Uzbek Journal of Physics
DOI: https//doi.org/10.52304/.v25i2.422

Simulation model for multirod configuration in end-side pumped solar lasers

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Received 28.03.2023, revised 04.06.2023

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Исследована многостержневая схема как одна из перспективных возможностей продвижения солнечных лазеров к более высоким эффективностям. Разработана end-to-end симуляционная модель с несколькими стержнями для продольно-поперечной накачки солнечного лазера. Модель позволяет определить все необходимые параметры и оценить все рабочие параметры солнечных лазеров. Обсуждена надежность разработанной модели. Для выбранных параметров показаны распределения поглощения и выходной мощности лазерного излучения.

Ключевые слова: Мульти-стержневый лазер, Nd:YAG, Ce:Nd:YAG, симуляционная модель

Multi-rod scheme is being studied as one of the promising pathways in advancing solar lasers toward higher efficiency. We developed an end-to-end simulation model with several rods for end-side pumped solar laser. The model allows the determination of all necessary parameters making it possible to estimate all performance characteristics of solar lasers. The robustness of the developed model is discussed. The absorption distributions and the output powers are demonstrated for the chosen parameters.

Keywords: Multi-rod laser, Nd:YAG, Ce:Nd:YAG, simulation, model.

I. Introduction

Exploiting solar energy is increasingly becoming very important as other energy resources are climate-toxic or to be about depleted. One of the many ideas to exploit abundant solar energy is the conversion of solar rays into a powerful laser beam. Since the first demonstration of a solar-pumped laser in 1963 using Dy^{2+}:CaF_2 crystal, solar-powered lasers are slowly but continually developing, attracting the attention of researchers [1, 2]. Solar lasers can find potential applications in science, industry and medicine, hydrogen production, and power transmission. For example, the magnesium is reduced from MgO (magnesium oxide) by solar-energy-pumped laser (sunlight laser hereafter) during sunshine and thus solar energy is stored in the form of magnesium [3].

Over the last few decades, the interest in solar lasers experienced ups and downs. At its initial phase, it can be argued that primitive steps are examined to improve solar laser efficiency. For example, the usage of larger primary solar concentrators to generate powerful laser beams comes to mind. Unsurprisingly, these attempts did not convince many researchers, resulting, to some extent, stagnation. However, recent technological advances made it possible to achieve experimental results that renewed the interest in solar lasers [4-6]. Another significant trigger was the development of modeling and simulation methods as well as the constantly improved computing power. These simulation models made checking various laser cavity models with different scenarios possible. Using a simulation model, authors of the work [7-9] proposed that internal and external sensitizers can significantly improve the power-to-power

efficiency of solar lasers. Recently, the role of sensitizers in efficiency improvement has been experimentally confirmed [10-11]. Even fundamental reasons for lower efficiency are being numerically studied [12], where authors show that thermal effects can significantly influence the output characteristics negatively.

One recent concept is using several rods in one cavity to achieve efficient solar lasers. For example, a seven-rod/seven-TEM00 mode beam Fresnel lens solar laser pumping approach is proposed [13]. In work [13], the most efficient simultaneous emissions of three continuous-wave 1064 nm solar laser beams are reported. For 356 W incoming solar power, 16.5 W continuous-wave total multimode solar laser power was measured, corresponding to 4.64% solar-to-laser conversion efficiency, 41.25 W/m^2 collection efficiency, and 7.64% slope efficiency. In a numerical study by a computer simulation [14], a new multirod system with a side-pumping scheme is proposed, increasing efficiency several times.

The above-mentioned experimental [15-18] and numerical studies [19] show that multirod solar lasers could potentially improve power-to-power efficiency, opening a new tendency. We suggest that another benefit of multirod schemes is that they can offer a way to scale up the power of solar lasers. Therefore, in this work, we aimed to create a simulation model for multirod solar lasers with an end-side pumping scheme. The proposed model allows one to analyze the output characteristics of multi-rod solar lasers.

II. Method

To develop the simulation model, the Monte-Carlo photon tracing method is used [6, 19, 20]. This method is frequently employed in our previous works, perfectly fitting for modeling complex optical systems within a geometric optics framework. Another great feature of the method is that it can consider the spectroscopic (mainly macroscopic) properties of materials involved in the process. Since our previous works give a detailed account of the method, we refrain from describing it here. For detailed information, we refer the reader to work [6].

III. Description of the solar laser setup

We here consider a solar laser that consists of the following parts and elements.

Parabolic concentrator. This work considers a parabolic reflector as the primary concentrator with a combination of heliostat mirrors. The surface reflectivity of the heliostat mirrors and silver-coated parabolic concentrator are set to 93.5% and 80%, respectively. The resulting reflectivity is then equal to 74.8%. The surface area of the parabolic concentrator is considered to be 0.5 m^2 of which the laser system hinders 0.1 m^2 area. These parameters can be tuned or easily adjusted in our simulation model.

An aspheric lens. An aspheric lens (Fig. 1) located between the cavity and the primary concentrator system is used to further focus rays coming from the concentrator. The lens is transparent with a diameter of 8.4 cm.

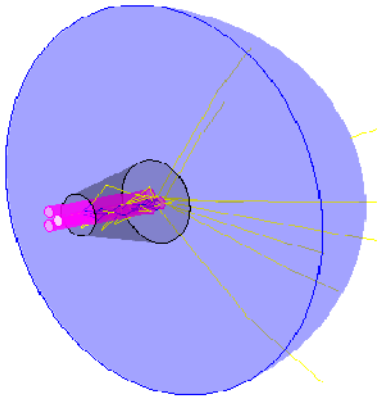


Figure 1. The secondary cavity (blue)

Cone-shaped cavity. The secondary concentrator, which takes the truncated cone shape, helps direct scattered rays back to the rods (Fig. 2).

The cone with a height of 1.9 cm where the base diameter is D=0.9 cm and the top diameter is d=0.45 cm considered. Another critical parameter is the inner surface reflectivity which is set to 0.94.

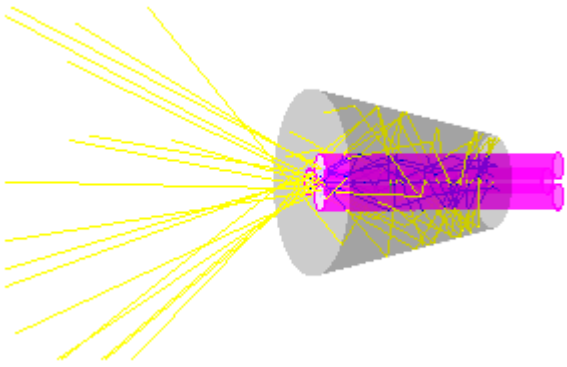


Figure 2. The secondary cavity.

Multirod configuration. Our simulations used the famous Nd:YAG crystals with many desired physical properties for solar lasers.

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Despite its obvious low spectral overlap (Fig. 3) Nd:YAG is the preferred choice due to its thermal and mechanical properties. Another crystal we used was Ce:Nd:YAG. Introducing Ce ions into Nd:YAG increases the overlap (Fig. 4).

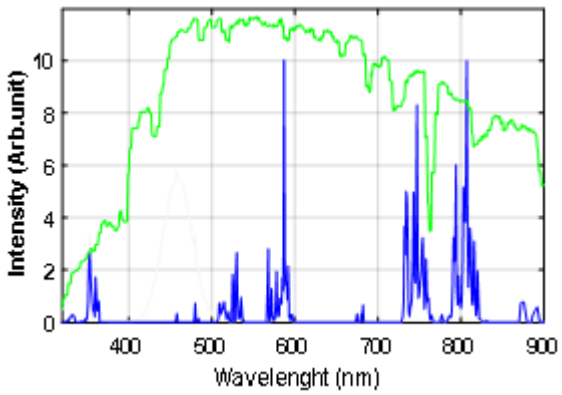


Figure 3. Solar spectrum and the absorption spectrum of Nd:YAG.

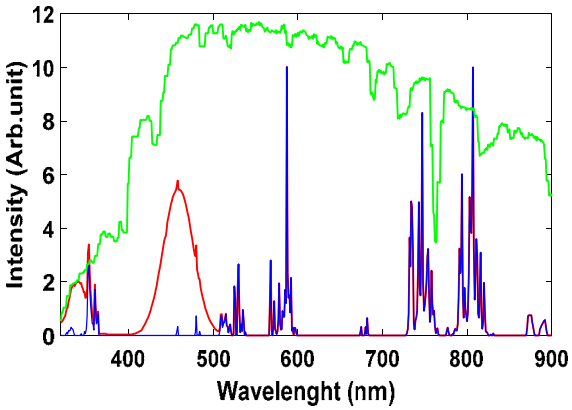


Figure 4.Solar spectrum and the absorption spectrum of Ce:Nd:YAG

IV. Results and discussion

The primary purpose of the developed simulation model is to calculate the pumping efficiency of the considered setup. Then based on that, one can further optimize the multirod solar lasers. However, solar laser power-to-power efficiency is determined by the pumping efficiency and several other factors, such as thermal effects and the pumping distribution. Our model facilitates allow to analyse these factors too.

The absorption distribution. Monte-Carlo photon tracing method allows to estimate the absorption distribution, so we plotted the distributions for three Nd:YAG rods (Fig.5) and three Ce:Nd:YAG rods (Fig. 6). The analysis of these figures show that the initial focal spot is the main contributor to the pumping efficiency. The inserted color bars indicate the difference in the absorption for three Nd:YAG rods and three Ce:Nd:YAG rods. This distribution behaviour is expected because as mentioned above the spectral overlap is different for two cases. Also, this signals of robustness of the simulation model.

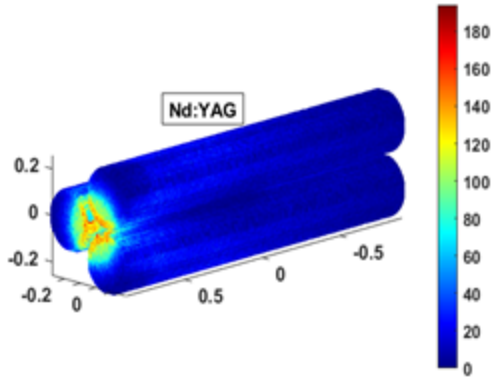


Figure 5. The absorption distribution of Nd:YAG.

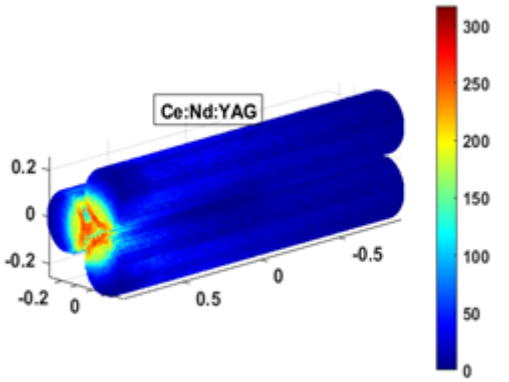


Figure 6. The absorption distribution of Ce:Nd:YAG.

The pumping efficiency. The estimated pumping efficiencies (Table 1) determined from our model were used for the calculation of the laser output by the recursive relationship [14]

$$\varphi = \tau_c \iiint\limits_{volume} \frac{R_p(1+f) - fN_t/\tau}{(1+f) + V/(\varphi c \sigma_e \tau |u|^2)} dV, \qquad (1)$$

where $R_p(r)$ – the pump rate; φ – the total number of photons in the cavity; $f = \sigma_a / \sigma_e$, c – the speed of light; σ_e and σ_a – the effective cross-sections for emission and absorption; τ – the effective lifetime of the upper laser level, V – the volume of cavity

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including the active medium, $u(r)$ – the cavity mode distribution. Then the output power is defined as

$$P_{out} = k\varphi, \quad (2)$$

where the proportionality coefficient $k = h\nu\gamma_2 c / 2L_e$ is (where γ_2 an output mirror transmission and L_e – the cavity length) depended on resonator mirrors and cavity length.

Eq. (1) is derived from the space-dependent rate equations for the quasi-three-level laser systems without simplifying assumptions. Consequently, the accuracy is high despite its calculating inconvenience. However, the losses in the mirrors and the laser rod must be precisely specified. In our work, the parameters listed in Table 1 were used in the calculation of laser output:

Table 1. Necessary parameters.

Parameters	Nd: YAG	Ce:Nd: YAG
Pump efficiency P_{abs} / P_{pump}, calculated within the model	(7.74 ± 0.0017) %	(15 ± 0.0012) %
Pump efficiency N_{abs} / N_{pump}, calculated within the model	0.0675	0.1044
Internal loss	0.002	0.004
Quantum efficiency	0.95	0.9
Pump and resonator mode overlap found from resonator analysis	0.9	0.9

The obtained simulation results are plotted in Fig.7,

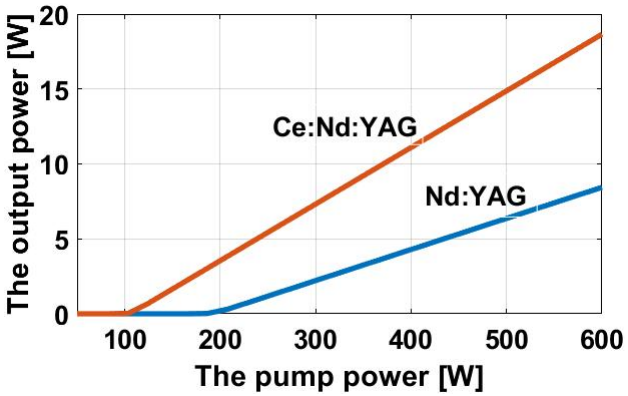


Figure 7. The output power of laser radiation vs input solar power for a parabolic concentrator with a diameter of 0.8 m.

Under the same pumping conditions, the values of pumping thresholds for Nd:YAG and Ce:Nd:YAG are 186 W and 103 W, respectively. The output values are 8.44 W and 18.65 W with 600 W solar radiation incident on the primary concentrator. The corresponding slope efficiencies for Nd:YAG and Ce:Nd:YAG are 2.04% and 3.75%, respectively.

V. Conclusion

Nowadays, a multirod scheme is being studied as one of possible concepts in the advancement of solar laser toward higher efficiency. For the purpose of conducting further insightful study, we developed end-to-end simulation model for end-side pumped solar laser with several rods. The model allows to determine all necessary parameters making it possible to calculate all performance characteristics of solar lasers. The absorption distributions and the output powers are demonstrated for the chosen parameters. At the moment, based this developed model, we are examining possible advantages and disadvantages of multirod scheme in solar lasers.

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Кўп актив муҳитли қуёш лазелари учун симулиацион модел

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Ҳозирги вақтда қуёш лазерини юқори самарадорликка эришишда мумкин бўлган тушунчалардан бири сифатида кўп кристалли схема ўрганилмоқда. Кейинчалик чуқур тадқиқотлар ўтказиш учун биз бир нечта кристаллар билан оптик дамланадиган қуёш лазерининг тўлиқ симуляция моделини ишлаб чиқдик. Модел барча керакли параметрларни аниқлаш имконини беради, бу эса қуёш лазерларининг барча ишлаш характеристикаларини ҳисоблаш имконини беради. Танланган параметрлар учун ютилиш тақсимоти ва чиқиш қувватлари кўрсатилган. Ҳозирги вақтда ушбу ишлаб чиқилган моделга асосланиб, биз қуёш лазерларида кўп кристалли схеманинг мумкин бўлган афзалликлари ва камчиликларини кўриб чиқмоқдамиз.

Калит сўзлар: кўп-стерженьли лазер, Nd:YAG, Ce:Nd:YAG, симуляция модели.

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