Investigation of spectrally-dependent phonon relaxation mechanism in Yb:YAG gain media and its consequences for thin disk laser performance

P Severová, S S Nagisetty, M Chyla, T Miura¹, A Endo, M Smrž and T Mocik

Hilase Centre IOP ASCR, Za Radnici 828, 252 41 Dolní Brezany, Czech Republic

E-mail: patricie.severova@hilase.cz

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Abstract

Nonlinear phonon relaxation in Yb:YAG gain media has previously been investigated, and a hypothesis correlating photo-induced free electrons and heat generation in crystals pumped at a wavelength of 940 nm was established (Brandt et al 2011 Appl. Phys. B 102 765–8). Later, we demonstrated efficient suppression of nonlinear phonon relaxation by zero-phonon line (ZPL) pumping of Yb:YAG (969 nm). However, no hypothesis has yet been tested that correlates the heat load and the free electrons in Yb:YAG media. We investigate, both theoretically and experimentally, the behaviour of an Yb:YAG slab pumped by a high-power laser diode at a conventional broadband line (absorption maximum at 941 nm) and a ZPL (absorption maximum at 969 nm), and we compare the generated photocurrent, temperature, and absorbed pump power for those two pump wavelengths. Although the hypothesis established by Brandt et al (2011 Appl. Phys. B 102 765–8) was not confirmed, and the measured photocurrent was identical for the two pump wavelengths, our measurement contributes to the knowledge of the inner processes in Yb:YAG active media. In the following steps we characterized an Yb:YAG thin disk laser, measured the spectrally-resolved absorption and disk surface temperature, and optimised our predictive model of thin disk behaviour. All the experimental and theoretical results are reported.

Keywords: Yb:YAG, thin disk, photocurrent, thermal effects, numerical modelling

(Some figures may appear in colour only in the online journal)
make Yb:YAG suitable for the generation of picosecond and femtosecond pulses. Its relatively low quantum defect and good thermal properties permit the scaling of output power to the kW level [3, 4]. The gain medium is usually pumped at a broad absorption line with a peak at 941 nm and a full width at half maximum (FWHM) of approximately 10 nm [5]. In the following paragraphs, we call this a conventional broadband line (CBL). The main advantage of this kind of pumping is the availability of cheap, high-power laser diodes emitting at around 941 nm and with an average output power of up to tens of kW in a quasi-continuous wave or continuous wave (CW) regime, or tens of kW of peak power with a low duty cycle in a pulse regime [3]. However, heavy thermal loading and a rapid temperature rise of gain media was reported for the CBL type of pumping of thin disk lasers operated at room temperature [6]. Another possibility is to pump Yb:YAG directly to the upper laser level at a wavelength of 969 nm; so-called zero-phonon line (ZPL) pumping. ZPL pumping increases laser efficiency [7], and reduces gain medium temperature due to a smaller quantum defect of only 5.9%, unlike that for CBL pumping, where the quantum defect is 8.6%. Smrz et al also reported [6] that ZPL pumping can suppress nonlinear phonon relaxation processes, which among other factors cause a rapid temperature increase [8]. Although this last mentioned effect was observed, its mechanism is not clear.

On the other hand, Brandt et al [9] measured photoconductivity in Yb:YAG induced by light exposure at a wavelength of 940 nm. They proposed a hypothesis that the generation of free electrons can release a significant amount of heat, which then causes a nonlinear rise in crystal temperature and is also responsible for the reduction in laser efficiency at high Yb$^{3+}$ ion concentrations that is described in [8]. No similar hypothesis for ZPL pumping has yet been evaluated.

In this paper, we report on an investigation of the physical factors affecting the temperature of Yb:YAG in cases of high-power pumping, with special emphasis on thin-disk configuration. We used a combination of experimental and theoretical approaches to compare the influence of the pump wavelength and the laser operational regime on absorption and emission processes and the consequences of a rising heat load. We also measured and compared the photocurrents induced in Yb:YAG by CBL and ZPL pumping. This is, to the best of our knowledge, the first measurement of the induced photocurrent in a Yb:YAG crystal irradiated by pump photons at 969 nm.

2. Experimental measurements

Two experiments were performed to investigate heat generation processes causing unwanted effects in Yb:YAG material. We first looked for relationships between pump wavelength, absorption, surface temperature, and laser output power in a CW regime using an Yb:YAG thin disk amplifier. We then measured the generation of free electrons via photoconductivity induced in an Yb:YAG crystal by pump light irradiation, and compared the results for CBL and ZPL pumping.

2.1. Set-ups

To realise the simultaneous measurement of surface temperature, pump power, and laser output power, we used the experimental set-up shown in figure 1(a). A 7 at.% Yb$^{3+}$ doped YAG disk, with a thickness of 220 µm and a diameter of 10 mm, was installed in a commercially available pump head. The disk was given a highly reflective coating on its reverse side at the pump and laser wavelengths. It was soldered on a CuW heatsink and water-cooled at 288 K [6]. For the pump source, we used CW fiber-coupled Diolas laser diodes, both for ZPL and CBL pumping, so that the diode modules could be exchanged without significant effects on alignment. The spectrum of the CBL pump source had a peak at 937 nm at a low output power level (figure 1(b)). For ZPL pumping, a volume Bragg grating stabilized the diode spectrum at a wavelength of 969 nm, with a FWHM < 1 nm (figure 1(c)) to fit the narrow absorption peak of the Yb:YAG [5]. The pump spot was 3.1 mm. The pump chamber, consisting of a parabolic mirror and retroreflective prisms, realised 12 V-passes through the thin disk. Residual, unabsorbed pump radiation was measured by a thermopile power meter head in order to calculate the actual value of absorbed pump power in the gain medium (figure 1(a)). A thermal camera placed in front of the thin disk measured the temperature profile of the thin disk surface in real time.

To realize a CW laser regime, we built a multimode V-shaped cavity. It consists of a curved mirror with a 5 m radius of curvature and a flat output coupler. The laser output power was measured by a power meter. We tested three different output couplers with transmittances of 3%, 5%, and 10% at a laser emission wavelength of 1030 nm, and we compared laser efficiencies for pumping at 937 nm and 969 nm. The highest efficiency was reached with a 5% output coupler for both pump wavelengths, and therefore, this output coupler was finally used in the experiments. Losses of coatings and pump optics after the 12 V-passes of the pump beam through the pump chamber were evaluated by inserting an undoped YAG disk with the same coating and dimensions instead of the Yb:YAG thin disk, and measuring the transmitted power. The difference between the input and transmitted power of the pump light at 937 and 969 nm was similar. Optical losses were 21% in both cases.

The set-up for photoconductivity measurement generally followed the layout used in [9], but several changes were made, as shown in figures 2(a) and (b). To create an efficient, electrically conductive connection between the YAG crystal and the high-voltage power supply, we used an indium tin oxide (ITO) layer sputtered on a covering window made of optical glass. A conductive pad placed between the copper and the holder worked as a second electrode. The window, Yb:YAG crystal, copper block heatsink with a gold layer, and the conductive pad were firmly clamped together and fixed to a breadboard. Both electrodes were connected to the test equipment by a thin wire fixed to the conductive layers. The generated photocurrent was measured by a Keithley 6514 picoammeter. We applied 500 V across the crystal to analyze the photoconductivity of Yb:YAG under varying conditions.
Because the laboratory is a clean room with a stabilised temperature and low humidity (30%), we did not place the system under any additional protection. The tested crystal was a 15 at.% Yb$^{3+}$ doped YAG crystal with a thickness of 2 mm. Since our intention was a comparison of photoconductivity under varying pump wavelengths, only the fibre-coupled pump source was exchangeable during the experiment. Two fibre-coupled diodes from BWT Company, with a core diameter of 200 $\mu$m, numerical aperture (NA) 0.22 and maximal power reaching 25 W at 940 nm and 969 nm, were used as pump sources. The ZPL pump diode was spectrally stabilised by integrated Bragg gratings as already mentioned, and the wavelength of the CBL pump source was slightly controllable by changing the laser diode’s cooling temperature. The optical system imaging pump light into the crystal consisted of two lenses, $F_1$ and $F_2$ (figure 2(a)), with focal lengths of $f_1 = 4.5$ mm and $f_2 = 75$ mm. Yb:YAG was placed at the focal position of the $F_2$ lens. The pump spot for the CBL pump was circular, with a diameter on the crystal of 310 $\mu$m, and slightly elliptic, with main axes of 300 $\mu$m and 320 $\mu$m, for the ZPL pumping. Table 1 summarises all the parameters of the components used and the pump light properties.

We performed additional surface temperature measurement of Yb:YAG during this experiment, using an FLIR E50 camera. However, the ITO window had to be removed because of its opacity in the operational spectral region of the camera (around 10 $\mu$m). Therefore, we could not measure photoconductivity and temperature simultaneously.

2.2. Results and discussion

First, we investigated the dependence of material absorption on pump wavelength, operational regime, and pump power density in the set-up described in figure 1(a). We calculated the absorbed power density $I_{abs}$ from the measured incident power $P_{in}$ and power leakage $P_l$. The diameter of the pumped area on the thin disk $D = 3.1$ mm. We introduced as variables a function loss with pump power $P$ in, optical losses for one pass $l_1$, the average absorption of one pass $A_1$, and the number of passes $n$. The function calculated the total loss of pump power at disk module optics as the sum of partial losses for each pass. For each input power, $l_1$ and $A_1$ were derived from measured optical losses for 12 passes and unabsorbed power. $I_{abs} = \frac{P_{in}}{S} - \frac{P_l}{S} = Loss\left(P_{in}, l_1, A_1, n, S\right)$. (1)

$S$ is the calculated pumped area:

$S = \pi\left(\frac{D}{2}\right)^2$. (2)

Figure 3 shows the absorbed power density $I_{abs}$ related to the pump power density $I_p$. For both pump wavelengths in a fluorescence (FL, non-lasing) operational regime, the amount of absorbed power density is significantly lower than for the lasing regime (LAS), and the curves show signs of saturation. ZPL pumping starts to saturate at a lower power density than does CBL pumping. Close to the maximum applied power density at 5.3 kW cm$^{-2}$, the difference in $I_{abs}$ between the FL
and LAS regimes is $0.47 \text{ kW cm}^{-2}$ for the CBL pumping but $0.58 \text{ kW cm}^{-2}$ for the ZPL pumping. In the laser regime, the absorption rate rises linearly and identically for the two pump wavelengths.

The shapes of all curves corresponded well with the model reported by Sato et al [10]. They calculated that the pump saturation power density was higher for the ZPL pumping than for the CBL pumping, and reported that the absorption effect in both pumping schemes was recovered during laser action. They verified their model result by measurement of the absorption coefficient of a 1 at.% Nd-doped YVO$_4$ crystal of 1 mm thickness, pumped by a Ti:sapphire laser, and placed in a plano-concave resonator. In our experiment, complex absorption measurement for an Yb:YAG thin disk laser at both pump wavelengths was carried out for the first time.

The laser output power measurement method is demonstrated in figure 4. As shown above, the amount of absorbed power density is the same for the two pumping wavelengths in the laser regime (figure 3), and laser output power is 15% higher for ZPL pumping than for CBL pumping. The reason

### Table 1. Summary of components used in the experiment.

| Component       | Specifications and typical dimensions                                      | Experimental condition                                      |
|-----------------|---------------------------------------------------------------------------|------------------------------------------------------------|
| Window          | One-side indium tin oxide (ITO layer 25 × 25 mm$^2$, thickness 5 mm       | HV is applied via a thin wire soldered to the ITO layer     |
| Crystal         | 15 at.% Yb$^{3+}$:YAG, thickness 2 mm                                      | Photoconductivity controlled by pump intensity             |
| Cu block        | Gold-plated mirror with copper substrate, diameter 25 mm, thickness 5 mm | Serves as a passive heat sink and an electrode              |
| CBL diode       | 940 nm, 25 W, wavelength temperature stabilised, fibre core diameter     | Imaged beam diameter 310 μm                                |
|                 | 200 μm, NA 0.22, manufacturer BWT                                         |                                                            |
| ZPL diode       | 969 nm, 25 W, Bragg grating stabilised wavelength, fibre core diameter    | Imaged beam dimensions 300 × 320 μm (main axes)            |
|                 | 200 μm, NA 0.22, manufacturer BWT                                         | Imaging telescope                                          |
| Lens $F_1$      | Plano-convex, $f = 4.5$ mm, diameter 12.5 mm                              | Imaging telescope                                          |
| Lens $F_2$      | Plano-convex, $f = 75$ mm, diameter 25 mm                                 |                                                            |
for the improved laser output at 969 nm pumping is probably the significantly lower temperature of the lasing material for this pump wavelength (figure 5).

To describe the heat load of the Yb:YAG thin disk, we measured the disk surface temperature. The peak surface temperature ($T_{\text{max}}$) was then taken, for comparison (figure 5). The rate of peak temperature increase is proportional to the quantum defect for the respective wavelengths in both operational regimes at the absorbed power density ($I_{\text{abs}}$) < 2.4 kW cm$^{-2}$. The difference in both the quantum defects and the temperatures between the ZPL and the CBL pumping is equal to 32%. However, nonlinear phonon relaxation characterised by a nonlinear rise of disk surface temperature shows up following an increase in the pump power density for CBL pumping. Close to the pump power density of 3 kW cm$^{-2}$ and the FL regime, the maximal temperature reached on the thin disk surface differs by more than 36% for the different pump wavelengths. Cooling and other conditions were the same for both pump wavelengths. Therefore, the maximal temperature values reflected directly the amount of heat additional to the quantum defect.

Since [9] relates this excessive heat for CBL pumping to free carrier generation, we proposed to repeat the experiment for both pumping schemes (see figure 2). The experiment was carried out on a small Yb:YAG slab with higher Yb doping than was used in the Yb:YAG thin disk experiment. To identify whether the photocurrent was being measured in the nonlinear phonon relaxation regime, the peak surface temperature of the CBL-pumped 15% Yb:YAG was measured, compared with the maximal thin disk temperature measured in the previous experiment (figure 5), and complemented with the calculated maximal surface temperature for the 2 mm Yb:YAG crystal under the same conditions. The results are shown in figure 6. Nonlinear phonon relaxation was detected in experimental measurements. Therefore, we can say that the photocurrent was measured above pump intensities, where the nonlinear temperature increase starts. We did not include temperature measurement for ZPL pumping, because in that case, nonlinear phonon relaxation does not appear and temperature measurement in this configuration is not sufficiently precise to compare absolute values for the two pump wavelengths. For an absorbed power density of > 6 kW cm$^{-2}$, the air-cooled holder of the crystal was overheated and we could not measure temperature above this value. The difference between the detected temperatures of the thin disk and the slab may be a consequence of different gain medium geometry, thickness, pump mode diameter, cooling scheme and efficiency, or Yb doping concentration.

The pump wavelength-dependent photocurrent for variable absorbed power density is reported in figure 7. Experimental data points are averaged over six or seven measurements for ZPL and CBL pumping, respectively. They are linearly fitted, and the vertical bars show root mean square values of the experimental error. In the case of CBL pumping, we observed photocurrent saturation at 16 kW cm$^{-2}$ of the absorbed power density.
density. The same effect was observed by Brandt et al [9]. However, contrary to our expectations, the results show that the measured photocurrent has similar values and rates of increase for the two pump wavelengths. These data indicate that the generation of free charge carriers is probably not the reason for nonlinear phonon relaxation and excessive heat load in the Yb:YAG pumped by CBL.

3. Simulations

In order to clarify how absorbed power contributes to thin disk temperature, and how to improve our further theoretical predictions, we made several simple numerical simulations where the thermal distribution in the disk was calculated. The input parameters used in the calculation are summarized in table 2. Calculations were compared with the surface temperature measurement using a thermal camera (figure 4), as carried out during the thin disk experiment (figure 1).

The numerical calculations of temperature distribution were based on finite element analysis (FEA), which solved the heat equation in cylindrical symmetry [11]:

$$\frac{1}{r} \frac{\partial}{\partial r} \left( \lambda_{rr} \frac{\partial T}{\partial r} \right) + \frac{\partial}{\partial z} \left( \lambda_{zz} \frac{\partial T}{\partial z} \right) = -q$$

(3)

where $T$ [K] is temperature, $\lambda_{rr}$, $\lambda_{zz}$ [W/Km] are components of a heat conductivity tensor, $r$ and $z$ are coordinates, and $q$ [W m$^{-3}$] is a volume heat source. The last parameter expresses how much of the absorbed pump power is converted into waste heat. We want to separate the part of the heat in the thin disk that comes from the quantum defect only, and the part generated by other processes. Therefore, the heat source $q$ was calculated as follows:

$$q = \varepsilon \frac{P_{abs}}{V} f_{SG}$$

(4)

where $P_{abs}$ is the absorbed power, $V$ is the pumped volume, $f_{SG}$ is a function expressing the super-Gaussian shape of the pump beam, and $\varepsilon$ is a quantum defect parameter:

$$\varepsilon = 1 - \frac{\lambda_{pump}}{\lambda_{laser}}$$

(5)

where $\lambda_{pump}$ and $\lambda_{laser}$ are pump beam and signal beam wavelengths, respectively.

We took the measurement results of the actual absorbed pump power (figure 3) and used them as input for the volume heat source (4). This empirical approach should include all effects related to heat generation through quantum defect, according to (5), and excluding parasitic phenomena causing nonlinear phonon relaxation since we do not know its mechanisms. Despite this simplification, this approach should finally improve our future predictions, as shown later. The modelled peak thin disk surface temperature $T_{max}$, depending on operational regime, CBL and ZPL pumping, is summarized in figures 8(a) and (b).
From the data it is obvious that we can separate heat resulting from absorbed power and quantum defect only, and heat originating from other processes. The modelling results in figure 8(a) show that heat in the thin disk pumped by CBL and without laser action is given by the pump power and quantum defect only up to 2.4 kW cm$^{-2}$ of actual absorbed pump power density, which corresponds with 4.04 kW cm$^{-2}$ of pump power density. For higher absorbed power densities, nonlinear processes appear in the experimental results. Conversely, the ZPL-pumped thin disk in the FL regime shows only quantum defect originating from the heat source, and nonlinear phonon relaxation is negligible, which confirms our previous observations [6].

The results for the laser regime are summarised in figure 8(b). For both pump wavelengths, the simulated values fit with the experimental results. Therefore, no other heat sources than the quantum defect are expected to significantly affect disk temperature.

4. Conclusion

We used a combination of experimental measurement and numerical calculation to investigate differing absorption and thermal behaviours of a Yb:YAG thin disk under differing pump conditions and operational regimes. We confirmed that zero phonon line pumping leads to the suppression of nonlinear phonon relaxation, and that the generated amount of heat is proportional to the quantum defect, whereas for pumping at CBL a parasitic heat source appears from the absorbed pump power density at approximately 2.4 kW cm$^{-2}$ in the fluorescence regime. Laser operation partially suppresses it, because of the faster depopulation of upper energy levels. However, the theory developed in [9] relating additional heat source to photo-induced generation of free carriers was not confirmed since, unlike with very different temperatures, we measured almost identical conductivity of the Yb:YAG under the two pumping conditions. Therefore, we conclude that nonlinear phonon relaxation has no connection with the generation of free charge carriers, which still has no satisfactory explanation. Further experimental investigation of the phenomenon is planned.

Finally, experimentally measured data were used as an input for an improved model of a thin disk laser. The calculated surface temperature was compared with the experimental data, and we proved the better accuracy of the model using experimentally measured absorption than that of a model based on spectroscopically measured data. The experimental data probably include some of the internal processes which are absent in the theoretical data. The accuracy of the model is now sufficient for design and subsequent improvement of thin disk lasers at the Hilase facility [3].

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