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

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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.

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 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^2 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 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 Cr^{3+}:GSGG, 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) Cr^{3+}:LICAF is alternatively considered since its excellent properties similar to Cr^{3+}: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.

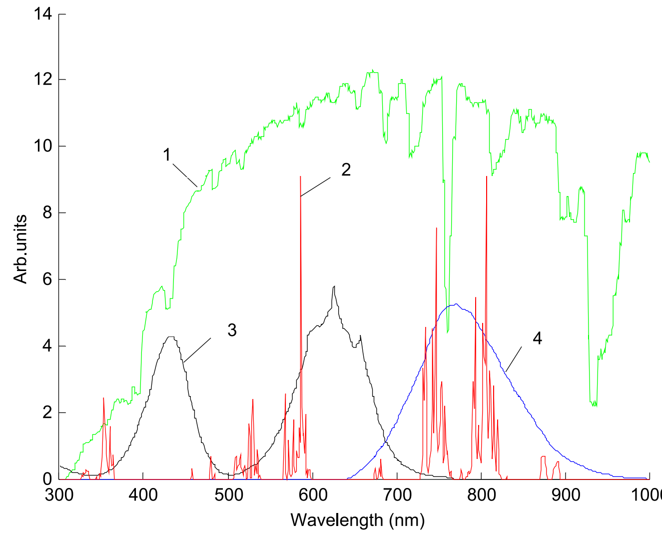

Fig. 2. 1- standard solar spectrum, 2- Nd:YAG absorption spectrum, 3,4-Cr:LiCAF absorption and emission spectra respectively.

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 mm × 22 mm rectangular cross-section was used to both transmit and homogenize the concentrated solar radiation from the focal zone of a 2.88 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 [15] with adequate accuracy showing that the model is a good representation of real system.

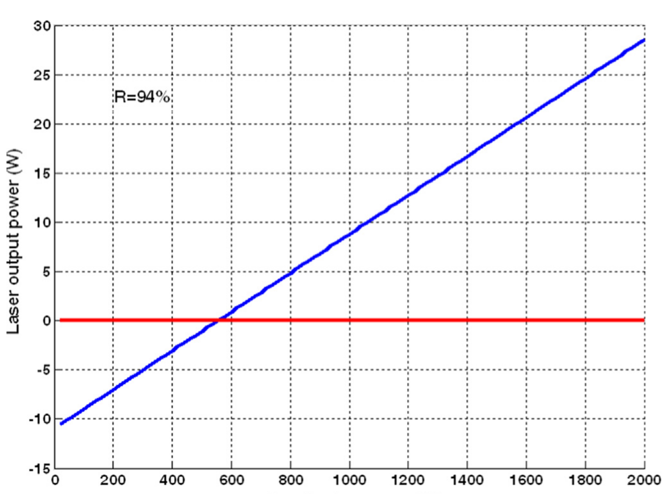

Fig. 1. Calculated input-output dependence based on simulation results for laser system of [15].

To optimize this configuration in the next part we have conducted simulation calculations for various designs with frequency converter on Cr^{3+}:LiCAF. The crystal of Cr: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 (Cr: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 × 40 × 120 mm^3, internal sizes of pumping chamber were 14 × 40 × 12 mm^3, the sizes of frequency converter were 14 × 40 × 3 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 Ce:Nd: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 Cr:LiCAF is considered. The additional increase is observed when we combined Ce:Nd:YAG (instead of Nd:YAG) and Cr: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.

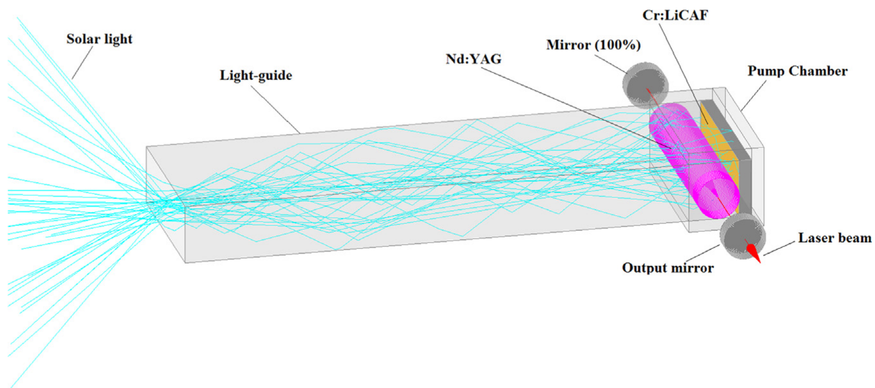

Fig. 3. Side-pumped laser design with a frequency converter.

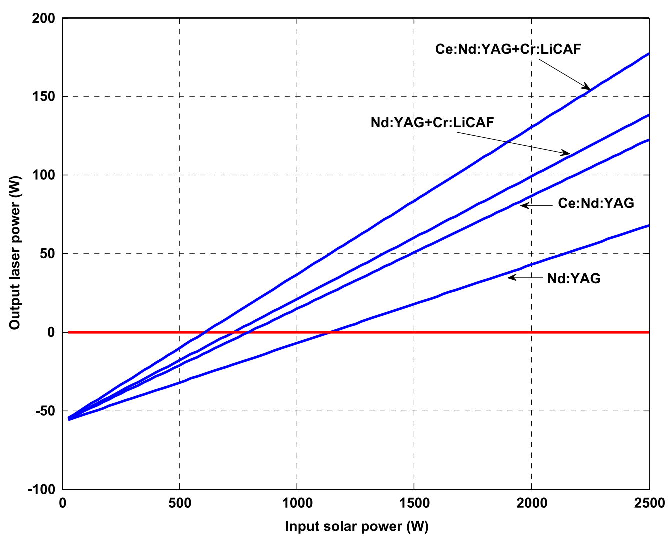

Fig. 4. Input-output dependences for side-pumped laser design with and without frequency converter.

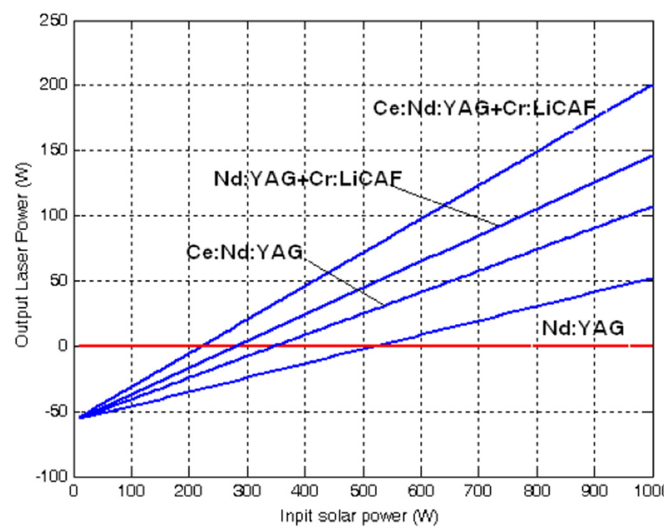

Fig. 5. Output laser power vs. input solar power for parabolic concentrator with a diameter of 1 m.

Performance analyses have been conducted for the laser layout described in [14] replacing only the frequency converter to Cr: LiCAF.

Calculations have been carried out for the standard parameters of Nd:YAG sizes of $\phi 10 \times 50$ mm and chromium concentration of 2% for Cr:LiCAF. The thickness of Cr:LiCAF was 10 mm. The remained parameters were the same as in [14]. Simulation calculations have been done to determine the main figure of merit, the overall pumping efficiency which is equal to maximal slope efficiency that would be attained if the extraction efficiency were unity. Thus the maximal result we have obtained was 0.33 for the Nd:Ce:YAG+Cr:LiCAF which was more than two times of pumping efficiency of 0.14 for Nd:YAG alone.

In the next stage these results are used for calculations the dependencies of output laser power on the incidence solar power. Some results for the output mirror reflectance of 95% are plotted in Fig. 5 for comparisons.

Thus the obtained results exhibit significant increase in solar pumped Nd:YAG laser efficiency when Cr:LiCAF is used as an external frequency converter for both end-pumping and side-pumping configurations of the laser system. As it can be seen from Fig. 5 the increase in pumping efficiency from 0.14 to 0.33 resulted in more than four-fold increase in output laser power. The best combination was end-pumped Nd:Ce:YAG+Cr:LiCAF laser system for which we obtained about 120 W output laser power when the input solar power incident to the 1m diameter parabolic concentrator was 700 W (at earth surface). This means the possibility of achieving the laser power of 150 W/m^2 from unit area at earth surface that is five times of the maximum laser power from unit area achieved to date. For comparisons full results for both of end and side-pumping schemes are summarized in Table 1. As it can be seen from the table the pumping efficiency of end-pumping scheme is about two times higher than that side-pumping scheme for all the combinations considered.

3. Conclusion

The possibility of increase the efficiency of solar pumped Nd: YAG laser using a new simple approach based on the use of Cr: LiCAF as an external frequency converter (frequency down-shifter) of large amount of unabsorbed solar photons is studied. Both the end-pumping and side-pumping schemes of solar laser systems are considered. The highest pumping efficiency of 33% has been

Table 1
Pumping efficiencies for different combinations.

Active medium	Frequency converter	Side-pumping efficiency	End-pumping efficiency
Nd:YAG	–	0.08	0.14
Ce:Nd:YAG	–	0.11	0.21
Nd:YAG	Cr:LiCAF	0.12	0.26
Ce:Nd:YAG	Cr:LiCAF	0.15	0.33

obtained in the case of end-pumping scheme which is equal to maximal slope efficiency that would be attained if the extraction efficiency were unity. Although the end-pumping scheme has higher pumping efficiency, the side-pumping scheme is easier to manipulate for power scaling (by increasing the size of solar concentrator) as well as for the further increase the pumping efficiency (for instance by using multi-element configurations).

The Cr:LiCAF as we think can be good alternative to any other frequency converters in the field of solar-to-laser power conversion including approach based on adding sensitizer ions as a co-dopant to the active mediums.

Main advantages of usage of such external frequency converters would be the reduced thermal load on the active medium, possibility of use different host materials for active medium and frequency converter, less rigid requirements for thermal properties (thermally induced birefringence, lens effect) of frequency converter and also possibility of independent control of temperature in active medium and frequency converter when needed.

We hope the results of this study will play significant role in making spotty progress in the field of solar pumped lasers.

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