Side-pumped continuous-wave Cr:Nd:YAG ceramic solar laser

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Abstract:	To clarify the advantages of Cr:Nd:YAG ceramics rods in solar-pumped lasers, a fused silica light guide with rectangular cross-section is coupled to a compound V-shaped cavity within which a 7 mm diameter 0.1 at% Cr: 1.0 at% Nd:YAG ceramic rod is uniformly pumped. The highly concentrated solar radiation at the focal spot of a 2 m diameter stationary parabolic mirror is transformed into a uniform pump radiation by the light guide. Efficient pump light absorption is achieved by pumping uniformly the ceramic rod within the V-shaped cavity. Optimum pumping parameters and solar laser output powers are found through ZEMAX© non-sequential ray-tracing and LASCAD© laser cavity analysis codes. 33.6 W continuous-wave laser power is measured, corresponding to 1.32 times enhancement over our previous results with a 4 mm diameter Nd:YAG single-crystal rod. High slope efficiency of 2.6% is also registered. The solar laser output performances of both the ceramic and the single-crystal rods are finally compared, revealing the relative advantage of the Cr:Nd:YAG rod in conversion efficiency. Low scattering coefficient of 0.0018 cm-1 is deduced for the ceramic rod. Heat load is considered as a key factor affecting the ceramic laser output performance.
Response to Reviewers:	See attachment Answers to the Reviewers' comments: Dear Reviewer 1 Many thanks for your very helpful and insightful comments We would like to answer your comments one by one Reviewer #1: I believe that the paper presents an interesting result. However, there are many significant misunderstanding and unclear points which should be considered before further review. 1. In Fig.5, they are comparing ceramic Cr.Nd YAG and Nd YAG crystal data but two conditions are completely

different. The size is different and input source is
different. I doubt this comparison and it is not
scientific. In addition, "Input solar power" in horizontal
axis is misleading. They should put real incident solar
power on the collecting mirror. The incident solar
power of two experiments is almost 4 times different.

With due respects, we think reviewer 1 has not been very careful in examining the manuscript.
In Fig.5, we are comparing ceramic Cr:Nd:YAG and Nd:YAG crystal data, the solar energy collection concentration system in PROMES-CNRS has the same size and reflectivity. The input solar irradiances are only slightly different for the two experiments in 2011 and 2012 respectively. The side-pumped Nd:YAG laser output performances, published by Optics and Laser Technology in 2012 (Ref.10), are compared to the present results.
Also from the comments of " the incident solar power of the two experiments are almost 4 times different", the reviewer might have mistakenly considered our Fresnel lens end-pumped solar laser published by Optics Express in 2011(Ref. 8) for his comparison. We did not compare this end-pumped result with the present results in Fig. 5.
The collected solar power at the focus has been widely adopted as input solar power in many publications on solar-pumped lasers by Arashi (Ref 4), Weksler (Ref.5), Lando(Ref.7), Yabe (Applied Physics Letters in 2007, Optics Letters in 2008), Liang (Ref. 8) etc, so we prefer not changing the rules during the game.

2. The authors mentioned 33.4W output but its collection efficiency
is only 10W/m2 and a half of their previous result. This means
the proposed scheme might have some difficulty in scaling up.
This point should be discussed.

Once again, the reviewer must have mistakenly compared the 10W/m2 collection efficiency with the 19.3 W/m2 value in Reference 8, which matches well with "a half of their previous result". Instead, our previous result in Ref. 10 was only 9.6W/m2 with the same PROMES-CNRS system, so the collection efficiency is slightly enhanced by using Cr:Nd:YAG ceramic rod in 2012.
As mentioned in the manuscript, the total reflectivity of the whole solar energy collection and concentration system is only 59%. The back surface silver-coated plane mirror and parabolic mirror have more than 20 year´s service history. The collection efficiency can be largely improved by using front surface silver-coated mirrors.

3. On page 3, they claimed the demerit of using optical fiber.
However, I did not find the superiority of their system for
long distant transportation of many beams. This should be
essential because we can not use huge mirror for obtaining
MW class laser but we need to use 1000 bundles of kW laser,
because no one show the feasibility of huge laser by single
optical system.

We only mention some shortcomings of optical fibers for laser power transmission. We are admirers of the renewable large-scale Mg recovery scheme proposed by Professor T. Yabe with many optical fiber bundles for kW laser. Besides, we are also interested in the multi-rods solar-pumped laser scheme at the focus of the 1MW solar furnace as proposed by Uzbekistan scientists, without optical fibers in this case.

4. As for the beam quality, I would like to know the size of the
beam spot which might be used to calculate the divergence
of the beam.

Far field laser beam divergence measurement was carried out again.
We have measured the 1/e2 beam spot size of about 150 mm diameter, 10 meters away from the laser output coupler.

5. In the previous paper, they used CPC but now are using

tapered cavity. I would like to know the reason of the change and how it changes the result.

The following text has been added to the revised manuscript:
Since there is only less than 16% spectral overlap between the solar emission spectrum and Nd:YAG absorption spectrum, the absorbed solar pump power is limited. The compact CPC cavity is used to achieve efficient pumping along the 4 mm diameter Nd:YAG rod. ZEMAX© and LASCAD© numerical analysis has also indicated the effectiveness of the CPC scheme in attaining the maximum laser output power from the Nd:YAG rod. Since the overlap between the solar emission spectrum and Cr:Nd:YAG absorption spectrum can theoretically reach 40%, there are more absorbed solar pump power available, large diameter ceramic rod can then be used to achieve more laser output power. The compound cavity is adopted to pump the 7 mm diameter Cr:Nd:YAG ceramic rod. The rod diameter is also optimized by both ZEMAX© and LASCAD© analysis. The compound V-shaped pump cavity ensures the nearly top-hat absorbed pumped flux distribution, as shown in Fig.4, which drastically reduces the laser beam divergence, when compared to other end-pumped configurations.
The heat load of the 7 mm diameter Cr:Nd:YAG ceramic rod within the compound cavity is also lower than that of the 4 mm diameter single-crystal Nd:YAG rod within the CPC cavity. On the one hand, the Cr:Nd:YAG rod provides enhanced laser output performance within the large compound cavity, on the other hand, the Nd:YAG rod produce also its maximum laser output power within the compact CPC cavity, so the comparison between the ceramic and single-crystal laser rods are made within different pumping cavities, where the advantages of each laser rod, and therefore the laser output performances can be fully exploited.

6. On page 10, "the temperature dependent reduction of the 1064 nm stimulated emission ...[9]" but there is no description on stimulated emission in ref.[9]. The authors should not write a misunderstanding sentence.

Yes, the sentence has been changed to:
Side-pumping configuration provides the best heat load distribution along the rod and the temperature dependent reduction of the 1064 nm stimulated emission cross-section
of Cr:Nd:YAG ceramic crystal [14] is not as significant as the case of end-pumped configurations.

7. The quality of ceramic laser depends on the production condition. Therefore the scattering loss changes depending on the lod. If the authors are careful enough, ref.[9] did not say the inferiority of the ceramic YAG but the ceramic they used has the high scattering coefficient. This is important because the quality changes one by one and should be improved for industrial application. Therefore they should remove the word "doubts" in abstract and introduction and so on.

Yes, the words doubt have been removed in the revised manuscript

8. Regarding the scattering coefficient, the authors mentioned on 9 that "0.004cm-1, as predicted in Ref.[9]". This is misleading because it was measured by integrated sphere but was not predicted. In addition, agreement with published value ref.[17] has no meaning because the ceramic quality is not so stable.

Yes, "0.004cm-1, as predicted in Ref.[9]" has been changed to,
"0.004cm-1, as measured in Ref.[9]"
The sentence”which agrees well with the published value of 0.002 cm-1 [17]" has been removed in the revised manuscript.

Dear Reviewer 2

Many thanks for your very insightful and helpful comments.
We would like to answer your concerns one by one

Reviewer #2: Solar laser attracts more attentions in research due to the potential applications in clean energy field. The authors present a comprehensive work on side-pumped CW Cr:Nd:YAG ceramic solar laser. The simulation as well as experimental results are very valuable reference for people working in this field. Nevertheless, a few issues are not clearly addressed in the manuscript.

1. Page 3, lines 39-40 describe the inner wall of the V-shaped pump cavity. What is the material of the V-shaped cavity? Why not have the pump cavity directly coated with gold or silver but bonded with a silver-coated aluminum foil?

The V-shaped cavity is bounded with silver-coated aluminum foil with 94% reflectivity by now. A gold-coated cavity will not reflect efficiently some useful solar pump power below 500 nm. Silver coating is not used due to the possible contamination with cooling water. Protected silver coating will be considered in the future version.

2. Page 6, line 44 to page 7, line 14 describe how the M2 parameter was measured, the method they used was too much simplified. Normally, the transverse beam profile at minimum five positions need to be recorded in order to fit the hyperbolic curve, so that the beam waist and far field divergence can be determined. The author only measured a very near field(5 mm) beam width and a far field beam width (1500 mm), the beam divergence calculated from these two values was not correct, therefore, the following up calculations of M2 and Figure of merit B were not reliable. In the same paragraph, the author mentioned that the diffraction-limited Gaussian beam of the same wavelength was 0.019 degree, how was this value calculated?

The following text has been added to replace the original text in the revised manuscript:

A linear fiber-optic array for measuring the one-dimensional laser beam intensity distribution in the near field is placed 5 mm away from the output coupler along the optical axis of the laser rod [8, 10]. 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.

For far field laser beam profile measurement, a 10” x 10” industrial standard laser alignment thermal sensitive paper ZAP-IT@ is positioned 10 m away from the output coupler. Assuming 3 mm reading error in the thermal sensitive paper, less than 2% laser beam diameter measurement error is ensured.

The laser beam divergence θ is found by adopting the
Eq. (1):
see attachment(1)

Where ϕ1 = 7.0 mm and ϕ2 = 150 mm are the measured laser beam diameters at 1/e2 width, 5 mm and

10 m away from the output mirror respectively and L is the distance between these two points.

M2 factor is then calculated as:

see attachment(2)

where = 0.015º is the divergence of diffraction-limited Gaussian beam for 1.064 m and 1280 m, as calculated by LASCAD© laser beam propagation method for the 7mm diameter rod.
For -2 m RoC output coupler, Mx2 = 27.5 ± 3% and My2 = 28.3 ± 3% are experimentally determined, indicating a near symmetric beam profile. Figure of merit B of 0.44 × 10-1 W is finally calculated. Even though this value is 6.5 times lower than our previous record of 2.9 × 10-1 W [10], it is still 6.7 times higher than that of the most recent end-pumped solar laser [9].

3. In section 4, the authors made some comparison between Nd:YAG and Cr, Nd: YAG ceramic, the experimental conditions were very different, e. g., the size of the crystal, mode volume of the resonator and pumping scheme were all different in two cases. But the authors put the results into one figure, (Fig. 5) and made comparison of the output and efficiency. So the conclusion based on this is not convincing, because other factors which could also influence the output power and efficiency were not excluded.

The following text has been added to the revised manuscript:
Since there is only less than 16% spectral overlap between the solar emission spectrum and Nd:YAG absorption spectrum, the absorbed solar pump power is limited. The compact CPC cavity is used to achieve efficient pumping along the 4 mm diameter Nd:YAG rod. ZEMAX© and LASCAD© numerical analysis has also indicated the effectiveness of the CPC scheme in attaining the maximum laser output power from the Nd:YAG rod. Since the overlap between the solar emission spectrum and Cr:Nd:YAG absorption spectrum can theoretically reach 40%, there are more absorbed solar pump power available, large diameter ceramic rod can then be used to achieve more laser output power. The compound cavity is adopted to pump the 7 mm diameter Cr:Nd:YAG ceramic rod. The rod diameter is also optimized by both ZEMAX© and LASCAD© analysis. The compound V-shaped pump cavity ensures the nearly top-hat absorbed pumped flux distribution, as shown in Fig.4, which drastically reduces the laser beam divergence, when compared to other end-pumped configurations.
The heat load of the 7 mm diameter Cr:Nd:YAG ceramic rod within the compound cavity is also lower than that of the 4 mm diameter single-crystal Nd:YAG rod within the CPC cavity. On the one hand, the Cr:Nd:YAG rod provides enhanced laser output performance within the large compound cavity, on the other hand, the Nd:YAG rod produce also its maximum laser output power within the compact CPC cavity, so the comparison between the ceramic and single-crystal laser rods are made within different pumping cavities, where the advantages of each laser rod, and therefore the laser output performances can be fully exploited.

4. Page 10, line 2, the scattering loss of 0.018 cm-1, one zero was missing, the correct value should be 0.0018 cm-1.

Yes, the correct value of 0.0018cm-1 has been added to the revised manuscript.

Side-pumped continuous-wave Cr:Nd:YAG ceramic solar laser

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Abstract To clarify the advantages of Cr:Nd:YAG ceramics rods in solar-pumped lasers, a fused silica light guide with rectangular cross-section is coupled to a compound V-shaped cavity within which a 7 mm diameter 0.1 at% Cr: 1.0 at% Nd:YAG ceramic rod is uniformly pumped. The highly concentrated solar radiation at the focal spot of a 2 m diameter stationary parabolic mirror is transformed into a uniform pump radiation by the light guide. Efficient pump light absorption is achieved by pumping uniformly the ceramic rod within the V-shaped cavity. Optimum pumping parameters and solar laser output powers are found through ZEMAX© non-sequential ray-tracing and LASCAD© laser cavity analysis codes. 33.6 W continuous-wave laser power is measured, corresponding to 1.32 times enhancement over our previous results with a 4 mm diameter Nd:YAG single-crystal rod. High slope efficiency of 2.6% is also registered. The solar laser output performances of both the ceramic and the single-crystal rods are finally compared, revealing the relative advantage of the Cr:Nd:YAG rod in conversion efficiency. Low scattering coefficient of 0.0018 cm^{-1} is deduced for the ceramic rod. Heat load is considered as a key factor affecting the ceramic laser output performance.

1 Introduction

Solar-pumped lasers have 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. This technology has a large potential for many applications, e.g. high-temperature materials processing, free space laser communications, space to earth power transmission, and so on. The renewable recovery of Mg from MgO is another very interesting topic for solar-pumped lasers [2]. Ultra-high brightness renewable solar-pumped laser beams can be very conveniently focused to heat the magnesium oxide to more than 4000 K and thus create pure magnesium. Magnesium can be easily stored and transported in the form of "pellets" and, when necessary, reacts with water to produce both hydrogen and thermal energy for fuel cell vehicles and other applications.

The first solar-pumped laser was reported by Young in 1966 [3]. Since then, researchers have been exploiting both parabolic mirrors and Fresnel lenses to attain enough concentrated solar radiation at focal point and several pumping schemes have been constructed for enhancing solar laser output performances [1-12]. 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 [1, 2, 11-13]. The sensitizer Cr^{3+} ions have broad absorption bands in the visible region. By the $^4T_2$ to $^4A_2$ 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 is 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 is higher than that of Nd:YAG. However, this tendency gradually decreases with increasing repetition rates [13].

Despite the interests in Cr:Nd:YAG ceramic medium, researchers have achieved significant laser efficiencies with different Nd:YAG single-crystal rods. 19.3 W/m^2 collection efficiency has been reported by us last year [8] with a 4 mm diameter Nd:YAG single-crystal rod pumped through a 0.9 m diameter Fresnel lens. The most recent solar-pumped laser with a liquid light guide lens and also a 6 mm diameter Nd:YAG rod has produced 30.0 W/m^2 collection efficiency, despite its very low laser beam brightness figure of merit B = 6.6×10^{-3} W. The collection efficiency with the Nd:YAG rod is unexpectedly better than that with Cr:Nd:YAG ceramic rods [9]. Large scattering loss of 0.004 cm^{-1} for Cr: Nd;YAG ceramics is considered as the main reason for this unfavorable surprise. While it is clear about the effectiveness of Nd:YAG single-crystal rods for solar laser operation, there still exist, in our opinion, some concerns about the advantages of Cr:Nd:YAG ceramic medium in solar-pumped lasers.

Although the most efficient laser systems have end-pumping approaches, side-pumping is an effective configuration for power scaling as it gives uniform absorption along the rod axis and spreads the absorbed power within the laser medium, reducing hence the associated thermal loading problems. The solar laser beam brightness from a side-pumping configuration can be higher than those by end-pumping configurations with Fresnel lenses. Indeed, significant improvement in solar-pumped laser beam brightness has been achieved by us in 2011 with the same PROMES-CNRS medium size heliostat-parabolic mirror system. By side-pumping the 4 mm diameter 30mm length Nd:YAG single-crystal rod through a light guide / modified 2D-CPC cavity, record-high brightness figure of merit of 2.9×10^{-1} W is registered [10]. Therefore, light guide side-pumping configuration is chosen here for comparing the laser performances of both the Cr:Nd:YAG ceramic and the Nd:YAG single-crystal rod.

Fresnel lenses have attracted much more attentions of solar laser researchers. 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. The advantage of having a fixed laser head at the focus of a stationary parabolic mirror becomes much more pronounced when an 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 will not be avoided, 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.

2. Side-pumped Cr: Nd: YAG ceramic solar laser system

2.1 PROMES-CNRS medium size solar furnace

A large plane mirror with 36 segments (0.5 m × 0.5 m each) is mounted on a two-axis heliostat which tracks the sun continuously, redirecting the incoming solar radiation towards the 2 m diameter stationary parabolic mirror, as shown in Fig.1 (a). An effective collection area of 2.88 m^2 is measured from the parabolic mirror. All the mirrors are back-surface silver coated, so only 59% of incoming solar radiation is successfully focused to the focal zone, about 0.85 m away from the center of the parabolic mirror. In clear sunny days in Odeillo, more than 1.8 kW solar powers can be focused into a 15 mm diameter light spot, reaching the peak flux of 16 W/mm^2. The laser head, as indicated in Fig. 1 is mounted on an automatic X-Y-Z axis mechanical support. The concentrated solar radiation at the focus is collected by the light guide with rectangular cross-section, as shown in Fig.1

Fig. 1

2.2 Fused silica light guide with tracking error compensation capacity

The fused silica light guide of high optical purity (99.995%), with 16 mm × 22 mm input end / output end cross-sections and 140 mm length, is manufactured by Beijing Aomolin Ltd. The measured transmission efficiency of the light guide is 76%. The laser power output stability depends on how well the Sun is tracked. Heliostat tracking errors move the center of the absorption distribution along the laser rod, resulting in both less output power and a non-uniform beam profile. The use of the light guide is essential to overcome this problem. As indicated in Fig. 2, the light guide serves as a beam homogenizer by transforming the near-Gaussian profile of the concentrated light spot at its input end into a uniform pump distribution at its output end [10]. Uniform absorbed pump distribution along the ceramic rod is achieved.

Fig.2

The tracking error of the heliostat shifts the focal spot at the input face of the light guide, resulting only in a uniform reduction in power intensity at its output end. The absorbed pump power profile within the laser rod, and hence the laser power, is not significantly affected.

2.3 Compound V-shaped pump cavity

The compound V-shaped pump cavity plays an important role by coupling the pump radiation from the output end face of the light guide into the 7 mm diameter 30 mm length 0.1 at% Cr:1.0 at% Nd:YAG ceramic rod. To improve the absorbed pump distribution, the compound V-shaped pump cavity is optimized by ZEMAX© non-sequential ray-tracing code. With an entrance aperture of 21 mm × 23 mm, 24 mm depth and 9 mm separation between the output end of the guide and the rod optical axis, as shown in Fig. 3, this cavity is effective in coupling the light rays with different incidence angles into the laser rod. For example, ray 1 pass through the rod once and is bounced back by the lower plane section A of the cavity, so that double-pass absorption of the pump radiation is obtained. While ray 2 pass through the rod only once, ray 3 passes through the rod twice, due to the successive reflections from the two symmetric plane sections B. The upper plane section C of the cavity redirects the ray 4 to the laser rod so that at least one passage can be accomplished. A relatively large pump cavity is designed to allow a simultaneous lateral access to cooling water, ensuring hence a uniform thermal load along the laser rod. Both the ceramic rod and the cavity are actively cooled by water with 7 L/min flow rate. The inner wall of the whole pumping cavity is bonded with a protected silver-coated aluminum foil with 94% reflectivity.

Fig. 3

The standard solar spectra [15] for one-and-a-half air mass (AM1.5) are used as the reference data for consulting the spectral irradiance ($W/m^2/nm$) at each wavelength. 0.27^o solar divergence half-angle is assumed. The absorption spectra of 0.1 at% Cr: 1.0 at% Nd:YAG ceramics has two broad absorption bands at approximately 440 nm ($^4A_2$ to $^4T_1$) and 600 nm ($^4A_2$ to $^4T_2$) [13]. It can be seen as the superposition of the absorptions of Nd:YAG and Cr:Nd:YAG. All the above peak wavelengths and their respective absorption coefficients are added to the glass catalogue for Cr:Nd:YAG material in ZEMAX© software. In order to reduce the thermal load along the laser rod, the IR radiation which does not contribute to lasing is firstly attenuated by the light guide and then filtered by the sufficient amount of cooling water flowing through the cavity. The effective pump power of the light source takes into account about 24% overlap between the absorption spectrum of the 0.1 at% Cr: 1.0 at% Nd:YAG medium [13] and the solar spectrum [15]. ZEMAX© ray-tracing code is used to both maximize the absorbed pump power and optimize the absorption profile within the rod, as shown in Fig. 4. The absorbed pump flux data from the ZEMAX© analysis is then processed by LASCAD© software. The stimulated emission cross-section of 2.38×10^{-19} cm^{-1}, the fluorescence life time of 220 μs [14] and a typical scattering loss of 0.002 cm^{-1} for the 0.1 at% Cr: 1.0 at% Nd:YAG medium are adopted in LASCAD© analysis. A concave-concave stable laser resonator of 300 mm length, an averaged solar pump wavelength of 560 nm [13] are used in the LASCAD© analysis. Output couplers of different reflectivity, ranging from 85% to 99%, are tested individually to maximize the multimode laser power. According to different resonant cavity parameters, various input solar power/output laser power characteristics are numerically analyzed. For example, the maximum solar laser power of 34.0 W can be achieved by adopting the 98% output coupler with -2 m radius of curvature (RoC) in LASCAD© analysis.

Fig. 4

At high average laser power, even a nearly uniform gain distribution in a water-cooled laser rod, as given in Fig.4, has been shown to induce a non-parabolic heat distribution as a result of the temperature dependence of the thermal conductivity. This results in a radially dependent refractive power of the thermal lens, which has a maximum along the rod axis [16]. Nevertheless, comparing to other end-pumping schemes, the laser beam divergence of our side-pumped Cr:Nd:YAG ceramic laser is found to be significantly reduced in LASCAD© analysis, due principally to the uniform absorbed pump distributions shown both in Fig.2 and Fig. 4.

3. Experimental results of the side-pumped Cr:Nd:YAG ceramic solar laser

The 7 mm diameter, 30 mm length 0.1 at% Cr: 1.0 at% Nd:YAG ceramic rod is supplied by Konoshima Chemical Co. Ltd. Japan. The optical resonator with 300 mm length is comprised of two opposing concave-concave mirrors at right angles to the optical axis of the rod, as shown in Fig.1. The rear mirror is high reflection coated (HR, 99.98%), while the output mirror is partial reflection coated (PR, 98%). Output mirrors with RoC varying between -0.5 m and -5 m are used to test the solar laser performances. The -2 m RoC output couplers offer the best solution. Four -2 m RoC output mirrors with 90%, 94%, 98% and 99% reflectivity are therefore chosen to study the solar input / laser output performances. Fig.5. shows the laser output power as a function of the input solar power at the focus.

Fig.5

We define the slope efficiency at the focus as $\eta_{focus,}$ since only the solar power at the focus of the parabolic mirror is considered in calculation. η_{laser} is then defined as the laser slope efficiency when the combined reflection losses of the heliostat-parabolic mirror system are taken into account. Direct solar irradiance is measured simultaneously during lasing with a Kipp & Zonen CH1 pyrheliometer on a Kipp & Zonen 2AP solar tracker. It varies between 930 and 1030 W/m^2 during the period of measurement in July, 2012. Laser output power is detected by a Molectron PowerMax 500D with less than 3% measurement uncertainty. Two sliding doors and a shutter with motorized blades are used to regulate the incoming solar power from the heliostat. To achieve the maximum laser power, the shutter is totally removed. The maximum laser output power of 33.6 W is measured for -2.0 m RoC output coupler with 98% reflectivity. The slope efficiency of η_{focus} = 2.6% is finally determined.

A linear fiber-optic array for measuring the one-dimensional laser beam intensity distribution in the near field is placed 5 mm away from the output coupler along the optical axis of the laser rod [8, 10]. 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.

For far field laser beam profile measurement, a 10” x 10” industrial standard laser alignment thermal sensitive paper ZAP-IT@ is positioned 10 m away from the output coupler. Assuming 3 mm reading error in the thermal sensitive paper, less than 2% laser beam diameter measurement error is ensured.

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

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

Where ϕ_1 = 7.0 mm and ϕ_2 = 150 mm are the measured laser beam diameters at $1/e^2$ width, 5 mm and 10 m away from the output mirror respectively and L is the distance between these two points.

M^2 factor is then calculated as: $$M^2 = \frac{\theta}{\theta_0} \quad (2)$$

where $\theta_0 = \frac{\lambda}{\pi\omega_0}$ = 0.015º is the divergence of diffraction-limited Gaussian beam for λ=1.064 µm and ω_0 =1280 µm, as calculated by LASCAD© laser beam propagation method for the 7 mm diameter rod. For -2 m RoC output coupler, M_x^2 = 27.5 ± 3% and M_y^2 = 28.3 ± 3% are experimentally determined, indicating a near symmetric beam profile. Figure of merit B of 0.44 × 10^{-1} W is finally calculated. Even though this value is 6.5 times lower than our previous record of 2.9 × 10^{-1} W [10], it is still 6.7 times higher than that of the most recent end-pumped solar laser [9].

4. Comparison of the laser performances of both Cr:Nd:YAG ceramic and Nd:YAG single-crystal rod

The light guide dimensions, the laser rod diameters and the cavity profiles have already been optimized by ZEMAX© and LASCAD© numerical analysis software. For maximizing individually the laser output power from each laser medium, the 7 mm diameter Cr:Nd:YAG ceramic rod is pumped by the compound V-shaped cavity in 2012 and the 4 mm diameter Nd:YAG single-crystal rod by the modified 2D/CPC cavity in

2011[10]. The fused silica light-guide with 16 mm × 22 mm cross-section is used for pumping the 7 mm diameter Cr:Nd:YAG ceramic rod. This light guide is only slightly thicker than the 14 mm × 22 mm cross-section light guide used for side pumping the 4 mm diameter Nd:YAG single-crystal rod. Both light guides have 140 mm length and are manufactured from same fused silica material. The cooling water is kept also at nearly the same working temperature of 20 ºC ± 2 ºC. From Fig.5, the following conclusions can be drawn:

1. In comparison to our last year´s results with the 4 mm diameter Nd:YAG single-crystal rod, as given by the lower dashed line in Fig. 5, there exists a general improvement in laser powers with the 7 mm diameter Cr:Nd:YAG ceramic rod. For the 98% reflectivity, -2 m RoC output coupler, for example, there is 132% laser power enhancement, as given by the upper solid line in Fig. 5. There exists also 118% improvement in slope efficiency at the focus, from 2.2% for the single-crystal rod to 2.6% for the ceramic rod.

2. There is no reduction in threshold power due to the use of the 7 mm diameter ceramic rod. It is not easy to initiate solar laser operation with less than 390 W solar powers at the focus.

For the 0.1 at% Cr: 1.0 at% Nd: YAG ceramic rod, a typical 0.002 cm^{-1} scattering loss is assumed in the LASCAD© analysis. Does this ceramic rod really have such a low scattering loss, or contrarily, it should have a much higher loss of 0.004 cm^{-1}, as measured in Ref. [9] ? Let us here deduce the scattering loss of the ceramic rod of our laser system by using the same equation as given in Ref. [9]. The laser output power can be expressed in terms of input power and measurable quantities as listed below:

$$P_{out} = \frac{1-R}{1+R}\left[\frac{2\eta}{2l\alpha - lnR}P_{in} - AI_s\right] \qquad (2)$$

In this equation, I_S the saturation gain, A the cross-section area of the laser rod, R the reflectivity of output coupler, α the scattering coefficient of laser material and l the length of laser medium. The conversion factor η can be expressed as $\eta = \eta_A\eta_Q\eta_S\eta_B$ where η_A, η_Q, η_S and η_B are the absorption efficiency, the quantum efficiency, the Stoke factor and the beam overlap efficiency, respectively. $2l\alpha$ expresses the two-way loss in the resonator. At the same input solar radiation and resonator configuration, conversion factor η is a constant value if we change only the reflectivity of output coupler. Now we examine Eq. (2) with three variables: conversion factor η, scattering coefficient α, saturation gain I_S. These variables could be determined with three simultaneous equations by changing the reflectivity of output couplers three times. Substituting measured solar input powers and laser output powers, as given in Fig.5, with reflectivity of output couplers of 94%, 98% and 99% into Eq. (2), we then get the determined variables. The scattering loss of only 0.0018 cm^{-1} is finally found by our analysis. The calculated I_S value of 2.38 kW/cm^2 also lies between the two published values [9, 17]. In conclusion, the scattering loss of the 0.1 at% Cr 1.0 at% Nd:YAG ceramic rod is less than 0.002 cm^{-1}. It is not responsible for the low efficiency of the ceramic solar-pumped lasers. By inserting the conversion factor of $\eta = 2.27\%$ into Eq. 2, we obtain a simple expression for laser slope efficiency:

$$\eta_{laser} = \frac{1-R}{1+R}\left[\frac{2\eta}{2l\alpha - \ln R}\right] \tag{3}$$

If, for example, the laser resonator has the following parameters: $R = 0.98$, $l = 3$ cm, $\alpha = 0.0018$ cm^{-1} and $\eta = 2.27\%$, then the laser slope efficiency $\eta_{laser} = 1.49\%$ is calculated. If only 59% combined reflectivity from both the heliostat and the parabolic mirror is taken into account, then the slope efficiency from the focus $\eta_{focus} = 2.53\%$ can finally be calculated, which matches well the experimental value of 2.6% in Fig. 5.

Since there is only less than 16% spectral overlap between the solar emission spectrum and Nd:YAG absorption spectrum, the absorbed solar pump power is limited. The compact CPC cavity is used to achieve efficient pumping along the 4 mm diameter Nd:YAG rod. ZEMAX© and LASCAD© numerical analysis has also indicated the effectiveness of the CPC scheme in attaining the maximum laser output power from the Nd:YAG rod. Since the overlap between the solar emission spectrum and Cr:Nd:YAG absorption spectrum can theoretically reach 40%, there are more absorbed solar pump power available, large diameter ceramic rod can then be used to achieve more laser output power. The compound cavity is adopted to pump the 7 mm diameter Cr:Nd:YAG ceramic rod. The rod diameter is also optimized by both ZEMAX© and LASCAD© analysis. The compound V-shaped pump cavity ensures the nearly top-hat absorbed pumped flux distribution, as shown in Fig.4, which drastically reduces the laser beam divergence, when compared to other end-pumped configurations.

The heat load of the 7 mm diameter Cr:Nd:YAG ceramic rod within the compound cavity is also lower than that of the 4 mm diameter single-crystal Nd:YAG rod within the CPC cavity. On the one hand, the Cr:Nd:YAG rod provides enhanced laser output performance within the large compound cavity, on the other hand, the Nd:YAG rod produce also its maximum laser output power within the compact CPC cavity, so the comparison between the ceramic and single-crystal laser rods are made within different pumping cavities, where the advantages of each laser rod, and therefore the laser output performances can be fully exploited.

Side-pumping configuration provides the best heat load distribution along the rod and the temperature dependent reduction of the 1064 nm stimulated emission cross-section of Cr:Nd:YAG ceramic crystal [14] is not as significant as the case of other end-pumped configurations. For this reason, there exists a general enhancement of solar laser power by side-pumping the Cr:Nd:YAG ceramic rod. Highly intense solar end-pumping will inevitably raise the thermal load of the ceramic rod, creating hot pump spots along the rod, the stimulated cross-section value of Cr:Nd:YAG ceramic rod will be reduced significantly. This, in our opinion, is the main reason of the relatively low laser efficiency of Cr:Nd:YAG ceramics rod in high solar power end-pumping configuration. The UV solarization effects and the IR heating can also severely influence the laser performance of the ceramics.

5. Conclusions

High power and high efficiency solar-pumped lasers have a large potential for many interesting applications. The radiation coupling and homogenization capacity of the fused silica light guide is combined with the light coupling properties of the compound V-shaped cavity to provide the efficient side-pumping to the 7 mm diameter 0.1 at% Cr: 1.0 at% Nd:YAG ceramic rod. The introduction of the rectangular cross-section light guide has also ensured a more stable laser emission than other pumping schemes. There exists a general improvement of about 132% in output laser power. 2.6% slope efficiency at the focus is also reached. The laser beam brightness figure of merit is, on the one hand, more than 6 times less than that by the 4 mm diameter Nd:YAG single-crystal rod and, on the other hand, still 6.7 times higher than that of the most recent end-pumped solar laser [9]. The ceramic rod has also the scattering loss of only 0.0018 cm^{-1}, as deduced from the output laser powers by different output coupling ratios. The non-uniform heat load problem along the laser rod is considered as the key factor affecting the ceramic output performances of solar-pumped lasers.

Acknowledgments

This research project (PTDC/FIS/103599/2008) was funded by the Science and Technology Foundation of Portuguese Ministry of Science, Technology and Higher Education (FCT-MCTES). Financial support by the Access to Research Infrastructures activity in the 7th Framework Program of the EU (SFERA Grant Agreement n. 228296) is gratefully acknowledged. We would like to express our thanks to Dr. Takashi Ito from Baikowski Japan Co. Ltd. for the helpful discussions about the scattering properties of the 0.1% Cr: 1.0 % Nd:YAG ceramic rod.

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Figure Captions

Fig.1 (a) PROMES-CNRS 2 m diameter solar concentrator with the Cr:Nd:YAG laser resonant cavity. (b) The mechanical components of the laser resonator.

Fig.2 Double-stage light guide / compound V-shaped pump cavity for the Cr:Nd:YAG laser rod.

Fig.3 Cross-sectional view of the compound V-shaped pump cavity

Fig.4 Absorbed pump flux distribution by non-sequential ray-tracing of the 7 mm diameter ceramic rod.

Fig.5 Cr:Nd:YAG and Nd:YAG laser output powers versus input solar power at the focus.

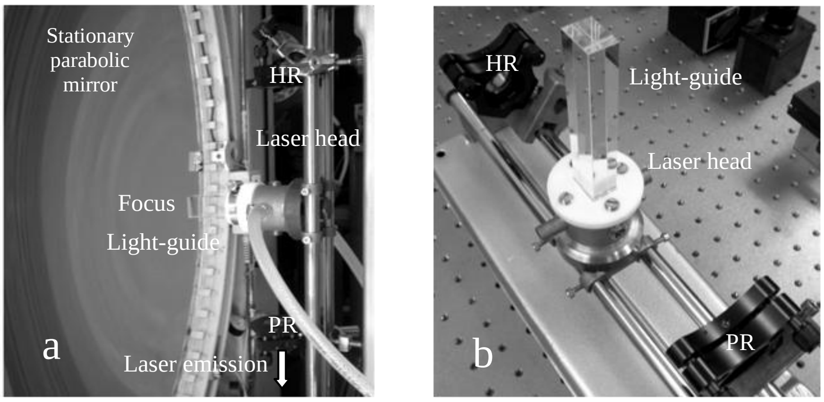
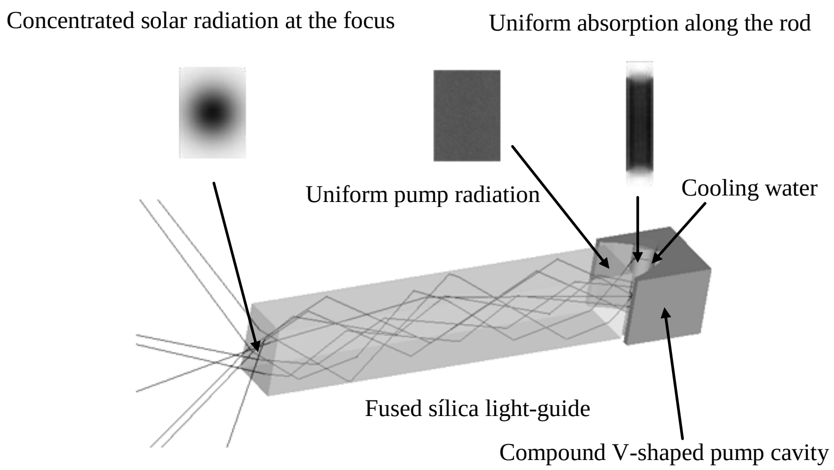

Stationary parabolic mirror
HR
Laser head
Focus
Light-guide
PR
a
Laser emission
HR
Light-guide
Laser head
b
PR

Fig. 1



Concentrated solar radiation at the focus
Uniform absorption along the rod
Uniform pump radiation
Cooling water
Fused sílica light-guide
Compound V-shaped pump cavity

Fig.2

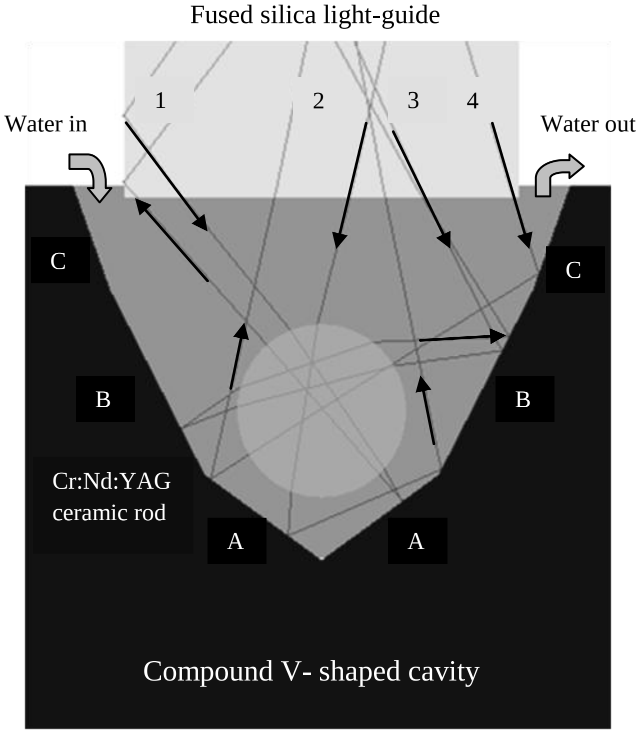

Fused silica light-guide
1
2
3
4
Water in
Water out
C
C
B
B
Cr:Nd:YAG
ceramic rod
A
A
Compound V- shaped cavity

Fig. 3

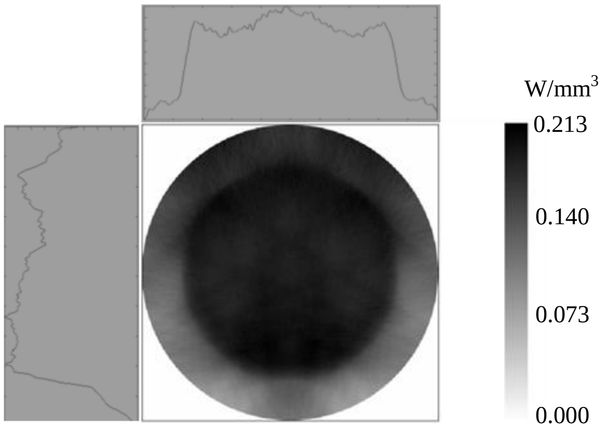
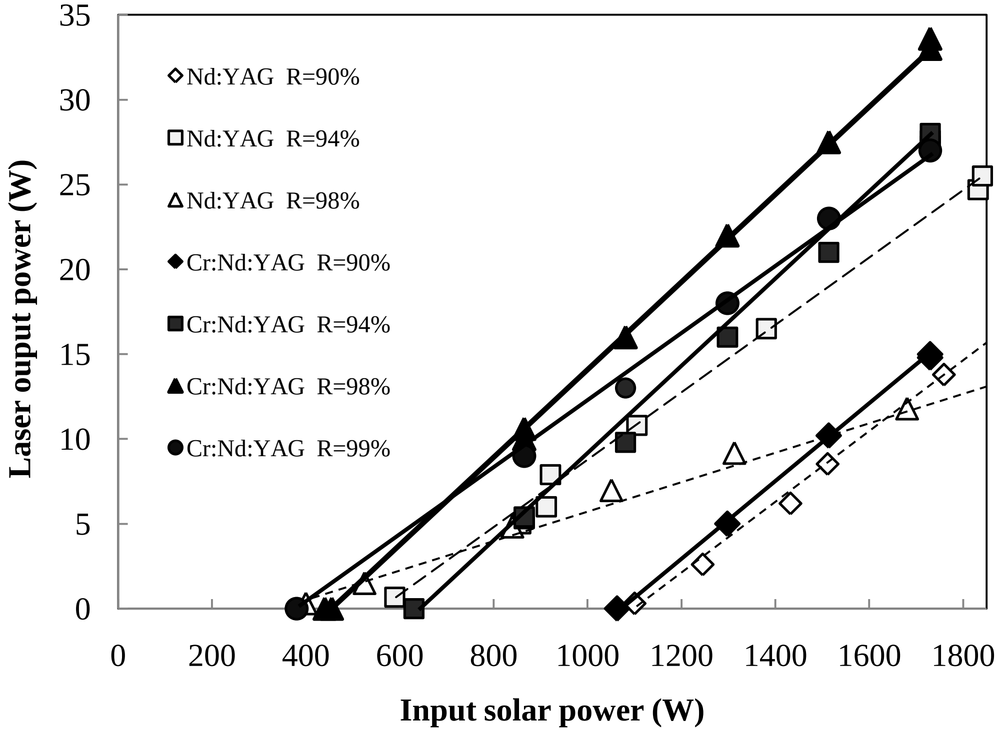


Fig. 4



Nd:YAG R=90%
Nd:YAG R=94%
Nd:YAG R=98%
Cr:Nd:YAG R=90%
Cr:Nd:YAG R=94%
Cr:Nd:YAG R=98%
Cr:Nd:YAG R=99%
Laser ouput power (W)
Input solar power (W)
0
5
10
15
20
25
30
35
0
200
400
600
800
1000
1200
1400
1600
1800

Fig.5

Answers to the Reviewers' comments:

Dear Reviewer 1

Many thanks for your very helpful and insightful comments

We would like to answer your comments one by one

Reviewer #1: I believe that the paper presents an interesting result. However, there are many significant misunderstanding and unclear points which should be considered before further review.

1. In Fig.5, they are comparing ceramic Cr.Nd YAG and Nd YAG crystal data but two conditions are completely different. The size is different and input source is different. I doubt this comparison and it is not scientific. In addition, "Input solar power" in horizontal axis is misleading. They should put real incident solar power on the collecting mirror. The incident solar power of two experiments is almost 4 times different.

With due respects, we think reviewer 1 has not been very careful in examining the manuscript.

In Fig.5, we are comparing ceramic Cr:Nd:YAG and Nd:YAG crystal data, the solar energy collection concentration system in PROMES-CNRS has the same size and reflectivity. The input solar irradiances are only slightly different for the two experiments in 2011 and 2012 respectively. The side-pumped Nd:YAG laser output performances, published by Optics and Laser Technology in 2012 (Ref.10), are compared to the present results.

Also from the comments of ” the incident solar power of the two experiments are almost 4 times different”, the reviewer might have mistakenly considered our Fresnel lens end-pumped solar laser published by Optics Express in 2011(Ref. 8) for his comparison. We did not compare this end-pumped result with the present results in Fig. 5.

The collected solar power at the focus has been widely adopted as input solar power in many publications on solar-pumped lasers by Arashi (Ref 4), Weksler (Ref.5), Lando(Ref.7), Yabe (Applied Physics Letters in 2007, Optics Letters in 2008), Liang (Ref. 8) etc, so we prefer not changing the rules during the game.

2. The authors mentioned 33.4W output but its collection efficiency is only 10W/m2 and a half of their previous result. This means the proposed scheme might have some difficulty in scaling up. This point should be discussed.

Once again, the reviewer must have mistakenly compared the $10W/m^2$ collection efficiency with the 19.3 W/m2 value in Reference 8, which matches well with “a half of their previous result”. Instead, our previous result in Ref. 10 was only $9.6W/m^2$ with the same PROMES-CNRS system, so the collection efficiency is slightly enhanced by using Cr:Nd:YAG ceramic rod in 2012.

As mentioned in the manuscript, the total reflectivity of the whole solar energy collection and concentration system is only 59%. The back surface silver-coated plane mirror and parabolic mirror have more than 20 year´s service history. The collection efficiency can be largely improved by using front surface silver-coated mirrors.

3. On page 3, they claimed the demerit of using optical fiber. However, I did not find the superiority of their system for long distant transportation of many beams. This should be essential because we can not use huge mirror for obtaining MW class laser but we need to use 1000 bundles of kW laser, because no one show the feasibility of huge laser by single optical system.

We only mention some shortcomings of optical fibers for laser power transmission. We are admirers of the renewable large-scale Mg recovery scheme proposed by Professor T. Yabe with many optical fiber bundles for kW laser. Besides, we are also interested in the multi-rods solar-pumped laser scheme at the focus of the 1MW solar furnace as proposed by Uzbekistan scientists, without optical fibers in this case.

4. As for the beam quality, I would like to know the size of the beam spot which might be used to calculate the divergence of the beam.

Far field laser beam divergence measurement was carried out again.

We have measured the $1/e^2$ beam spot size of about 150 mm diameter, 10 meters away from the laser output coupler.

5. In the previous paper, they used CPC but now are using tapered cavity. I would like to know the reason of the change and how it changes the result.

The following text has been added to the revised manuscript:

Since there is only less than 16% spectral overlap between the solar emission spectrum and Nd:YAG absorption spectrum, the absorbed solar pump power is limited. The compact CPC cavity is used to achieve efficient pumping along the 4 mm diameter Nd:YAG rod. ZEMAX© and LASCAD© numerical analysis has also indicated the effectiveness of the CPC scheme in attaining the maximum laser output power from the Nd:YAG rod. Since the overlap between the solar emission spectrum and Cr:Nd:YAG absorption spectrum can theoretically reach 40%, there are more absorbed solar pump power available, large diameter ceramic rod can then be used to achieve more laser output power. The compound cavity is adopted to pump the 7 mm diameter Cr:Nd:YAG ceramic rod. The rod diameter is also optimized by both ZEMAX© and LASCAD© analysis. The compound V-shaped pump cavity ensures the nearly top-hat absorbed pumped flux distribution, as shown in Fig.4, which drastically reduces the laser beam divergence, when compared to other end-pumped configurations.

The heat load of the 7 mm diameter Cr:Nd:YAG ceramic rod within the compound cavity is also lower than that of the 4 mm diameter single-crystal Nd:YAG rod within the CPC cavity. On the one hand, the Cr:Nd:YAG rod provides enhanced laser output performance within the large compound cavity, on the other hand, the Nd:YAG rod produce also its maximum laser output power within the compact CPC cavity, so the comparison between the ceramic and single-crystal laser rods are made within different pumping cavities, where the advantages of each laser rod, and therefore the laser output performances can be fully exploited.

6. On page 10, "the temperature dependent reduction of the 1064 nm stimulated emission ...[9]" but there is no description on stimulated emission in ref.[9]. The authors should not write a misunderstanding sentence.

Yes, the sentence has been changed to:

Side-pumping configuration provides the best heat load distribution along the rod and the temperature dependent reduction of the 1064 nm stimulated emission cross-section of Cr:Nd:YAG ceramic crystal [14] is not as significant as the case of end-pumped configurations.

7. The quality of ceramic laser depends on the production condition. Therefore the scattering loss changes depending on the lod. If the authors are careful enough, ref.[9] did not say the inferiority of the ceramic YAG but the ceramic they used has the high scattering coefficient. This is important because the quality changes one by one and should be improved for industrial application. Therefore they should remove the word "doubts" in abstract and introduction and so on.

Yes, the words doubt have been removed in the revised manuscript

8. Regarding the scattering coefficient, the authors mentioned on 9 that "0.004cm-1, as predicted in Ref.[9]". This is misleading because it was measured by integrated sphere but was not predicted. In addition, agreement with published value ref.[17] has no meaning because the ceramic quality is not so stable.

Yes, "0.004cm-1, as predicted in Ref.[9]" has been changed to,

"0.004cm-1, as measured in Ref.[9]"

The sentence"which agrees well with the published value of 0.002 cm^{-1} [17]" has been removed in the revised manuscript.

Dear Reviewer 2

Many thanks for your very insightful and helpful comments.

We would like to answer your concerns one by one

Reviewer #2: Solar laser attracts more attentions in research due to the potential applications in clean energy field. The authors present a comprehensive work on side-pumped CW Cr:Nd:YAG ceramic solar laser. The simulation as well as experimental results are very valuable reference for people working in this field. Nevertheless, a few issues are not clearly addressed in the manuscript.

1. Page 3, lines 39-40 describe the inner wall of the V-shaped pump cavity. What is the material of the V-shaped cavity? Why not have the pump cavity directly coated with gold or silver but bonded with a silver-coated aluminum foil?

The V-shaped cavity is bounded with silver-coated aluminum foil with 94% reflectivity by now. A gold-coated cavity will not reflect efficiently some useful solar pump power below 500 nm. Silver coating is not used due to the possible contamination with cooling water. Protected silver coating will be considered in the future version.

2. Page 6, line 44 to page 7, line 14 describe how the M2 parameter was measured, the method they used was too much simplified. Normally, the transverse beam profile at minimum five positions need to be recorded in order to fit the hyperbolic curve, so that the beam waist and far field divergence can be determined. The author only measured a very near field(5 mm) beam width and a far field beam width (1500 mm), the beam divergence calculated from these two values was not correct, therefore, the following up calculations of M2 and Figure of merit B were not reliable. In the same paragraph, the author mentioned that the diffraction-limited Gaussian beam of the same wavelength was 0.019 degree, how was this value calculated?

The following text has been added to replace the original text in the revised manuscript:

A linear fiber-optic array for measuring the one-dimensional laser beam intensity distribution in the near field is placed 5 mm away from the output coupler along the optical axis of the laser rod [8, 10]. 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.

For far field laser beam profile measurement, a 10” x 10” industrial standard laser alignment thermal sensitive paper ZAP-IT® is positioned 10 m away from the output coupler. Assuming 3 mm reading error in the thermal sensitive paper, less than 2% laser beam diameter measurement error is ensured.

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

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

Where ϕ_1 = 7.0 mm and ϕ_2 = 150 mm are the measured laser beam diameters at $1/e^2$ width, 5 mm and

10 m away from the output mirror respectively and *L* is the distance between these two points.

M^2 factor is then calculated as:

$$M^2 = \frac{\theta}{\theta_0} \quad (2)$$

where $\theta_0 = \frac{\lambda}{\pi \omega_0}$ = 0.015º is the divergence of diffraction-limited Gaussian beam for λ=1.064 μm and ω_0 = 1280 μm, as calculated by LASCAD© laser beam propagation method for the 7mm diameter rod.

For -2 m RoC output coupler, M_x^2 = 27.5 ± 3% and M_y^2 = 28.3 ± 3% are experimentally determined, indicating a near symmetric beam profile. Figure of merit B of 0.44 × 10^{-1} W is finally calculated. Even though this value is 6.5 times lower than our previous record of 2.9 × 10^{-1} W [10], it is still 6.7 times higher than that of the most recent end-pumped solar laser [9].

3. In section 4, the authors made some comparison between Nd:YAG and Cr, Nd: YAG ceramic, the experimental conditions were very different, e. g., the size of the crystal, mode volume of the resonator and pumping scheme were all different in two cases. But the authors put the results into one figure, (Fig. 5) and made comparison of the output and efficiency. So the conclusion based on this is not convincing, because other factors which could also influence the output power and efficiency were not excluded.

The following text has been added to the revised manuscript:

Since there is only less than 16% spectral overlap between the solar emission spectrum and Nd:YAG absorption spectrum, the absorbed solar pump power is limited. The compact CPC cavity is used to achieve efficient pumping along the 4 mm diameter Nd:YAG rod. ZEMAX© and LASCAD© numerical analysis has also indicated the effectiveness of the CPC scheme in attaining the maximum laser output power from the Nd:YAG rod. Since the overlap between the solar emission spectrum and Cr:Nd:YAG absorption spectrum can theoretically reach 40%, there are more absorbed solar pump power available, large diameter ceramic rod can then be used to achieve more laser output power. The compound cavity is adopted to pump the 7 mm diameter Cr:Nd:YAG ceramic rod. The rod diameter is also optimized by both ZEMAX© and LASCAD© analysis. The compound V-shaped pump cavity ensures the nearly top-hat absorbed pumped flux distribution, as shown in Fig.4, which drastically reduces the laser beam divergence, when compared to other end-pumped configurations.

The heat load of the 7 mm diameter Cr:Nd:YAG ceramic rod within the compound cavity is also lower than that of the 4 mm diameter single-crystal Nd:YAG rod within the CPC cavity. On the one hand, the Cr:Nd:YAG rod provides enhanced laser output performance within the large compound cavity, on the other hand, the Nd:YAG rod produce also its maximum laser output power within the compact CPC cavity, so the comparison between the ceramic and single-crystal laser rods are made within different pumping cavities, where the advantages of each laser rod, and therefore the laser output performances can be fully exploited.

4. Page 10, line 2, the scattering loss of 0.018 cm^{-1}, one zero was missing, the correct value should be 0.0018 cm-1.

Yes, the correct value of 0.0018cm^{-1} has been added to the revised manuscript.