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Diode-laser edge-pumped Nd:YAG/YAG lens-shaped composite laser

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ABSTRACT

A laser configuration made of a thin-disk Nd:YAG/YAG composite medium that consists of a circular Nd:YAG core bonded by diffusion to a circular undoped YAG and that has the shape of a plane-concave lens is presented. The pump is done through the undoped YAG edge, in a three-fold scheme, directly from the diode-laser optical fibers. Such a laser was built employing a Nd:YAG/YAG ceramics made of a 1.0-at.% Nd:YAG core of 2.0-mm diameter surrounded by a 10 mm in diameter YAG. The thickness was 180 μm at the center of Nd:YAG and 500 μm at the YAG edge. The Nd:YAG/YAG medium was attached to a water-cooled copper finger. At 2 Hz repetition rate the laser yielded pulses at 1.06 μm with energy E_p = 31.8 mJ under the pump at 807 nm with total energy E_{pump} = 114.6 mJ; the slope efficiency was 0.31. A decrease of laser pulse energy with the repetition rate was observed. This indicates that a better thermal management, which could be made through metallic bonding of Nd:YAG/YAG to the cooling system, is necessary.

1. Introduction

The thin-disk concept for diode-pumped solid-state lasers was introduced in 1994 at Stuttgart University [1]. In this scheme the laser medium is shaped as a thin disk, having one side mounted on a cooling system. Consequently, a high ratio between the area of the cooling surface and the active volume is obtained. Furthermore, thermal lensing is reduced due to the collinearity between the heat flux and the laser beam axis, which both are perpendicular on the thin-disk medium cooling side. On the other hand, the laser crystal has a small thickness, leading to a low absorption of the pump beam in a double-pass scheme. Multi-pass pumping, in which the unabsorbed pump beam is reimaged few times onto the laser crystal, was developed in order to overcome this issue.

The thin-disk geometry has proven to be very suitable for Yb:$Y_3Al_5O_{12}$ (Yb:YAG). Thus, the first experiments were performed with a 0.3-mm thick, 0.9-at.% Yb:YAG, in a four-pass pumping arrangement with a fiber-coupled diode laser; the Yb:YAG medium delivered 4.4 W continuous wave (cw) output power at 1.03 μm at a maximum slope efficiency, η_{sa} (with respect to the absorbed pump power) of 0.68. Later, in a 16-absorption passes of the pump beam, a 0.8-at.% Yb:YAG disk with thickness of 230 μm yielded 470 W cw power at optical efficiency, η_o (with respect to the input power) of 0.47. Also, scaling of the output power at kW level, i.e. 1070 W power with 0.48 optical efficiency, was obtained by employing four Yb:YAG thin disks [2]. In addition, multi-kW power operation was achieved in recent years during developing lasers for material processing [3,4]; moreover, an Yb:YAG thin-disk laser with 1.1 kW near fundamental mode power was reported [5]. The thin-disk configuration was also investigated for a large variety of other laser media, like Nd:YAG [6], Nd-vanadates [7–9], the monoclinic Yb:$YCa_4O(BO_3)_3$ medium [10], mixed sesquioxides [11], Yb:$CaGdAlO_4$ with wide wavelength tuning range [12] or Yb:LuAG [13], just to name few of them.

The pump of a thin-disk laser medium can be also performed from its side, in a radial (or edge) scheme. In a first arrangement, a composite Yb:YAG/YAG medium that consisted of a square Yb:YAG core surrounded by a circular undoped YAG, both of the same thickness, was radial pumped with fiber-coupled diode lasers in a four-fold geometry. Cw 90-W output power was obtained from a 400-μm thick Yb:YAG/YAG with a 10-at.% Yb:YAG square core of 2×2 mm^2 area [14]. Furthermore, more than 400-W cw output power was yielded by a circular 10-at.% Yb:YAG core of 3.7 mm diameter embedded in an undoped YAG of 10-mm diameter; the Yb:YAG/YAG laser was edge pumped with diode stacks [15].

Some other geometry has been proposed in order to pump a thin-disk like laser medium. For example, a circular Yb:YAG core can be bonded to an undoped YAG cap; the pump beam is inserted through the edges of the YAG cap and it propagates through total-internal reflections toward the Yb:YAG core where it is absorbed

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[16]. An asymmetric Yb:YAG/YAG composite hexagonal structure that is made of an Yb:YAG thin sheet and a diffusion-bonded undoped YAG material on top of Yb:YAG was proposed [17,18]. The pump through the YAG edge in a three-fold pump geometry was used to obtain more than 123-W cw power from a 0.28-mm thick, 8-at.% Yb:YAG [17]. Optimization of such a laser arrangement was discussed [18]. All these configurations [14–18] possess the advantage of simplicity regarding the optics used to couple the pump beam into the laser medium.

In this work we discuss the performances of a novel thin-disk Nd:YAG/YAG composite medium, which consists of a circular Nd:YAG core bonded by diffusion to a circular undoped YAG, and that has the shape of a plane-concave lens [19]. This design allows the pump to be made through the undoped YAG edge, directly from the diode-laser optical fiber with no need for additional optics. In the experiments we used a Nd:YAG/YAG made of a 1.0-at.% Nd:YAG core of 2.0-mm diameter surrounded by a 10 mm in diameter YAG. The Nd:YAG core thickness was 180 μm at its center and the YAG edge was 500-μm thick. The pump was done with fiber-coupled diode lasers in a three-fold scheme. At low, 2 Hz, repetition rate this laser yielded pulses with energy $E_p = 31.8$ mJ at 1.06 μm for the pump at 807 nm with total energy $E_{pump} = 114.6$ mJ, corresponding to an overall optical-to-optical efficiency $\eta_o \sim 0.28$. The slope efficiency was $\eta_s = 0.31$. It is worthwhile to mention that in our preliminary work [19], laser pulses with energy $E_p = 16$ mJ for the pump with pulses of energy $E_{pump} = 62$ mJ were obtained. Thus, scaling was demonstrated in the present report. Furthermore, the variation of laser pulse energy E_p with the repetition rate (up to 60 Hz) is investigated, the change of E_p with the resonator length is determined and measurements of the Nd:YAG core temperature are made in lasing and non-lasing conditions.

2. The Nd:YAG/YAG lens-shaped composite medium

A sketch of the laser configuration is presented in Fig. 1. The active medium is a circular core, in our case Nd:YAG of diameter ϕ_{core}, which is surrounded by an undoped YAG of diameter ϕ_{out} (as shown in Fig. 1a). Such a structure can be easily obtained nowadays, for example by diffusion bonding of ceramic media. Fiber-coupled diode lasers are considered for pumping. In order to couple directly the pump into the medium, with no additional optics, the Nd:YAG/YAG is shaped as a plane-concave divergent lens.

A model based on ray tracing was developed (Fig. 1b) in order to choose the characteristics of Nd:YAG and those of YAG. In simulations an optical fiber with diameter of 400 μm and numerical aperture NA of 0.22 was considered; consequently, the YAG edge thickness was set at $d_2 = 500$ μm. The pump wavelength was 807 nm. For Nd:YAG core, several values of Nd doping between 1.0 at.% and 2.0 at.% were considered, whereas the diameter ϕ_{core} was varied between 1.0 mm and 2.0 mm. In addition, for each Nd:YAG core, the diameter ϕ_{out} of the undoped YAG was changed from 5 mm up to 15 mm. The pump-beam absorption efficiency, η_a and the distribution into Nd:YAG of the absorbed pump beam were evaluated.

As an example, the expected absorption efficiency, η_a is shown in Fig. 2 for a Nd:YAG with $\phi_{core} = 2.0$ mm, having a doping level of 1.0 at.% and 2.0-at.% Nd and thickness d_1 of 50 μm and 200 μm. It is worthwhile to mention that in modeling the ray tracing was limited to a double pass of Nd:YAG, i.e. from left to right, as shown in Fig. 1b, but also from right to left for the unabsorbed pump beam that is transmitted through Nd:YAG and then it is reflected back to the Nd:YAG core by YAG side opposite to the optical fiber. One could see that absorption η_a larger than 0.75 can be obtained in the 1.0-at.% Nd:YAG core, whereas increasing Nd doping at 2.0-at.% can improve η_a up to 0.95. Based on such modeling and considering also the absorbed pump-beam distribution, the Nd:YAG doping level and its diameter were chosen as 1.0-at.% Nd and $\phi_{core} = 2.0$ mm, respectively, whereas the undoped YAG diameter was set at $d_2 = 10$ mm.

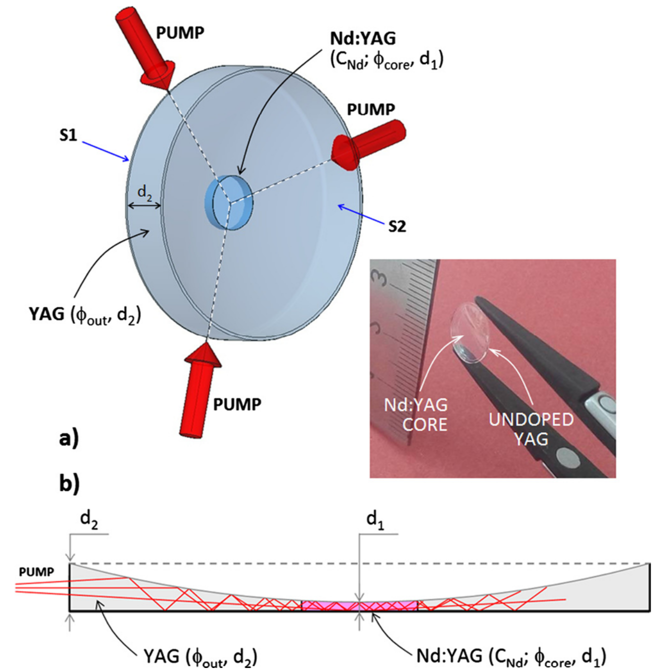

Fig. 1. (a) A sketch of the Nd:YAG/YAG lens-shaped composite ceramic is shown. Inset is a photo of the medium. (b) Cross-section of Nd:YAG/YAG and ray tracing for a single pump beam is illustrated.

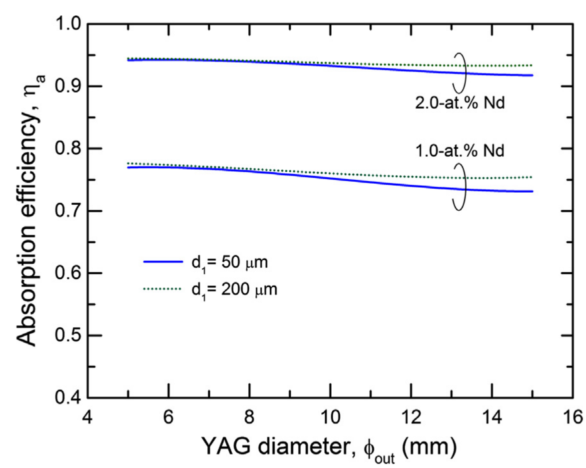

Fig. 2. Absorption efficiency η_a versus diameter ϕ_{out} of undoped YAG for Nd:YAG core of 1.0 at.% and 2.0-at.% Nd and thickness d_1 of 50 μm and 200 μm; Nd:YAG with $\phi_{core} = 2.0$ mm.

The Nd:YAG/YAG composite medium of 500-μm thickness was cut from a ceramic Nd:YAG/YAG rod manufactured by Konoshima Chemical Co., Japan. It was then shaped like a plane-concave lens (Fig. 1b), with a thickness at Nd:YAG center of $d_1 = 180$ μm (this was the smallest thickness that could be obtained in laboratory conditions). The flat side was polished at laser grade. A photo of Nd:YAG/YAG ceramic lens-like medium is shown in the inset of Fig. 1a.

3. The laser performances. Experiments and discussion

The plane surface of Nd:YAG/YAG (S1 in Fig. 1a) was coated high-reflectivity (reflectivity, R > 0.999) at the laser wavelength of 1.06 µm. The medium was attached with side S1 to a copper mount using a thermo-conductive paste; the copper mount was cooled by circulating water. The Nd:YAG/YAG concave side (S2 in Fig. 1a) was coated antireflection (transmission $T > 0.998$) at 1.06 µm. The pump was done at 807 nm with fiber-coupled (diameter of 400 µm, numerical aperture NA = 0.22) diode lasers (JOLD-120-QPXP-2P, Jenoptik, Germany) that were arranged in a three-fold geometry. The diodes were operated in quasi-continuous-wave regime; the pump-pulse duration was 250 µs and the repetition rate could be varied between few and 60 Hz. The resonator was obtained between surface S1 of Nd:YAG/YAG and a concave out-coupling mirror (OCM) with 50-mm radius. The laser head is shown in Fig. 3. Also, a typical fluorescence image of Nd:YAG core, which was recorded with a Spiricon camera (model SP620U, 190-1100-nm spectral range), is presented in the inset of Fig. 3.

The laser pulse energy E_p is shown in Fig. 4 versus total pump energy, E_{pump} at 2 Hz repetition rate, for a short 15-mm long resonator. With an OCM of transmission $T = 0.10$, the laser delivered pulses with $E_p = 31.8$ mJ; the total pump energy was $E_{pump} = 114.6$ mJ and thus overall optical-to-optical efficiency reached $\eta_o \sim 0.28$. Slope efficiency was $\eta_s = 0.31$. It is worthwhile to mention that if the pump-beam absorption efficiency is considered, i.e. $\eta_a \sim 0.75$, the optical-to-optical efficiency at the maximum pump energy and slope efficiency are evaluated to $\eta_{oa} \sim 0.37$ and $\eta_{sa} \sim 0.41$, respectively (both with respect to the absorbed pump energy). The laser beam distribution was multi-mode (as shown in the inset of Fig. 4). We mention also that in a separate experiment the variation of E_p was measured versus the resonator length. The OCM had $T = 0.10$, the repetition rate was 2 Hz and the pump was done at high level ($E_{pump} \sim 103$ mJ). In these conditions the resonator length could be increased up to 45 mm and only a small decrease, below 1.6%, of the pulse energy E_p was measured in comparison with the 15-mm long resonator.

The laser performances at high repetition rate are very important for scaling. In Fig. 5 the pulse energy E_p is presented versus the pump repetition rate for a fixed pump energy $E_{pump} = 93$ mJ. It was concluded that increasing the repetition rate from 2 Hz to 60 Hz (this was the maximum repetition rate available in our experiments) decreased E_p from 24.1 mJ to 21.4 mJ, i.e. by ~11%. The Nd:YAG core temperature was measured with a FLIR T620 thermal camera (−40 °C to +150 °C range, ±2 °C accuracy). It was observed that while at low repetition rate the temperature could

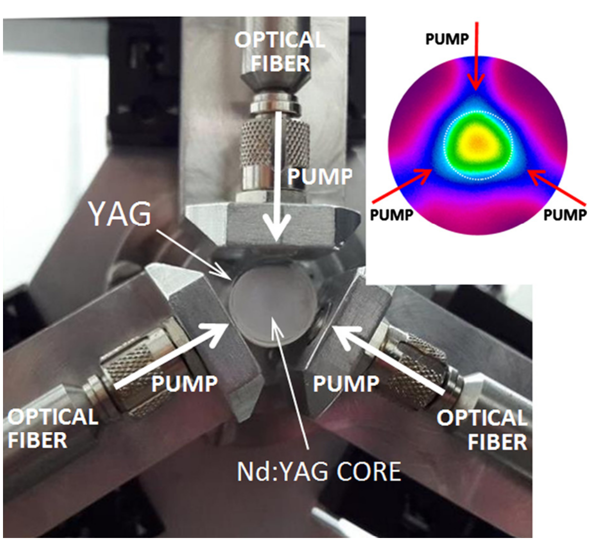

Fig. 3. A photo of the Nd:YAG/YAG medium mounted on the cooling finger is shown. Inset is a fluorescence image of Nd:YAG core. The position of Nd:YAG core was indicated by dashed circle.

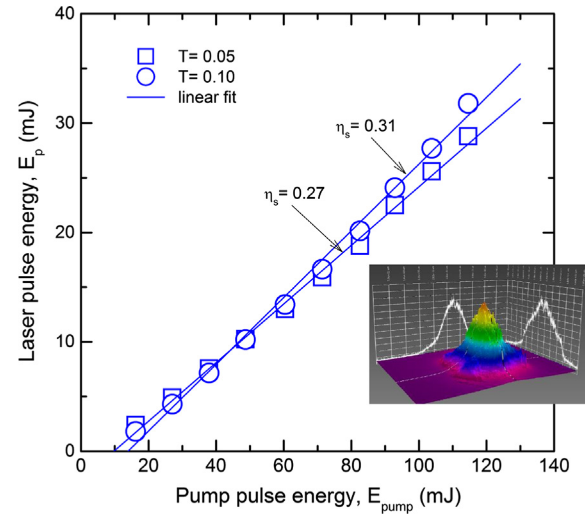

Fig. 4. Laser pulse energy E_p versus total energy of pumping E_{pump} at 2 Hz repetition and a 15-mm long resonator. Inset is a distribution of the laser beam at maximum E_p.

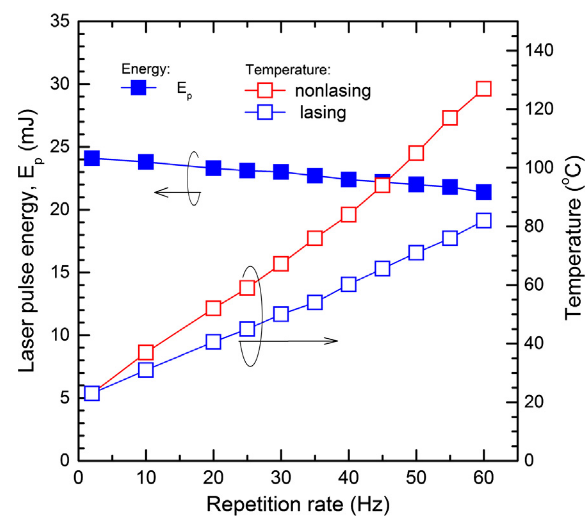

Fig. 5. Laser pulse energy E_p and temperature at the center of Nd:YAG core versus repetition rate. Resonator length of 15 mm, pump energy $E_{pump} = 93$ mJ, OCM with $T = 0.10$.

be maintained at room temperature, at 60 Hz repetition rate the maximum temperature increased up to 82 °C, under lasing condition. Furthermore, this temperature reached 127 °C when laser emission was stopped.

Detailed results are presented in Fig. 6 for 10 Hz, 40 Hz and 60 Hz pump repetition rate. Thus, at 10 Hz the laser pulse energy reached $E_p = 31.2$ mJ for $E_{pump} = 114.6$ mJ (Fig. 6a); the slope efficiency was $\eta_s = 0.30$. The maximum temperature of Nd:YAG core was 36 °C under lasing and 44.5 °C under non-lasing condition (Fig. 6b). On the other hand, for increased repetition rate of 40 Hz and 60 Hz the pulse energy E_p was 29.4 mJ and 27.8 mJ, respectively (Fig. 6a); this represents a decrease by ~6% and ~11% in comparison with E_p measured at 10 Hz. The slope efficiency decreased also, at $\eta_s = 0.26$ for 60 Hz repetition rate. When lasing, the maximum temperature reached 69.5 °C at 40 Hz and 98.7 °C at 60 Hz repetition rate (Fig. 6b). Stopping of laser emission results in a further increase of Nd:YAG temperature, to 100.7 °C at 40 Hz and even up to 158 °C at 60 Hz. Thus, at this stage better managements of thermal effects induced in Nd:YAG and thus improved laser

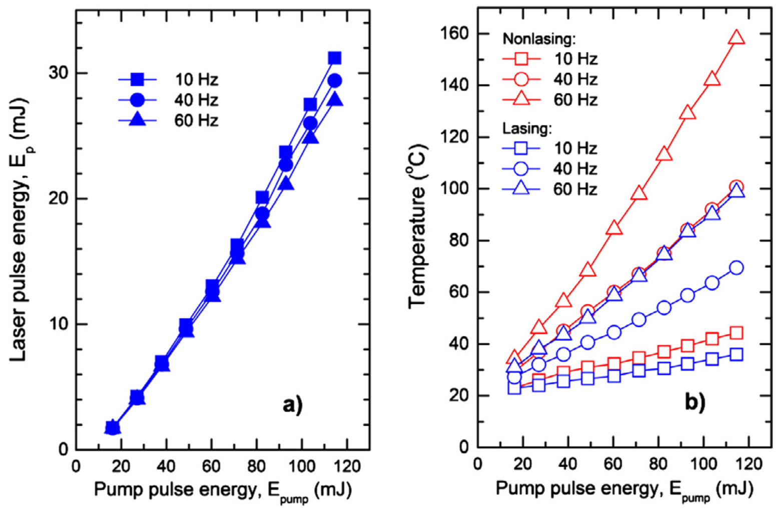

Fig. 6. (a) Laser pulse energy E_p and (b) Temperature at the center of Nd:YAG versus E_{pump} at various pump pulse repetition rate. Resonator length of 15 mm, OCM with T = 0.10.

performances are expected by soldering the Nd:YAG/YAG medium at the cooling system by metallic layers. This approach will be considered in future investigations.

4. Conclusions

In summary, we present a novel laser configuration that consists of a Nd:YAG/YAG composite medium having a Nd:YAG circular core surrounded by an undoped YAG circular region. The medium is shaped like a plane-concave lens, a geometry that allows the pump directly from the optical fiber of a diode laser, without any additional optics. For the experiments we built a three-fold edge-pumped Nd:YAG/YAG laser, with a 1.0-at.% Nd:YAG core of 2.0-mm diameter and 180-μm thickness at the center and a 10 mm in diameter YAG having 500-μm thickness of the edge. At 2 Hz repetition rate the laser yielded pulses with 31.8 mJ energy at 1.06 μm under the pump with 114.6-mJ energy at 807 nm; the slope efficiency was 0.31. An investigation of the laser performances for repetition rate up to 60 Hz was done. It is concluded that soldering the Nd:YAG/YAG medium to the cooling head with metallic layer has to be considered in further experiments for power scaling.

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