



# Solar pumped Nd:YAG laser efficiency enhancement using Cr:LiCAF frequency down-shifter

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## ARTICLE INFO

### Article history:

Received 20 March 2016

Received in revised form

18 May 2016

Accepted 31 May 2016

Available online 4 June 2016

### Keywords:

Solar pumped laser

Nd:YAG

Cr:LiCAF

Solar concentrator

## ABSTRACT

The possibility of increase of Nd:YAG solar pumped lasers pumping efficiency with the use of Cr:LiCAF as a solar spectrum frequency-down-shifting element is studied by the simulation calculation method. Comparative analyses of side- and end-pumping schemes are conducted. The numerical experiments have been conducted for combinations of Nd:YAG active medium and Cr:LiCAF for both side- and end-pumping configurations. It is shown that the use of Cr:LiCAF frequency down-shifter significantly increases the pumping efficiency of Nd:YAG active medium in both cases. In addition the replacement of Nd:YAG with cerium co-doped Nd:YAG have shown possibility of further increase the efficiency.

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## 1. Introduction

High efficient solar pumped laser sources hold promise for enabling of innumerable novel applications in a variety of fields ranging from industry to scientific and technological fields. It would not be possible even to list all the myriad tasks, in basic science in routine technology, now being performed by lasers.

A number of researches on solar pumped laser have been conducted since the advent of laser itself [1–11]. However, the maximum conversion efficiency was in the range of few percents and not enough for wide spreading of solar-pumped lasers commercially. Furthermore, the preceding works mainly focused on obtaining higher laser output power. The improvement of conversion efficiency by adding  $\text{Cr}^{3+}$  ions as a co-dopant in Nd:YAG has been pointed out for a long time since it provides broad absorption bands suitable for capturing the sunlight spectrum. However, the production of such media had not been effective with the conventional technology such as crystal growth. Nanotechnology has made it possible to achieve high transparency, large-size, homogeneous solid state laser materials. A solar pumped laser system with the use of a Fresnel lens and a Cr:Nd:YAG ceramic laser medium has been demonstrated [12]. The experiments were conducted with the combination of a 4 m<sup>2</sup> Fresnel lens and the solar cavity as a secondary power concentrator. But the maximum conversion efficiency from sunlight to laser was about 4%. In [13] using 0.9 m diameter Fresnel lens as an solar

collector a 4 mm diameter, 25 mm length 1.0 at% Nd:YAG single-crystal rod and a 0.1 at% Cr: 1.0 at% Nd:YAG ceramic rod are pumped alternatively within a conical cavity through a secondary concentrator. As authors reported it has been experimentally observed a moderate, but not significant, advantage of Cr:Nd:YAG ceramics over Nd:YAG single-crystal medium in both solar laser conversion and slope efficiency. With the Nd:YAG rod, the maximum laser power was 12.3 W. With the Cr:Nd:YAG ceramic rod, the maximum laser power was 13.5 W. There was only a 9% increase in slope efficiency.

Another candidate for improving the conversion efficiency of solar pumped lasers was a Cr:Nd:GSGG. Though this active medium had the best optical properties such as broad absorption bands, good overlap between emission spectrum of sensitizing (Cr) ions and absorption spectrum of active (Nd) ions, and consequently efficient energy transfer between them, the low thermal conductivity was the main problem in scaling up the solar-to-laser power conversion efficiency.

Thus, the preceding attempts to increase the conversion efficiency of solar pumped lasers by adding  $\text{Cr}^{3+}$  ions (sensitizers) as a co-dopant in different laser active mediums did not give rise to further progress in solar-to-laser power conversion for now. In this connection in [14] we proposed a new approach based on the use of sensitizers outside the active medium, namely the use of external solar spectrum frequency converters to enhance the pumping efficiency of Nd:YAG active medium. It had been studied  $\text{Cr}^{3+}$ :GSGG,  $\text{Cr}^{3+}$ :YAG materials as an external frequency converters to the Nd:YAG or Ce:Nd:YAG active mediums and it was shown more than two-fold increase of pumping efficiencies of active mediums used. It was considered end-pumping scheme.

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Although the most efficient laser systems have end pumping approaches, side-pumping is an effective configuration for power scaling as it allows uniform absorption along the rod axis within the laser medium, reducing hence the associated thermal loading problems. The solar laser beam quality from a side-pumping configuration can be better than those by end-pumping configurations. Therefore, as a continuation of our research [14] on enhancement of solar-laser-power conversion efficiency in addition to the end-pumping scheme the light guide side-pumping configuration is also considered here for comparing the laser performances of the Nd:YAG active medium with and without external solar spectrum frequency converters. As an external frequency converter (frequency down-shifter)  $\text{Cr}^{3+}:\text{LiCAF}$  is alternatively considered since its excellent properties similar to  $\text{Cr}^{3+}:\text{GSGG}$ .

Performance analyses have been conducted by the use of a model described in our previous work [14]. The model is implemented in MATLAB. To demonstrate that the model used is a reasonable representation of the actual system the model validation is also performed by modeling some of existing real solar laser systems and comparing the simulation results with real system measurements.

## 2. Model validation and simulation results

Before considering the possibility of increase the efficiency of different solar pumped laser designs we checked the model for validity. To validate the simulation model [14] the laser system reported in [15] is chosen because there were all the parameters there needed for calculations to reproduce its results. On the other hand that report was chosen for modeling because of its configuration that was close to one which we consider here for the analyses of possibility of increase of Nd:YAG solar lasers pumping efficiency.

### 2.1. Side-pumping scheme

As reported in [15] a fused silica light guide of  $14 \text{ mm} \times 22 \text{ mm}$  rectangular cross-section was used to both transmit and homogenize the concentrated solar radiation from the focal zone of a  $2.88 \text{ m}^2$  parabolic mirror to the entrance aperture of a modified 2D-CPC flooded pump cavity, within which a 4 mm diameter rod is efficiently pumped. 2.2% slope efficiency was reached. Our simulation outcomes (Fig. 1.) correspond to the experimental results of

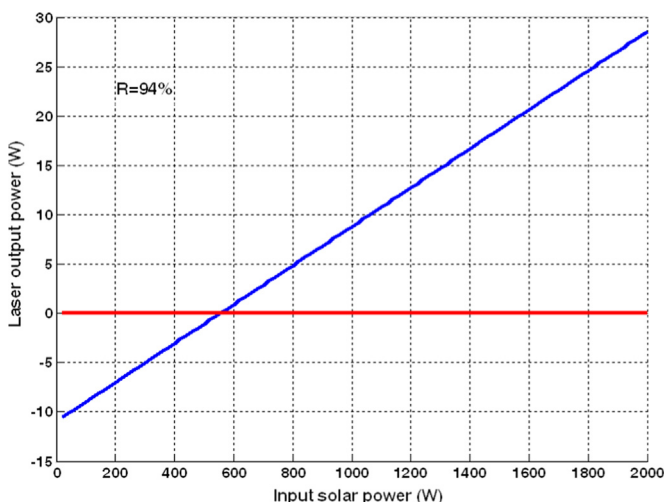


Fig. 1. Calculated input-output dependence based on simulation results for laser system of [15].

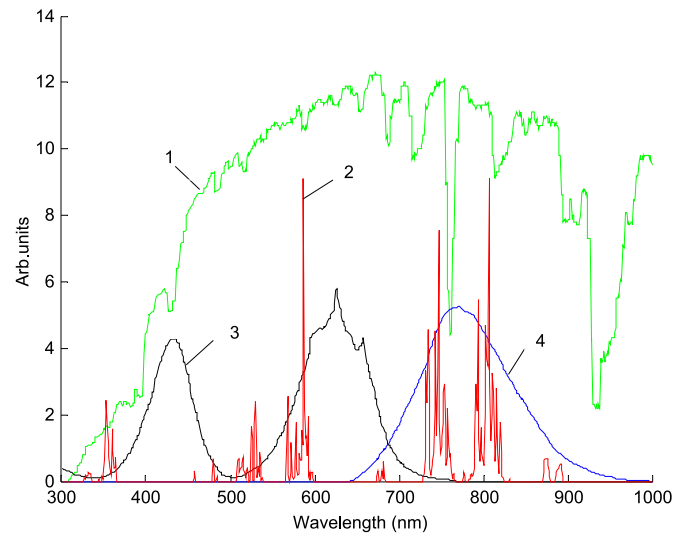


Fig. 2. 1- standard solar spectrum, 2- Nd:YAG absorption spectrum, 3,4-Cr:LiCAF absorption and emission spectra respectively.

[15] with adequate accuracy showing that the model is a good representation of real system.

To optimize this configuration in the next part we have conducted simulation calculations for various designs with frequency converter on  $\text{Cr}^{3+}:\text{LiCAF}$ . The crystal of  $\text{Cr}:\text{LiCAF}$  shows very attractive optical spectroscopic properties for a potential frequency converter, such as two broad absorption bands around 425 nm and 625 nm which overlap well with the wide range of solar spectrum and emission band that falls within the region of strong absorption lines of Nd:YAG (Fig. 2).

The optimized design is shown in Fig. 3, where in order to increase the collection efficiency, in contrast to the concentrating system used in [15] the heliostat was not used and the pumping chamber had rectangular form with the frequency converter ( $\text{Cr}:\text{LiCAF}$ ) as shown in the figure.

The parameters used were: Nd:YAG active medium with the sizes of 10 mm in diameter and 50 mm in length, light-guide sizes were  $14 \times 40 \times 120 \text{ mm}^3$ , internal sizes of pumping chamber were  $14 \times 40 \times 12 \text{ mm}^3$ , the sizes of frequency converter were  $14 \times 40 \times 3 \text{ mm}^3$ . The reflectivity of parabolic concentrator was assumed to be 80% (instead of 64% of two-stage concentrating system of [15]) and in clear sunny days, 2.5 kW solar power could be focused into a 15 mm diameter focal spot.

For comparisons the simulation calculations have been carried out for the options with and without frequency converter for both Nd:YAG and  $\text{Ce}:\text{Nd}:\text{YAG}$  active mediums. The final results of these simulations are presented in Fig. 4.

The Fig. 4 shows that the use of frequency converter can increase the output power in about two times in the case of side pumping scheme when the combination of Nd:YAG and  $\text{Cr}:\text{LiCAF}$  is considered. The additional increase is observed when we combined  $\text{Ce}:\text{Nd}:\text{YAG}$  (instead of Nd:YAG) and  $\text{Cr}:\text{LiCAF}$ . In this case the output power was in about 2.5 times higher than the case with Nd:YAG without frequency converter. The further increase of efficiency is possible when the end-pumping scheme is used. In the next section we describe the simulation results for the end-pumping scheme.

### 2.2. End-pumping scheme

Simulation calculations for end-pumping scheme with composite active medium have been carried out for parabolic-dish solar concentrator with a diameter of 1 m and focal length of 0.5 m.

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