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Stable solar-pumped TEM_{00}-mode 1064 nm laser emission by a monolithic fused silica twisted light guide

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ABSTRACT

To improve TEM_{00}-mode solar-pumped laser output power stability, a monolithic fused silica twisted light guide was firstly produced and then combined with both a 2D-CPC (Compound Parabolic Concentrator) and a 2 V-shaped cavity to achieve uniform pumping along a 3 mm diameter, 50 mm length, 1.0 at.% Nd^{3+}:YAG rod through an heliostat-parabolic mirror system. Based on both refractive and total internal reflection principles, the light guide provided an effective solution to both guiding and redistributing highly concentrated solar radiations. A near-Gaussian profile focal spot was transformed into a uniform rectangular-shaped light column, facilitating further pump light coupling into the long and thin laser rod within the 2 V-shaped pump cavity. Optimum pumping parameters and solar laser output powers were found through both ZEMAX© non-sequential ray-tracing and LASCAD© laser cavity analysis codes. The light guide reduced considerably the thermal lensing effects of the solar laser. 2.7 W continuous-wave TEM_{00}-mode ($M_2 \leq 1.05$) 1064 nm solar laser emission with 2.3 W/m^2 collection efficiency and, more importantly, with 1.7% stability was finally achieved, being significantly more stable than the previous TEM_{00}-mode solar lasers.

1. Introduction

Shortly after the invention of laser, the idea of directly converting free broad-band solar radiation into coherent narrow-band laser radiation appeared (Young, 1966). If lasers are needed in remote locations where sunlight is abundant and the other forms of energy are scarce, a solar laser would seem to be a natural choice. Broadband, temporally constant, sunlight can be 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. Compared to other electrically powered lasers, solar lasers are much more simple and reliable due to the complete elimination of artificial pump sources and their associated electrical power generation and power conditioning equipment. Thus, 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, leading to numerous environmental and economic benefits. The solar laser technology has therefore great potentials for various space applications, such as Earth, ocean, and atmospheric sensing, laser power beaming, free space communications (Guan et al., 2017). Powered by abundant solar energy, solar laser are also suitable for many terrestrial applications such as high temperature materials processing, magnesium–hydrogen energy cycle (Yabe et al., 2006). Many applications listed above can only be feasible with lasers of high-beam-quality, most preferably, in TEM_{00}-mode since it produces the smallest beam divergence, the highest power density and, hence, the highest brightness (Overton, 2013).

The growing importance of solar-pumped lasers has attracted considerable attention. Many studies have already been carried out to improve solar laser efficiencies (Young, 1966; Arashi et al., 1984; Weksler and Shwartz, 1988; Lando et al., 2003; Yabe et al., 2007; Ohkubo et al., 2009; Liang and Almeida (2011), Liang et al., 2013, 2016a,b, 2017; Payziyev et al., 2011; Payziyev and Makhmudov, 2016; Dinh et al., 2012; Almeida et al., 2012, 2013, 2015; Xu et al., 2014; Guan et al., 2017). Since the sunlight does not provide enough flux to initiate laser emission, additional

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focusing optics are needed to both collect and concentrate the solar radiation to excite laser medium. Parabolic mirrors have long been explored to achieve tight focusing of incoming solar radiation (Young, 1966; Arashi et al., 1984; Weksler and Shwartz, 1988; Lando et al., 2003; Payziyev et al., 2011; Payziyev and Makhmudov, 2016; Almeida et al., 2012, 2013, 2015; Liang et al., 2013, 2015, 2016a,b, 2017). To maximize the solar radiation that impinges on the laser crystal, the 3D-CPC, the 2D-CPC and the V-shaped pump cavity are usually used as secondary and tertiary concentrators in solar lasers because they can either compress or wrap the concentrated solar radiations from their input aperture to the laser rod and give an additional concentration. Nevertheless, significant progresses in solar laser efficiency have been made in the last decade after the adoption of Fresnel lenses as primary solar concentrators (Yabe et al., 2007; Ohkubo et al., 2009; Liang and Almeida, 2011; Dinh et al., 2012; Xu et al., 2014; Guan et al., 2017). 30.0 W/m^2 collection efficiency, defined by the ratio between laser output power and primary concentrator area (Lando et al., 1995), was attained by pumping a 6 mm diameter, 100 mm 4 m^2 area large Fresnel lens (Dinh et al., 2012). However, very large $M_x^2 = M_y^2 = 137$ factors have been associated with this approach, resulting in very poor beam quality, only 0.0064 W value of the beam brightness figure of merit – defined as the ratio between laser power and the product of M_x^2 and M_y^2. Most recently, 31.5 W/m^2 multimode, 7.9 W/m^2 TEM$_{00}$-mode solar laser collection efficiencies were achieved (Liang et al., 2017) by using the heliostat-parabolic mirror system in the PROMES – CNRS (Procedes, Materiaux et Energie Solaire – Centre National de la Recherche Scientifique) in France, surpassing the previous record (Dinh et al., 2012) by the 4 m^2 Fresnel lens installed on a solar tracker. Even though Fresnel lenses have been preferred due to their simplicity, easy availability, and low cost, there still exist practical inconveniences, regarding to their use in solar lasers. The laser head pumped by the Fresnel lens solar concentration system moved together with the whole solar tracking structure (Yabe et al., 2007; Liang and Almeida, 2013), an optical fiber thus became necessary for the transportation of solar laser radiation to a fixed target position. This in turn affected negatively the efficiency of the whole solar laser system due to optical fiber transmission loss. The advantage of having an indoor laser head at the focus of a heliostat primary concentrator system has become much more obvious for applications such as material processing where a vacuum chamber should usually be installed nearby. Moreover, Fresnel lenses also cause a significant dispersion of solar radiation spectrum along its focal zone, hindering further efficient solar pump light concentration into the thin laser rod by both secondary and tertiary concentrators.

Because of its smooth intensity profile, 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: TEM$_{00}$-mode. To achieve this, several pumping schemes have been built. TEM$_{00}$-mode solar lasers can have either side-pumping or end-pumping configurations (Arashi et al., 1984; Brauch et al., 1991). Although the most efficient laser systems have end-pumping approaches, the thermal lensing effects caused by non-uniform distribution of pump light in these pumping configurations affect negatively their efficiencies. Side-pumping configuration can present higher brightness as it allows a uniform absorption distribution along the rod axis and spreads the absorbed power within the laser medium, reducing the associated thermal loading problems. Besides, the free access to both rod ends permits the optimization of more laser resonator parameters, improving largely the laser beam quality and enabling the efficient extraction of solar laser in fundamental mode. Minimizing a laser rod volume reduces cost, and reducing the diameter makes the rod more resistant to thermal stress. Also, as the rod acts as an aperture, by pumping a small diameter laser rod, high-order resonator modes can be suppressed by large diffraction losses, and beam quality improves (Lando et al., 2003). For these reasons, we have been insisting on improving the TEM$_{00}$-mode solar laser power and beam profile by side-pumping small diameter rod (Liang and Almeida, 2013; Liang et al., 2015).

In order to clearly understand all the previous TEM$_{00}$-mode solar laser performances, research details are summarized in Table 1. Some literatures (Geraldes and Liang, 2008; Pereira and Liang, 2009; Liang and Pereira, 2009; Almeida and Liang, 2012) are merely numerical simulations for the improvement of fundamental mode solar laser output performance, while others already include experimental results (Liang and Almeida, 2013; Vistas et al., 2015; Almeida et al., 2015; Liang et al., 2015, 2016, 2017). Direct solar laser pumping configuration was firstly tested (Liang and Almeida, 2013; Vistas et al., 2015; Liang et al., 2015, 2017), where the concentrated solar radiation at the focus was efficiently coupled within the laser rod, through either a fused silica aspheric lens, or a semi-cylindrical lens or an ellipsoidal-shaped lens, allowing the efficient generation of fundamental mode laser power, resulting also, unfortunately, in stronger thermal lensing and a non-uniform distribution along the laser rod. Fused silica light guide with large rectangular cross section can be used in indirect pumping configuration, uniform pump light distribution was attained, but efficient light coupling from the light guide to the laser rod was affected (Almeida et al., 2015; Liang et al., 2015). 5.5 W continuous-wave TEM$_{00}$-mode 1064 nm laser power was registered (Almeida et al., 2015), however, serious laser beam stability problem was found with further increase in pump power, laser output power approached to a peak value and then dropped abruptly, meaning that the laser resonator operation had moved out of stability zone as the thermal lensing effect got stronger and finally the laser stopped oscillating. A more stable continuous-wave TEM$_{00}$-mode 1064 nm solar laser power of 4.4 W was also measured (Liang et al., 2015), but at the cost of relatively low collection efficiency of 1.91 W/m^2 (Liang et al., 2015). Most recently, 9.3 W continuous-wave TEM$_{00}$-mode 1064 nm solar laser power was measured, corresponding to 7.9 W/m^2 TEM$_{00}$-mode solar laser collection efficiency. However, most efficient end-side-pumping of a 4 mm diameter 35 mm length Nd^{3+}:YAG rod through a large aspheric lens has introduced a non-uniform absorbed pump light distribution, resulting in the TEM$_{00}$ – mode beam with only $M^2 \leq 1.2$. The beam stability was sensible to the variation of the thermal focal length of the rod. Also most recently, a non-symmetric fused silica twisted light-guide was used to achieve nearly uniform pumping along a 3 mm diameter and 50 mm length Nd:YAG single-crystal rod (Bouadjemine et al., 2017). 2.3 W continuous-wave fundamental mode 1064 nm solar laser power was measured, corresponding to 1.96 W/m^2 TEM$_{00}$ mode solar laser collection efficiency and 2.2 W laser beam brightness figure of merit. The non-symmetric twisted light guide in Table 1 provided a nearly uniform pump profile along the rod and further enhancements in both light guide architecture and solar laser collection efficiency are possible.

To improvement of the fundamental mode solar laser performance, the monolithic fused silica twisted light guide will be introduce in this paper. Based on the refractive and total internal reflection principles, the light guide, by serving also as a beam homogenizer, transformed the near Gaussian profile of the concentrated light spot at its large square input face into a uniform pump light distribution at its rectangular output end, facilitating further efficient light coupling into a long and thin laser rod. Fused silica was an ideal optical material for transmitting highly concentrated solar energy, it had a low coefficient of thermal expansion, and was resistant to scratching and thermal shock and it had a high optical purity 99.999%. To provide the desired form of the twisted light guide, two techniques were possible, shaping the light guide in