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Solar-Pumped TEM_{00} Mode Nd:YAG laser

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Abstract: Here we show a significant advance in solar-pumped laser beam brightness by utilizing a 1.0 m diameter Fresnel lens and a 3 mm diameter Nd:YAG single-crystal rod. The incoming solar radiation is firstly focused by the Fresnel lens on a solar tracker. A large aspheric lens and a 2D-CPC concentrator are then combined to further compress the concentrated solar radiation along the thin laser rod within a V-shaped pumping cavity. 2.3 W cw TEM_{00} ($M^2 \leq 1.1$) solar laser power is finally produced, attaining 1.9 W laser beam brightness figure of merit, which is 6.6 times higher than the previous record. For multimode operation, 8.1 W cw laser power is produced, corresponding to 143 % enhancement in collection efficiency.

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OCIS codes: *(140.0140) Laser and laser optics; (140.3570) Lasers, single-mode; (140.3410) Laser resonators; (140.3530) Lasers, neodymium.*

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1. Introduction

The conversion of sunlight into laser light by direct solar pumping is of ever-increasing importance because broadband, temporally constant, sunlight is converted into laser light, which can be a source of narrowband, collimated, rapidly pulsed, radiation with the possibility of obtaining extremely high brightness and intensity. Nonlinear processes, such as harmonic generation, might be used to obtain broad wavelength coverage, including the ultraviolet wavelengths, where the solar flux is very weak. The direct excitation of large lasers by sunlight offers the prospect of a drastic reduction in the cost of coherent optical radiation for high average power applications. Up to now solar pumped lasers have not been viewed from this perspective. Among the potential applications of solar lasers are earth, ocean, and atmospheric sensing; detecting, illuminating, and tracking hard targets in space; deep space communications. Renewable solar lasers are also very promising for many terrestrial applications. The first solar-pumped solid-state laser was reported by Young in 1966 [1]. Since then, researchers have been improving constantly the solar laser performance [2-10]. The most-widely used Nd:YAG single-crystal material has been demonstrated as an excellent material under solar pumping because of its superior thermal conductivity, high quantum efficiency and mechanical strength characteristics compared to other host materials [6-10]. Significant solar laser collection efficiencies have been achieved by end-pumping small diameter Nd:YAG single-crystal rods [6]. The most recent Nd:YAG solar laser has produced the record collection efficiency of 30.0 W/m^2 with a large diameter Nd:YAG rod [7]. However, brightness is one of the most important parameters of a laser beam. It is given by the laser power divided by the product of the beam spot area and its solid angle divergence. This product is proportional to the square of beam quality factor M^2. Brightness figure of merit is thus defined [4] as the ratio between laser power and the product of M_x^2 and M_y^2. The highest brightness figure of merit of an end-pumped solar laser with Fresnel lens is 0.086 W [6]. Despite the successful production of 120 W cw solar laser power, very large beam quality factors, $M_x^2 = M_y^2 = 137$, have also been measured [7], resulting in only 0.0064 W brightness figure of merit. Although the most efficient laser systems have end-pumping approaches, side-pumping is an effective configuration for power scaling as it gives uniform absorption along the rod axis and spreads the absorbed power along the laser rod, reducing the associated thermal loading problems. Besides, the free access to both rod ends allows the optimization of more laser resonator parameters, improving largely laser beam quality. The record brightness figure of merit of 0.29 W has been achieved by side-pumping a 4 mm diameter, 30 mm length Nd:YAG rod, by a heliostat-parabolic mirror solar energy collection and concentration system [8].

Because of its smooth intensity profile, low divergence and ability to be focused to diffraction-limited spot, it is highly desirable to operate a solar-pumped laser in the lowest-mode possible: $\mathbf{TEM_{00}}$ mode. Unfortunately, to the best of our knowledge, there is still no report on the successful production of $\mathbf{TEM_{00}}$ solar laser power by a Fresnel lens. A substantial progress in solar laser beam brightness with the Fresnel lens is reported here. The incoming solar radiation from the sun is efficiently compressed onto the 3 mm diameter, 30 mm length Nd:YAG rod by a series of optical concentrators: the first-stage Fresnel lens, the second-stage large fused silica aspheric lens, the third-stage 2D-CPC (Compound Parabolic Concentrator) concentrator [12] and finally the V-shaped pumping cavity. 2.3 W cw $\mathbf{TEM_{00}}$ laser power ($M^2 \leq 1.1$) is successfully produced, corresponding to 1.9 W beam brightness figure of merit, which is 6.6 times larger than the previous record [8]. The $\mathbf{TEM_{00}}$ laser power collection efficiency also reaches 2.93W/m^2.

2. $\mathbf{TEM_{00}}$ mode Nd:YAG solar laser pumping approach

As shown in Fig.1, the solar-pumped $\mathbf{TEM_{00}}$ mode Nd:YAG laser system is composed of the first-stage 1.0 m diameter Fresnel lens, the laser head and its associated asymmetric optical resonator, all mounted on a two-axis solar tracker that follows automatically the Sun´s movement. The two-axis solar tracker is supplied by Shandong Huayi Sunlight Solar Energy Industry Co., Ltd. The Fresnel lens is supplied by Shandong Yuying Optical Instruments Co., Ltd. The Fresnel lens has 1.3 m focal length. The measured transmission efficiency is 76%. The concentrated solar power at the focal spot averaged over 2 min is 590 W for 890 W/m^2 solar irradiance. The measured full width at half maximum is 13 mm at the minimum focal waist. Mechanical adjustments in X-Y-Z directions allow an easy alignment in the focal zone. Coarse angular adjustments are also very helpful for achieving the maximum laser output power.

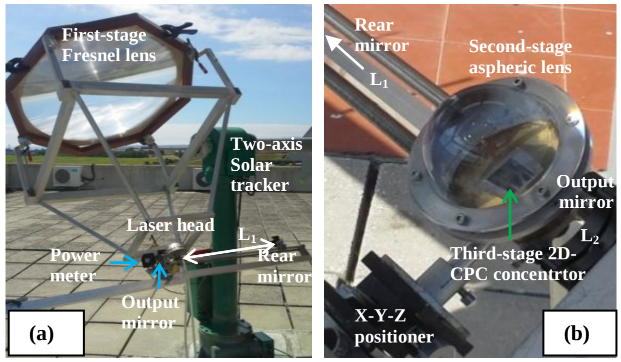

Fig.1. (a) The solar-pumped TEM_{00} mode Nd:YAG laser system (b) The laser head.

The laser head is composed of the second-stage large fused silica aspheric lens, the third-stage 2D-CPC concentrator and the V-shaped pumping cavity within which the Nd:YAG rod is mounted. The large curved input face of the aspheric lens, the dimensions of the 2D-CPC concentrator is designed to compress the concentrated solar radiations from the focal zone onto the thin laser rod. To manufacture the large aspheric lens, an 85 mm diameter, 50 mm length fused silica rod of 99.999% optical purity from Beijing Kinglass Quartz Co., Ltd. is ground and polished to its final dimensions. The aspheric input face has 43 mm radius and r^2 rear parameter of -0.0005. The third-stage 2D-CPC concentrator has 18 mm × 23 mm large rectangular input aperture, 8 mm × 23 mm narrow rectangular output aperture and is 10 mm in height, as shown in both Fig. 1(b) and Fig. 2. The 2D-CPC is used to convert the rays from 18 mm × 23 mm large-aperture emitting into a small angle, 25° for example, to 8 mm × 23 mm small-aperture emitting into a large angle, 70° for example, thus the source étendue is preserved. This preservation implies that irradiance is larger at output aperture than at the entrance aperture, leading to a net concentration of the pump radiation [11, 12]. The V-shaped cavity is finally used to achieve an efficient multi-pass absorption of the highly concentrated pump radiation from the 8 mm × 23 mm output aperture. The inner walls of both the 2D-CPC hollow concentrator and the V-shaped pumping cavity are bonded with a protected silver-coated aluminum foil with 94% reflectivity. Distilled water with 6 Liter / min flow rate cools firstly the rod within the V-shaped cavity, then passes through the 2D-CPC concentrator and exits the laser head, as illustrated by Fig. 2. All the above optimized design parameters of the whole optical system are found by both non-sequential ray-tracing (ZEMAX^{TM}) and laser cavity design and analysis (LASCAD^{TM}) codes.

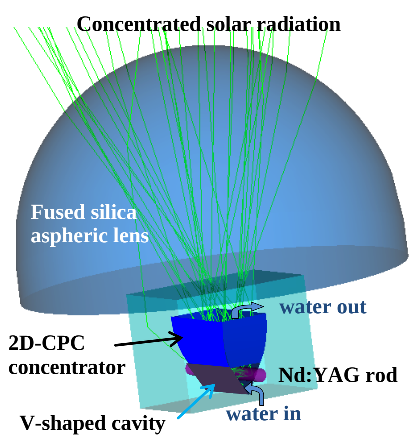

Fig. 2. Detailed 3D view of the solar laser head.

3. Solar laser oscillation experiments

3.1 Multimode solar laser oscillation with a symmetric optical resonator

For the solar irradiance of 890 W/m^2 in Lisbon area in July 2013, a 1.08 m diameter Fresnel lens collects about 580 W solar powers to its focal zone. The 3 mm diameter, 30 mm length Nd:YAG single-crystal rod is supplied by Altechna Co., Ltd. It has 1.0% Nd^{3+} concentration. Both ends of the rod are AR coated (R < 0.2% @ 1064 nm). The 300 mm length symmetric optical resonator is comprised of two opposing concave-concave mirrors at right angles to the optical axis of the rod. The rear mirror is high reflection coated (HR, 99.8% @ 1064 nm), while the output mirror is partial reflection coated (PR, 94%). A -0.8 m RoC (Radius of Curvature) output mirror with 94% reflectivity and a -2 m RoC rear mirror combination offers the maximum laser output power of 8.1 W, corresponding to the collection efficiency of 8.8 W/m^2, which is 1.43 times larger than the previous record of 6.2 W/m^2 [10]. The threshold solar power of about 220 W is measured in the focal zone. 2.35% slope efficiency is hence calculated. The concentrated solar power at the entrance face of the large aspheric lens and output laser power are respectively measured with a Molectron PowerMax 500D and a Thorlabs PM1100D laser power meters. Despite the enhanced laser output power, a large laser beam divergence of about 4 mrad is measured during the experiment. To enhance the laser beam quality, a large symmetric cavity with a -5 m RoC rear mirror positioned at L_1 = 387.5 mm and a -5 m RoC output mirror positioned at L_2 = 387.5 mm is tested. The maximum laser output power is reduced to 4.2 W, due to the high diffraction loss caused by both the 3 mm rod aperture and the large $L_T = L_1 + L_2$ = 775 mm optical resonator. Since our laboratory is based on the large open terrace of a building, the laser beam quality factors are determined by the measurement of the beam diameter at 1/e^2 at both a near-field position (40 mm from the output coupler) and a far-field position (6000 mm from the output coupler, nearly 8 times of L_T). A CINOGY UV-NIR beam profiler — CinCam CMOS is used to measure the laser beam diameters at 1/e^2 width. The laser beam divergence θ is found by adopting the Eq. (1):

$$\arctan\theta = (\phi_2 - \phi_1)/2L \qquad (1)$$

Where ϕ_1 and ϕ_2 mm are the measured laser beam diameters at 1/e^2 width, 40 mm and 6000 mm away from the output mirror respectively and L is the distance between these two points. M^2 factor is then calculated by Eq. (2):

$$M^2 = \theta/\theta_0 \qquad (2)$$

Where $\theta_0 = \lambda/\pi\omega_0$ is the divergence of diffraction-limited Gaussian beam for λ =1.064 μm and ω_0 = 650 μm, as calculated by LASCAD© laser beam propagation method for the 3 mm diameter, 30 mm length rod. This value can be also calibrated by measuring the laser beam diameter at 1/e^2 width, 40 mm from the output coupler, as indicated by Fig.4. The laser beam quality factors of $M_x^2 \approx M_y^2$ = 3.2 can then be determined for the L_T = 775 mm, L_1 = 387.5 mm symmetric resonator. Despite the large reduction in output laser power, from 8.1 W to 4.2 W, its laser beam brightness figure of merit is increased to 0.41 W, as calculated by Eq. (3), surpassing the previous record by 1.4 times [8].

$$P_{Laser}/M_x^2 M_y^2 \qquad (3)$$

3.2 Fundamental mode solar laser oscillation with an asymmetric optical resonator

The absorbed pump flux data from the ZEMAX© analysis is processed by LASCAD© software for laser beam parameters analysis. The asymmetric optical resonator is found to be the best configuration for achieving fundamental mode laser operation. The cavity with a -5 m RoC rear mirror (HR 99.8%) positioned at L_1 = 675 mm and a -5 m RoC output mirror (PR 94%) positioned at L_2 = 100 mm offers the best **TEM_{00}** laser beam profile by

LASCAD© beam propagation method. It is worth noting that no TEM_{00} laser beam profile can be obtained by the previous symmetric resonator even with L_T = 775 mm.

For the solar irradiance of 890 W/m^2 in Lisbon area in August 2013, the 1.0 m diameter Fresnel lens collects about 550 W solar powers to its focal zone. The same 3 mm diameter, 30 mm length Nd:YAG rod is used to test its laser output performance of the asymmetric optical resonator, as shown in Fig. 1. It is comprised of two opposing concave-concave mirrors at right angles to the optical axis of the rod. The rear mirror is high reflection coated (HR, 99.8%), while the output mirror is partial reflection coated (PR, 94%). The output mirror is fixed at L_2 = 100 mm from the center of the laser rod, while the HR rear mirror can be positioned at L_1 = 100 mm to 675 mm from the center. The -5 m RoC rear mirror at L_1 = 675 mm and the -5 m RoC output mirror at L_2 = 100 mm combination provides the most favorable TEM_{00} solar laser beam profile, as shown in Fig. 4. Usually L_2 is fixed at 100 mm, the laser output powers and beam profiles for different L_1 (L_1 = 100 mm, 200 mm, 300 mm, 400 mm, 500 mm, 600 mm, 625 mm, 650mm, 675 mm respectively) are firstly analyzed by LASCAD© software and then confirmed by detailed measurements during the first 20 days of August, 2013, as given by Fig. 3.

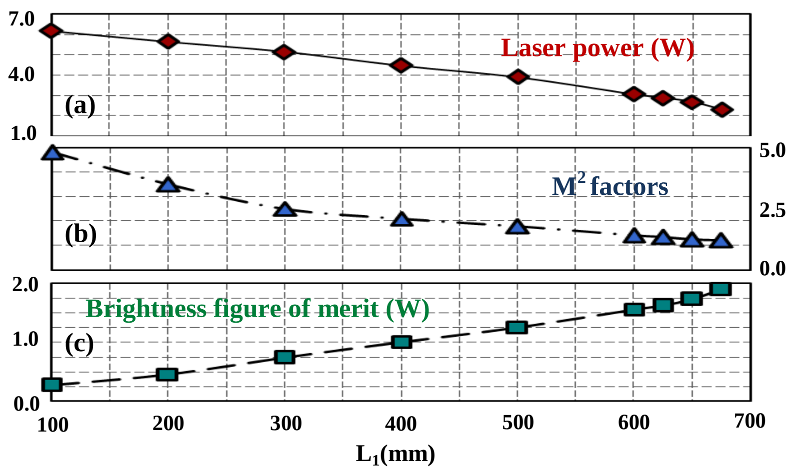

Fig. 3. Dependence of (a) laser power, (b) M^2 factor and (c) brightness figure of merit on resonator length L_1 is measured.

The laser output power decreases with the increase in L_1. The M^2 factor also decreases with the increase in L_1. The beam brightness figure of merit increases nearly linearly with the increase in L_1. On the one hand, 6.2 W solar laser power, M^2 = 4.8 are obtained for L_1 = 100 mm, resulting in 0.27 W brightness figure of merit; on the other hand, 2.3 W TEM_{00} ($M^2 \leq 1.1$) fundamental mode laser power is finally measured for L_1 = 675 mm, corresponding to the highest brightness figure of merit of 1.9 W.

Plots of the measured near-field laser beam output pattern (40 mm from the output coupler) are shown in Fig. 4. A close examination of the TEM_{00} mode shows that it differs slightly in laser beam diameters at 1/e^2 along both X and Y axis. The experimental TEM_{00} mode is slightly elliptical with axes 3 % and 9 % larger than the mode diameter of the empty resonator Gaussian mode. The ellipticity is caused by the slight change in absorbed pump distribution within the laser rod, caused by the slight misalignment between the laser head and the optimized focal position of the Fresnel lens. The measured average near-field laser beam diameter is 1.44 mm, as indicated by Fig. 4.

The far-field output pattern (6000 mm from the output coupler) represents also a good TEM_{00} Gaussian mode profile. The measured average laser beam diameter at 1/e^2 width at the far-field is 8.15 mm. Since L = 5960 mm, M^2 factor can be easily determined as 1.09 by using the Eq. (1-3). Considering both the solar tracking error and the laser head misalignment error during the laser emission, $M^2 \leq 1.1$ is finally considered as the final value of our solar laser beam quality factor.

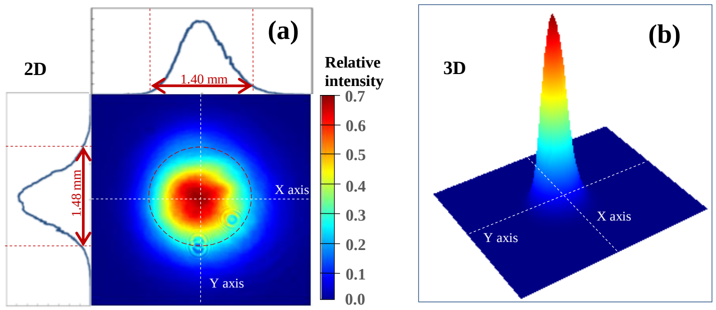

Fig. 4. Measured output laser 2D (a), 3D (b) beam profiles, 40 mm away from the output coupler.

4. Conclusions

The novel TEM_{00} solar laser system is composed of the first-stage Fresnel lens, the second-stage fused silica aspheric lens and the third-stage 2D-CPC concentrator. Finally the V-shaped pumping cavity is used to efficiently pump the 3 mm diameter, 30 mm length Nd:YAG rod. Optimum optical system design parameters in Section 2 are found through ZEMAX© software. Optimized solar laser power and beam parameters in Section 3 are found through LASCAD© numerical analysis. By adopting the large asymmetric concave-concave optical resonator, 2.3 W cw TEM_{00} ($M^2 \leq 1.1$) fundamental mode solar laser power is measured, corresponding to 1.9 W laser beam brightness figure of merit, which is 6.6 times larger than the previous record. The TEM_{00} laser power collection efficiency reaches 2.93 W/m^2. The solar laser output power, the M^2 factors and consequently the laser beam brightness figure of merit are strongly dependent on the laser cavity length L_1. These dependences are studied experimentally. Besides, the maximum side-pumped Nd:YAG solar laser power of 8.1 W is also obtained by using the compact 300 mm symmetric optical resonator, resulting in 143% enhancement over the previous record.

Acknowledgements

These research projects (PTDC/FIS/103599/2008 and PTDC/FIS/122420/2010) were funded by the Science and Technology Foundation of Portuguese Ministry of Science**,** Technology and Higher Education (FCT-MCTES).