# Design of high-brightness $TEM_{00}$-mode solar-pumped laser for renewable material processing

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## ABSTRACT

The conversion of sunlight into laser light by direct solar pumping is of ever-increasing importance because broadband, temporally constant, sunlight is 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. Nonlinear processes, such as harmonic generation, might be used to obtain broad wavelength coverage, including the ultraviolet wavelengths, where the solar flux is very weak. The 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 materials processing. This renewable laser has a large potential for many applications such as high-temperature materials processing, renewable magnesium-hydrogen energy cycle and so on. We propose here a scalable $TEM_{00}$ mode solar laser pumping scheme, which is composed of four first-stage 1.13 m diameter Fresnel lenses with its respective folding mirrors mounted on a two-axis automatic solar tracker. Concentrated solar power at the four focal spots of these Fresnel lenses are focused individually along a common 3.5 mm diameter, 70 mm length Nd:YAG rod via four pairs of second-stage fused-silica spherical lenses and third-stage 2D-CPCs (Compound Parabolic Concentrator), sitting just above the laser rod which is also double-pass pumped by four V-shaped pumping cavities. Distilled water cools both the rod and the concentrators. 15.4 W $TEM_{00}$ solar laser power is numerically calculated, corresponding to 6.7 times enhancement in laser beam brightness.

**Keywords:** $TEM_{00,}$ solar-pumped, high brightness, material processing, laser cavity, Fresnel lens, solar concentrator, Nd:YAG

## 1. INTRODUCTION

The direct conversion of sunlight into laser light is of ever-increasing importance for obtaining extremely high brightness coherent radiations. Among the potential applications of solar lasers are earth, ocean, and atmospheric sensing; detecting, illuminating, and tracking hard targets in space; deep space communications. Renewable solar lasers are also very promising for terrestrial applications such as laser material processing. The 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. Up to now solar-pumped lasers have not been viewed from this perspective.

The first solar-pumped solid-state laser was reported by Young in 1966 [1]. Since the sunlight does not provide enough flux to initiate laser emission, additional focusing systems are required to both collect and concentrate the solar radiation to their focal zones. Parabolic mirrors have been primarily exploited to achieve tight focusing of incoming solar radiation [2-6]. Large-size Fresnel lens solar pumping schemes have only surfaced within the past seven years [7]. 19.3W/m$^2$ collection efficiency has been achieved by end-side-pumping a 4 mm diameter, 25 mm length Nd:YAG single-crystal rod [8]. Record-high collection efficiency of 30 W/m$^2$ has been produced in 2012 with a 6 mm diameter, 100 mm length Nd:YAG rod. However, very large $M_x^2 = M_y^2 = 137$ factors have also been reported simultaneously [9], resulting in a dismal brightness figure of merit - defined as the ratio between laser power and the product of $M_x^2$ and $M_y^2$ – of only 0.0064 W, which corresponds to less than 50 W/mm$^2$ laser intensity at the focal spot with 40 mm focal lens.

Because of its smooth intensity profile, low divergence and ability to be focused to diffraction-limited spot, it is highly desirable to operate a solar-pumped laser in the lowest-mode possible: $TEM_{00}$ mode. Side-pumping configurations are very suitable for laser power scaling. They allow a more uniform pump absorption profile along the laser medium. The

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associated thermal loading problems can hence be reduced. Besides, the free access to both rod ends permits the optimization of more laser resonator parameters, improving largely the laser beam quality. Therefore, their brightness figure of merit can be higher than that of end-pumping approaches. 0.29 W solar laser beam brightness figure of merit has been achieved in 2011, by side-pumping a 4 mm diameter Nd:YAG rod through the heliostat-parabolic mirror system in PROMES-CNRS [10]. This has remained as a record-high value until most recently, 1.9 W solar laser beam brightness figure of merit has been reported by side-pumping a 3 mm diameter, 30 mm length Nd:YAG rod through a first-stage Fresnel lens, a second-stage fused silica aspheric lens, a third-stage 2D-CPC concentrator and finally a V-shaped pumping cavity [11]. This result has surpassed the previous record value [10] by 6.6 times, but unfortunately, only 2.3 W solar laser power operating in the lowest fundamental mode ($TEM_{00}$) has been produced. The $TEM_{\mathbf{00}}$ solar laser power collection efficiency is also limited to 2.93W/m$^2$.

To improve substantially the solar laser beam brightness, a scalable $TEM_{00}$ mode solar laser pumping scheme is proposed here to pump efficiently the 3.5 mm diameter, 70 mm length Nd:YAG rod by four Fresnel lens – folding mirror solar energy collection and concentration system. The incoming solar radiation is firstly collected and concentrated by the four Fresnel lenses. Each lens is then followed by its plane folding mirror which redirects the concentrated solar light towards a laser head with spherical lenses and 2D-CPC concentrators. The thin Nd:YAG rod is finally double-pass pumped within the four V-shaped pumping cavities. Water is used to ensure both the effective removal of the generated heat and the efficient light coupling from the spherical lenses to the thin rod. Optimum pumping conditions and laser resonator parameters are found through ZEMAX© and LASCAD© numerical analysis respectively. In one hand, high multimode solar laser power of 69 W is calculated for the 3.5 mm diameter, 70 mm length rod, reaching the collection efficiency of 17.25 W/m$^2$. On the other hand, record high $TEM_{00}$ solar laser power of 15.4 W is numerically achieved with the same rod, being 6.7 times higher than the previous record [11] and 2390 times more than that of the most powerful Nd:YAG laser [9]. Heat dissipations are much more efficient due to the use of the thin rod. Moreover, a near uniform absorbed pump profile along the thin rod is achieved, alleviating largely the thermal lensing problems of high-power solar lasers.

## 2. FOUR FRESNEL LENSES SIDE-PUMPING APPROACH

The primary solar energy collection and concentration system in Fig. 1 is formed by both four Fresnel lenses ($F_1$-$F_4$) for both collecting and concentrating the incoming solar radiation and four plane folding mirrors ($M_1$-$M_4$) for reflecting the concentrated solar radiation from the Fresnel lenses towards the laser head, located in the focal zone.

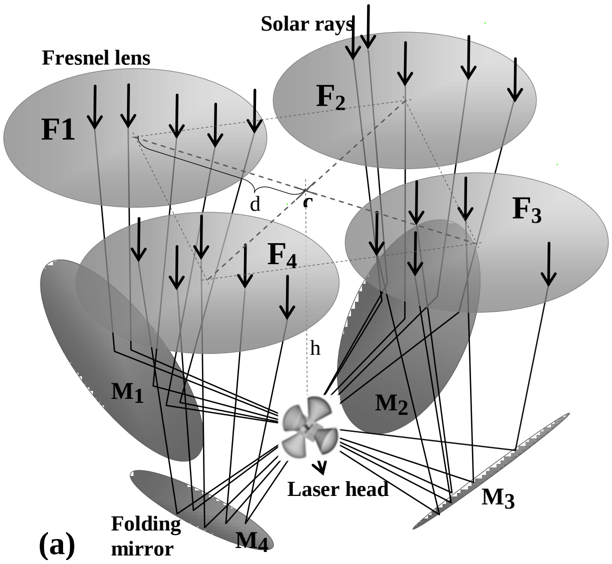

Figure 1. Design of the solar laser scheme with 4 Fresnel lenses - 4 plane folding mirrors. The laser head is placed along the focal position of the Fresnel lenses.

Each Fresnel lens has 1.13 m diameter and 2 m focal length. The center of each Fresnel lens is positioned d = 855 mm away from their common center c, which is located h = 1145 mm above the center of the laser head, as shown in Fig 1. The folding mirrors are placed 1115 mm, 1130 mm, 1145 mm and 1160 mm below their respective Fresnel lens, making $45^{\circ}$ angle with the lens optical axis. The concentrated solar power can hence be focused along the 3.5 mm diameter, 70 mm length rod, as shown in both Fig. 1 and Fig. 3.

Solar tracking can be achieved by mounting the whole laser system onto a two-axis solar tracker that follows the Sun continuously in direct tracking mode. The two stepper motors of the tracker are controlled by both an electronic control unit with GPS (Global Positioning System) guidance for quick solar orientation with 1.0°accuracy and a photo sensing unit for accurate tracking with 0.1° accuracy.

The Fresnel lenses are made of Polymethyl Methacrylate (PMMA) material, which is transparent at visible and near infrared (NIR) wavelengths, and cuts undesirable solar radiation beyond 2200 nm and below 350 nm. An averaged transmission efficiency of 78 % is numerically calculated for each Fresnel lens. Experimental transmission efficiency of 77.4% confirms the above numerical result. Considering 95 % reflectivity of each folding mirror, 1 $m^2$ solar collection area for each Fresnel lens and 950 $W/m^2$ terrestrial solar fluxes, about 700 W solar power can be attained in the focal zone of each Fresnel lens. For the whole system with 4 $m^2$, no less than 2800 W solar power is expected to reach the laser head.

## 3. SOLAR ENERGY CONCENTRATION BY SPHERICAL LENSES, 2D-CPC CONCENTRATORS AND V-SHAPED CAVITIES

The laser head is composed of four second-stage fused silica spherical lenses, four third-stage 2D-CPC concentrators and four V-shaped pumping cavities within which the Nd:YAG rod is mounted. Fused silica is an ideal optical material for solar laser pumping, since it is transparent over the Nd:YAG absorption spectrum. It has a high softening point and is resistant to scratching and thermal shock which also makes it very suitable for ultra-high power solar pumping. High optical quality fused silica concentrators (99.999%) can be manufactured by optical machining and polishing.

The highly concentrated solar radiation from the Fresnel lens - folding mirror system is further compressed to the Nd:YAG laser rod through the spherical lenses, the 2D-CPC concentrators and the V-shaped cavities, as shown in Fig. 2. The curved input face of the spherical lens, the dimensions of the 2D-CPC concentrator are both designed to compress the concentrated solar radiations from the focal zone along the thin laser rod. To manufacture the large aspheric lens, a 65 mm diameter, 50 mm length fused silica rod of 99.999% optical purity is ground and polished to its final dimensions. Each spherical input face has 40 mm radius. The output end of each spherical lens is polished to conical shape with $D_1$= 65 mm, $D_2$ = 30 mm and H = 35 mm in order to facilitate easy mounting to the laser head.

Each third-stage 2D-CPC concentrator has 12 mm × 16 mm large rectangular input aperture, 8.5 mm × 14 mm rectangular output aperture and is 10 mm in height, as shown in Fig. 2. The 2D-CPC is used to convert the rays from 12 mm × 16 mm large-aperture emitting into a small angle, less than $40^{\circ}$ for example, to 8.5 mm × 14 mm small-aperture emitting into a large angle, $65^{\circ}$ for example, thus the source étendue is preserved. This preservation implies that irradiance is larger at output aperture than at the entrance aperture, leading to a net concentration of the pump radiation. Efficient optical coupling between the output end faces of the spherical lenses and the 2D-CPC concentrators are obtained by cooling water at 6Liter/min flow rate.

The V-shaped cavity is finally used to achieve efficient double-pass absorption of the highly concentrated pump radiation from the 8.5 mm × 14 mm output aperture. The inner walls of both the 2D-CPC hollow concentrator and the V-shaped pumping cavity are bonded with a protected silver-coated aluminum foil with 94 % reflectivity.

Distilled water cools firstly the rod within the V-shaped cavity, then passes through the 2D-CPC concentrator and exits the laser head from the spaces between the output end of the spherical lens and 12 mm x 16 mm input aperture of the 2D-CPC concentrator. All the above optimized design parameters of the whole optical system are found by both non-sequential ray-tracing (ZEMAX$^{TM}$) and laser cavity design and analysis (LASCAD$^{TM}$) codes.

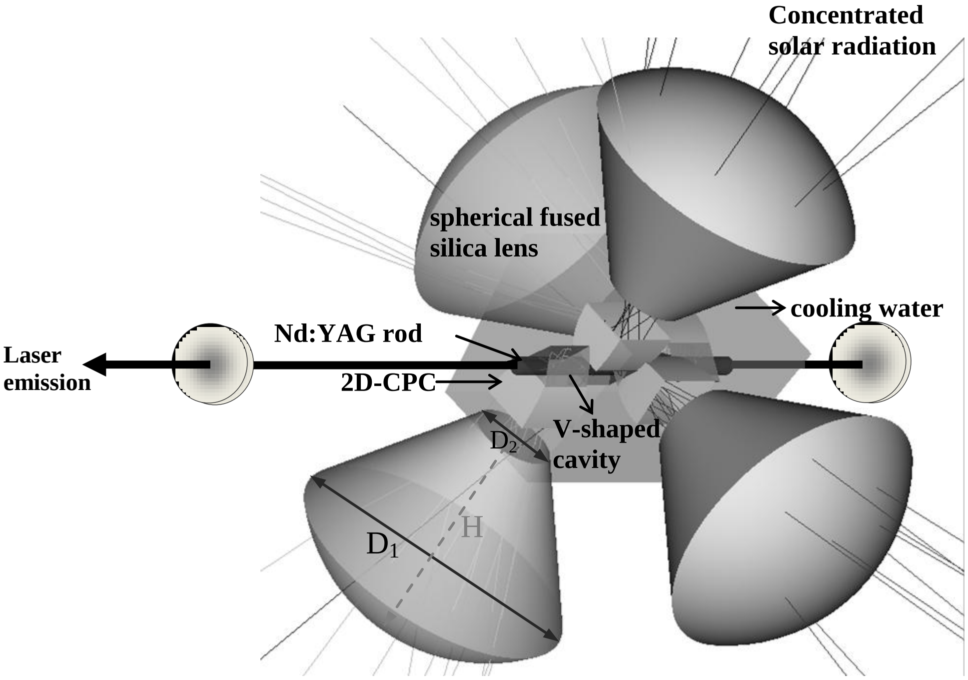

Figure 2. Detailed view of the laser head composed of the fused silica spherical lens, 2D-CPC cavities and V-shaped pumping cavities, all asymmetrically mounted to pump the 3.5 mm diameter, 70 mm length Nd:YAG rod.

## 4. NUMERICAL ANALYSIS OF THE ND:YAG SOLAR LASER PERFORMANCE

### 4.1 Optical design parameters of the solar laser system

All the design parameters of the solar-pumping scheme are optimized through ZEMAX© non-sequential ray-tracing. The standard solar spectrum for one-and-a-half air mass (AM1.5) [12] is used as the reference data for consulting the spectral irradiance ($W/m^2/nm$) at each wavelength. The terrestrial solar irradiance of 950 $W/m^2$ is considered in ZEMAX© software. The effective pump power of the light source takes into account the 16% overlap between the Nd:YAG absorption spectrum and the solar spectrum [13]. The half-angle of 0.27° subtended by the sun is also considered in the analysis. The absorption spectrum of Polymethyl Methacrylate (PMMA), fused silica and water materials are included in ZEMAX© numerical data to account for absorption losses. Despite the small overlap between the Nd:YAG absorption spectrum and the solar spectrum, Nd:YAG has been demonstrated as the best material under solar pumping because of its superior characteristic on thermal conductivity, high quantum efficiency and mechanical strength compared to other host materials. For 1.1 at% $Nd^{3+}$ -doped YAG single-crystal medium, 22 absorption peaks are defined in ZEMAX© numerical data. All the peak wavelengths and their respective absorption coefficients are added to the glass catalogue in ZEMAX© software. Solar irradiance values for the above mentioned 22 peak absorption wavelengths could be consulted from the standard solar spectra for AM1.5 and saved as source wavelength data. During ray-tracing, the active medium is divided into a total of 18000 zones. The path length in each zone is found. With this value and the effective absorption coefficient, the absorbed power within the laser medium can be calculated by summing up the absorbed pump radiation of all zones. The absorbed pump flux data from the ZEMAX© analysis is then processed by LASCAD© software to study the laser beam parameters of the Nd:YAG single-crystal rods.

The grey-scale absorbed pump flux distribution within both the central and longitudinal cross-sections of the 3.5 mm diameter 70 mm length Nd:YAG rod are shown in Fig. 3. Black color means near maximum pump absorption, whereas white means little or no absorption. The absorption of pump light along the rod is also clearly observed in Fig. 3. A uniform pump absorption profile along the rod can also be obtained by using 2D-CPC of different dimensions. However, the total laser output $TEM_{00}$ power will be reduced. This scalable pumping concept alleviates the thermal lensing effects and the laser beam divergence is significantly reduced. Thus, solar laser brightness figure of merit can be significantly improved.

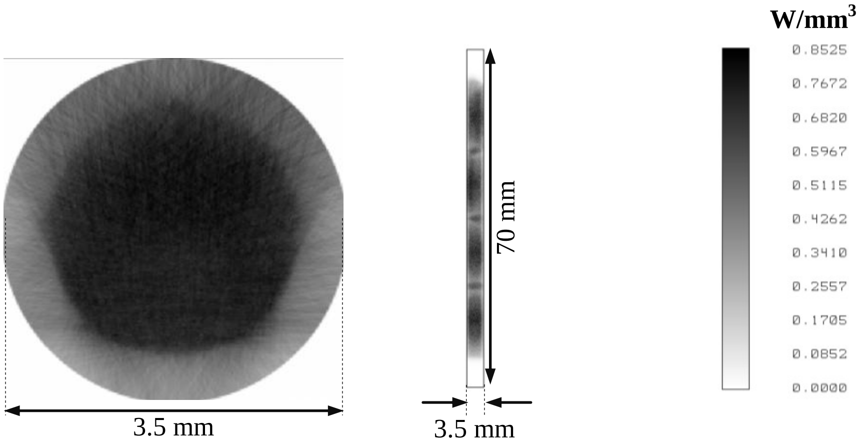

Figure 3. Absorbed pump flux distribution along both the central and longitudinal cross-sections of the D = 3.5 mm, L = 70 mm Nd:YAG rod.

In LASCAD© analysis the optical resonator is comprised of two opposing parallel mirrors at right angles to the axis of the laser medium. The amount of feedback is determined by the reflectivity of the mirrors. One end mirror is high reflection coated, corresponding to the HR-coated surface of the active medium. The output coupler is partial reflection coated, with reflectivity variable between 80 - 99 % according to different laser medium diameters. A 900 mm length resonator is chosen in LASCAD© software. The adoption of the output coupler with -2 m radius of curvature (RoC) radius leads to less laser beam divergence compared to that with smaller RoCs. Large RoCs will inevitably introduce higher diffraction losses, reducing the production of $TEM_{00}$ laser power. For the optimization of the laser system, the Nd:YAG laser output power is also numerically studied as function of the active medium diameter and length. Optimum solar laser performances are numerically attained with 3.5 mm Nd:YAG rod.

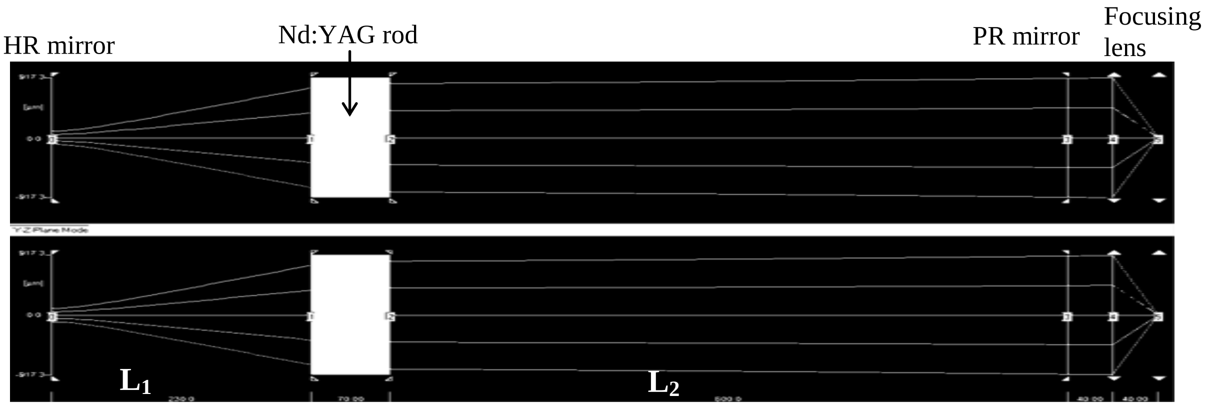

Figure 4. Asymmetrical laser resonant cavity for the efficient production of $TEM_{00}$ solar laser power.

The absorbed pump flux data from the ZEMAX© analysis is processed by LASCAD© software for laser beam parameters analysis. The asymmetric optical resonator is found to be the best configuration for achieving fundamental mode laser operation [10]. The cavity with a - 2 m RoC rear mirror (HR 99.8 %) positioned at $L_1$ = 200 mm and a - 2 m RoC output mirror (PR 90 %) positioned at $L_2$ = 700 mm offers the best $TEM_{\mathbf{00}}$ laser beam profile by LASCAD© beam propagation method, as shown in Fig. 5. 15.4 W $TEM_{00}$ solar laser power is numerically deduced. This result is 6.7 times more than the previous record in solar laser beam brightness. 3.85W/m² $TEM_{00}$ solar laser collection efficiency calculated is also 131 % more than the previous record [10]. It is also worth noting that no $TEM_{\mathbf{00}}$ laser beam profile can be obtained by symmetric resonator even with $L_T = L_1 + L_2$ = 900 mm. Short symmetric laser cavity, $L_1 = L_2$ = 200 mm, $L_T$ = 400 mm can lead to high multimode solar laser power of 69 W, corresponding to 17.25 W/m² collection efficiency.

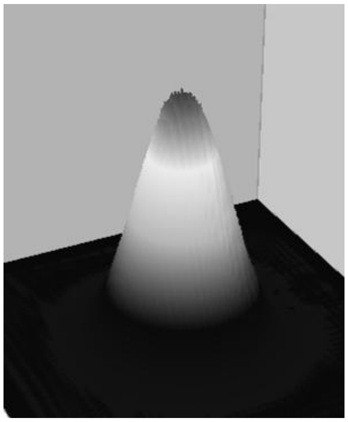

Figure 5. Numerically calculated $TEM_{00}$ solar laser beam profile by LASCAD© beam propagation method.

For the smooth Gaussian laser beam profile with low divergence, it is now possible to focus 15.4 W $TEM_{00}$ solar laser beam to the diffraction-limited spot of less than 30 μm diameter, when a focusing lens with 40 mm focal length is used, as shown in Fig. 4, corresponding to a peak intensity of more than $5000W/mm^2$. Solar-pumped laser has therefore a large potential for many applications, such as high-temperature materials processing, renewable magnesium-hydrogen energy cycle.

## 4. CONCLUSIONS

A scalable solar-pumped laser pumping configuration is put forward in this paper. It is composed of four Fresnel lens with four folding mirrors, the secondary concentrator with four spherical input face, 2D-CPC concentrators, and finally the V-shaped reflectors for double-pass pumping if a long and thin Nd:YAG laser rod. Optimum optical pumping conditions are found through ZEMAX© software. Optimized laser resonator parameters are found through LASCAD© numerical analysis. On one hand, high order multimode solar laser power of 69W is attained with the 400 mm symmetric laser cavity, leading to $17.25W/m^2$ collection efficiency. On the other hand, the lowest-mode possible: $\mathbf{TEM_{00}}$ mode is obtained with asymmetric laser resonant cavity. The record-high solar laser beam brightness figure of merit of 15.4 W is numerically predicted for the 3.5 mm diameter, 70 mm length Nd:YAG rod. This result corresponds to 6.7 times enhancement over the record. The proposed solar laser configuration provides hence an effective solution to reaching both high laser power and high beam quality, essential for the success of many solar-pumped laser applications.

## ACKNOWLEDGMENTS

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