Simulation and experimental verification of enhanced Nd:YAG solar lasers using wavelength conversion dyes.

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***Abstract*—Solar lasers based on Nd:YAG are limited by the spectral overlap between the absorption and the solar spectrum. Using a ray tracing model, a greater than two times increase in absorption can be shown when wavelength converting dyes are used in the cooling system surrounding the laser crystal. The predicted increase in absorption is experimentally verified.**

Keywords—Solar Laser, Ray Tracing, Wavelength conversion, Nd:YAG

I. INTRODUCTION

Direct sun pumped solar lasers have remained a research curiosity due to their relatively low conversion efficiency. Despite this there has been a steady rate of improvement, often focussing on increasingly complex multi-stage sunlight concentration systems [1-4]. Currently the record conversion efficiency is 41.25 W/m^2 [5], corresponding to a sun power to laser power efficiency of 4.64%. Good quality commercial solar panels exceed 22% sunlight to electrical conversion efficiencies [6] and the best semiconductor diode lasers can exceed 50% electrical to optical efficiencies [7], resulting in indirect sun to laser efficiencies of >11%. For direct pumped solar lasers to become practical they need to exceed these efficiencies.

The efficiency is strongly limited by the spectral overlap of sunlight with the absorption features in vibronic crystal lasers. While Nd:YAG is ideal from a laser perspective, it is limited to only 13.2% absorption purely by this overlap. Some efforts have been made to work around this using Ce:Nd:YAG which has led to record efficiencies [5]. Alternative approaches showing promise might utilise semiconductor laser materials [8] or use wavelength conversion systems such as quantum dots [9] or florescent dyes which we investigate here.

II. NUMERICAL SIMULATION

We use a ray tracing simulation which was written in Matlab from scratch by our research group. The key components of the model are described in [10]. A schematic of the ray tracing geometry is shown in Fig. 1. The angle and position distribution of the rays generated is defined to match the primary concentrator we use in experimental work and have wavelengths assigned to match an AM 1.5 solar spectrum. In the model the rays can be absorbed in the Nd:YAG if their wavelength overlaps with the absorption spectrum and can also interact with the cooling water which surrounds the rod and the diffusely reflective chamber wall. The use of the diffusely reflective chamber wall increases the average distance the rays propagate through the Nd:YAG rod as they are reflected from the chamber wall using Lambertian scattering.

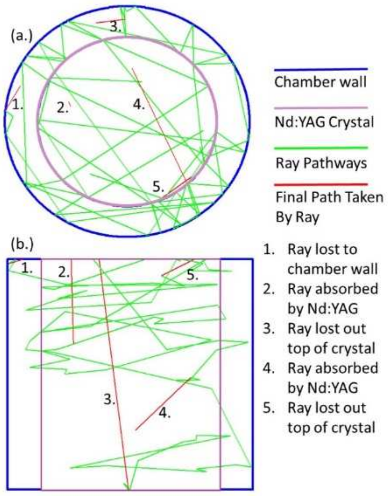

Fig. 1. Schematic diagram of the geometry of the ray tracing model. (a) shows a small number of rays propagating through the model viewed from the input face and (b) shows the same rays viewed from the side. Five example rays are shown demonstrating the main ways rays are absorbed or lost from the system.

In this work we extend the model by adding a wavelength converting process to model the inclusion of either fluorescein or styryl 9M dye into the cooling liquid between the laser crystal and the chamber wall. To do this we include the absorption and emission profile of the dye with the absorption peak normalised to the percentage likelihood of interaction. In all cases the model was run for 100000 rays and these were propagated until their intensity had fallen to 0.1% of their initial intensity.

The results of the simulations are shown in Fig. 2. for fluorescein and styryl 9M respectively. In the case of fluorescein the spectral overlap between the emission of the dye and the absorption in Nd:YAG is low, so we were only expecting a modest increase in absorption. Our model predicts a 4.1% increase in the amount of incoming sunlight absorbed when the chance of interaction approaches 100%. We modelled fluorescein as it is a low-cost fluorescent dye which is not harmful to the environment, so provides a simple route to experimental verification.

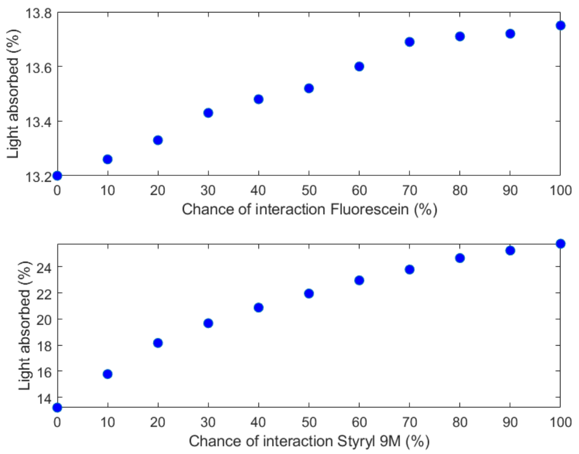

Fig. 2. Modelled percentage of input sunlight absorbed in the Nd:YAG laser rod as a function of the chance of interaction with fluorescein dye (top) and styryl 9M (bottom).

In the case of styryl 9M dye the significantly improved spectral overlap leads to a substantial increase in the modelled absorption, reaching a maximum of 25.8% of the total incoming sunlight, from 13.2% when no dye is present.

Fig. 3. shows the modelled laser performance using the parameters of the solar laser we reported in [10] and the modelled Nd:YAG absorption with wavelength conversion dyes reported here. This laser uses a Fresnel lens with primary area 0.0829 m^2 and no secondary concentration. Using this we are able to get 35 W of sunlight to enter the laser rod when the solar intensity is 1000 W/m^2. Our model predicts a small increase with fluorescein dye, but a substantial increase from 27.5 W/m^2 to 84 W/m^2 for styryl 9M. If this can be experimentally realised it will represent a sun to laser efficiency of 8.4%.

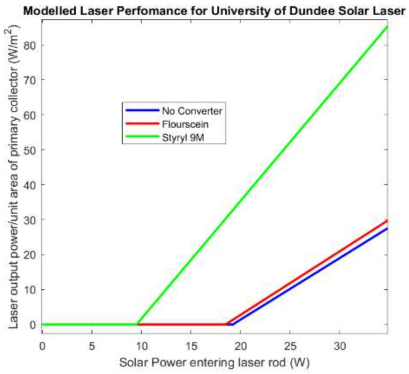

Fig. 3. Modelled laser performance using fluorescein and styryl 9M dyes.

III. EXPERIMENTAL MEASUREMENTS

To experimentally verify the modelled increase in performance we measured the intensity of 1064 nm emission from a 3mm diameter, 10mm length laser rod in a setup with the same dimensions as the model using fluorescein dye. We used a microscopy illumination lamp (Thorlabs OSL2) instead of natural sunlight and filtered out all light beyond 900nm using a low pass filter. The light was focussed on the front of the laser rod and the intensity of 1064 nm emission from the Nd:YAG was measured using a photodiode which had both a 900 nm long pass filter and a 10 nm notch filter centred at 1064 nm in front to remove any background light from the measurements. The measured Nd:YAG emission as a function of dye concentration is shown in Fig. 4. We measured a 3.6% increase in 1064 nm emission at a concentration of 0.18% by weight fluorescein in water in the cooling system verifying the modelled performance.

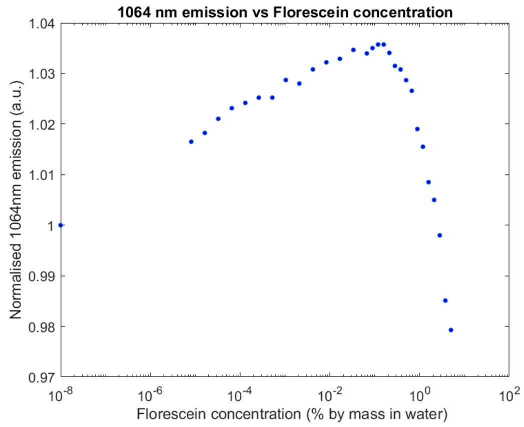

Fig. 4. Nd:YAG emission as a function of fluorescein concentration normalised to pure water in the cooling system.

IV. CONCLUSIONS

We numerically simulate the use of wavelength converting fluorescent dyes as a route to increasing the overall efficiency of Nd:YAG solar lasers. We model and experimentally verify a 4.1% increase in 1064 nm emission in the case of fluorescein dye and model a ~2x increase if styryl 9M is used. If this performance can be experimentally realised, a route to sunlight to laser light efficiencies approaching 10% becomes realisable.

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