, 0.28 mm, 0.60 mm, 0.90 mm, 1.20 mm, and 1.60 mm. The presence of energy intensity fluctuations in the orange (5), blue (4), and green (3) concentric lines suggests the formation of the doughnut-shaped beam through the merging of two TEM$_{10}$ mode beams, resulting in the absence of rotational asymmetry. The central part of the beam contributes to about 20% of the maximum intensity, which increases to 60% at the brown ring (2). The thickness measured between the brown (2) and blue (4) rings is approximately 0.31 mm.

Table 3 provides a summary of the doughnut-shaped solar laser beam comparison between the current work and the study conducted by Vistas et al. [6]. This work demonstrated the production of a doughnut-shaped solar laser beam with a higher depletion depth, with 41% of maximum energy intensity at the center compared to 57% of the previous doughnut-shaped solar beam [6]. Additionally, the thickness of the beam is 1.63 times larger at 60% of the energy intensity, compared to that of Vistas et al. [6], despite having a beam size that is 1.63 times larger. The solar laser collection efficiency is 1.32 times larger...
compared to that of Vistas et al. [6]. Nevertheless, the present doughnut-shaped beam was achieved with a collector size that is 0.32 times smaller and requires 0.19 times less energy.

Figure 10. (a,b) Represents the energy intensity distribution of the doughnut-shaped laser beam of 1.34 W power with higher depletion depth produced with a solar focal power of 123.8 W at the 0.228 m² collector. (c,d) depict the energy intensity distribution of the doughnut-shaped solar laser beam reported by Vistas et al. at 4.6 W power with a higher depletion depth achieved with a solar focal power of 636 W using a collector area of 1.0 m² [6].

Table 3. Comparison of the doughnut-shaped solar laser beam performance from the current work with that reported by Vistas et al. [27] in terms of highest collection efficiency.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Vistas et al., 2019 [6]</th>
<th>This Work</th>
<th>Improvements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sky status</td>
<td>Clear</td>
<td>Clear</td>
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<tr>
<td>Primary concentrator</td>
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<td>Parabolic mirror (PROMES-CNRS)</td>
<td></td>
</tr>
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<td>59%</td>
<td></td>
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<td>Via heliostat</td>
<td></td>
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<td>Solar irradiance</td>
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<td></td>
</tr>
<tr>
<td>Effective collection area</td>
<td>1.000 m²</td>
<td>0.226 m²</td>
<td>×0.32</td>
</tr>
<tr>
<td>Maximum solar power at the focus</td>
<td>636.0 W</td>
<td>123.8 W</td>
<td>×0.19</td>
</tr>
<tr>
<td>Maximum laser power</td>
<td>4.50 W</td>
<td>1.34 W</td>
<td>×0.30</td>
</tr>
<tr>
<td>Solar collection efficiency</td>
<td>4.50 W/m²</td>
<td>5.93 W/m²</td>
<td>×1.32</td>
</tr>
<tr>
<td>Solar-to-laser conversion efficiency at the focus</td>
<td>0.70%</td>
<td>1.08%</td>
<td>×1.41</td>
</tr>
<tr>
<td>Maximum intensity at the center</td>
<td>57%</td>
<td>41%</td>
<td>×0.89</td>
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<tr>
<td>Beam size (diameter)</td>
<td>1.6 mm</td>
<td>2.6 mm</td>
<td>×1.63</td>
</tr>
<tr>
<td>Energy wall thickness</td>
<td>0.31 mm</td>
<td>0.52 mm</td>
<td>×1.63</td>
</tr>
<tr>
<td>(60% at maximum energy intensity)</td>
<td></td>
<td></td>
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</tbody>
</table>
5. Conclusions

This article presents the successful production of a doughnut-shaped solar laser beam by end-side-pumping a Ce:Nd:YAG rod using a parabolic mirror with a relatively small collection area. The study elucidated that the generation of the doughnut-shaped beam is contingent upon the amount of solar energy pumped into the crystal while maintaining a fixed resonant cavity length. It was observed that the obstruction of solar energy by clouds inhibited the production of the doughnut-shaped beam due to the weakened solar wavelength intensity required for its formation, highlighting the direct relationship between the availability of solar energy and the generation of the desired beam shape. The study also demonstrated that employing a collection area of 0.226 m$^2$ enabled the production of a doughnut-shaped solar laser beam with a higher collection efficiency of 5.96 W/m$^2$, surpassing the efficiency from the Vistas et al. measurements by a factor of 1.32. Additionally, operating with larger focal solar power, achieved through a larger collection area of 0.332 m$^2$, resulted in a more pronounced depletion of the doughnut-shaped solar laser beam. This enhanced depletion depth is considerably appealing for a wide range of applications that rely on doughnut-shaped beams.

The findings presented in this study advance our understanding of the production of doughnut-shaped solar laser beams and their dependence on solar energy input. Further research in this area could explore optimization strategies to improve beam performance, including beam shaping techniques, energy efficiency enhancement, and the development of innovative and concentrated collection methods. Harnessing solar power to generate doughnut-shaped laser beams offers significant potential in various fields, driving technological advancements and environmental benefits. This promotes potential sustainability within the industry by enabling improved optimal efficiency, cost-effectiveness, and a reduced carbon footprint through the ability to control the power density of solar laser beams.


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