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High-efficiency solar laser pumping by a modified ring-array concentrator

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ABSTRACT

To considerably improve solar laser efficiency, a 5.5 mm diameter 20 mm length Nd:YAG single-crystal rod can be efficiently pumped by highly concentrated solar radiation through a modified ring-array concentrator. Composed of several coaxial parabolic reflective rings and a small diameter Fresnel lens, the 1.5 m diameter modified ring-array concentrator can focus tightly incoming solar radiation into a 5.0 mm full width at half maximum focal spot. An innovative aspherical fused silica concentrator allows further pump light concentration into the Nd:YAG rod at the focal zone. A simple water cooling scheme within the aspherical concentrator constitutes another highlight of this scheme. Strong dependency of solar laser power on the rim angle of the ring-array concentrator was found through ZEMAX™ and LASCAD© analyses. 67.8 W continuous-wave 1064 nm solar laser power at 38.4 W/m^2 collection efficiency was numerically calculated, being 1.22 times more than the previous record. Besides, 1.29, 1.03 and 1.85 times improvements in conversion, slope efficiencies and brightness figure of merit, respectively, were numerically achieved. The tracking error influence on solar laser output power was numerically calculated.

1. Introduction

Sun-powered lasers are highly desirable in providing cost-effective coherent laser radiation in an environmentally friendly way, especially in places where the Sun is abundant and other energy sources are scarce. Therefore, achieving narrow-band solar laser radiation through its direct conversion from broad-band sunlight with high efficiency is a major goal for many laser applications such as deep space communications or atmospheric and ocean sensing [1].

For the last fifty years, several researchers [2–7], starting with Young in 1966 [2], have used parabolic mirrors to highly concentrate incoming sunlight into a laser medium. In 1984, H. Arashi et al. have successfully obtained 18 W multimode laser emission by pumping a 4 mm diameter, 75 mm length Nd:YAG single-crystal rod within a water-cooled flow tube in the focus of a 78.5 m^2 parabolic reflector, attaining 0.23 W/m^2 collection efficiency [4]. Later, in 2003, M. Lando et al. increased the solar laser collection efficiency to 6.7 W/m^2 by using a primary parabolic mirror and a secondary compound parabolic concentrator (CPC) to pump a 6 mm diameter, 72 mm length Nd:YAG rod [6].

By using Fresnel lenses for solar laser pumping, significant progresses were achieved in the last ten years with several pumping approaches [8–12]. In 2007, T. Yabe et al. reached a collection efficiency of 18.7 W/m^2 by pumping a 3–9 mm diameter and 100 mm length Cr:Nd:YAG ceramic laser rod through a 1.4 m^2 Fresnel lens [8]. In 2011, D. Liang and J. Almeida achieved 19.3 W/m^2 collection efficiency by pumping a 4 mm diameter, 25 mm length Nd:YAG crystal rod through a 0.64 m^2 Fresnel lens, revitalizing the great usefulness of Nd:YAG medium [9]. One year after, T. Dinh et al. achieved 30.0 W/m^2 collection efficiency by using a 6 mm diameter, 100 mm length Nd:YAG crystal rod pumped through a 4 m^2 Fresnel lens [10]. However, only 0.0064 W laser beam brightness figure of merit, defined as the ratio between laser power and the product of $M_x{}^2$ and $M_y{}^2$ factors [6], was achieved [10]. In 2017, D. Liang et al. attained a new record of 31.5 W/m^2 solar laser collection efficiency by end-side-pumping a 4 mm diameter, 35 mm length Nd:YAG through a heliostat–parabolic mirror system in Procédés, Matériaux et Énergie Solaire — Center National de la Recherche Scientifique (PROMES-CNRS) [13]. However, with the heliostat–parabolic mirror combination, shadows from laser cavity and its mechanical supporting structure reduces the effective solar energy collection area.

Ring-array solar concentrator (RAC) design concept was introduced by V. Vasylyev and S. Vasylyev. It consists of a set of parabolic reflective rings mounted coaxially to avoid shading effect from either incoming or reflected light among parabolic rings. Its focal spot in the rear side of the collector is created by superposition of rays from the reflective rings [14]. This configuration allows efficient combination of components, reducing the shadow areas between incoming solar rays and the laser head, as compared with the heliostat–parabolic mirror system. The RAC also has no chromatic aberration along its focal zone, providing higher solar concentration efficiencies as compared with Fresnel lenses.

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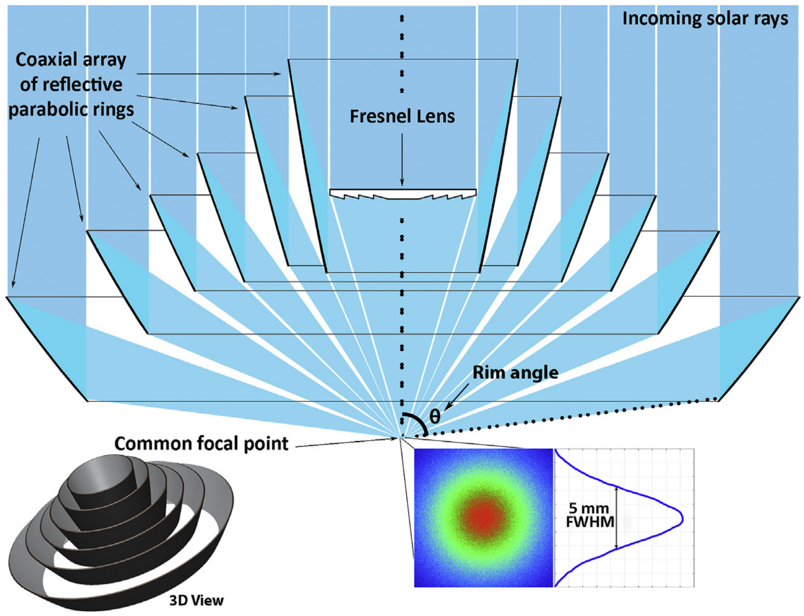

Fig. 1. Longitudinal cut of the six parabolic reflectors ring-array with a small Fresnel lens. Pump light distribution at the common focal point has 5.0 mm FWHM diameter.

A novel 1.5 m diameter RAC with short focal length is proposed to pump efficiently a solar laser head through tight focusing, enabling a compact solar laser design. Additionally, as a modified version of classical RAC, a small Fresnel lens was added in the center of the assembly. The laser head is composed of the aspherical fused silica concentrator, the Nd:YAG rod and a pump cavity. The solar laser design and its output parameters were optimized through Zemax™ and LASCAD© numerical analyses. Both analytical and numerical analyses were made to ensure the optimized laser output performances. 67.8 W continuous-wave solar laser power was numerically attained, corresponding to 38.4 W/m^2 collection efficiency, 1.22 times more than the previous record [13].

The most popular Nd:YAG crystal rod was used in this study, due to its excellent thermal conductivity, high quantum efficiency and tensile strength, making it a good candidate to produce solar laser radiation efficiently. It is also worth noting that the proposed RAC solar laser scheme is also valid for pumping other solar laser materials such as Cr:Nd:YAG ceramic medium [8], Nd:Ce:YAG [15], Alexandrite single-crystal media [16]. Composite laser rods such as YAG–Nd:YAG–YAG undoped–doped–undoped, and Nd:YAG grooved rods [17] can all be successfully pumped in the focal zone of the modified RAC solar concentrator. High solar laser efficiencies can be expected by pumping the above-mentioned laser media by our proposed compact RAC solar laser pumping approach.

2. Modified ring-array assembly

Together with the light refractions by the small Fresnel lens, the proposed RAC assembly provides a compact solar laser system since it is based on single reflection on each parabolic surface as indicated by Fig. 1. Solar rays from each parabolic ring with proper radius superimposes on a single 5.0 mm full width at half maximum (FWHM) diameter near Gaussian focal spot. To achieve the maximum solar concentration efficiency and to avoid shading effect, the number of rings, the radius and spacing between each ring were optimized by ZEMAX™ optical design software.

In Fig. 2 is represented the entire assembly in two different perspectives and dimensions for the six RAC rings, from the larger one with 1500 mm diameter to the smaller one with 280 mm diameter. The RAC assembly is 655 mm in height. Each ring is silver-coated on its parabolic surface with 95% reflectivity and has 1 mm thickness. The central small Fresnel lens has 280 mm diameter, 3 mm thickness and 460 mm focal length. Table 1 gives the key dimensions considered for each of the six rings, the radius of curvature and the maximum and minimum apertures.

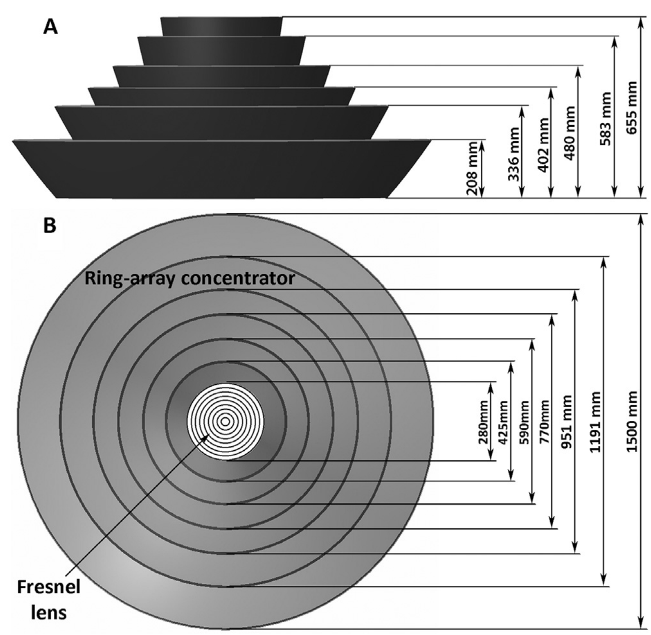

Fig. 2. (A) Side view and (B) top view of the modified ring-array concentrator.

3. Solar laser head and 1064 nm laser resonant cavity

The aspheric fused silica concentrator and the small silver-coated pump cavity are the most important components of the laser head. The entire laser head is 36.5 mm in height and 35.6 mm in diameter. The aspheric concentrator and the pump cavity are mechanically fixed on a basement where both the laser rod and water cooling channels are integrated. Fig. 3 shows the laser head, laser rod absorption profile (red