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High conversion efficiency solar laser pumping by a light-guide/2D-CPC cavity

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ABSTRACT

A simple and efficient light-guide/2D-CPC solar pumping approach is proposed. A fused silica light-guide assembly is used to transmit 6 kW concentrated solar power from the focal spot of a large parabolic mirror to the entrance aperture of a 2D-CPC pump cavity, where a long and thin Nd:YAG rod is efficiently pumped. Numerical calculations are made for different light-guides, 2D-CPC cavities and laser rods. The laser output power is investigated through finite element analysis. With 4 mm diameter rod, the maximum calculated laser power of 75.8 W is obtained, corresponding to the conversion efficiency of more than 11 W/m^2. The tracking error dependent laser power losses are lower than 4%. A small scale prototype was constructed and tested, reaching 8.1 W/m^2 conversion efficiency.

1. Introduction

The idea of directly converting broad-band solar radiation into coherent and narrow-band laser radiation has gained an increasing importance. If lasers are needed in remote locations where sunlight is abundant and other forms of energy are scarce, a solar laser would seem to be a natural choice. Compared to electrically powered lasers, the solar laser is much simpler and more reliable due to the complete elimination of the electrical power generation and power conditioning equipment. This technology is particularly attractive for space applications where extended run times are required and where compactness, reliability, and efficiency are critical. Since the first reported Nd:YAG solar laser [1], improvement in the laser efficiency has always been a key issue in solar-pumped laser researches [2–4]. Recently, a more efficient solar laser system has been put forward, achieving a conversion efficiency of 18.7 W/m^2 by using a Cr^{3+}:YAG laser rod [5]. The Nd:YAG solar laser efficiency and beam quality still need, however, further improvements before it can compete with the diode-pumped solid-state lasers.

A typical solar-pumped Nd:YAG laser utilizes a two-stage system that incorporates a first-stage primary parabolic mirror and a second-stage CPC concentrator. The laser head and its associated optics are usually placed near or directly at the focus of the collector. Non-imaging optics plays an important role in solar lasers by providing means for concentrating sunlight to intensities approaching the theoretical limit. The compound parabolic concentrator [6] (CPC) gives the maximum concentration for a two dimensional cavity. Although the non-imaging cavity provides a large amount of pump power, it does not give a Gaussian absorption pumping profile [7], affecting hence the laser beam quality. For low-average-power applications, in which thermal lensing is moderate, the overlap of the laser mode with an excitation peaked at the centre of the rod can be advantageous. However, at high-average-power, even a uniform gain distribution in a water-cooled laser rod has been shown to induce a non-parabolic heat distribution as a result of the temperature dependence of the thermal conductivity [8]. This results in a radially dependent refractive power of the thermal lens, with a maximum on the rod axis. When the absorption profile is centrally peaked, the temperature on the axis increases further, resulting in stronger thermal lensing at the centre, higher-order aberrations at the periphery, and larger stress in the laser rod compared with those of uniform excitation. Consequently, a power deposition that has a slight minimum at the centre of the rod can be useful to scale to high-average-powers. Minimizing a laser rod volume reduces cost, and reducing the diameter makes the rod more resistant to thermal stress. Also, with smaller rod diameter, high-order resonator modes are suppressed by large diffraction losses, and beam quality improves.

The resonator stability depends also on how well the Sun is tracked. Tracking displacements move the centre of the absorption distribution inside the laser crystal [9]. If the centre of the thermal lensing moves, it acts as a resonator misalignment and less output laser power is obtained. Tracking error compensation is therefore needed to obtain a stable laser performance [10].

The fused silica and hollow lens ducts have been successfully used for end-pumping solid-state lasers [11,12]. The proposed fused silica light-guide assembly consists of three fused silica light-guides of rectangular cross-section by which the concentrated solar power of circular spot from the primary parabolic concentrator is both efficiently collected and transformed into a

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rectangular light column, facilitating the further light coupling into the small diameter laser medium by a 2D-CPC cavity. The proposed system demonstrates low sensibility to the minor angular tracking errors. The calculated laser conversion efficiency of 11 W/m^2 and the optical efficiency of 27% for the 4 mm diameter, 80 mm length Nd:YAG laser rod are reported here. Tracking error dependent laser power losses lower than 4% are numerically obtained. Experimental results of small scale prototype are reported with a maximum laser output power of 14.4 W for an absorbed solar pump power of 71.3 W, corresponding to the conversion efficiency of 8.1 W/m^2.

2. Numerical calculations

2.1. Solar spectra, tabulated model of absorption for Nd:YAG material and overlap between the Nd:YAG absorption spectra and the solar spectra

The standard solar spectra [13] for one and a half air mass (AM1.5) are used as the reference data for consulting the spectral irradiance (W/m^2/nm) at each wavelength. The irradiance cumulative integral of the whole solar spectra equals the typical terrestrial value of 900 W/m^2, which agrees well with the experimental data [4].

For Nd:YAG laser material, 22 absorption peaks ranging between 527 nm and 880 nm are defined in the Monte Carlo ray-tracing software. For a 1.1 at.% Nd:YAG laser medium, the highest absorption coefficient reaches $\alpha = 10\ \text{cm}^{-1}$, while the lowest is about $\alpha = 1.5\ \text{cm}^{-1}$. The averaged FWHM absorption bandwidth of each peak is about 1 nm [14]. All the above central wavelengths and their respective absorption coefficients are added to the glass catalogue for Nd:YAG material. On the other hand, the solar irradiance values of the 22 central wavelengths can be consulted from the standard solar spectra for AM1.5 and saved as the source wavelength data.

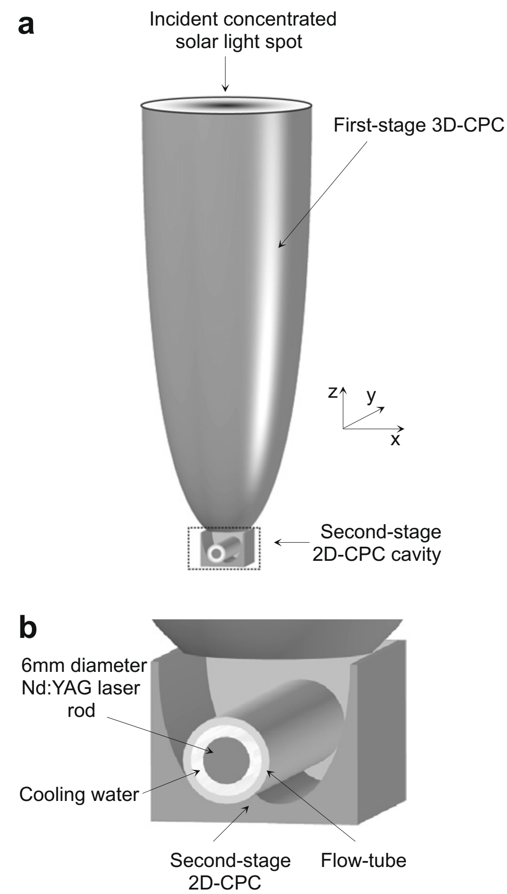

Fig. 1. (a) Double-stage 3D-CPC/2D-CPC scheme, and (b) enlarged view of the 2D-CPC cavity with the laser rod of 6mm diameter and 72 mm length.

2.2. Double-stage 3D-CPC/2D-CPC cavity

The astigmatic corrected target aligned (ACTA) solar concentrator system [4] provided the effective approach for pumping the solar laser crystal, enabling the convenient placement of the laser system on a horizontal optical table. The double-stage secondary concentrator shown in Fig. 1 is consisted of a 3D-CPC reflector followed by a 2D-CPC reflector. Concentrated solar light at 11.5° half angle cone entered the 3D-CPC, which funneled the light beam out at 55° half angle. The emitted light entered the 33×24 mm^2 aperture of the 2D-CPC, illuminating an anti-reflection end-coated 1.1% Nd:YAG laser rod, 6 mm in diameter and 72 mm in length, mounted inside a quartz flow-tube along the 2D-CPC axis. The laser resonator design was commonly plane-parallel. For the segmented primary parabolic mirror with 6.85 m^2 collection area, 45 W laser power was measured.

2.2.1. Numerical analysis for the double-stage 3D-CPC/2D-CPC cavity

Several factors are important for the correct numerical analysis of the 3D-CPC/2D-CPC solar laser cavity. Eighty-five percent reflectivity for the first-stage ACTA mirror, 90% for the folding mirror and 95% for all the other reflector surfaces are assumed. For the terrestrial insolation of 900 W/m^2, 6165 W of solar power reaches the first-stage ACTA mirror. If 14% overlap between the Nd:YAG absorption spectra and the solar spectra is considered [2], the total absorbable solar power lying within the Nd:YAG absorption bands equals to 864 W. Other non-useful solar power is either filtered or simply passes through the rod without significant absorption. The power of 864 W is hence the final value attributed to a circular light source of 3.4 m diameter, representing the absorbable incoming radiation to the ACTA mirror, in the ray-tracing. The solar half angle of 0.27° is also considered.

The reported dimensions of the first-stage ACTA solar collector are utilized in the ray-tracing software. The profiles of both the 3D-CPC and the 2D-CPC [4] are essential for designing both the axially symmetric 3D-CPC concentrator and the 2D-CPC pumping cavity. The laser rod, the cooling water and the flow-tube are dimensioned directly in the ray-tracing software.

For the efficient cooling of the laser rod, the water gap between its surface and the inner surface of the flow-tube is set at 1.5 mm. The quartz flow-tube wall thickness is 1 mm. The side surface of both the laser rod and the flow-tube are modeled as uncoated. The solar spectra absorption coefficients for both cooling water and quartz flow-tube are defined accordingly. The cylindrical rod is divided into a total of 40,000 zones. During ray-tracing, the path length in each intercepted zone is found. With this value and the absorption coefficients of the 22 absorption wavelengths for the Nd:YAG material, the power absorbed by the laser rod can be calculated by summing up the absorbed pump radiation of all the zones within the rod. The absorption distributions for the laser rod of 72 mm length and 3 mm to 6 mm diameters are analyzed in Section 2.4.

2.3. Double-stage light-guide/2D-CPC cavity

A double-stage light-guide/2D-CPC cavity is here proposed. In order to make a correct comparison with the 3D-CPC/2D-CPC cavity, the input-end of the proposed cavity, shown in Fig. 2, is placed at the focal region of a primary parabolic concentrator of 3.4 m