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Nd:YAG laser diode-pumped directly into the emitting level at 938 nm

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Abstract: We present the first demonstration of Nd:YAG laser pumped directly in band at 938 nm with a high-brightness fiber-coupled laser diode. Up to 6 W of CW laser emission at 1064 nm have been obtained under an absorbed pump power of 28 W at 938 nm. A comparison between 808 nm and 938 nm pumping, realized by thermal cartography, demonstrates the very low heat generation of in-band pumping. Numerical simulations were also implemented to study and discuss the laser performance of our system.

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OCIS codes: (140.3530) Lasers, neodymium; (140.3480) Lasers, diode-pumped, (140.6810) Thermal effects.

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1. Introduction

It is well known that the power scaling of bulk solid-state lasers is limited by local thermal effects induced by the optical pumping. Deleterious consequences on the beam quality and on the laser performance are often observed when the pump power increases. A large number of strategies have been implemented to manage thermal effects. One way is the design of the gain medium including the cooling efficiency and the pump distribution inside the medium: thin disk [1], low doped rod [2] or slabs [3], and glass fibers [4] represent technological solutions to limit the heating effect. However, the most fundamental way is to reduce the energy difference between a pump photon and a laser photon. As an example, the so called quantum defect is much lower in Yb:YAG (pumped at 940 nm, laser at 1030 nm) than in Nd:YAG (pumped at 808 nm, laser at 1064 nm): 9% versus 24%. This explains why Yb:YAG is so widely used for high power lasers. The decrease of the quantum defect in Nd^{3+}-doped media is nevertheless possible by pumping directly in the emitting level. Indeed, reduction of thermal effects has been clearly demonstrated with a pump at 869 nm [5] and 885 nm [6] using a Ti:Sapphire laser or high-brightness laser diodes as pump source at 885 nm [7] and thin and long crystal rods have also been used to increase the absorption length by total internal reflections of the pump beam [8, 9]. It is possible to go further in this way by pumping the Nd^{3+} ion from the upper level of the fundamental manifold, using pump wavelengths at 938 nm or 946 nm. Hence this leads to a quantum defect of 12% (and 11 % respectively) which is very close to the Yb:YAG one. A first demonstration has been recently reported [10] with a Ti:Sapphire laser as a pump source at 946 nm. As the absorption peaks are very low and narrow (1nm full width at half maximum) at 946 nm and at 938 nm, the diffraction limited beam and the narrow spectral linewidth of the Ti:Sapphire laser were very useful: an output power of 60 mW was obtained for a double pass pumping at 946 nm in a 6 cm long 1.1 at.% doped Nd:YAG crystal. However, the use of a Ti:Sapphire pump laser is definitely not relevant in terms of overall efficiency, compactness and low cost solution. Clearly, diode-pumping Nd:YAG at 938 nm or at 946 nm is a challenge since common high-power laser diodes generally have a spectral width much larger than 1 nm and a beam quality far away from a TEM_{00} beam. Indeed, the key point is to confine the pump photons in the laser mode, despite the very small absorption. As done in fiber lasers or in some configurations with bulk media [2, 9, 11], one solution is to guide the pump beam in order to increase the absorption volume. We present here the use of a small diameter Nd:YAG rod as light guide and demonstrate diode-pumping of Nd:YAG laser at 938 nm for the first time to our knowledge. In order to investigate the interest of in-band pumping at 938 nm compared to 808 nm, we carried out thermal measurements using an infrared imager. Next, we present the laser performance obtained and discuss different ways of improvements by means of temperature dependant numerical simulations.

2. Thermal study of in-band pumping at 938 nm

In our experiment (Fig. 1), we used a thin crystal rod of 1 mm in diameter and 35 mm long with a doping rate of 0.7 at.% in Nd^{3+} grown by the Czochralski growing process. This rod was end-pumped by a fiber coupled laser diode provided by Spectra Physics emitting a maximum output power of 200 W at 940 nm. The core diameter of the pumping fiber was 200 µm with a NA of 0.22. We intentionally limited the power to 120 W: beyond this level, the central wavelength of the laser diode shifted in excess compared to the 938 nm absorption peak. Pumping optics were composed of two doublets (focal length of 50 mm and 100 mm) such that the pump beam diameter is 400 µm on the crystal. Taking into account a M^2 factor of 40 for the pump beam, we assumed that more than the last third part of the rod length acts as a guide thanks to the high index difference between air and Nd:YAG (n_{YAG}=1.82). To ensure the guiding effect properly, the rod barrel was carefully polished to optical quality. The rod end faces were AR coated at both pump and lasing wavelengths. The Nd:YAG rod was surrounded by thermal grease and mounted in a pair of 0.5 mm depth V-grooves made in copper to insure an homogeneous temperature over the whole crystal surface. We checked the

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guiding efficiency with a laser diode at 980 nm with the same characteristics of the one at 938 nm: the transmission was higher than 90% in one pass. By comparing the guiding efficiency with and without thermal grease, we measured that 2 % are lost due to the thermal grease contribution. The other 8 % are attributed to scattering losses at the rod surface. We controlled the temperature of the rod by a thermoelectric Peltier element placed under the rod mount. The temperature of the input pumped face was monitored by an infrared imager in a setup previously developed [12, 13].

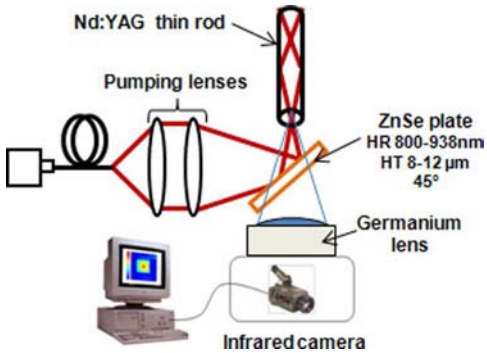

Fig. 1. Experimental setup for absorption measurement and thermal mapping.

At room temperature, the pump absorption was so low (only 19 %) that even at 120 W of pump power, the temperature increase induced by the pumping was not detectable. Fortunately, Goldring et al. [10] showed that the absorption can be improved by a global temperature increase, as the upper level of the ground state manifold is more populated. In our case, the crystal rod was heated up to a temperature of 150°C which was the upper limit before the degradation of the thermal grease around the rod. As shown on Fig. 2, the absorption can be significantly improved by this way.

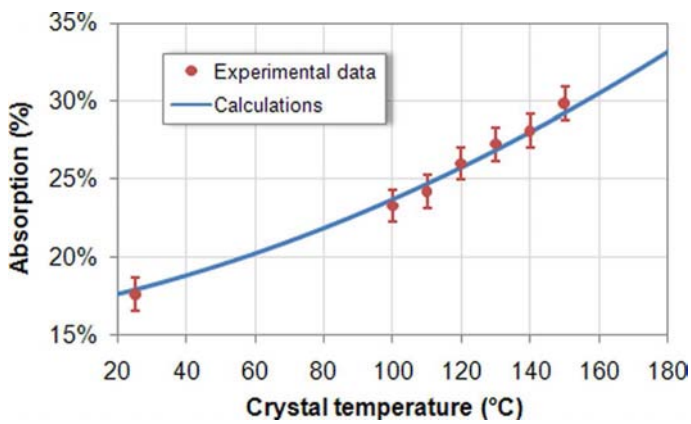

Fig. 2. Evolution of the absorption percentage with the crystal temperature for 120 W of incident pump power from the diode at 938 nm.

Before investigating the laser performance, we evaluated the pumping heat generation with infrared camera (see Fig. 1). Temperature mapping of the pumped face is an excellent way to evaluate the temperature gradient between the center and the edge of an end-pumped laser rod of radius r_0. Assuming the hypotheses detailed in [13] are valid, this gradient is given by the formula:

$$T(r,z) - T(r_0,z) = -\frac{\eta_H}{4\pi.K_c}\frac{dP}{dz}(z).f(r,z) \qquad (1)$$

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Where η_H is the fractional thermal loading, dP/dz (z) represents evolution of the pump power along the z axis, and f(r,z) is a geometrical function depending on the pump geometry. These measurements were carried out at a mount temperature of 150°C. This time the effect of the 938 nm pump heating was clearly visible on the temperature difference between the mount and the crystal (Fig. 3). Nevertheless, it is worth to note that the transverse gradient remained very low with 938 nm pumping.

For the sake of comparison, we pumped the crystal at 808 nm exactly under the same conditions: same pump geometry and same longitudinal deposited pump power density (denoted dP/dz(z) in Eq.(1)). The Table 1 shows the experimental data for the two pumping conditions. At 808 nm, the experiment was carried out at room temperature.

Table 1. Incident pump power and absorption coefficient for the two pumping wavelengths.

Pumping wavelengths	α *(cm^{-1})*	P_{inc} *(W)*	$\alpha . P_{inc}$ = **dP/dz** *(W/m)*
808 nm	1.19	6.5	773.5
938 nm	0.079	97.5	770.3

As shown on Fig. 3, the maximum temperature difference is much higher with a pumping at 808 nm and the transverse temperature gradient is much more significant. Hence, the pumping at 938 nm is clearly a way to reduce local heating and its deleterious effects on laser operation.

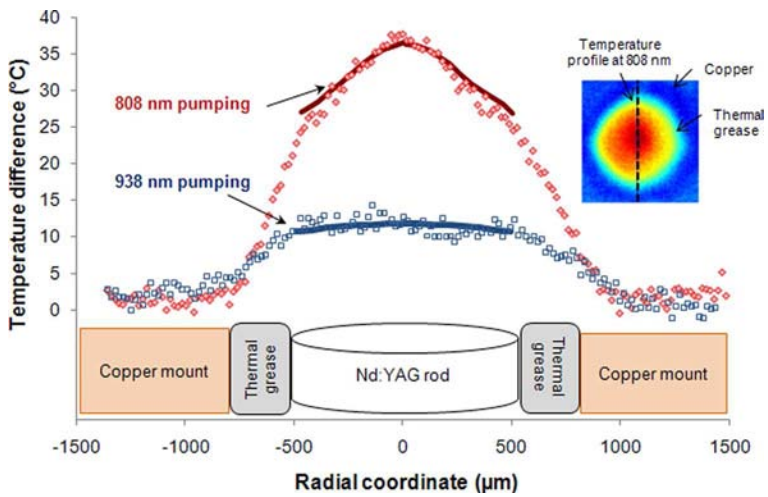

Fig. 3. Experimental temperature profiles of the pumped end-face at 808 nm (red) and 938 nm (blue). The reference (0°C) is the crystal mount temperature. Dots correspond to the experiments and solid lines to the FEA calculations. Image of the pumped face with a power of 6.7 W at 808 nm is shown in the inset.

These thermal cartographic measurements were confronted to thermal FEA calculations. As shown on Fig. 3, an excellent agreement has been obtained by adjusting the values of the fractional thermal loading to 0.4 and 0.12 for pumping wavelengths at 808 nm and 938 nm respectively. From FEA calculations, we derived the index variation in each point of the crystal and consequently the thermal lens has been calculated the simulations. We found a thermal focal length around 240 mm long for 28 W of absorbed pump power at 938 nm and as short as 55 mm for the same absorbed pump power at 808 nm. Thus, the thermal lens effect is drastically reduced by in-band pumping at 938 nm.

The next part of this work deals with the study of laser action under diode pumping at 938 nm.

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3. Laser results

In this experiment, we used two imaging doublets of 50 mm and 160 mm respectively in order to achieve a pump spot into the gain medium of 640 µm in diameter (see on Fig. 4). We studied the CW regime using the experimental setup shown on Fig. 4. We used a two-mirror cavity setup to achieve laser emission. The first mirror (M1) was a 50 mm radius dichroic meniscus coated to be highly transparent at the pump wavelength (T=90%) and highly reflective at 1064 nm (R=99.5%). The output coupler (M2) was a 100 mm radius concave mirror with a transmission coefficient of 10% at 1064 nm. It is worth to note that the thermal lens of 240 mm has a negligible influence on the beam size in this bi-concave cavity. The cavity length and the output coupler transmission were adjusted experimentally in order to maximize the laser output power. To benefit from the best absorption coefficient shown formerly, we fixed the crystal temperature at 150°C for each pump power.

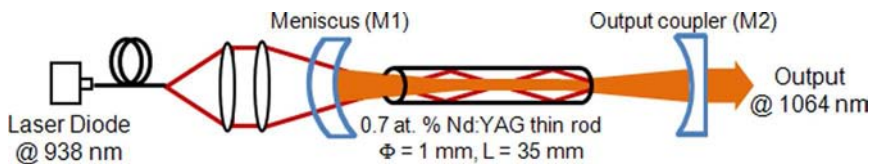

Fig. 4. Experimental laser setup

The laser efficiency is also depicted on Fig. 5. We have obtained a maximum output power of 6 W for an absorbed pump power of 28 W at 938 nm (incident pump power of 120 W). This corresponds to a slope efficiency of 28 %.

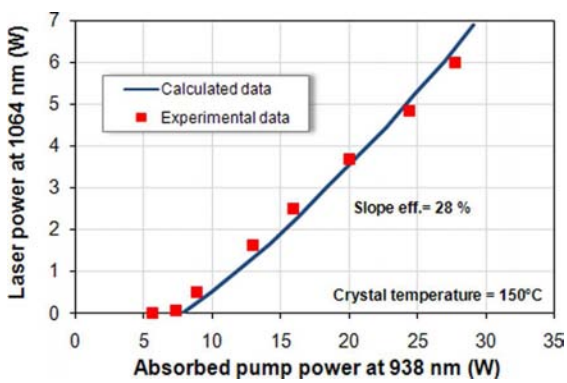

Fig. 5. Maximum output power at 1064 nm as a function of absorbed pump power at 938 nm for a fixed crystal temperature of 150°C.

Even if it is the first demonstration of a Nd:YAG diode-pumped at 938 nm, this efficiency remains lower than the one obtained under Ti:Sapphire pumping at 946 nm (42 %) [10] and much lower than expected by the quantum defect (88%).

The last part of our work is devoted to the analysis of this low efficiency and to present several ways of improvements.

4. Discussions and ways of improvements

We first checked that neither parasitic oscillations nor ASE occurred. Consequently, the laser efficiency was not limited by a parasitic reduction of the population inversion.

Then we carried out numerical simulations of the laser output power by taking into account the spatial overlap between the pump and the signal. According to the length of our cavity (150 mm) and the measured M^2 beam quality factor at a value of 7, the use of a beam propagation software allowed us to estimate a multimode beam waist radius of 300 µm inside the gain medium. For the simulation, the crystal temperature was set at 150°C same as in the experiment. The Fig. 5 shows a good agreement between the simulation and the experimental

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results proving that the key parameter for efficient laser action is the overlap between the pump and the signal. It is particularly reduced in the third part of the rod, where the pump beam is the largest (because it is guided).

To improve this overlap, one can think to improve the absorption, reducing the contribution of the guided pump in the last third part of the crystal. The increase of the overall rod temperature stands as a possibility as shown on Fig. 2. To demonstrate the influence of the temperature, we computed the absorption versus temperature. We took into account temperature dependence of effective absorption cross section at 938 nm according to the Boltzmann distribution, and the temperature dependant spectral overlap between the laser diode emission spectrum and the absorption spectrum. We calculated the overlap to be 39 % at room temperature taking into account the measured width of our laser diode (2.5 nm) and the absorption linewidth temperature dependence given by Goldring & al.[10]. The calculated values for the absorption matched perfectly the experimental data (see on Fig. 2). Then we use our simulations already validated by the previous experimental results and we calculated the output power versus the temperature for an incident pump power of 120 W. For that, we took into account the decrease of the emission cross section at 1064 nm versus temperature, firstly measured by Rapaport & al. [14] and extended by Dong & al. [15]. The simulations are reported on Fig. 6. Between 100°C and 150°C, the calculated laser power is in good agreement with the experimental data.

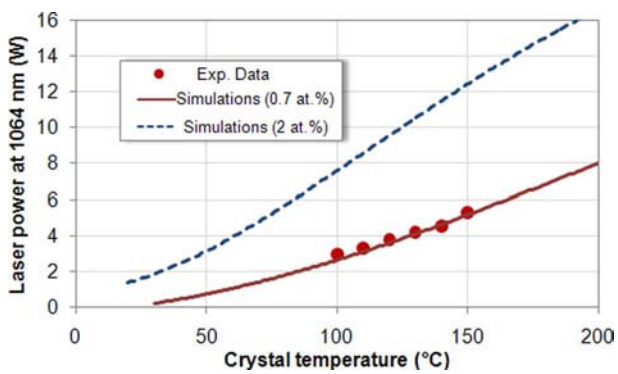

Fig. 6. Measured (*circle*) and calculated laser power at 1064 nm for doping rates of 0.7 at.% (*solid line*) and 2 at.% (*dashed line*) as a function of the crystal temperature between 25°C and 200°C for an incident pump power of 120 W at 938 nm.

As one can see on Fig. 6, the laser output power is enhanced as the absorption is increased with crystal temperature rising. Nevertheless, Kaminskii has demonstrated that parasitic effects could occur beyond 200°C [16]. In fact, thermal population of the lower laser state level (resulting in reabsorption at the laser wavelength) and upper laser level depletion (caused by thermal population of upper levels such as $^4F_{5/2}$, $^4H_{9/2}$ and beyond) should probably affect the laser performance at higher temperatures.

Another way to improve the absorption is to increase the doping level. Thus, we calculated the laser power that could be obtained by using a 2 at.% crystal rod instead of a 0.7 at.% one with the same geometry (35 mm long and 1 mm in diameter). As demonstrated by Dong & al. [15], highly doped Nd:YAG crystal can be grown with good crystalline quality. However, the reduced fluorescence lifetime by concentration quenching (145 µs for a 2 at.% of doping rate) has to be taken into account. The same configuration of pump guiding setup and laser beam parameters is imposed in these calculations. An important increase of laser power is expected by using a higher doping rate of the crystal rod: more than 12 W of laser power for an absorbed pump power of 72 W could be obtained at a crystal temperature of 150°C.

Finally, we demonstrated that increasing the crystal temperature and the doping rate could be an efficient mean for laser power scaling but a careful attention to thermal parasitic effects occurring beyond 200°C is required.

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5. Conclusions

We have realized what we believe to be the first demonstration of a Nd:YAG laser diode-pumped at 938 nm. We obtained up to 6 W at 1064 nm for an absorbed pump power of 28 W at a temperature operation of 150°C on the crystal rod. Moreover, we prove experimentally for the first time that pumping at 938 nm induces a much lower heat generation than pumping at 808 nm. To improve the laser efficiency, one could increase the absorption. The use of longer rod or special pump laser diodes with narrow spectrum and wavelength stabilization would be helpful in that way. One could also improve the overlap between the pump and the signal with a rod having a core-clad configuration. In any case, this demonstration could open the way of more powerful Nd:YAG laser as the thermal effects are dramatically limited.

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