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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$_{oo}$-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$_{oo}$-mode (M^2 ≤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$_{oo}$-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 $\mathrm{TEM}_{\mathbf{OO}}$-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 $\mathrm{TEM}_{\mathbf{OO}}$-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 $\mathrm{TEM}_{\mathbf{OO}}$-mode ($M^2 \leq 1.2$) was then measured, corresponding to 7.9 W/m^2 $\mathrm{TEM}_{\mathbf{OO}}$-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.

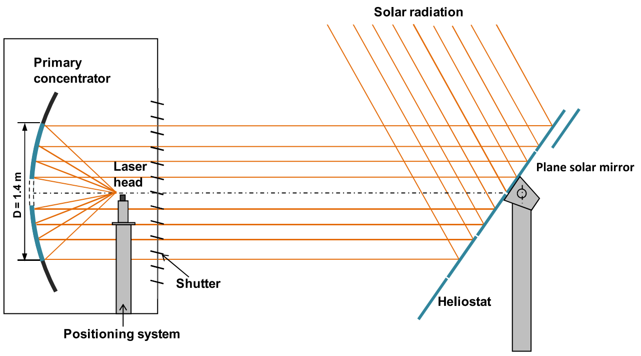

Fig. 1. Schematics of the PROMES – CNRS heliostat – parabolic mirror system for pumping a solar laser head.

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...