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Solar-pumped Nd:YAG laser with 31.5 W/m^2 multimode and 7.9 W/m^2 TEM$_{00}$-mode collection efficiencies

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ABSTRACT

We report here significant progresses in both multimode and TEM$_{00}$-mode solar-pumped laser collection efficiencies by end-side-pumping a 4.0 mm diameter 35 mm length Nd: YAG single-crystal rod with a heliostat-parabolic mirror solar energy concentration system. An aspheric fused silica lens was used to couple the concentrated solar radiations from the focal zone of a 1.4 m effective diameter parabolic mirror into the laser rod within a conical pumping cavity. 37.2 W continuous-wave multimode solar laser power was measured, corresponding to 31.5 W/m^2 multimode laser collection efficiency and 8.9% slope efficiency. 9.3 W continuous-wave TEM$_{00}$-mode ($M^2 \leq 1.2$) solar laser power and consequently 7.9 W/m^2 fundamental-mode laser collection efficiency was registered, doubling the previous record.

1. Introduction

Sunlight is a free and abundant energy source and technologies exploiting it are experiencing an impressive development. Among them, solar-pumped laser is considered as one of the most promising technologies. The direct excitation of large renewable lasers by natural sunlight may provide cost-effective production of coherent optical radiations, leading to numerous environmental and economical benefits in the years to come. Solar-pumped lasers are natural candidates for applications where sunlight is plentiful and other forms of energy sources are scarce. The direct conversion of free sunlight into laser light is by itself a very interesting topic of laser physics. Broadband sunlight is converted into laser light, which can be a source of narrowband, collimated radiations with the possibility of obtaining extremely high brightness and intensity. Powered by abundant solar energy, solar laser has large potentials for terrestrial applications such as high-temperature materials processing and magnesium-hydrogen energy cycle. It might also provide effective solutions to space applications such as atmospheric and ocean sensing; laser beaming; deep space communications; orbital space debris removal etc. Highly efficient multimode and TEM$_{00}$-mode solar laser with excellent beam profile [1] are all indispensable for the above mentioned applications.

Since 1966, primary parabolic mirrors have been utilized by Young [2] and other researchers [3–7] to achieve tight focusing of incoming solar radiation for the excitation of a laser medium. By mounting directly a 4 mm diameter, 75 mm length Nd:YAG single-crystal rod within a 50 mm diameter water-cooled flow tube at the focus of a 78.5 m^2 area parabolic mirror, 18 W multimode solar laser power was successfully produced in 1984 [4], leading to 0.23 W/m^2 laser collection efficiency – defined as solar laser power achieved per unit area of a primary collector (W/m^2). With CPC (Compound Parabolic Concentrator) secondary and tertiary concentrators, solar laser collection efficiencies were gradually boosted to 6.7 W/m^2 in 2003 [6]. Most significant progresses in solar laser efficiency have been made in the last decade by Fresnel lens solar laser pumping approaches [8–12]. 18.7 W/m^2 solar laser collection efficiency was firstly reported in 2007 by pumping a 3–9 mm diameter and 100 mm length Cr:Nd:YAG ceramic laser rod with a 1.4 m^2 area Fresnel lens [8]. 19.3 W/m^2 laser collection efficiency was later achieved in 2011 by exciting a 4 mm diameter, 25 mm length Nd:YAG single-crystal rod through a 0.64 m^2 area Fresnel lens [9]. This result triggered the discussions about which medium between Cr:Nd:YAG ceramics and Nd:YAG single-crystal was more suitable for solar-pumped lasers, and consequently in 2012, record-high collection efficiency of 30.0 W/m^2 was attained by pumping a 6 mm diameter, 100 mm length Nd:YAG single-crystal rod through a 4 m^2 area Fresnel lens [10]. However, very large M_x^2 = M_y^2 =137 factors have been associated with this pumping approach, leading to a low laser beam brightness figure of merit – defined as the ratio between laser power and the product of M_x^2 and M_y^2 [1,6] – of only 0.0064 W. A substantial progress in solar laser beam brightness was reported in 2013 [1,12]. A large aspheric lens and a 2D-CPC concentrator were combined to further compress the concentrated

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solar radiation from a 1.0 m diameter Fresnel lens into a 3 mm diameter, 30 mm length Nd:YAG rod within a V-shaped pumping cavity. 2.3 W continuous-wave TEM_{00}-mode solar laser power ($M^2 \leq 1.1$) was produced, corresponding to the fundamental mode slope efficiency of 0.7% and the collection efficiency of 2.93 W/m^2. Most recently, 4.5 W continuous-wave TEM_{00}-mode solar laser power ($M^2 \leq 1.05$) was obtained [13] by pumping a 4 mm diameter, 34 mm length grooved Nd:YAG rod with 1.13 m^2 effective collection area parabolic mirror in the PROMES -CNRS (Procedes, Materiaux et Energie Solaire – Centre National de la Recherche Scientifique). An ellipsoid-shaped fused silica secondary concentrator and a 2V-shaped pumping cavity was combined to achieve an efficient side-pumping to the grooved Nd:YAG rod at the focus of the horizontal-axis parabolic mirror in the PROMES -CNRS solar laboratory, resulting in 4.0 W/m^2 TEM_{00}-mode laser collection efficiency.

By end-side-pumping the 4 mm diameter 35 mm length Nd:YAG single-crystal rod with the same PROMES-CNRS heliostat-parabolic mirror solar energy concentration system [13], significant progresses in both multimode and TEM_{00}-mode solar laser collection efficiencies are reported here. The aspheric fused silica lens was essential for concentrating efficiently the solar radiation from the focus of the 1.4 m effective diameter parabolic mirror into the laser rod within the conical pumping cavity. 37.2 W continuous-wave multimode solar laser power was firstly measured, leading to 31.5 W/m^2 multimode solar laser collection efficiency, being 5% more than the previous record [10]. 9.3 W continuous-wave TEM_{00}-mode ($M^2 \leq 1.2$) was then measured, corresponding to 7.9 W/m^2 TEM_{00}-mode laser collection efficiency and consequently twice of the previous record [13]. The design parameters of our high-efficiency solar laser system, carefully optimized by ZEMAX© and LASCAD© softwares, will be explained in Sections 2 and 3. Experiments on multimode continuous-wave solar laser operation will then be discussed in Section 4. Experiments on TEM_{00}-mode continuous-wave solar laser oscillation will be given in Section 5, finally followed by conclusions in Section 6.

2. High-efficiency end-side-pumped Nd:YAG solar laser by the heliostat-parabolic mirror system

2.1. Solar energy collection and concentration system

A large plane mirror (3.0 m×3.0 m) with 36 small flat segments (0.5 m×0.5 m each), mounted on a two-axis heliostat, redirected incoming solar radiation towards the horizontal-axis primary parabolic mirror. The reflected parallel solar rays actually illuminated everything in its way, including the shutter, the 2 m diameter, 850 mm focal length parabolic mirror, the door and the external walls of the solar laboratory. We used only the 1.4 m diameter central area of the mirror, as illustrated in both Figs. 1 and 2.

Since all the mirrors in Fig. 1 were back-surface silver coated, only 59% of incoming solar radiation was effectively focused to the focal zone. There were several reasons contributing to low total reflectivity: 1. High iron contents glass substrate materials (10 mm thick for the parabolic mirror and 5 mm for the plane mirror) were used to build the mirrors. Considerable absorption loss therefore occurred. 2. There were no anti-reflection coatings on the front surfaces of these mirrors. 3. Over 70 year´s usage since 1943. For a typical solar irradiance of 1000 W/m^2 in Odeillo, July 2016, about 700 W solar power was focused into a highly concentrated pump light spot with near-Gaussian distribution of 11 mm full width at half maximum (FWHM) in the focal zone of the primary parabolic mirror.

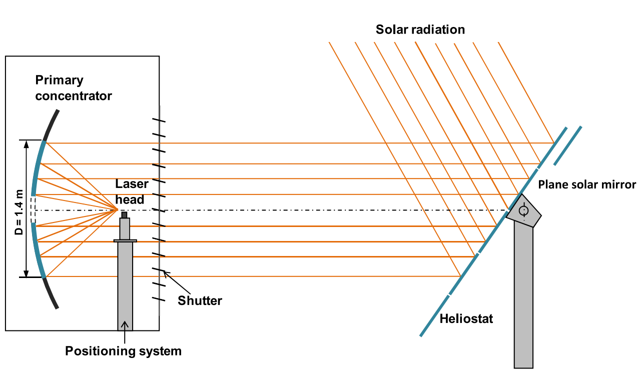

Fig. 1. Schematics of the PROMES – CNRS heliostat – parabolic mirror system for pumping a solar laser head.

Fig. 2a presents the experimental setup for achieving the maximum multimode solar laser power by mounting the partial reflection (PR) 1064 nm output mirror only 11 mm away from the laser rod, while Fig. 2b shows the approach for attaining the maximum TEM_{00}-mode solar laser power by placing the PR1064nm output mirror 430 mm away from the same laser rod. The details of both multimode and TEM_{00} mode solar laser operations in Fig. 2 will be explained in their respective sections later.

2.2. Solar laser head with the aspheric fused silica lens, the Nd:YAG rod and the conical pump cavity

To reduce the maximum input solar power at the focus, we limited the input solar power at focus by masking the external annular area of the 2.0 m diameter parabolic mirror so that only its 1.4 m diameter central circular area was utilized, as shown in Figs. 1 and 2. After discounting the shading effects of a large plane solar mirror, a shutter, an X-Y-Z axes positioning system, a multi-angle vice, a 0.3 m diameter central opening on the parabolic mirror and the solar laser head, as shown in Figs. 1 and 2, 1.18 m^2 effective solar energy collection area was calculated. The laser head was fixed on the X-Y-Z axes positioning system through the multi-angle vice, ensuring its accurate and easy optical alignment in the focal zone. As shown in Figs. 2 and 4, the laser head was composed of the aspheric fused silica lens and the conical-shaped pump cavity, within which the Nd:YAG rod was mounted. The large fused silica aspheric lens was 84 mm in diameter, 38 mm in height, 45 mm in front surface radius of curvature and −0.005 in rear r^2 parameter. The output end face of the lens had a plane surface. The aspheric lens coupled efficiently the concentrated solar radiation from the focal zone into the Nd:YAG rod. For end-pumping, one part of the concentrated radiation was directly focused onto the high-reflection (HR 1064 nm) end face coatings of the rod by the aspheric lens. As shown in Figs. 3 and 4, the HR coatings reflected the 1064 nm oscillating laser radiation within the resonant cavity, but allowed the passage of other solar pumping wavelengths. For side-pumping, another part of the radiation that did not hit the HR 1064 nm coatings was guided into the conical cavity with D_1 =22 mm / D_2 =9.0 mm input/output diameters and H =29 mm height. The zigzag passage of the rays within the small pump cavity ensured efficient multi-pass side-pumping to the rod, as illustrated in Fig. 3. The inner wall of the pumping cavity was bonded with a protected silver-coated aluminum foil with 94% reflectivity. The Nd:YAG rod, the conical pump cavity and the output end face of the aspheric lens were all actively cooled by water at 6 L/min flow rate. The maximum contact between the coolant and the rod was essential for the removal of the generated heat. The central region of the aspheric lens output face was in direct contact with the cooling water, ensuring hence an efficient light coupling of the concentrated solar radiation from the aspheric lens into the rod. There was 10 mm space between the aspheric lens output end face and the HR1064 nm coatings of the rod, more than enough for the exit of cooling water. Besides, both fused silica material and cooling water were useful for partially preventing both UV solarization and IR heating to the laser rod...

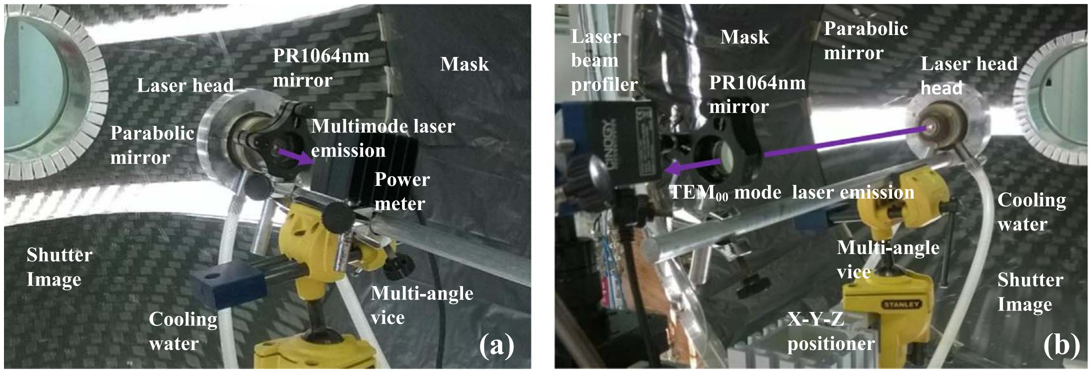

Fig. 2. (a) Laser head and output coupler were separated by 11 mm for producing the maximum multimode laser power (b) Laser head and output coupler were separated by 430 mm for the generation of TEM_{00}- mode laser power.

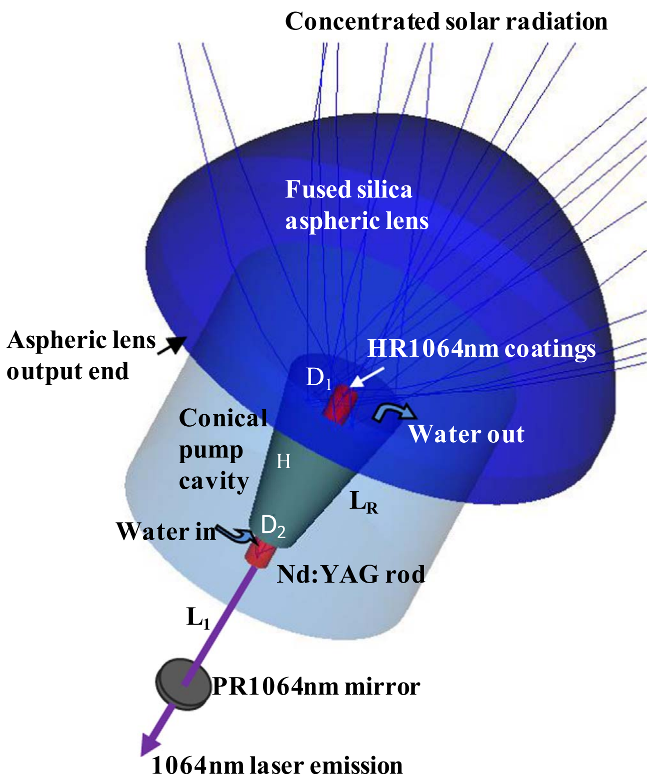

Fig. 3. Design of Nd: YAG laser head, composed of the fused silica aspheric lens, the conical pump cavity and the Nd: YAG rod, which were all actively cooled by water.

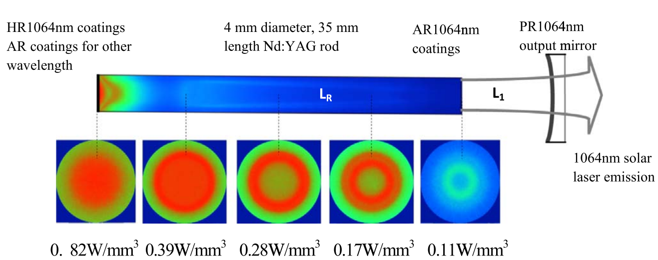

Fig. 4. Absorbed pump-flux distributions along both one longitudinal central cross-section and five transversal cross-sections of the 4 mm diameter, 35 mm length Nd: YAG rod, by end-side-pumping scheme in Fig. 3. 0.82 W/mm^3 0.39 W/mm^3 0.28 W/mm^3 0.17 W/mm^3 0.11 W/mm^3.

3. Numerical optimization of the design parameters by ZEMAX© and LASCAD© softwares

Similar to our previous numerical analysis on solar lasers [7,9,12,13,15], all the above mentioned design parameters of the solar laser system in Figs. 1–3 were firstly optimized by non-sequential ray-tracing (ZEMAX©) software for achieving the maximum absorbed pump power. The pump-flux distributions along both one longitudinal central cross-section and five transversal cross-sections in end-side-pumping configuration are given in Fig. 4. Red color means near maximum pump absorption, whereas blue means little or no absorption. Absorbed pump light distributions presented a strong non-uniform distribution along the laser rod, as shown by the central longitudinal absorbed pump flux distribution along the laser rod. Nevertheless, this was the distribution that ensured the maximum absorbed pump power by the rod. During ray-tracing, the 4 mm diameter, 35 mm length active medium was divided into 18,000 zones. The path length in each zone was found. With this value and the effective absorption coefficient of Nd:YAG material [15], the absorbed power within the laser medium was calculated by summing up the absorbed pump radiation of all zones. The absorbed pump flux data from the ZEMAX© analysis was then processed by LASCAD© software to optimize solar laser output performances.

Laser cavity design and analysis (LASCAD©) codes were then used to optimize laser output power and beam quality. The absorbed pump flux data from the ZEMAX© analysis was processed by LASCAD© software to optimize the laser resonator parameters. The stimulated emission cross-section of 2.8×10^{-19} cm^{-1}, the fluorescence life time of 230 μs and a typical absorption and scattering loss of 0.003 cm^{-1} for the 1.0 at% Nd:YAG medium were adopted in LASCAD© analysis. The mean absorbed and intensity-weighted solar pump wavelength of 660 nm was also used in the analysis. L_1 represents the separation length between the output end face anti-reflection (AR) 1064 nm coatings of the Nd:YAG rod and partial reflection (PR1064nm) output mirror, as shown in both Figs. 4 and 5. L_1 was the key parameter for achieving the highest fundamental mode power. PR1064nm mirrors of different reflectivity (R) and Radius of Curvature (RoC) were tested individually to optimize both multimode and TEM_{00}-mode laser power. For the 4 mm diameter, 1.0 at% Nd:YAG rod with L_R =35 mm, the amount of absorption and scattering losses was $2\alpha L_R$ =2.1%. Assuming 0.4% of imperfect HR and AR coating loss, the round-trip losses were increased to 2.5%. The diffraction losses depend heavily on rod diameter, resonator length and RoC of the resonator mirrors. LASCAD beam propagation method (BPM) gave 0.2% diffraction loss, resulting in a total round-trip loss of 2.7% for calculating the fundamental mode solar laser oscillation. For multimode laser operation, however, when the output coupler was placed very near the laser rod, the diffraction loss was less than 0.05%. Consequently, 37.8 W multimode solar laser power was numerically calculated for the optimized cavity length of L_1 =11 mm. The laser beam quality $M_x^2 \approx M_y^2$ =53.4 were numerically achieved for RoC =−10 m. 9.6 W TEM_{00}–mode laser power was numerically calculated with optimized cavity parameters of L_1 =430 mm, R =94% and RoC =−5 m for the PR1064nm mirror..

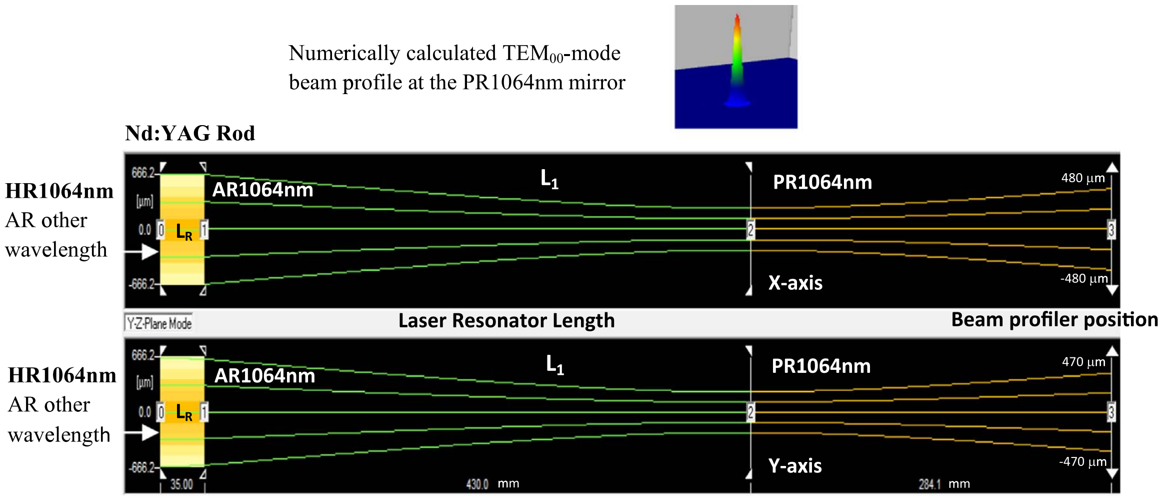

Fig. 5. Laser resonator configuration for the efficient extraction of fundamental mode solar laser power L_1 represents the separation length between AR1064 nm coatings and PR1064 nm mirror. Numerically calculated TEM_{00}-mode BPM beam profile at the PR1064 nm mirror is given in the inset image.

4. Multimode-mode continuous-wave solar laser oscillation

Based on the ZEMAX© and LASCAD© numerically optimized design parameters of the solar laser system in Section 3, a prototype solar laser was designed and built in Lisbon in the first half of 2016 and tested in the PROMES –CNRS during the month of July 2016. As shown in Figs. 4 and 5, the 4 mm diameter, 35 mm length Nd:YAG rod was HR1064nm coated (R ≥99.8%@1064 nm) on one end face and the other AR1064 nm coated (R ≤0.2% @1064 nm) on the other end face. To achieve maximum solar laser output power, a R =95%, RoC =−10 m output coupler was mounted 11 mm away from the AR 1064 nm output face of the laser rod, as indicated in Figs. 2a and 4. By varying the rotation angle of the shutter, different input solar power and output laser power were respectively measured with a Molectron PowerMax 500D and a Thorlabs PM1100D power meters respectively. Direct solar irradiance was measured simultaneously during laser with a Kipp & Zonen CH1 pyroheliometer on a Kipp & Zonen 2AP solar tracker. It varied between 950 W/m^2 and 1010 W/m^2 during the experiments. After considering all the shading effects in the primary concentrator, an effective collection area of 1.18 m^2 was adopted. For 1010 W/m^2 midday solar irradiance on 13th of July 2016, 700 W solar power was measured at the focus of the primary concentrator. Maximum multimode solar laser power of 37.2 W was successfully registered, corresponding to record-high collection efficiency of 31.5 W/m^2. This value is 5% more than the previous record of 30 W/m^2 by Fresnel lens direct solar tracking approach in 2012 [10]. Threshold laser power of 280 W was also measured, resulting in 8.9% solar laser slope efficiency which was 3.5% better than the previous record [10]. Considering the advantage of having a stable laser emission from a stationary solar laser head within the laboratory, rather than a solar laser head mounted onto a mobile solar tracker in outdoor environment [10], our solar laser might represent one-step further towards many interesting applications.

From Figs. 6, 8.9% solar laser slope efficiency was calculated for the R =95%, RoC =−10 m output mirror. This value represents an enhancement of 81.6% over the previous slope efficiency for Nd:YAG laser pumped by the same PROMES-CNRS solar facility [15]. Output mirror with R =94%, RoC =−5 m offered a slightly lower slope efficiency of 8.3%..

The laser beam quality factor – M^2 factors were measured according to ISO 11146-1 standards, by using a CINOGY UV-NIR beam profiler – CinCam CMOS. The measured solar laser beam profiles along the beam caustic are shown in Fig. 7a. The correspondingly solar laser beam widths, along with the extrapolated hyperbolic plot of the measured data, are given in Fig. 7b. For −10 m RoC output coupler,

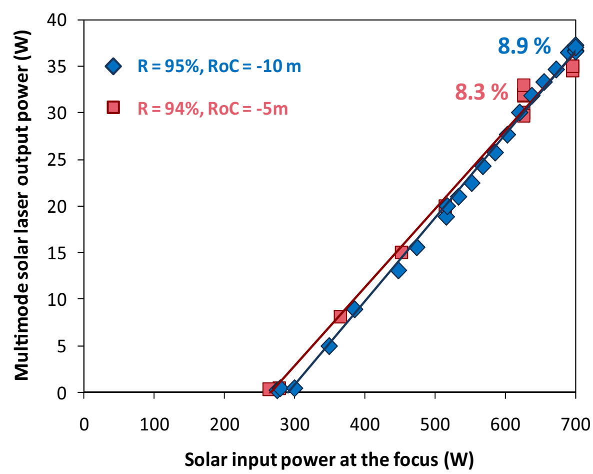

Fig. 6. Solar laser output power versus solar input power at the focus of the parabolic mirror, for R =95%, RoC =−10 m and R =94%, RoC =−5 m output couplers.

$M_x^2 \approx M_y^2$ =53.4 was experimentally determined, leading to laser beam brightness figure of merit of 0.013 W, two times higher than that of the previous record [10]..

5. TEM_{00}-mode continuous-wave solar laser oscillation

For 1.18 m^2 effective collection area and 1000 W/m^2 solar irradiance, the PROMES-CNRS heliostat- parabolic mirror system collected about 700 W solar powers to its focal zone. As mentioned in Section 3, the laser output powers and beam profiles at different L_1 were numerically optimized by LASCAD© software. In fundamental mode laser oscillation experiments, −5 m RoC output mirror with 94% reflectivity at L_1 =430 mm offered the maximum TEM_{00}-mode laser output power of 9.3 W, as shown in Fig. 8, when pumped by the maximum solar input power of 700 W, which matched well with the LASCAD© numerical simulation result of 9.5 W. 7.9 W/m^2 collection efficiencies were therefore calculated. The fundamental mode solar laser is designed to operate at the border of stability zone, as shown in Fig. 5. There were changes in the eigenmode radius of the cavity at the PR1064 nm mirror, which is caused by the thermal lensing effect of the laser rod. Both pump mode-laser mode overlap and diffraction loss at the PR1064 nm mirror depend on the thermal lensing effect and consequently on the pump intensity [14]. When there is a larger diffraction loss, the extracted power from the laser rod decreases, so that as thermal lensing effect get stronger until finally laser resonator

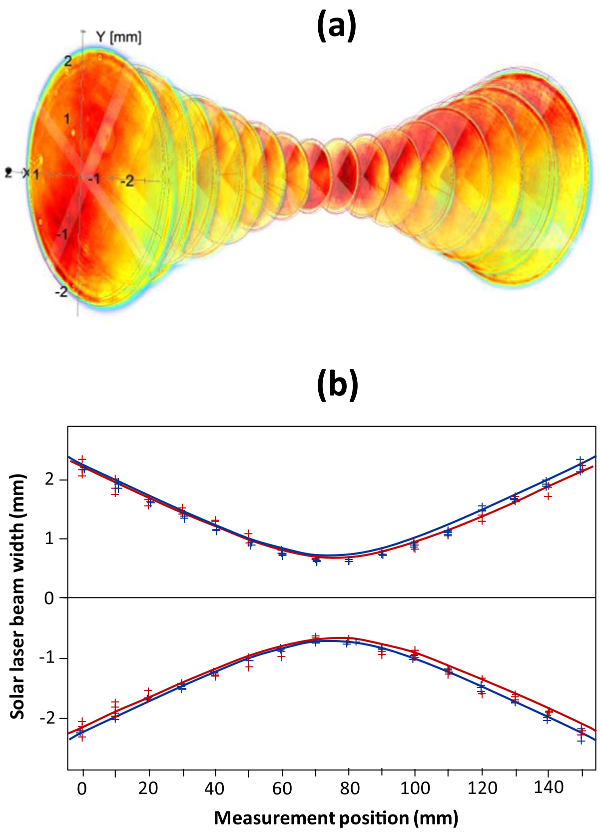

Fig. 7. (a) 2D and (b) caustic fit measurements of the multimode solar laser beam.

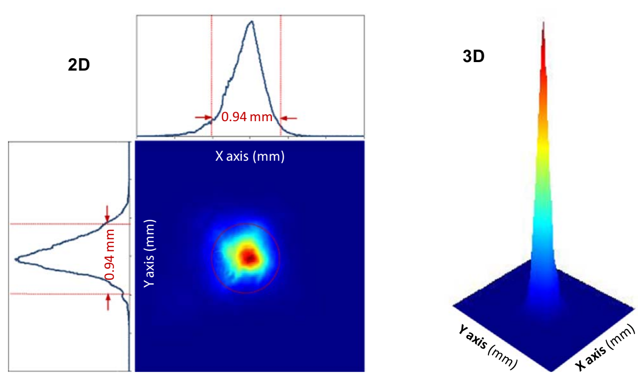

Fig. 8. Measured TEM_{00}-mode output laser beam 2D and 3D profiles 284 mm away from the PR1064 nm mirror.

became unstable and the laser stops oscillating. Since fundamental mode laser beam was at its highest flux level right at the PR1064nm output mirror, a CINOGY UV-NIR beam profiler - CinCam CMOS was placed 284 mm away from the mirror in order to avoid damaging the CMOS detector, as shown in Figs. 2b and 5. To measure the beam diameters at $1/e^2$ width under extremely high 1064 nm laser radiation, another 95% 1064 nm ROC =∞ output mirror was added before the CMOS detector, acting as an extra laser beam attenuator and reducing the 1064 nm laser power level only mW level for the detector. Considering the heliostat orientation error during laser emission, $M_x^2 \approx M_y^2 \leq 1.2$ were considered as adequate values for describing the laser beam quality in Fig. 8. Solar laser beam figure of merit was therefore calculated as 6.46 W, corresponding to 74% more than the previous record [10]. There were good agreement between the measured beam widths (0.94 mm) in Fig. 8 and the numerically analyzed ones (± 470–480 µm) at beam profiler position in Fig. 5..

6. Conclusions

The 37.2 W multimode, 9.3 W TEM_{00}-mode solar-pumped Nd:YAG laser was composed of the first-stage heliostat-parabolic mirror solar energy collection and concentration system, the second-stage fused silica aspheric lens and the third-stage conical-shaped pumping cavity, within which the 4 mm diameter, 35 mm length grooved Nd:YAG rod was efficiently pumped. Optimum optical pumping system design parameters were found through ZEMAX© software. Optimum solar laser power and beam parameters were found through LASCAD© numerical analysis. 37.2 W continuous-wave multimode solar laser power was firstly measured, corresponding to 31.5 W/m² multimode solar laser collection efficiency and 8.9% slope efficiency. By adopting the asymmetric large-mode laser resonant cavity, 9.3 W continuous-wave TEM_{00}-mode ($M^2 \leq 1.2$) solar laser power was measured. 7.9 W/m² TEM_{00}-mode collection efficiency is 2.6 times higher than the previous record by the Fresnel lens [12] and nearly 2 times higher than the previous record by the parabolic mirror [13]. Stable emission of the most efficient solar laser power from a stationary solar laboratory, both in multimode and fundamental mode regimes, could constitute one step further for many interesting applications for solar-powered lasers.

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