

Highly efficient solar-pumped Nd:YAG laser

Dawei Liang,* and Joana Almeida

CEFITEC, Departamento de Física, FCT, Universidade Nova de Lisboa, 2829-516, Campus de Caparica, Portugal
*dl@fct.unl.pt

Abstract: The recent progress in solar-pumped laser with Fresnel lens and Cr:Nd:YAG ceramic medium has revitalized solar laser researches, revealing a promising future for renewable reduction of magnesium from magnesium oxide. Here we show a big advance in solar laser collection efficiency by utilizing an economical Fresnel lens and a most widely used Nd:YAG single-crystal rod. The incoming solar radiation from the sun is focused by a 0.9 m diameter Fresnel lens. A dielectric totally internally reflecting secondary concentrator is employed to couple the concentrated solar radiation from the focal zone to a 4 mm diameter Nd:YAG rod within a conical pumping cavity. 12.3 W cw laser power is produced, corresponding to 19.3 W/m² collection efficiency, which is 2.9 times larger than the previous results with Nd:YAG single-crystal medium. Record-high slope efficiency of 3.9% is also registered. Laser beam quality is considerably improved by pumping a 3 mm diameter Nd:YAG rod.

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1. Introduction

Our planet receives more energy from the Sun in one hour than all humankind consumes in an entire year. And yet despite this, solar power still only contributes towards a tiny fraction of our energy requirements. The idea of directly converting broad-band solar radiation into coherent and narrow-band laser radiation has gained an ever-increasing importance in recent years [1]. Compared to electrically powered lasers, solar laser is much simpler and more reliable due to the complete elimination of the electrical power generation and conditioning equipments. The direct pumping of solid-state laser from sunlight to laser light saves two energy conversion steps and is inherently more efficient. However, much less consideration has been devoted to direct solar-pumped lasers and thus the technology is currently much less mature. Since the first cw one-watt Nd:YAG (Neodymium Doped Yttrium Aluminum Garnet, $\text{Nd}^{3+}:\text{Y}_3\text{Al}_5\text{O}_{12}$) sun-pumped laser [2], a few solar lasers have been tested [3–7]. Primary parabolic mirrors are generally adopted to achieve tight focusing of incoming solar radiation. In the category of solar laser collection efficiency, we divide the emitted laser power by primary collector area. The record-high collection efficiency with a Nd:YAG single-crystal rod was 6.7 W/m^2 [6]. Typical slope efficiencies are generally less than 2.4% [2–7]. The recent progress with Fresnel lens and Cr:Nd:YAG ceramic laser medium has revitalized the solar laser researches by providing $18.7\text{--}19.5 \text{ W/m}^2$ collection efficiency [8–11]. Researchers are now highly motivated to build the most efficient solar-pumped lasers for the reduction of magnesium (Mg) from magnesium oxide (MgO). Large amounts of heat and hydrogen (H_2) are given off from the reaction of magnesium with water. Mg can be an alternative to fossil fuel. But for a magnesium combustion engine to function as a practical source of renewable energy, the lasers need to be pumped by solar power. The importance of high efficiency economical solar-pumped laser is becoming more evident than ever before.

To improve the efficiency of Nd^{3+} -doped YAG laser, cross-pumped Cr^{3+} and Nd^{3+} co-doped YAG ceramic material has attracted more attentions in recent years [8–12]. The sensitizer Cr^{3+} ions have broad absorption bands in the visible region. By the ${}^4\text{T}_2$ to ${}^4\text{A}_2$ transition of Cr^{3+} ions, energy is transferred from Cr^{3+} to Nd^{3+} ions. For single-shot laser operation with a 0.1 at% Cr^{3+} and 1.0 at% Nd^{3+} co-doped YAG ceramic rod, the laser efficiency was found to be more than twice that of a 1.0 at% Nd^{3+} :YAG ceramic rod. At low repetition rates, the average output power of Cr:Nd:YAG rod was higher than that of Nd:YAG. However, this ratio gradually decreased with increasing repetition rates. The thermal effect of Cr:Nd:YAG rod was also higher than that of Nd:YAG in high-repetition operation. Although the Cr:Nd:YAG rod was more efficient for low-repetition rate application, it might not be suitable for high-repetition rate and CW laser operations [12].

Since the natural sunlight does not provide power density sufficient enough for lasing, additional focusing systems are required to convert solar power into laser radiation. A typical solar laser utilizes a two-stage system that incorporates a first-stage primary parabolic mirror and a second-stage compound parabolic concentrator (CPC). Non-imaging optics plays an important role in solar concentrators by providing means for concentrating sunlight to intensities approaching the theoretical limit [13]. However, pump radiation pass through an active medium only once in a CPC chamber. Therefore, small diameter rod cannot be efficiently pumped due to its short absorption paths. For this reason, 6–10 mm diameter rods were generally utilized in recent solar lasers [5–10]. Pumping small diameter rod is very attractive but challenging for solar laser researchers. Minimizing a laser rod volume reduces cost, and reducing the diameter makes the rod more resistant to thermal stress. Also, with smaller rod, laser beam quality can be improved [6]. Besides, what has motivated us most is the possible large advance in laser efficiency. Substantial reduction in threshold pump power is also expected.

Fresnel lens is cost-effective, but the largely dispersed radiation distributed along its focal zone hampers further efficient light concentration to a thin rod. For this reason, a novel secondary laser pumping scheme becomes indispensable. Dielectric totally internally reflecting concentrator (DTIRC) was originally designed for photovoltaic applications [14–16]. A modified version of the DTIRC with a large curved input face and a small planar output face is utilized by us to concentrate efficiently the solar radiations from the focal zone to the thin rod, which is mounted within the conical pumping cavity. Cooling water also plays a crucial role in ensuring efficient light coupling between the output end of the DTIRC and the rod. Efficient absorption of pump radiation is achieved through both direct end-pumping and multi-pass side-pumping within the cavity. Optimized parameters of the Fresnel lens, the DTIRC and the conical cavity are found by non-sequential ray-tracing code (ZEMAXTM). Optimized laser resonator parameters are obtained by laser cavity design and analysis code (LASCADTM).

Fresnel lens is chosen to make our prototype economically competitive. 3-4 mm diameter and 25 mm length 1.0 at % Nd:YAG single-crystal rods are selected, this being the most well-known and readily available solid-state laser material in its simplest configuration. With the 4 mm diameter rod, maximum laser output power is 12.3 W, corresponding to 19.3 W/m² collection efficiency, which is 2.9 times larger than the previous record of 6.7 W/m² with a large diameter Nd:YAG rod and a mirror type concentrator [6]. This result is, to the best of our knowledge, the highest collection efficiency achieved with Nd:YAG medium. It is even slightly higher than the collection efficiency of 18.7 W/m² by utilizing a large Cr:Nd:YAG ceramic rod and a 1.3 m² Fresnel lens [8]. Considerable enhancement in laser beam quality is achieved by pumping the 3 mm diameter Nd:YAG rod. The large increase in slope efficiency and the substantial reduction in threshold pump power are also interesting features of our prototype solar laser.

2. High collection efficiency Nd:YAG solar laser system



Fig. 1. The Nd:YAG solar-pumped laser system with a 0.9 m diameter Fresnel lens and a laser head positioned in its focal zone.

As shown in Fig. 1, the Nd:YAG solar-pumped laser system is composed of the 0.9 m diameter Fresnel lens mounted on a two-axis solar tracker that follows automatically the sun's movement. The solar tracker is supplied by Shandong Huayi Sunlight Solar Energy Industry Co., Ltd. The Fresnel lens (NTK CF1200) is supplied by Nihon Tokushu Kogaku Jushi Co., Ltd. The Fresnel lens is made of Polymethyl Methacrylate (PMMA) material, which is transparent at visible and near infrared wavelengths, but absorbs the infrared radiation beyond 2200 nm and cut undesirable UV solar radiation below 350 nm. We find that 78.6% of incoming solar radiation is focused to the focal zone about 1.2 m away from the Fresnel lens. In fact, the concentrated solar power at the focal point averaged over 2 min is 445 W for

source sunlight of 890 W/m^2 . The measured full width at half maximum beam waist is about 12 mm. Mechanical adjustments in X-Y-Z directions allow the alignment of the laser head in the focal zone. Coarse angular adjustments around X, Y and Z axis are also helpful for achieving the maximum laser output power.

The laser head is composed of the DTIRC coupled to the conical pumping cavity where the 3-4 mm diameter Nd:YAG rod is mounted. Chromatic aberration of the Fresnel lens spread the focal spots of different wavelengths along its large focal region, so it is difficult to couple efficiently all the concentrated radiations within this region into a small laser rod by a conventional lens. The modified DTIRC is therefore designed to overcome this difficulty. The large curved input face is designed to both collect and compress the concentrated solar radiation from the large focal zone to the upper end face of the laser rod, as indicated in Fig. 2. For end-pumping, one part of the radiation, represented by ray A, is focused onto the upper end face of the rod by either the direct focusing from the curved face or also by the indirect total internal reflections from the side walls of the DTIRC, as represented by ray B.

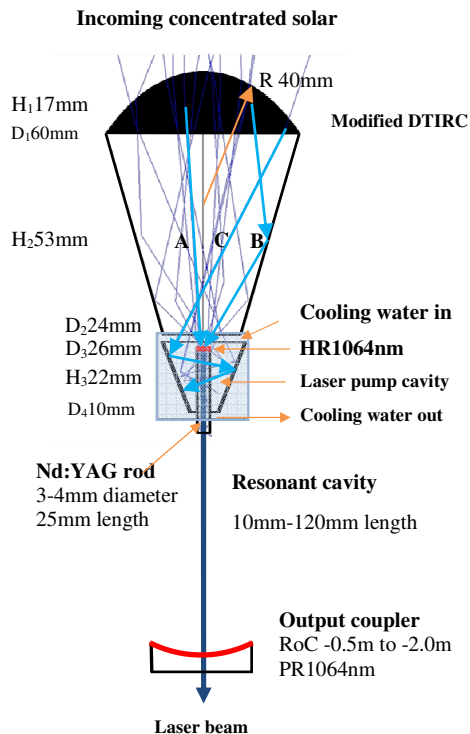


Fig. 2. The Nd:YAG laser head is composed of the DTIRC coupled to the conical pump cavity where a 3-4 mm diameter rod is efficiently pumped. A concave output coupler is optically aligned along the rod axis.

For side-pumping, another part of the radiation not hitting the end face of the rod, represented by ray C, is also guided into the small conical cavity with $D_3 = 26 \text{ mm}$ input diameter, $D_4 = 10 \text{ mm}$ output diameter and $H_3 = 22 \text{ mm}$ cavity height. The zigzag passage of the rays within the cavity ensures a multi-pass side-pumping to the rod.

All the design parameters in Fig. 2 are optimized by ZEMAX™ non-sequential ray-tracing software in order to obtain the maximum absorbed pump power within the Nd:YAG rod. To enhance light coupling efficiency, the laser head is mounted 1.17 m away from the Fresnel lens, 3 cm above the beam waist position of the focal zone. To maximize the output laser power, laser resonator parameters with - 0.5 m radius of curvature (RoC) and 120 mm cavity

length are obtained by LASCADTM laser cavity design and analysis code. As shown in Fig. 2, the laser cavity length can be varied from 10 mm to 120 mm. It can also be extended to more than 200 mm. The M^2 factor can be largely reduced in this case.

To manufacture the DTIRC, a 99.995% optical purity fused silica rod with 60 mm diameter and 100 mm length is supplied by Beijing Kinglass Quartz Co., Ltd. It is firstly ground and polished to form the curved input face with $R = 40$ mm, $D_1 = 60$ mm diameter and $H_1 = 17$ mm height. The conical section of the DTIRC is then machined and polished to the dimensions of $D_1 = 60$ mm, $D_2 = 24$ mm and $H_2 = 53$ mm, as shown in Fig. 2. The polished DTIRC is finally cut away from the 60 mm diameter fused silica rod. The $D_2 = 24$ mm planar output end of the DTIRC is also ground and polished. This end face is in direct contact with cooling water, which ensures an efficient light coupling to the rod. The water flow rate is 6 liter / min. The inner wall of the pumping cavity is bonded with a protected silver-coated aluminum foil with 94% reflectivity. The maximum contact between coolant and the rod is essential for the removal of the dissipated heat. Both fused silica material and cooling water are useful for partially preventing both UV solarization and IR heating to the laser rod.

3. Laser oscillation experiments

For the solar irradiance of 890 W/m^2 in Lisbon area in August 2011, the 0.9 m diameter Fresnel lens collects 445 W solar power to its focal zone. The 3-4 mm diameter Nd:YAG single-crystal rods are supplied by Altechna Co.Ltd. They have 1.0 at % Nd^{3+} concentration. The upper end of the rod is directly deposited with HR coating which effectively reflects the laser emission wavelength ($R > 99.8\%$ @ 1064 nm), while allows the passage of other pump wavelength ($T > 95\%$ @ 808 nm). The lower end is AR coated ($R < 0.2\%$ @ 1064 nm). The laser resonator is formed by both a -0.5 m RoC output coupler and the HR reflector. The output coupler is placed 100 mm away from the rod, as indicated by Fig. 2. The reflectivity of the coupler varies between 94% and 98%. The concentrated solar power at the entrance face of the DTIRC and output laser powers are respectively measured with a Molectron PowerMax 500D and a Thorlabs PM1100D laser power meters.

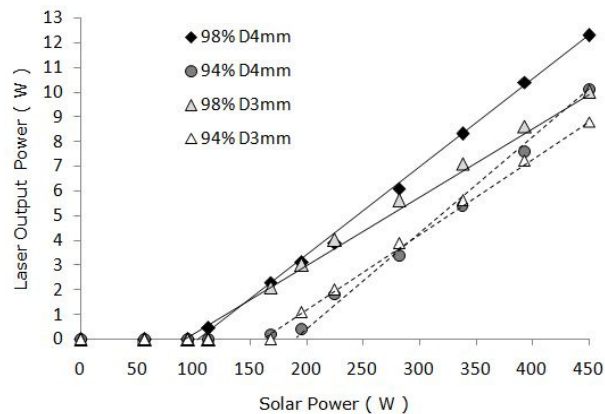


Fig. 3. Solar laser output power versus concentrated solar power in the focal zone of the Fresnel lens.

For 445 W solar power at the focus and a -0.5 m RoC output coupler with 98% reflectivity, 12.3 W solar laser power is successfully measured, corresponding to 19.3 W/m^2 collection efficiency, which is 2.9 times larger than the previous record of 6.7 W/m^2 [6]. The value is even slightly better than the maximum collection efficiency of 18.7 W/m^2 attained by using a large expensive Cr:Nd:YAG ceramic rod and a 1.3 m^2 Fresnel lens [8]. By blocking progressively the incoming solar radiations with pizza slice type masks, placed in front of the Fresnel lens, different solar power levels are obtained and the laser output power can then be

measured correspondingly. The threshold pump power of 94 W is measured in the focal zone, which is far less than the several hundred watts for the recent solar lasers. The slope efficiency of 3.5% is hence achieved, which is 146% higher than the previous record [3]. For 100 mm resonant cavity length and -0.5 m RoC, a 24 mm diameter circularly symmetric laser beam profile is marked slowly on an opaque material, 1 m away from the output coupler.

A linear fiber-optic array for measuring the one-dimensional laser beam intensity distribution is placed, 5 mm and 1000 mm respectively, away from the output coupler along the optical axis of the laser rod. The 32 mm width, 128 optical fibers linear array is used to collect and transmit laser light to a Fairchild CCD 153A 512-element linear image sensor via a neutral density attenuator. This fiber-optic device has 0.25 mm core pitch resolution, so less than 2% laser beam diameter measurement error is found. This flexible fiber optic bundle has 2 m length. Outdoor solar laser beam diameter measurement is hence facilitated.

The laser beam divergence θ was found by adopting the Eq. (1):

$$\arctan \theta = \frac{\phi_2 - \phi_1}{2L} \quad (1)$$

where ϕ_1 and ϕ_2 are the measured laser beam diameters at $1/e^2$ width, 5 mm and 1000 mm away from the output mirror respectively, and L is the distance between these two points. M^2 factor are then calculated as the ratio of the measured beam divergence θ and that of a diffraction-limited Gaussian beam of the same wavelength, which is 0.019° for the Nd:YAG laser wavelength. $M^2 = 30$ is determined for -0.5 m RoC coupler, as indicated by Table 1. For 100 mm cavity length with a -2 m RoC, the laser beam divergence is largely reduced to $M^2 = 12$. Despite the reduction of output laser power from 12.3 W to 9.0 W, significant increase in laser beam brightness is clearly noticeable by the fast marking rate on the opaque material.

As shown in Fig. 3, a 94% output coupler is also used to extract 10.1 W laser power. Despite the high threshold pump power of 187 W, high slope efficiency of 3.9% is achieved, corresponding to 162.5% enhancement in relation to the previous record [3]. The threshold powers of both 94 W at 98% reflectivity and 187 W at 94% reflectivity for the 4mm rod are used to calculate the round-trip loss of the laser resonant cavity. 1.7% round-trip loss is hence determined according to Findlay-Clay method [17]. Considering the absorption loss coefficient of 0.003 cm^{-1} @ 1064 nm for the Nd:YAG rod and 0.2% diffraction loss in LASCAD analysis, the 1.7% round-trip loss by Findlay-Clay analysis matches well with the sum of absorption and diffraction losses.

To enhance laser beam quality, a 3 mm diameter Nd:YAG rod is also pumped. The experimental results are given in Fig. 3 and Table 1. An output coupler with -0.5 m RoC and 98% reflectivity is used to extract 10.2 W laser power, corresponding to the slope efficiency of 2.9%. The threshold power of 90 W is measured. By using another -0.5 m RoC output coupler with 94% reflectivity, only 8.9 W laser power is extracted. The threshold pump power is increased to 160 W. The slope efficiency is also slightly increased to 3.1%. Compared to the case of the 4 mm rod, the laser beam divergence is significantly reduced by using the 3 mm rod. For 100 mm cavity length and the -0.5 m RoC, 17 mm diameter circularly symmetric beam profile is marked on the opaque material, placed also 1 m away from the output mirror. $M^2 = 21$ is then determined.

Table 1. Measurements of the Laser Performance

Nd:YAG rod diameter	4mm		3mm	
Reflectivity (%)	98%		98%	
Output mirror RoC (m)	-0.5	-2m	-0.5m	-2m
Laser Beam Power				
Laser power (W)	12.3	9.0	10.2	9.7
Collection efficiency (W/m ²)	19.3	14.1	16.0	15.2
Improvement over the previous record [6] (%)	289	210	239	227
Slope efficiency (%)	3.5	2.6	2.9	2.8
Improvement over the previous record [3] (%)	146	108	121	117
Laser Beam Quality				
M ² factor	30.0	12.0	21.0	10.6
Figure of merit B (W)	1.4 × 10⁻²	6.3 × 10⁻²	2.3 × 10⁻²	8.6 × 10⁻²
Improvement over the previous record [6] (%)	44	197	72	269

For 100 mm cavity length and -2 m RoC, the output laser power is reduced to less than 9.7 W. However, a 10 mm diameter circularly symmetric beam profile is quickly marked on the opaque material placed at 1 m distance. $M^2 = 10.6$ is hence attained. Brightness is the most significant parameter of a laser beam. It is defined as 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 B is defined [6] as the ratio between laser power and the product of M_x^2 and M_y^2 for an asymmetric beam profile. For symmetric beam profile, $M_x^2 = M_y^2 = M^2$. High figure of merit of 8.6×10^{-2} W is calculated in this case, as indicated in Table 1. The value is 269% larger than the previous record [6].

4. Conclusions

Due to the superior light collection and concentration capability of both the DTIRC and the small conical pumping cavity, the 4 mm diameter Nd:YAG laser rod is most efficiently pumped through the 0.9 m diameter Fresnel lens. 12.3 W is successfully produced, corresponding to the collection efficiency of 19.3 W/m². It is 2.9 times higher than the previous record-high efficiency of 6.7 W/m² achieved with large Nd:YAG rod. It is even slightly better than that of the Cr:Nd:YAG ceramic solar laser. The threshold pump power at the focus is as low as 94 W. The laser slope efficiency is also largely increased to 3.9%. The use of 3 mm Nd:YAG rod has considerably reduced the laser beam divergence. 8.6×10^{-2} W brightness figure of merit is obtained. This value is 269% larger than the previous record. The prototype solar laser is both small and powerful. Due to the low pump power threshold, the laser can be oscillated easily even on low irradiance days with thin clouds. The Nd:YAG single-crystal rods are produced by matured technology and exhibit much less solarization effect than the Cr:Nd:YAG ceramic rods. The renewable reduction of magnesium by solar-pumped laser can be more economical and reliable. With this novel pumping configuration, a bright future is envisaged for both Nd:YAG and Cr:Nd:YAG solar-pumped lasers.

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