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A path to renewable Mg reduction from MgO by a continuous-wave Cr:Nd:YAG ceramic solar laser

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ABSTRACT

The first successful ablation of magnesium oxide through a home-made continuous-wave Cr:Nd:YAG ceramic solar laser is reported. A stationary heliostat-parabolic mirror solar energy collection and concentration system was used. A stable continuous-wave laser output power of 19.2 W was attained with laser beam brightness figure of merit 7.6 times higher than that of the previous scheme, enabling therefore the direct ablation of pure magnesium by our solar-pumped laser with only 1.6 m^2 effective collection area. This could be an important step towards renewable magnesium production, offering multiple advantages, such as reducing agent avoidance, in relation to that of the previous Fresnel lens Cr:Nd:YAG continuous-wave solar laser system.

1. Introduction

Converting the solar radiation, the most plentiful available form of energy, into a coherent monochromatic source of radiation has been in the minds of laser researchers almost since the laser invention, although not much attention has been paid to the subject [1–7]. This direct conversion allows the construction of much simpler and more reliable systems than those that rely on electrical power [7,8]. Solar lasers may prove useful in areas such as deep space communications, laser power beaming, orbital space debris removal, atmospheric/ocean sensing and material processing [8,9]. Particularly, they enable magnesium production from magnesium oxide, which can be used as an infinitely recyclable fuel [10,11].

Nowadays, research on solar lasers is focused mainly on enhancing collection efficiency and laser beam brightness, which are the main limitations of this technology [12]. Several pumping schemes have been built to attain these goals. Significant improvements have been achieved with systems that use Fresnel lens or resort to a parabolic mirror system to primarily concentrate the solar radiation. Fresnel lenses have attracted much more attentions of solar laser researchers [12–18]. The advantage of heliostat-parabolic mirror system for solar laser research is, however, comparatively neglected in recent years. We have, instead, insisted on using the heliostat-parabolic mirror system. Unlike Fresnel lens, heliostat – parabolic mirror systems allow the laser head to be mounted in a fixed position, which makes the laser more suitable for practical applications [18]. This advantage becomes much more pronounced when a Mg reduction vacuum chamber is to be installed nearby. The solar laser head pumped by a Fresnel lens usually moves together with the whole tracking structure, an optical fiber thus becomes inevitable for the transportation of solar laser power from the laser head to the reduction chamber. Beside a lot of practical inconveniences, fiber optic transmission loss is inevitable, which will influence negatively the final collection efficiency of the whole laser system. It is therefore very meaningful to improve the performance of the solar laser pumped through a heliostat-parabolic mirror solar energy collection and concentration system. The ultra-high power heliostat-parabolic mirror system, such as the 1 MW solar furnace of PROMES-CNRS in France, might well become a super solar laser power station in the future [19].

In current solar laser systems, laser active medium is generally Nd: YAG or Cr:Nd: YAG, the last one being chosen to improve efficiency [13,20], although its superiority is still controversial [21]. In this way, 1064 nm laser wavelength is obtained. Unfortunately, at 1064 nm wavelength, magnesium oxide absolute diffuse reflectance is very high (about 95.5% [22]), whereby it requires a lot

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of energy to induce some effect. To the best of the present knowledge based on available literature, pure magnesium oxide laser ablation at this wavelength has only been performed in pulsed mode laser operation. Continuous-wave lasers are technologically simpler than pulsed lasers and can also be used for ablation, however, the shorter the laser pulses, the higher the confinement of thermal energy deposited on the sample and the faster material reaches vaporization temperature; since heat energy diffusion through the lattice diminishes [23,24]. Therefore, using 1064 nm wavelength continuous-wave lasers, more energy is required to ablate the same amount of material [23], which can be very challenging. Some alternative attempts to produce magnesium from magnesium oxide through laser ablation have therefore been experimented, mainly by Yabe and his co-workers, by using either electrically powered pulsed Nd:YAG or continuous-wave CO_2 lasers [10,25]. To facilitate magnesium production, magnesium oxide mixture with reducing agents was proposed [26,27], reducing the necessary energy for magnesium metal vapour production [28]. A continuous-wave Cr:Nd:YAG solar laser with a Fresnel lens as primary concentrator was used for magnesium production from magnesium oxide with silicon as reducing agent [20]. This laser system relied on an active medium with large volume, which is a generally expensive and present serious thermal problem. In fact, thermal effects had led to some instability in output power, which dropped about 10 W within 60 s 53 W continuous-wave Cr:Nd:YAG solar laser with large and discrepant $M_x^2=60$ and $M_x^2=193$ laser beam factors was obtained, leading to 482 W/mm^2 concentrated solar laser flux on the sample [20]. After serving their purpose, reducing agents must be deoxidised by an environmental friendly method in order to maintain the renewable energy cycle, which increases the system complexity. Moreover, the reducing agent may contaminate the final product, making the situation even more intricate [26].

In this paper, a home-made heliostat-parabolic mirror solar laser system using Cr:Nd:YAG ceramic laser medium is presented for renewable laser ablation of pure MgO. Optimum pumping conditions and solar laser beam parameters were found through ZEMAX and LASCAD numerical analysis, respectively. Experiments were carried out at Faculdade de Ciências e Tecnologia – Universidade NOVA de Lisboa solar laboratory. A stable continuous-wave output power of 19.2 W with relatively good laser beam quality ($M_x^2=22.7$ $M_y^2=24.1$) was achieved, leading to 7.6 times improvement in laser beam brightness figure of merit - defined by the ratio between laser power and M^2 factors – compared to the previous value of Cr: Nd:YAG ceramic solar laser for MgO ablation [19]. The generated laser beam was then focused on a pure magnesium oxide sample and the effects of laser-sample interaction were analyzed. A hole with 8 μm average diameter was produced through solar laser ablation, opening the possibility of future magnesium reduction from magnesium oxide without reducing agent.

2. The Cr:Nd:YAG ceramic solar laser system

A large plane mirror with 4 segments (1.16 m × 1.27 m each), mounted on a two-axis heliostat (DezhouGaokeli Hydraulic Co., Ltd., China), redirects the incoming solar radiation towards the stationary parabolic mirror with 1.5 m diameter, 0.66 m focal length and 60° rim angle, as shown in Fig. 1.

All the mirrors are back-surface silver coated. The plane mirror segments were provided by Flabeg Solar GmbH & Co KG, Germany. Their glass substrate is 4 mm thick, with low iron content, which allows 93.5% reflectance of the incoming radiation. Parabolic mirror's glass substrate is 10 mm thick, with high iron content, reducing the mirror's reflectivity to about 80%. About 75% of incoming solar radiation is hence effectively focused to the focal zone.

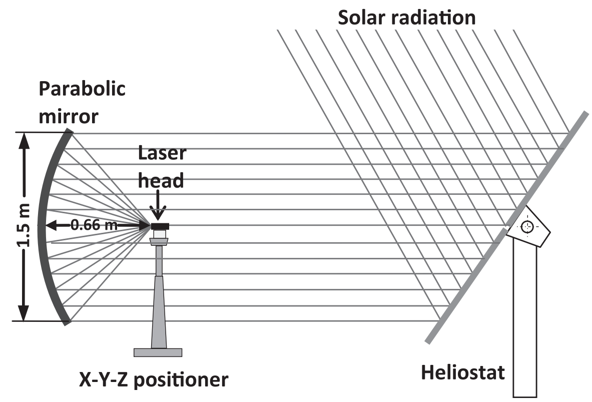

Fig. 1. Scheme of the NOVA heliostat-parabolic mirror system.

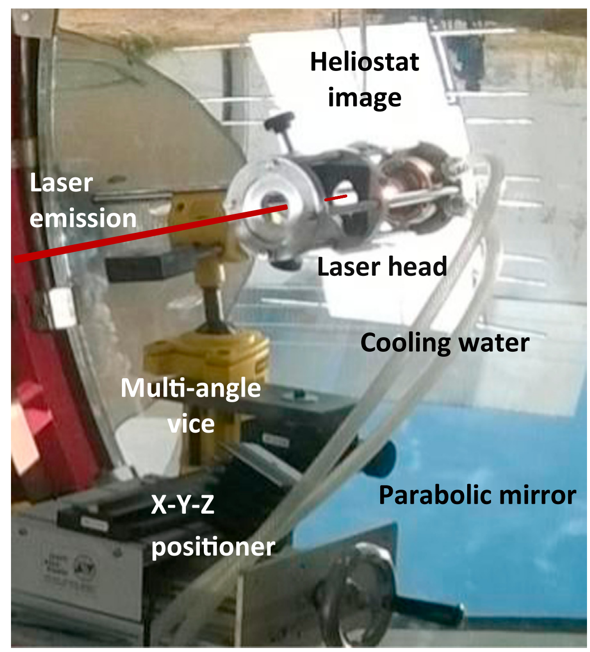

Fig. 2. Experimental set up of Cr:Nd:YAG solar-pumped laser.

The laser head is mechanically mounted to an X-Y-Z axis positioning system by using a multi-angle vice, as shown in Fig. 2, ensuring an accurate optical alignment in the focal zone. After discounting the shadow effects of the laser head and its mechanical supports, an effective collection area of about 1.6 m^2 is measured.

A fused silica window, manufactured from a fused silica plate with 99.995% purity (supplied by Beijing Kinglass Quartz Co., Ltd), allows radiation to pass through and get into a conical pumping cavity, within which the Cr:Nd:YAG ceramic rod was mounted, as illustrated in Fig. 3. Distilled water is used as a coolant, flowing at a rate of 6 l per min. Fused silica is an ideal optical material for high flux solar pumping, since it has a low coefficient of thermal expansion and it is resistant to scratching and thermal shock. Fused silica material is also transparent over Nd: YAG absorption spectrum and, along with water, plays an important role in reducing the thermal load along the laser rod by partially filtering both UV and IR radiations, which do not contribute to lasing. The pumping cavity, whose inner wall is bonded with a protected silver-coated aluminium foil with 94% reflectivity, has 26 mm input diameter, 8 mm output diameter and 22 mm height. This configuration