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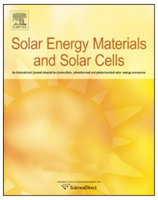

Solar-pumped TEM_{00} mode Nd:YAG laser by a heliostat—Parabolic mirror system

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ABSTRACT

Here we report a significant advance in solar-pumped laser beam brightness by pumping a 3 mm diameter Nd:YAG single-crystal rod with a heliostat-parabolic mirror system. The incoming solar radiation is first collected and focused by the system. A rectangular fused silica light guide and a 2D-CPC concentrator are then combined to further compress the concentrated solar radiation into the laser rod within a V-shaped pumping cavity. 4.4 W continuous-wave $\mathbf{TEM_{00}}$ mode ($M^2 \leq 1.05$) 1064 nm solar laser power is finally produced, attaining 4.0 W laser beam brightness figure of merit, which is 2.1 times higher than the previous record by a Fresnel lens. 0.81% $\mathbf{TEM_{00}}$ mode laser slope efficiency is achieved.

1. Introduction

The conversion of sunlight into laser light by direct solar pumping is of ever-increasing importance because broadband sunlight is converted into laser light, which can be a source of narrowband, collimated, rapidly pulsed, radiations with the possibility of obtaining extremely high brightness and intensity. Among the potential applications of solar lasers are earth, ocean, and atmospheric sensing; laser beaming; deep space communications. Renewable laser has also a large potential for many terrestrial applications, e.g. high-temperature materials processing, magnesium–hydrogen energy cycle and so on. All the above mentioned applications can be feasible with high-beam-quality, most preferably, $\mathbf{TEM_{00}}$ mode solar-pumped laser [1]. The direct excitation of large lasers by sunlight also offers the prospect of a drastic reduction in the cost of coherent optical radiation for high average power applications, leading to numerous environmental and economical benefits.

Since the sunlight does not provide enough flux to initiate laser emission, additional focusing systems are needed to both collect and concentrate the solar radiation to excite laser medium. Parabolic mirrors have long been explored by Young [2] and other researchers [3–7] to achieve tight focusing of incoming solar radiation. Large-size Fresnel lens solar pumping has become popular in recent years [8]. 19.3 W/m^2 collection efficiency was achieved by exciting a 4 mm diameter, 25 mm length Nd:YAG single-crystal rod with a 0.64 m^2 Fresnel lens [9]. Record-high collection efficiency of 30.0 W/m^2 was attained by pumping a 6 mm diameter, 100 mm length Nd:YAG rod with a 4 m^2 Fresnel lens. However, very large $M_x^2 = M_y^2 = 137$ factors have been associated with this approach [10], resulting in a dismal laser beam brightness figure of merit – defined as the ratio between laser power and the product of M_x^2 and M_y^2 [6] – of only 0.0064 W. Because of its smooth intensity profile, very low divergence and ability to be focused to a diffraction-limited spot, it is highly desirable to operate a solar-pumped laser in the lowest-mode possible: $\mathbf{TEM_{00}}$ mode. A substantial progress in solar laser beam brightness with the Fresnel lens was reported in 2013 [1,11]. The incoming solar radiation was efficiently focused into the 3 mm diameter, 30 mm length Nd:YAG rod by a series of optical concentrators: a first-stage Fresnel lens, a second-stage large fused silica aspheric lens, a third-stage 2D-Compound Parabolic Concentrator (2D-CPC) and finally a V-shaped pumping cavity. 2.3 W continuous-wave $\mathbf{TEM_{00}}$ mode solar laser power ($M^2 \leq 1.1$) was produced, corresponding to 1.9 W laser beam brightness figure of merit.

As mentioned above, Fresnel lenses have attracted much more attentions in recent years [8–11]. However, a solar laser head pumped by a Fresnel lens usually moves together with the whole solar tracking structure, an optical fiber thus becomes inevitable for the transportation of solar laser radiation to a desirable place outside the focal zone. Beside a lot of practical inconveniences, fiber optic transmission loss occurs, which will degrade the collection efficiency of the whole solar laser system. Heliostat-parabolic mirror solar energy collection and concentration systems

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are comparatively neglected in recent years, resulting only in a slow progress in solar laser beam brightness figure of merit from 0.086 W in 2003 [6] to 0.29 W in 2012 [12]. The advantage of a fixed laser head at the focus of a stationary parabolic mirror becomes much more pronounced for applications such as laser beaming and material processing. It is therefore very meaningful to largely enhance the solar laser brightness of a heliostat-parabolic mirror system. Unfortunately, to the best of our knowledge, there is still no report on high-brightness solar laser oscillation by this system. The radiation transmission and homogenization capacity of the rectangular fused silica light guide is combined with the light focusing properties of both the 2D-CPC concentrator and the V-shaped cavity to provide efficient side-pumping to the 3 mm diameter 1.0 at% Nd:YAG rod. 4.4 W continuous-wave $\mathbf{TEM_{00}}$ mode solar laser power ($M^2 \leq 1.05$) is measured, corresponding to 2.1 times enhancement in brightness figure of merit over the previous record by a 0.95 m^2 Fresnel lens [11]. It is also 13.8 times higher than the previous record with the same PROMES-CNRS solar facility [12]. To the best of our knowledge, this is the first report on $\mathbf{TEM_{00}}$ mode continuous-wave solar laser operation with the heliostat-parabolic mirror system.

2. Solar-pumped TEM$_{00}$ mode Nd:YAG laser by the heliostat-parabolic mirror system

2.1. Solar energy concentration by the PROMES-CNRS heliostat-parabolic system

A plane mirror with 36 segments (0.5 m × 0.5 m each) is mounted on a two-axis heliostat which redirects the incoming solar radiation towards the 2.0 m diameter PROMES-CNRS stationary parabolic mirror, as illustrated in Fig. 1. After considering the shading effects of a shutter, two *X*–*Z* axis mechanical supports and an asymmetrical solar laser cavity, as shown in Fig. 2, 2.3 m^2 effective collection area is attributed to the parabolic mirror. All the mirrors are back-surface coated with silver, so only 59% of incoming solar radiation is focused to the focal zone, 0.85 m away from the center of the parabolic mirror. For typical clear sunny days with an average solar irradiance of 950 W/m^2 in Odeillo, about 1.29 kW solar power can be focused into a near-Gaussian light spot with 10 mm full width at half maximum (FWHM).

2.2. Rectangular fused silica light guide

The asymmetric laser resonant cavity, as shown in Fig. 2, is fixed on an *X*–*Z* axis positioner which is mounted on another automatic *X*–*Z* axis mechanical support by using a multi-angle vice, ensuring therefore an accurate optical alignment in the focal zone. The asymmetric cavity is also tilted upward so that the laser emission can be directed to a safe place near the laboratory ceiling, 6.0 m away from the output mirror. The solar laser head is composed of the rectangular fused silica light guide, the 2D-CPC secondary concentrator and the V-shaped pump cavity, as indicated in Fig. 3. The concentrated solar radiation at the focus of the parabolic mirror is first collected by the light guide with 10 mm × 15 mm input end and guided to its 12 mm × 18 mm output end. To manufacture the light guide, a fused silica rod of 99.999% optical purity, with 12 mm × 18 mm rectangular cross section and 100 mm length, is ground and polished to its final dimension. The slightly inclined side faces of the guide ensure an easy mechanical fixing of the guide to the laser head. The measured transmission efficiency of the light guide is 82%. Heliostat orientation errors usually move the center of the absorption distribution within the laser rod, resulting in both a lower laser output power and a non-uniform beam profile. The light guide with rectangular cross-section is essential to overcoming this problem, serving as a beam homogenizer by transforming the near-Gaussian profile of the concentrated light spot at its input end into a uniform pump light distribution at its output end [13]. Uniform absorbed pump distribution along the laser rod is achieved. Despite the slight shift of the focal spot at the input face, caused by the orientation error of the heliostat, a uniform distribution in pump flux is still observed at the output end. The absorbed pump profile within the rod, and hence the laser power, is not significantly affected.

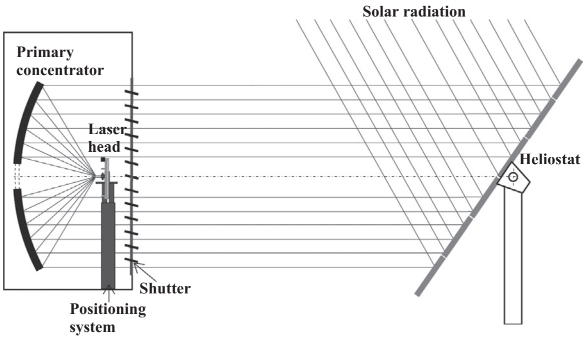

Fig. 1. Scheme of the PROMES – CNRS heliostat – parabolic mirror system.

2.3. The 2D-CPC secondary concentrator and the V-shaped pump cavity

The 2D-CPC concentrator has 14 mm × 20 mm rectangular large-input-aperture, 8 mm × 20 mm small-output-aperture and is 10 mm in height, as shown in Fig. 3. The 2D-CPC is used to convert the rays from the large-input-aperture emitting into a small angle, 35° for example, to the small-output-aperture emitting into a large angle, 60° for example, thus the source étendue is preserved [14]. This preservation implies that irradiance is larger at the output aperture than at the input aperture, leading to a net concentration of the pump radiation. The 60° V-shaped cavity is finally used to achieve an efficient absorption of the highly concentrated pump radiation from the 8 mm × 20 mm small-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 l/min flow rate cools first the rod within the V-shaped cavity, then passes through the hollow 2D-CPC concentrator and exits the laser head from the space between the light guide and the large-input-aperture of the 2D-CPC concentrator. Cooling water also ensures an efficient light coupling from the guide to the rod. All the above optimized design parameters of the whole laser system are found by both non-sequential ray-tracing (ZEMAX^{TM}) and laser cavity design and analysis (LASCAD^{TM}) codes.

3. TEM$_{00}$ mode continuous-wave solar laser oscillation

For 2.3 m^2 effective collection area and 915 W/m^2 solar irradiance, the heliostat parabolic mirror system collects 1240 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 output mirror is fixed at $L_1 = 100$ mm from the rod center, while the HR rear mirror can be positioned at $L_2 = 100$ mm to 600 mm from the rod center, as shown in Fig. 2. The rear mirror is high reflection coated (HR, 99.8% @ 1064 nm), while the output mirror is partial reflection coated (PR, usually 90–98%). For $L_1 = 100$ mm, the laser output powers and beam profiles at different L_2 are first numerically analyzed by LASCAD© software and then confirmed by the measurements in July, 2014. TEM_{00} laser output power for a −5 m RoC (Radius of Curvature)