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Advancement of sunlight-pumped-laser performance by a ring-array sunlight concentrator

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This paper presents a numerical investigation in the enhancement of the sunlight pumped laser performance using a system of ring-array sunlight flux concentrator. The sunlight resulting from the focal zone of a ring-array concentrator of 1.0 m diameter is further focused by an aspheric lens of fused silica material inside a Nd doped YAG rod (Neodymium-doped Yttrium Aluminum Garnet) of 4.0 mm diameter and 16 mm length housed in a conically shaped pump cavity. A computed sunlight pumped laser power of 31.0 W is obtained with a laser oscillation started for a pump power of 153.84 W, 5.2 % slope efficiency, and 4.13 % solar-to-laser power conversion efficiency. The achieved solar laser power resulted in a collection efficiency of a 39.5 W/m^2, representing 1.030 and 1.035 times greater than the record results by the same kind of concentrator. 0.032 W brightness figure of merit is also computed, corresponding to 1.60 and 1.52 times more than the previous records. More importantly, a large improvement in thermal performance is achieved with a maximum stress intensity of 106.2 N/mm^2, being nearly 50% lower than the previous results.

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Keywords: Thermal performance, Ring-array sunlight flux concentrator, Sunlight-pumped laser, Nd doped YAG medium

1. Introduction

Sunlight-pumped laser systems have appeared as a promising technology for converting sunlight directly into laser light. It offers a wide range of applications in both terrestrial and space domains. The pioneering research on sunlight pumped lasers was conducted by Kiss et al. and C. G. Young in the early 1960s [1, 2]. Since then, numerous researchers have contributed to the enhancement of sunlight pumped laser systems. Some notable contributors include Arashi et al. [3], Weskler et al. [4], Vasylyev et al. [5], Lando et al. [6, 7], Saiki et al. [8], Yabe et al. [9], Xu et al. [10], Dinh et al. [11], Payziyev et al. [12, 13], Bouadjemine et al., [14], Mehellou et al. [15], Guan et al., [16], Liang et al. [17 - 28], Almeida et al. [29 - 36], Vistas et al. [37 - 45], Garcia et al. [46 - 51], Matos et al. [52], Tibúrcio et al. [53 - 58], Costa et al. [59, 65], Boutaka et al. [66], Catela et al. [67 - 71], Cai et al. [72, 73], which have made significant progress in improving the performance of sunlight pumped lasers.

Another way in enhancing the solar-to-laser power conversion systems has began in 1997 by Ueda et al. [74]. The proposed optical device was based on the fiber lasers pumped with natural sunlight. Since then, researches about solar pumped fiber lasers have attracted ever-growing attention for their high conversion efficiency, good thermal effect, simple and stable structure [75]. Substantial improvements in solar fiber lasers have been made by Mizuno et al. [76], Masuda et al. [77, 78], Endo et al. [79], Guo et al. [80, 81], Xiang et al. [82], Zhu et al. [83].

The solar laser power production capacity of any solar laser systems can be designated by several parameters, the laser slope efficiency, the laser beams brightness, the collection efficiency and so on.

Collection efficiency (defined as the ratio between the laser output power and the collection surface of the first solar concentrator [4, 6, 7]) is generally considered as one of the main figures of merit that describe the lasers competence and it has been progressively improved since the appearance sunlight pumped laser.

Records collection efficiencies, for single beam sunlight pumped lasers, were obtained by the end-side pumping method of the active medium [9, 11, 16, 17, 23, 24, 52, 53, 72], (Table 1 recapitulates the main research in which high collection efficiencies have been recorded from the first significant result achieved by Yabe et al. in 2007).

Table 1. Records sunlight-pumped lasers collection efficiencies

Source	Primary concentrator		Active medium			Laser power (W)	Collection efficiency (W/m^2)
	Kind	Collection area	Type	Diameter (mm)	Length (mm)		
Yabe et al., 2007 [9]	Fresnel lens	1.3 m^2	Cr: Nd: YAG	9.0	100	24.4	18.7
Liang and Almeida, 2011 [17]	Fresnel lens	0.64 m^2	Nd: YAG	4.0	34	12.3	19.3
Dinh et al., 2012 [11]	Fresnel lens	4 m^2	Nd: YAG	6.0	100	120	30.00
Liang al., 2017 [23]	Parabolic mirror	1.54 m^2	Nd: YAG	4.0	35	37.2	31.50
Guan et al., 2018 [16]	Fresnel lens	1.03 m^2	Nd: YAG	6.0	95	33.1	32.10
Liang al., 2018 [24]	Parabolic mirror	1.0 m^2	Cr: Nd: YAG	4.5	35	32.5	32.50
Tibúrcio et al., 2018 [53]	Ring-array concentrator	1.76 m^2	Nd: YAG	5.0	20	67.3	38.20
Matos et al., 2018 [52]	Ring-array concentrator	1.76 m^2	Nd: YAG	5.5	20	67.8	38.40
Cai et al., 2023 [72]	Fresnel lens	0.69 m^2	Ce: Nd: YAG	6.0	95	26.93	38.80
Present Work	Ring-array concentrator	0.78 m^2	Nd: YAG	4.0	16	31.0	39.5

Although, end pumping approach is known for its high efficiency, it often leads to thermal loading issues due to the absorbed pump light focused at the end part of the laser rod [20]. The thermally induced effects constitute the principal constraints limiting the enhancement of the sunlight pumped laser's performance. Therefore, it is highly advisable to consider designs that lead to overcome the limitations caused by the thermal issues.

Thermal problems in lasers are the consequences of the manner whereby the absorbed pump light is spread into the active medium. The distribution of the absorbed pump light is governed on the one hand by the sunlight concentration system and on the other hand by the pumping approach. The aim of this work is to apply a concentration system in the sunlight pumped laser systems that lead to overcome this issue. The concentration system is a series of ring-array concentrators (RAC) designed for the sunlight flux concentration by Garcia et al. [47].

The RAC is chosen because it shows the advantage of diminishing the shadow zones between the incoming sunlight and the laser head, as compared with parabolic mirror. Moreover, the RAC avoids the dispersion phenomenon of the sunlight spectrum along the Fresnel lens focal zone, and provides higher solar collection efficiencies, as compared with Fresnel lenses.

The application of this type of concentrators has led to an advancement in collection efficiency, of 1.030 and 1.035 times greater than the preceding records and a computed brightness figure of merit, 1.60 and 1.52 times more than the previous results, moreover, the stress intensity was reduced to nearly 50% compared to the outcomes previously recorded [52, 53], which represents an additional advantage of the considered system.

2. Sunlight-pumped Nd: YAG lasers through a RAC

2.1. Ring-array sunlight concentrator

Fig. 1 illustrates a ring-array concentrator system consisting of seven concentric rings, each with its diameter and radius of curvature. All the rings adopt an off-axis parabolic profile and have a reflectance of 95%. To maximize the use of the collection surface, a circular Fresnel lens is sited at the RAC central zone. The Fresnel lens is fabricated by a material named polymethyl methacrylate (PMMA), this matter is transparent at the pump wavelengths of the Nd doped YAG, absorbing, and cutting the undesirable wavelengths for Nd: YAG pumping. The detail parameters of the Fresnel lens are explained in the following table (Table 2).

Table 2. Parameters of the Fresnel lens

Diameter (mm)	92.37
Focal length (mm)	413.27
Thickness (mm)	3
Groove pitch (mm)	0.75
Depth of the groove (mm)	0.3
Radius of curvature (mm)	208.13
Transmissivity	92 %

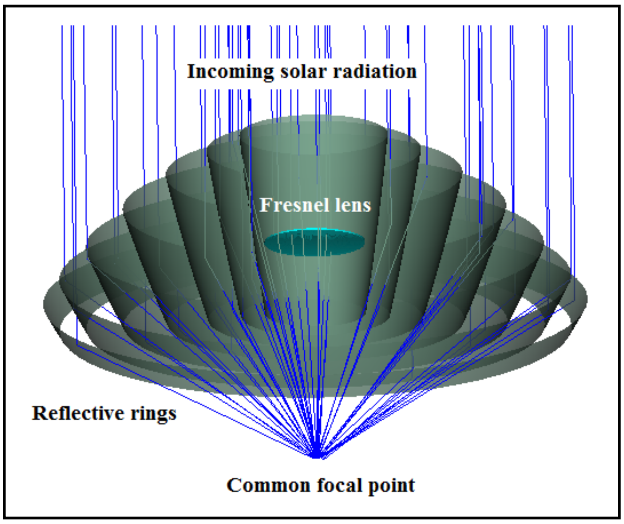

Fig. 1. RAC design formed by seven rings and a Fresnel lens (color online)

To complete the description of the ring-array concentrator system, its parameters computed by ZEMAX© software are summarized in Table 3.

The maximum aperture of the large reflective ring with 1.0 m diameter creates a 0.785 m^2 effective solar light collection area. Given an average sun radiance of 950 W/m^2, the RAC system is able to focus 745.75 W of solar power into a 4.5-mm full-width at half maximum diameter near-Gaussian light spot 250 mm away from the minimum aperture center of the considered ring, as depicted in Fig. 2.

Table 3. Parameters of the rings forming the RAC

Reflective ring	Ring 1	Ring 2	Ring 3	Ring 4	Ring 5	Ring 6	Ring 7
Maximum aperture (mm)	500	470	420.84	352.33	272.62	197.08	136.45
Minimum aperture (mm)	470	420.84	352.33	272.62	197.08	136.45	92.37
Radius of curvature (mm)	282.35	237.07	177.88	115.19	64.28	31.99	14.84
Vertical location in relation to the focal plane (mm)	250.00	255.00	260.00	265.00	270.00	275.00	280.00

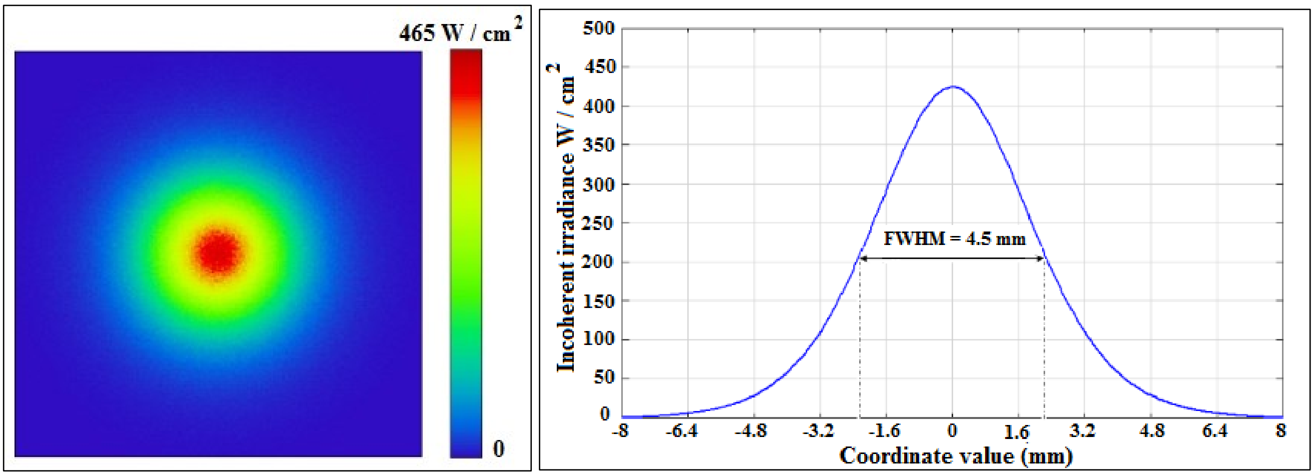

Fig. 2. Focused sunlight distribution by the RAC (color online)

2.2. Sunlight-pumped laser-head

The solar laser head is comprised of an aspheric lens of an extremely transparent glass made from fusing silica and followed by a pump cavity of a conical configuration placed at the optical axis of the system, where a rod of Nd doped YAG is positioned. Fig. 3 illustrates the laser-head arrangement.

Table 4 displays the laser head components and their dimensions.

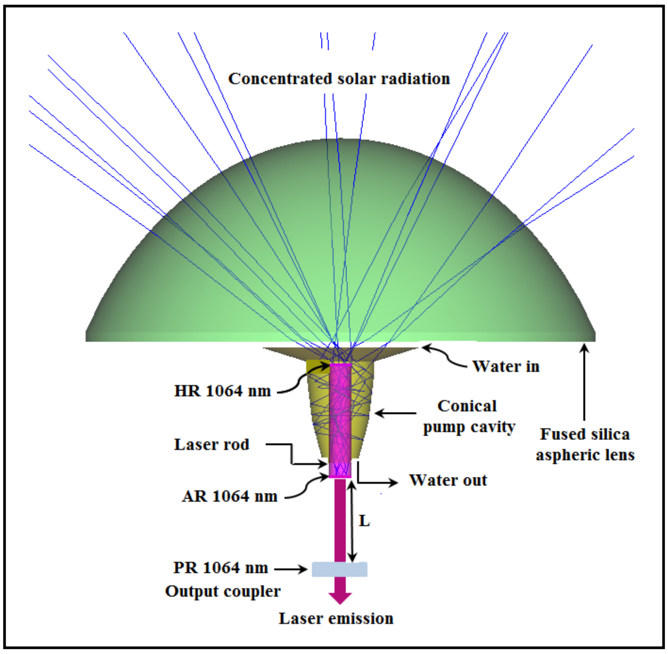

Fig. 3. 3D conception of the solar laser head system (color online)

Table 4. Dimensions of the laser head components

Components					
Aspheric lens of Fused silica		Conically shaped pump cavity		Nd: YAG rod	
Dimensions	Values	Dimensions	Values	Dimensions	Values
Diameter (mm)	90	Input diameter (mm)	12	Diameter (mm)	4
Height (mm)	36	Output diameter (mm)	6		
Radius of curvature of the front surface (mm)	50	Height (mm)	18	Length (mm)	16
Rear r^2 factor	- 0.003				

The aspheric lens further concentrates and couples efficiently the sunlight from the focal point of the RAC to the Nd doped YAG rod. As exhibited in Fig. 3, the major part of the focused sunlight converges towards the end zone of the rod, while the remaining part is oriented to the side of the rod with the help of the hollowed conically shaped pump cavity whose inner face has a reflectivity of 98 %. To ensure an efficient removal of the created heat into the laser rod and consequently, avoiding its heating, the water is used to cool the whole consisting of the Nd doped YAG rod, the hollow conically shaped pump cavity, and the flat zone of the aspheric lens. The water is chosen as a coolant because of its excellent thermal proprieties and its low viscosity.

3. Representation of the simulation by ZEMAX© and LASCAD© of the RAC sunlight-pumped Nd doped YAG laser system

The ZEMAX© non-sequential ray-tracing approach was utilized to attain the optimized conception parameters of the RAC sunlight-pumped Nd doped YAG laser system. The 22 wavelengths of the absorption peaks, each with the corresponding coefficient of absorption of the 1.0 at. % Nd doped YAG laser-crystal were inserted into the ZEMAX© digital data [73]. The absorption spectrum and the wavelength dependent refractive indexes of the fused silica and the cooling water were in turn introduced in the ZEMAX© digital data.

The effective pump power of the light source, resulting from the 16 % overlap between the Nd: YAG absorption spectrum and the solar spectrum was adopted. The total absorbed pump power can be calculated after the division of the active medium into 18,000 zones so that the path length could be found. With this value and the effective absorption coefficient, the absorbed pump power within the laser rod was calculated, summing up the absorbed pump radiation of all zones. The detector volume, comprised of 27000 voxels, is used to help register the data regarding the absorbed pump power in the rod. Through this number of voxels, 10×10^6 analysis rays and 200 rays from the source, accurate results and good image resolution from the detector were acquired. The number of source rays was largely reduced when extracting the subsystem figures (Figs. 1 and 3) to obtain clear images. Fig. 4 presents the computed absorbed pump flux distribution along the Nd doped YAG rod.

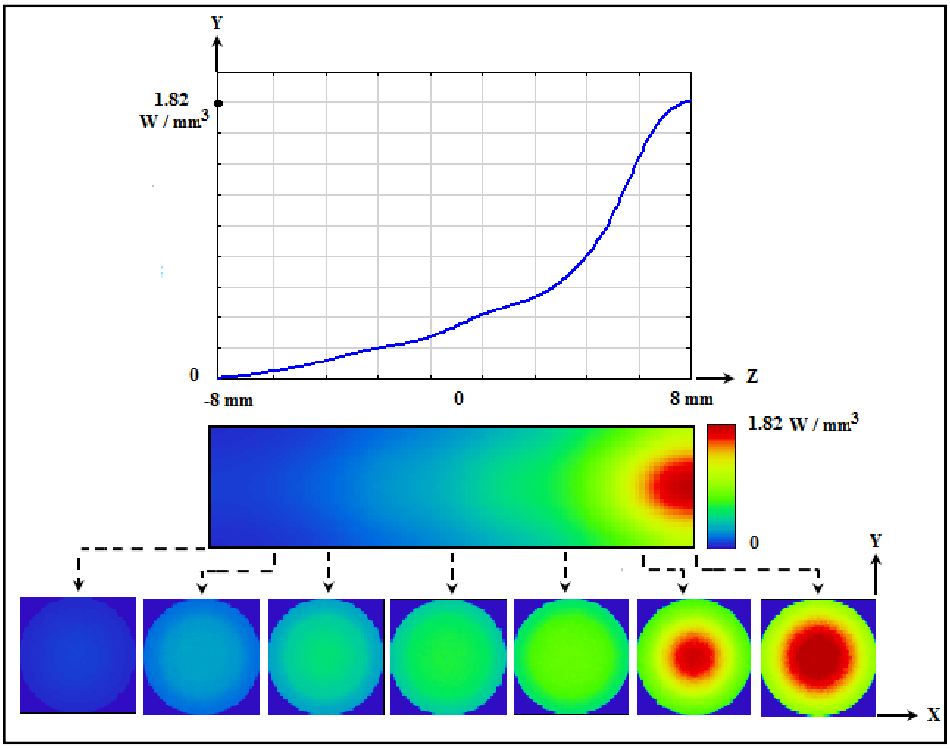

Fig. 4. Distribution of the absorbed exciting flux throughout the length of Nd doped YAG rod at the focus of the RAC (color online)

The absorbed pump power data deduced from ZEMAX© software is then included in LASCAD© software to obtain the most effective laser resonator parameters. The parameters presented in Table 5 of the 1.0 at. % Nd doped YAG medium were implemented in the LASCAD© investigation.

Table 5. Characteristics of the 1.0 at. % Nd doped YAG medium

Cross section of the stimulated emission (cm^{-1})	2.8×10^{-19}
Fluorescence life time (μs)	230
Absorption and scattering loss (cm^{-1})	0.003
Average of the solar pump wavelength (nm)	660

To obtain the highest possible laser power in multimode operation, the upper end face of the rod of 4 mm diameter and 16 mm length is HR 1064 nm coated (the laser emission wavelength). The lower end face is antireflection (AR) coated for the same wavelength. The output coupler is partial reflection (PR) coated (PR at 1064 nm) and located 10 mm (L= 10 mm) away from the laser rod bottom (AR face), as shown in Fig. 3. The asymmetric optical laser resonator is hence formed by both HR 1064 nm reflector and PR 1064 nm output coupler, with 95% reflectivity and -1 m radius of curvature, as depicted in Fig. 5.

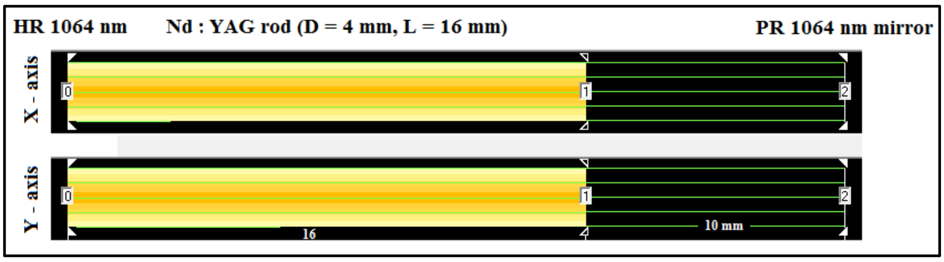

Fig. 5. Sunlight-pumped laser resonator for the multimode operation (color online)

Table 6 shows the components of the optical laser resonator and their main parameters.

Table 6. Components of the optical laser resonator

Reflector of HR for 1064 nm	Radius of curvature (m)	-1
Output coupler of PR for 1064 nm		
Length of the resonator cavity (mm)		26
Average of the solar pump wavelength (nm)		660

The output power of the sunlight pumped laser is dependent on the laser rod diameter, as shown in Fig. 6. 31.0 W continues wave was computed for 4 mm rod diameter, 16 mm rod length, and a 95% reflectivity of the output coupler, leading to a collection-efficiency of 39.5-W/m^2. This value is 1.03 and 1.035 times greater than the precedent record results attained by the same kind of concentrator [52, 53].

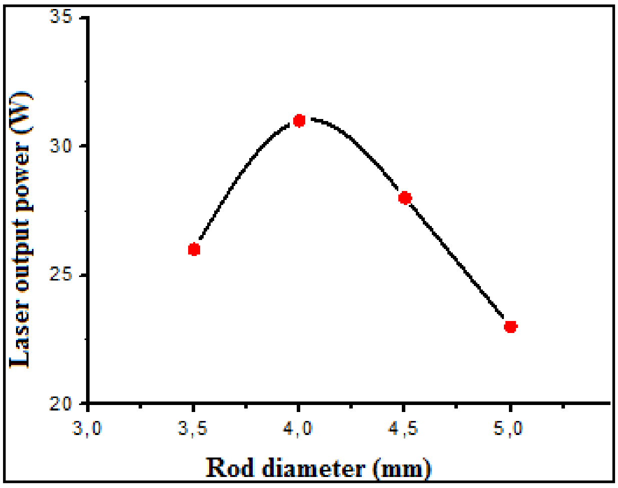

Fig. 6. Computed laser output power as function of the Nd doped YAG rod diameter

The study of the proposed solar pumped laser system performance led to achieve a solar-to-laser power conversion efficiency (the solar laser power divided by the incoming solar power) of 4.13 % and a threshold pump power of 153.84 W (the minimum amount of pump power, needed to get the laser oscillation started), resulting in 5.2 % solar laser slope efficiency (obtained by plotting the laser output power versus the incoming solar power) (Fig. 7).

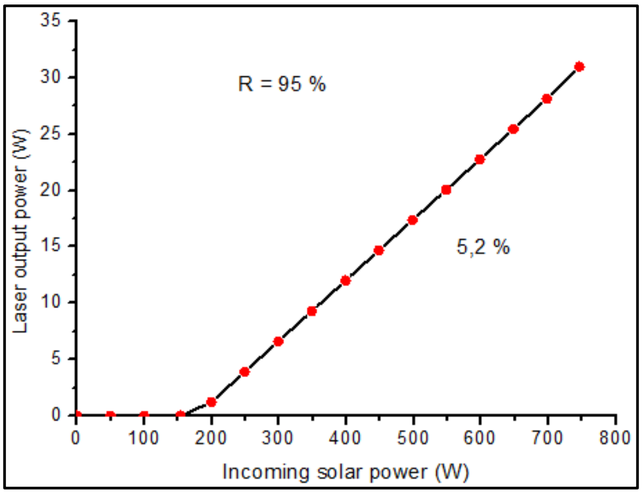

Fig. 7. Solar laser output power as a function of incoming solar power

4. Thermal performance numerically optimizing of Nd doped YAG rod

The data from ZEMAX© software of the absorbed pump flux of Nd doped YAG rod of 4 mm diameter and 16 mm length, is incorporated in LASCAD© digital study to deduce the thermal induced effects values.

The concentrated absorbed pump flux distribution at the extremity of the rod is the main origin of the major thermal issues. Fig. 8 presents the maximum computed values of the heat load (1.43 W / mm^3), the temperature (367 K), and the stress intensity (106.2 N / mm^2).

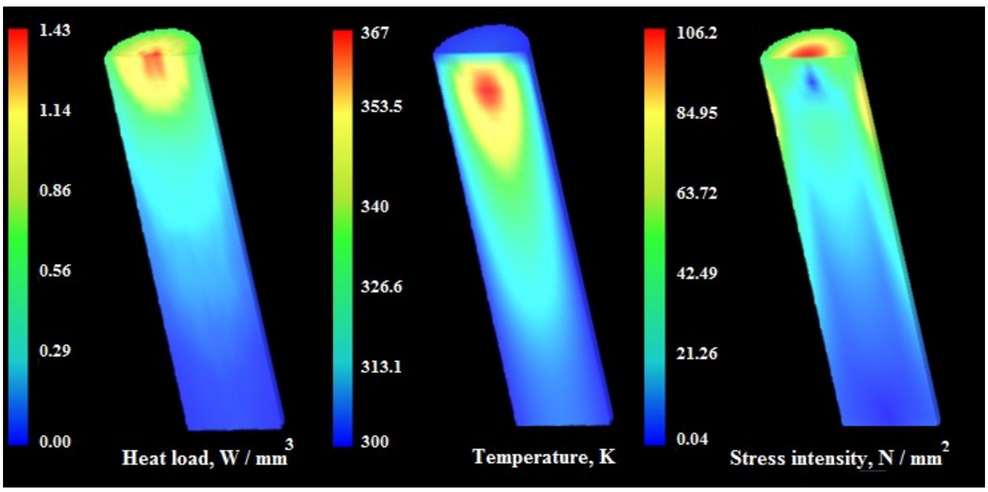

Fig. 8. Distributions of the heat load, the temperature, and the stress intensity of the Nd doped YAG rod (color online)

Table 7 indicates the thermal performances of the Nd doped YAG rod.

Table 7. Thermal performances of the Nd doped YAG rod

Rod dimensions (mm)	Length = 16
	Diameter = 4
Absorbed pump power (W)	82.3
Heat load (W/mm^3)	1.43
Temperature (K)	367
Stress (N/mm^2)	106.2
Laser power (W)	31

It is noteworthy that the calculated stress intensity represents almost the half of the limit of the stress fracture of the Nd doped YAG medium which is 200 N ∕ mm^2. This leads, generally, to an efficient sunlight-pumped Nd doped YAG laser functioning and allows to generate a high laser beam quality in the fundamental mode operating regime.

Table 8. Comparison of the computed results of this study and the results of [52, 53]

Parameters	Re. [52]	Ref. [53]	Present study	Enhancement with respect to Refs. [52], [53] (Times)	
Number of rings	06	13	07	-	-
Collection area (m^2)	1.76	1.76	0.78	-	-
Max. concentrated sunlight (W)	1544	1544	740	-	-
Collection efficiency (W/m^2)	38.4	38.2	39.5	1.029	1.034
Laser output (W)	67.8	67.3	31	-	-
M^2 factors	55	56	31	-	-
Brightness figure of merit (W)	0.024	0.021	0.032	1.60	1.52
Solar-to-laser power conversion efficiency (%)	4.0	4.0	4.13	1.033	1.033
Slope efficiency (%)	5.3	5.4	5.2	-	-
				Decreasing in relation to Refs. [52], [53] (%)	
Threshold pump power (W)	426	319.4	153.84	-	-
Heat load (W/mm^3)	1.23	1.5	1.43	-	4.6
Temperature (K)	431.2	425	367	14.9	13.65
Stress (N/mm^2)	180.8	215	106.2	41.3	50.6

According to Table 8, besides the attainment of a low threshold pump power, the improvement of the collection efficiency and the brightness figure of merit, there is a large enhancement of the thermal performance by the proposed sunlight-pumped Nd doped YAG laser system with the ray ring concentrator designed for the solar flux concentration, compared to the results of [52] and [53]. The thermally induced effects are largely reduced, which leads to a stress-free operation of the laser system, consequently, an efficient sunlight-pumped laser regime can be achieved.

5. Conclusion

A sunlight pumped laser design using the conceived RAC for the solar flux concentration was computed by firstly ZEMAX© then by LASCAD© software's. Improvements in the collection efficiency (39.5 W/m^2), the brightness figure of merit (0.032 W), and the thermal performances (reduction of 50 % of the stress intensity) were attained. The computed results of this investigation are recapitulated in Table 7 and compared to the precedent record results of the systems employing the same kind of concentrator.

By examining these results, it is obvious that the proposed structure with the designed ray ring concentrator for the solar flux concentration can be considered as an interesting model that motivates the researches for improving the sunlight pumped lasers thermal performance and consequently, enhancing their efficiencies.

The substantial reduction of the associated thermal loading effects in the Nd doped YAG rod allows to the sunlight-pumped laser systems a long duration of operating without damaging the laser medium as well as the possibility of their use in high laser power mode. It is also important to note that the suggested sunlight-pumped laser model is also effective for generating a high laser beam quality in TEM_{00} sunlight-pumped laser mode.

Disclosures

The authors declare no conflicts of interest.

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