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Taking advantage of the pump beam confinement and the excellent thermal management offered by Nd:YAG single crystal fibers, we demonstrated a maximum output power of 34 W at 946 nm for an incident pump power of 86 W. A high slope efficiency of 53 % was obtained. There was no rollover observed in the efficiency curves and the maximum output power was only limited by the available pump power.

Recent developments of laser sources using the $^4F_{3/2}$-$^4I_{9/2}$ transition of Nd:YAG to obtain emission at 946 nm, have been mostly driven by the demand of high power blue laser sources. Frequency doubled 946 nm lasers have numerous potential applications such as biological and medical diagnostics, trace gas detection, Raman spectroscopy. UV light generation which can be obtained by frequency quadrupling is also of great interest for many applications such as ozone remote sensing or writing of fiber Bragg grating.

Since the first demonstrations of a diode-pumped Nd:YAG quasi three level laser in 1987 [1,2], the development of high brightness diode-pumped sources has lead to the design of multiwatt continuous-wave lasers. The highest cw power ever achieved at 946 nm are in the range of the few ten's of watts : 15 W in a bulk end-pumped configuration [3], 25 W with a thin disk laser [4] and 105 W with a planar waveguide [5]. These output power values are far below what can be obtained with Nd:YAG for 1064 nm or 1338 nm four level transitions producing over hundred watts [6,7]. Indeed, the design of a high power 946 nm Nd:YAG laser is difficult for several reasons. It is a quasi three level transition and the emission cross section is about one order of magnitude lower than at 1064 nm. It implies working with high pump intensities in order to obtain efficient laser operation. It is therefore necessary to focus the pump beam on a small diameter. Using typical high power fiber coupled laser diodes (for example with core diameter of 400 µm and a numerical aperture of 0.22), the pump beam Rayleigh length is relatively short and the crystal length is then limited to a few millimeters. To ensure a good overlap between pump and laser beams and a large overall absorption, a high doping concentration has to be used, typically in the order of 1 %. This leads limitation of the performance at 946 nm in multiple ways. Firstly, non radiative effects as fluorescence quenching and energy transfer upconversion occcur at this doping level. These processes do not only limit the population inversion but also induce an extra heat load which contributes to the crystal temperature increase. Secondly, the high absorption coefficient leads to high local temperature increase, particularly on the pumped face of the crystal. The temperature gradients induce signal beam deformations and mechanical stress which can even lead to the crystal fracture. Moreover, crystal properties such as thermal conductivity and thermo-optic coefficient also evolve in a disadvantageous way with temperature inducing higher thermal lensing [8,9]. Finally, the population of the lower level increases with temperature and induces more reabsorption losses and shifts the oscillation threshold.

To keep both high pump intensity and low temperature increase different pump geometries have been used. Bonding of undoped caps to a laser crystal is one way to limit thermal effects caused by the deformation of the crystal faces. This technique was tested in a longitudinally-pumped, 1.1-at.% Nd:YAG composite crystal, but significant degradation of laser performance at 946 nm was observed for pump powers in excess of 30 W (M^2=13 at maximum pump power) [3]. The thin disk configuration represents a more efficient way to limit the temperature while allowing high pump intensity via multi-pass pumping. It has been used with the quasi three level transition in Nd:YAG but the low emission cross section requires to work with small pump beam diameters to have enough gain. It results in thermal effects which limit the power scaling [4,10]. Another way is optical guiding: pump confinement allows the use of Nd:YAG crystals with lower doping concentration and to reduce thermal effects. Pump guiding has been successfully used in a double clad 20 mm long planar waveguide with a 0.6% Nd^{3+} doping concentration [5]. Even if the output power was the highest with 105 W, the beam quality was very limited in the non-guided direction. For a 35 W output power, the M^2 beam quality factor was given to be respectively 2.8 and 56 in the guided and non-guided direction [11].

Nd:YAG single crystal fibers use the same concept of pump guiding but with lower doping concentration (0.2 %) and longer gain medium (50 mm) [12]. As opposed to the planar waveguide, the signal beam is in free propagation in the single crystal fiber, and its profile is defined by a cavity with two external mirrors for mode filtering. The concept of single crystal fiber has already been used successfully for a quasi-three level laser: the Yb:YAG with an output power of 50 W at 1030 nm [13]. Consequently, this laser crystal geometry seems to have a good potential for the development of high power quasi-three level Nd:YAG lasers at 946 nm.

In this paper, we report, for the first time to our knowledge, laser operation at 946 nm with a Nd:YAG single crystal fiber. By Finite Element Analysis (FEA), we firstly estimate the potential of this geometry compared to standard bulk crystals in terms of temperature. Then we present experimental results : temperature measurement by infrared imaging and performance of the Nd:YAG single crystal fiber at 946 nm.

Compared to a classical Nd:YAG crystal, single crystal fibers have two specificities : the low doping concentration (0.2 %) associated with a long length (50 mm) and the small section (1mm diameter). In order to understand the interest of this geometry, we carried out a comparison with a set of FEA temperature modelization for different Nd:YAG bulk crystals (1% or 0.2% doping rate with a square 3x3 mm section) and for a Nd:YAG single crystal fiber (0.2 % doping rate and 1 mm diameter). For the simulation, no attention was paid on the crystal lengths as we calculated the temperature of the pumped face assuming a radial heat flow. In order to simplify the calculations, we supposed also a perfect contact between the Nd:YAG and its mount, no saturation of absorption and a heat source coming only from the quantum defect between 808 nm and 946 nm (14.6%). The pump power was set at 86 W over a spot of 500 µm diameter: those conditions corresponded to the experimental setup described in the following. Figure 1 shows the temperature rise maps which were obtained as the results of the simulations. Lowering the doping concentration from 1% to 0.2% distributes the pumping heat load over a longer length and induces a significant decrease of the maximal temperature rises by over three times (from 194°C to 51°C). The small diameter of the single crystal fiber also induces a temperature reduction by over a factor of two (from 51°C to 19°C) by bringing the heat sink closer to the heat source.

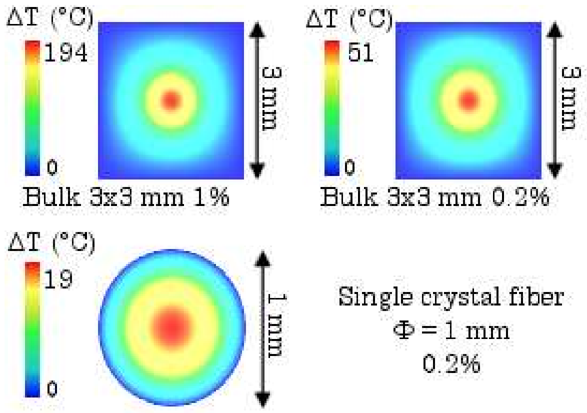

Fig. 1. Temperature rise maps calculated using finite elements analysis.

Consequently, the single crystal fiber geometry could be very useful to reduce the temperature increase and the associated gradient. However, the reduction of the transverse section led also to the reduction of the exchange surface with the mount. Consequently, the heat transfer coefficient between the mount and the single crystal fiber need to be as high as possible in order to take all the benefit of this geometry. This key point was experimentally investigated on a 0.2% Nd:YAG single crystal fiber with a diameter of 1 mm integrated in a water cooled TARANIS module provided by Fibercryst. The thermal contact between the module and the heat sink is ensured by a carbon foil. The water cooling temperature was 25°C during the experiment. The measurements were carried out on the pumped face with a thermal camera and a ZnSe beam splitter, in a setup similar to the one used by Chénais et al. [14]. Figure 2 shows the temperature increase map of the crystal for a pump power of 86 W. The temperature difference between the edge of the single crystal fiber and the crystal mount was found to be about 5°C. This very low difference shows the high quality of the thermal contact between the single crystal fiber and the cooling mount (copper block). It reveals also a maximal temperature increase of 31°C. This value was higher than the one calculated by FEA analysis. It is due to the higher quantum defect between the pump photons and fluorescence photons which is centered around 1134 nm whereas the laser emits at 946 nm. However, the temperature raise was kept reasonably small even at this high pumping power of 86 W predicting good performance for 946 nm laser operation.

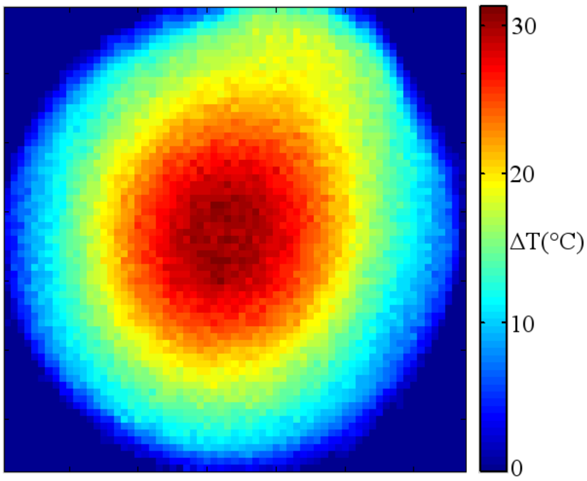

Fig. 2. Temperature increase map of the input face of a 0.2% doped Nd:YAG single crystal fiber under 86 W diode pumping over 500 µm at 808 nm.

As shown on figure 3, a simple linear cavity made of two concave mirrors was used for the experiment. The dichroïc meniscus M_1 had a radius of curvature of 100 mm, was highly reflective at 946 nm and had a low reflectivity at both 808 nm and 1064 nm in order to prevent parasitic oscillation. For the output coupler, we used concave mirrors with a radius of curvature of 100 mm, a high transmission at 1064 nm (T>80%) and transmission of 2%, 5%, 10% and 15% at 946 nm. The facets of the single crystal fiber were anti-reflection coated for a broadband spectral range between 600 nm and 1100 nm. The Nd:YAG crystal was 0.2% doped, 50 mm long and had a diameter of 1 mm. The water cooling temperature was set at 14°C during the experiment. The pump beam was delivered by a laser diode module coupled in a 400 µm core diameter fiber with a numerical aperture of 0.22. The output of the fiber was imaged inside the single crystal fiber using two doublets of focal length 60 mm and 80 mm. The maximum nominal output power of the diode was 110 W and the maximum incident pump power on the crystal was 86 W. The lasing wavelength was monitored with an optical spectrum analyzer and only laser emission at 946 nm has been observed. The output power versus the incident pump power is shown on figure 4 for the different transmissions of the output coupler.

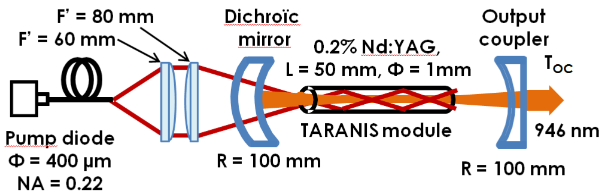

Fig. 3. Experimental setup.

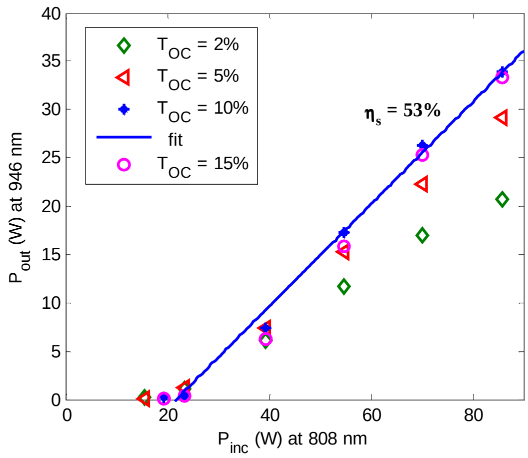

Fig. 4. Laser output power versus incident pump power for different output couplers.

The threshold was found for an incident pump power between 15 W and 20 W. The maximal slope efficiency was obtained for an output coupler with a 10% transmission and reached 53%. The maximum output power was 34 W for an incident pump power of 86 W which gives an optical conversion efficiency of 39.5%. At this power level, the M^2 beam quality factor was below 5 in both directions. In addition, no rollover was observed in the efficiency curves showing the limited impact of the temperature rise and thermal lensing provided by the 1 mm diameter single crystal fiber together a very efficient thermal management.

In conclusion, we have demonstrated that high power Nd:YAG 946 nm laser design is possible using single crystal fiber configuration. It offers good thermal management and provides pump energy confinement. A total output power of 34 W was obtained with high slope efficiency of 53% and with a relatively good beam quality. To the best of our knowledge, it is the highest output power ever reported for an end-pumped Nd:YAG laser emitting at 946 nm with a signal beam in free propagation in the laser cavity. It is also the highest brightness for a 946 nm laser source at this level of power.

Further power scaling can be considered since no roll over has been observed in the efficiency curves. The total output power was only limited by the available pump power. In particular, the full potential of the single crystal fibers could be used in a dual end pump configuration.

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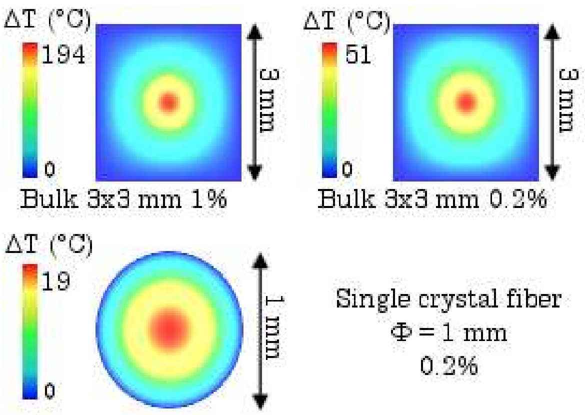
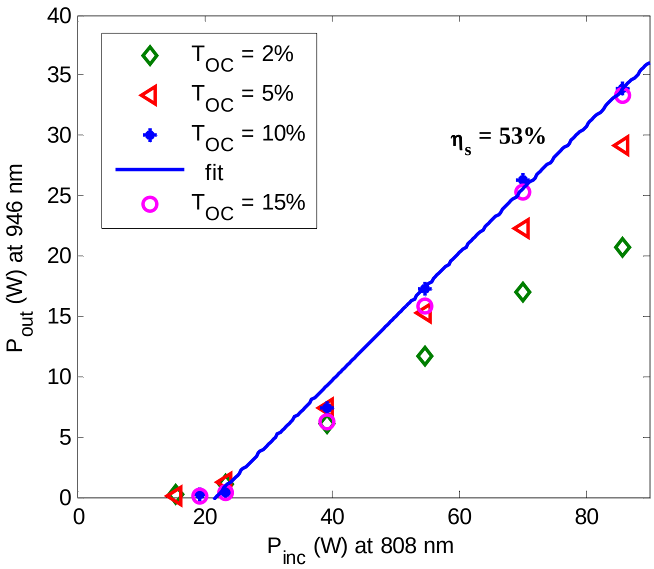
Fig. 1. Temperature map calculated using finite elements analysis.

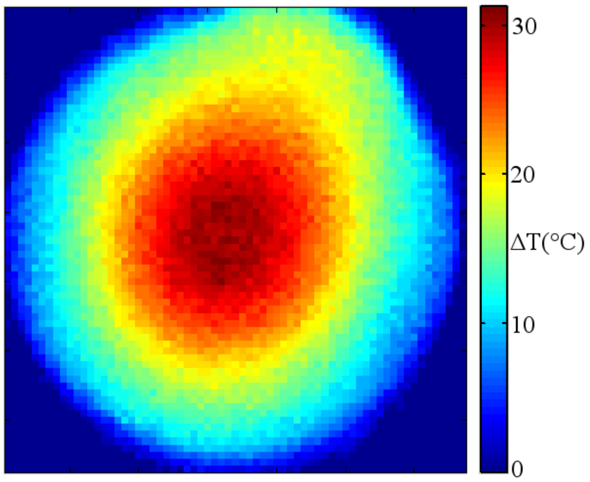
Fig. 2. Temperature increase map of the input face of a 0.2% doped Nd:YAG single crystal fiber under 86 W diode pumping over 500 µm at 808 nm.

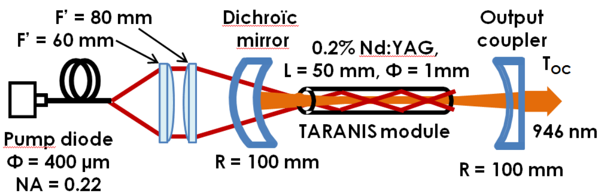
Fig. 3. Experimental setup.

Fig. 4. Laser output power versus incident pump power for different output couplers.


ΔT (°C)
194
0
3 mm
Bulk 3x3 mm 1%
ΔT (°C)
51
0
3 mm
Bulk 3x3 mm 0.2%
ΔT (°C)
19
0
1 mm
Single crystal fiber
Φ = 1 mm
0.2%


T_{OC} = 2%
T_{OC} = 5%
T_{OC} = 10%
fit
T_{OC} = 15%
η_s = 53%
P_{out} (W) at 946 nm
P_{inc} (W) at 808 nm
0
5
10
15
20
25
30
35
40
0
20
40
60
80


30
20
ΔT(°C)
10
0


F' = 80 mm
F' = 60 mm
Dichroïc mirror
0.2% Nd:YAG,
L = 50 mm, Φ = 1mm
Output coupler
T_{OC}
TARANIS module
946 nm
Pump diode
Φ = 400 µm
NA = 0.22
R = 100 mm
R = 100 mm