Crystalline fiber Ho^{3+}:YAG laser resonantly-pumped by high-spectral-brightness laser diodes

Antoine Berrou*[a], Thierry Ibach[a], Martin Schellhorn[a], Wentao Hu[b], Rob Lammert[b], Laurent Vaissié[b], Jeff Ungar[b] and Marc Eichhorn[a]

[a]French-German Research Institute of Saint-Louis (ISL), 5 rue du Général Cassagnou, Boîte Postale 70034, 68301 Saint-Louis Cedex, France;

[b]Laser Operations LLC-QPC Lasers Division, 15632 Roxford St., Sylmar, CA 91342-1265

ABSTRACT

Recent advances of high power and narrow bandwidth laser diodes emitting at 1.9 µm open the path to direct diode pumping of Ho^{3+}:YAG lasers. The usual method to pump such laser is to use thulium fiber laser which has an excellent beam quality with high power and narrow bandwidth emission. The draw back of this system is the low efficiency of this fiber laser and the increased overall complexity. In this paper we present first results of resonantly diode pumping of a Ho^{3+}:YAG laser with fiberlike geometry. The fiber coupled diode modules used for pumping in this work (BrightLock™ Ultra-500) produce each 25 W at 1.91 µm with 3 nm linewidth. The fiber has a core diameter of 600 µm with 0.22 numerical aperture. The Ho^{3+}:YAG crystal has a diameter of 1.2 mm, a length of 60 mm, a doping concentration of 0.75 at.% and is symmetrically pumped by two diode modules from both ends. Total internal reflection on the polished rod barrel allows a high pump intensity along the rod length. The Ho^{3+}:YAG laser cavity is composed of a high reflective flat mirror and a concave output coupler with a radius of curvature of 500 mm. With an output coupler of 50 % we measured a threshold of 11 W. The maximum output power was 11.87 W with a wavelength of 2.09 µm. The incident power to output power slope efficiency was 0.38 at currently 4 % of internal losses.

Keywords: Infrared lasers; diode-pumped lasers; solid-state lasers; Ho:YAG.

1. INTRODUCTION

The domain of application of high power laser sources emitting around 2.1 µm is very wide, spanning from medical applications through atmospheric monitoring to optical parametric oscillator pumping. Different techniques have been used to produce this radiation along the years. One of them is to pump a co-doped Ho^{3+}:Tm^{3+} crystal around 0.79 µm. However this approach suffers from limited slope efficiency due to different energy transfer processes used in the pumping and cooperative upconversion between Ho and Tm [1] which produce heat in the crystal with the consequence of reducing the beam quality. To avoid these drawbacks one solution is to pump a Ho^{3+}:YAG crystal at 1.9 µm, with the necessity to find an efficient 1.9 µm source. A good candidate is a Tm^{3+}:YLF laser diode pumped around 0.79 µm [2]. This laser gives good results but the combination of high power and good beam quality is difficult to reach. The most popular pump source for pumping a Ho^{3+}:YAG crystal is a Tm^{3+}:fiber laser. This source has the advantage that it can produce high power with excellent beam quality. However the commercial version, which is very easy to implement in the setup, uses a cascaded scheme that is not efficient. Due to the late development of high power diodes around 1.9 µm, they can be a good alternative to pump a Ho^{3+}:YAG laser. It can be advantageous in different ways such as efficiency, simplicity or compactness. A pioneer attempt of directly diode pumped a Ho^{3+}:YAG laser was performed before the commercialization of high power diode at 1.9 µm, thus it was performed with 6 diodes emitting each 0.7 W at 1.9 µm [3]. In addition to the relatively low power, these diodes were angle multiplexed and polarization coupled in order to pump the laser crystal, which drastically complexifies the setup. Therefore the output power was less than 0.7 W even at low heat sink temperature. With the development of diode stacks at this wavelength it is now possible to generate 40 W of output power with 150 W of pump power [4]. This setup gave an output beam quality factor of $M^2 \sim 4$, and around 4 mJ was obtained when Q-switched at kHz repetition rate. Another drawback of these stacks is that the pump linewidth

*antoine.berrou@isl.eu; phone +33 389 69 50 64

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is 22 nm which is larger than the absorption peak of the Ho^{3+}:YAG crystal. Thus a major part of the pump power is not efficiently used. In order to improve the efficiency, narrow bandwidth diode should be used. A first attempt has been realized with 1.907 µm diodes with 6.1 nm bandwidth, but these diodes were limited to quasi continuous wave mode [5]. These diodes produce pulses of 6 ms at 2 Hz pulse repetition frequency. The Ho^{3+}:YAG output energy was less than 12 mJ at 140 mJ pump energy in free running oscillation.

In this paper we present our results on the development of a Ho^{3+}:YAG laser symmetrically pumped with two diode modules emitting at 1.91 µm.

2. DIODE MODULE AT 1.9 µm

The diode modules used in this article are manufactured by Laser Operation LLC. Each module consists of fiber coupled diodes emitting at 1.9 µm. The fiber has a core diameter of 600 µm and a numerical aperture of NA ≈ 0.22. The quality factor of the beam is then:

$$M^2 = \frac{\pi * \omega_0}{\lambda} * NA \approx 109$$

This number does not allow a traditional pumping scheme. Because in a longitudinal pumping scheme a large among of pump power would be lost, the efficiency would be very low. We will present our choice for the pumping scheme in the next section compensating for this effect of beam divergence and pump to mode overlap. The main characteristic of these diodes is that the wavelength is stabilized with an internal grating. This grating also contributes to narrow the linewidth to 3 nm in comparison to more than 20 nm of usual diodes emitting at 1.9 µm. The dependence of the wavelength as a function of the drive current can be seen on Figure 1. This dependence is linear with a slope of approximately 0.1 nm/A. The wavelength shift from threshold to maximum drive current is around 4 nm, which is relatively low for 2 µm diodes but it can still reduce the laser efficiency along the shift. The dependence of the wavelength as a function of the chiller temperature is also represented on Figure 1. It is approximately 0.1 nm/K.

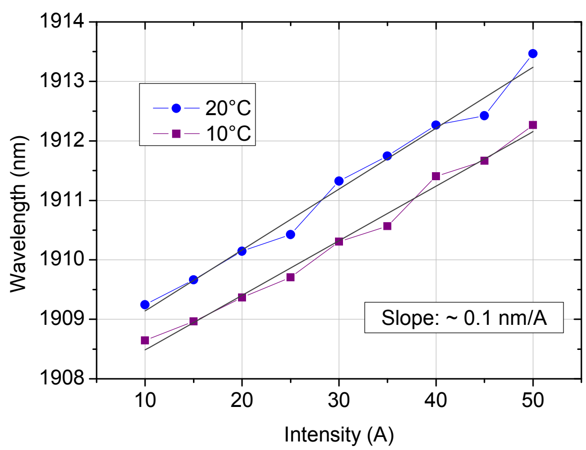

Figure 1 : Emission wavelength versus drive current for one diode module at two chiller temperatures.

The wavelength is not the only feature of the diode module that is dependent on the chiller temperature. As can been seen on Figure 2, the output power increases when the chiller temperature decreases. At maximum drive current the output power fluctuates from 26 W, when the chiller temperature is at 20 °C, to 28 W when the chiller temperature is fixed at 10 °C.

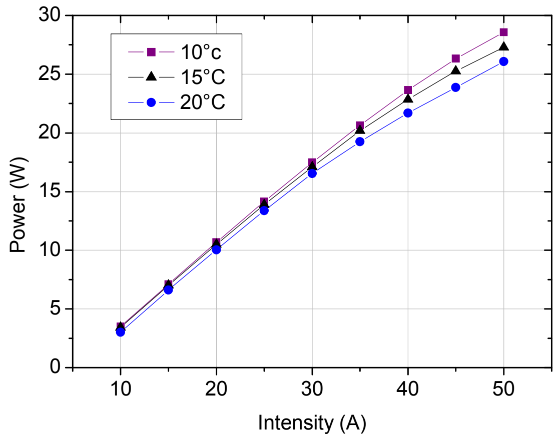

Figure 2 : Output power versus drive current for one diode module at three different chiller temperatures.

3. Ho^{3+}:YAG LASER

3.1 Experimental setup

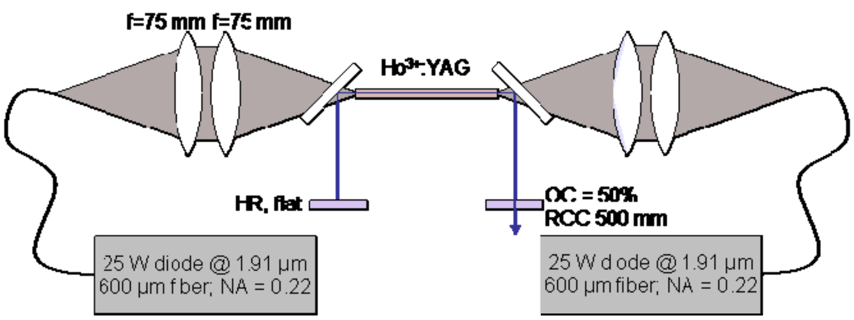

Figure 3 : Experimental setup. The fiber coupled diode module beams are imaged into the Ho:YAG crystal using a 1:1 telescope. The laser cavity is composed of a flat high reflective mirror (HR) and a curved (rcc 500 mm) output coupler (50 %).

Our experimental setup is depicted on Figure 3. The Ho^{3+}:YAG crystal is symmetrically pumped with the two diode modules. The fiber coupled module beam is focused into the Ho^{3+}:YAG crystal, through a dichroïc mirror, using a 1:1 telescope. The pump beam propagates in a Czochralski-grown 0.75at.% doped Ho^{3+}:YAG crystal. The crystal is 60 mm long with a diameter of 1.2 mm. We mentioned earlier in this document that a longitudinal pumping architecture was not an efficient solution due to larger M^2 quality factor of the pump beam. Thus we chose to use total internal reflection in the crystal to keep the pump beam confined inside the crystal volume. The rod is wrapped in indium foil and pressed into a water cooled copper heat sink for thermal management. The laser cavity is composed of a flat high reflectivity (HR) mirror, a 500 mm radius of curvature concave output coupler and two dielectric pump mirrors at an angle of incidence of 45°. These mirrors are highly reflective at the laser wavelength and high transmissive for the pump (T > 90%), and their back surfaces are antireflection (AR) coated for the 1.91 µm pump light. The cavity is approximately 130 mm long, which was the minimum value that was mechanically possible in our case. The laser beam waist is then approximately constant along the crystal and is calculated to be approximately 380 µm without a thermal lens. This waist is a tradeoff between mode overlap and avoiding diffraction on the crystal end faces [6].

The absorption of our 60 mm long Ho^{3+}:YAG crystal as function of the diodes wavelength is reported on Figure 4. The absorption is greater than 88 % for the entire wavelength range cover by this module. During our experiments the temperature of the chiller was set to 10°C in order to improve the total amount of pump power absorbed. One could state that the wavelength at 10°C is around 1912 nm and the wavelength at 20°C is around 1913 nm (see Figure 1). And taking into account that the crystal absorption is greater at 1913 nm than at 1912 nm (see Figure 4), the chiller temperature should be set at 20°C instead of 10°C. But the power emitted by the diode is larger at 10°C than at 20°C (see Figure 2) and this difference compensate the lower absorption.

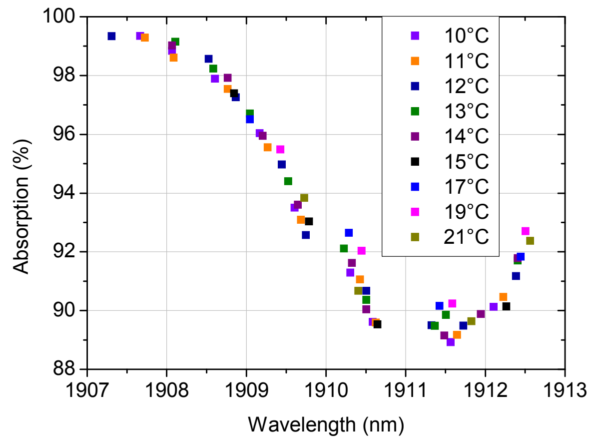

Figure 4 : Ho^{3+}:YAG crystal absorption versus wavelength for one diode module at different chiller temperatures.

3.2 Results

The output power of the Ho^{3+}:YAG laser was recorded for 7 different reflectivities of the output coupler (R = 50 %, 60 %, 70 %, 80 %, 90 %, 95 %, 99 %). The output power as function of incident power is reported on Figure 5. The laser threshold for an output coupler of R = 99 % was achieved for an incident power of 6.5 W. The maximum output power of approximately 12 W was reached with the four highest output couplers. The slope efficiency reaches 38 % with an output coupler of 50 %. This value is lower than expected which could be attributed to the fact that the emitting wavelength is around 1912 nm whereas the peak absorption wavelength of the Ho^{3+}:YAG crystal is centered at 1907 nm.

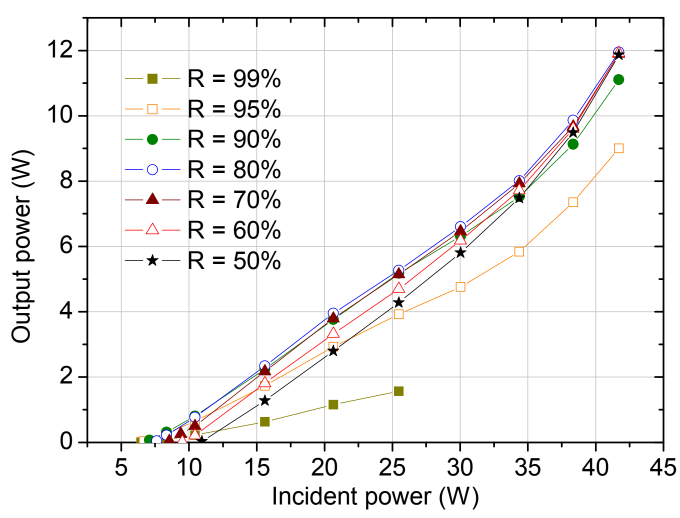

Figure 5 : Output power of the Ho^{3+}:YAG laser versus incident power for seven different output coupler reflectivities.

If we calculate the slope efficiency of the laser for the different output couplers, we can make a Caird analysis of this cavity [7]. This analysis will give information about the cavity losses and the intrinsic slope efficiency. The relationship between the slope efficiency (η_s), the intrinsic slope efficiency (η_0), the output coupler transmission (T_{OC}) and the losses in the cavity (Λ) is given by:

$$\eta_s^{-1} = \eta_0^{-1}\left(1 + \frac{\Lambda}{T_{oc}}\right)$$

The intrinsic slope efficiency of $\eta_0 = 43$ % and internal losses of $\Lambda = 4.2$ % were deduced (see Figure 6).

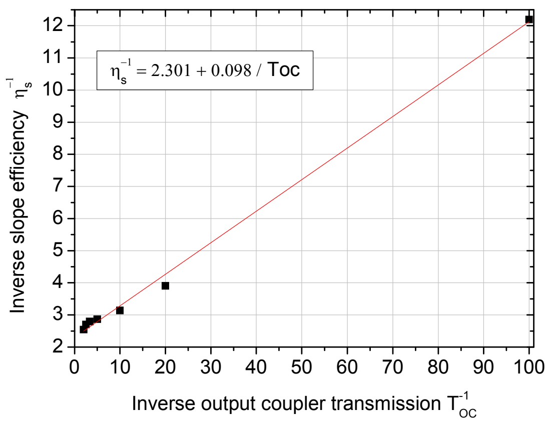

Figure 6 : The inverse slope efficiency versus the inverse output coupler transmission.

The emission wavelength of this laser depends on the output coupler transmission and on the pump power. For output coupler reflectivity higher than 70 % the laser wavelength was 2120 nm. For lower reflectivity the laser wavelength consisted of two lines one at 2090 nm and the other one at 2096 nm. The repartition of power between this two lines depended on the pump power. For low pump power the maximum output power was concentrated on the 2096 nm line. It is clear that the use of an etalon could favor one line over the other.

The laser beam was TEM_{00}, its quality factor was evaluated at full power. We measured an M^2 of approximately 1.2, which is excellent. However the beam was slightly elliptical probably due to non symmetrical heat extraction.

4. CONCLUSION AND OUTLOOK

In summary, the experimental results showed the efficient resonant diode pumping of a 2.1 µm Ho^{3+}:YAG laser in a crystalline fiberlike geometry. A maximum output power of 12 W in cw mode was observed when pumped with approximately 42 W of incident power. These first results show that these fiber coupled diodes together with this scheme are a promising 2 µm source. We plan to perform additional experiments in Q-switched mode, taking advantage of the high output power obtained with a low reflectivity output coupler.

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