

High-efficiency, high-power and low threshold Yb³⁺:YAG ceramic laser

Angela Pirri, Daniele Alderighi, Guido Toci and Matteo Vannini*

Istituto di Fisica Applicata "Carrara", IFAC-CNR
Via Madonna del Piano 10C, 50019 Sesto Fiorentino (FI)-Italy

* M.Vannini@ifac.cnr.it

Abstract: We present a high-power, high-efficiency and low threshold laser prototype based on doped ceramic Yb³⁺:YAG. We achieved an output power of 9 W with a slope efficiency of 73% and a threshold of 1 W at 1030 nm in quasi-Continuous Wave (QCW). Moreover, we obtained an output power 7.7 W with a slope efficiency of 60% in Continuous Wave (CW). Finally, a characterization of a low losses tunable cavity for several laser wavelengths with an output power exceeding 5 W is reported.

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1. Introduction

Ytterbium-doped materials has been considered a promising and attractive way to build up efficient and high-power diode-pumped solid-state lasers (DPSSLs) with short duration pulses. This is mainly related to the peculiar physical properties of ytterbium ion as a broad emission band and wide range of tunability, a long lifetime emission, a simple energy level scheme (just two manifolds), a low quantum defect, as well as to the availability of suitable crystalline and ceramic hosts with good thermo-mechanical properties. The main drawback is the thermal population present on the higher level of the lower manifold causing an increase of the laser threshold. This problem can be overcome by the use of high intensity pump lasers, or by controlling the thermal population of the lower laser level by means of cryogenic cooling. Although excellent experimental results have been obtained by using doped crystals [1–7], recently many efforts have been focused on transparent polycrystalline ceramics. In principle, if compared with single crystals, ceramics permit a more uniform distribution and a higher dopant concentrations, while optical properties are preserved. Moreover, they are easier to fabricate and less expensive due to the lower processing temperature and to the shorter processing time. Finally, ceramics exhibit better mechanical properties than their crystalline counterparts. In particular, in the case of YAG-based gain materials the fracture toughness of undoped ceramic samples was found to be about five times higher than YAG monocrystals, see [8]. As a consequence, YAG ceramics can withstand higher thermo-mechanical stresses with respect to YAG crystals, making them more suitable for high intensity laser pumping.

Since 2003 when the first laser oscillations was demonstrated [9], several relevant experimental results have been obtained with ytterbium doped ceramics such as Y_2O_3 [10,11], Lu_2O_3 [12] or YAG. To focus on YAG ceramic, with a transversely pumped, composite microchip laser, Tsunekane *et al.* [13] have been achieved a power level of 520 W in QCW operation and 414 W in CW operation, at fixed wavelength. Concerning the longitudinally pumped, Nakamura *et al.* [14] have been obtained an output power of 6.8 W with a slope efficiency of 72%. Until now, the largest tuning range reported in literature spans from 990 to 1110 nm, with a maximum output power of 163 mW at 1033.42 nm [15]. With regard to the generation of short pulses, 237 ps of pulse duration was achieved from Yb:YAG/Cr:YAG microchip ceramic laser [16] while the shortest pulse, that is 286 fs at 1033.5 nm [17], was reached so far with a mode-locked oscillator.

This paper is devoted to explore the overall potentiality of a laser prototype based on a 9.8% doped ceramic Yb^{3+} :YAG pumping in QCW and in CW operation mode at room temperature. Moreover an in-depth characterization of a low losses tunable cavity was carried out. The effects on the laser performance due to the thermally-induced load by the laser pump are studied by setting different Duty Factors (DF). We performed systematic measurements of the ceramic absorption dependence on the pump intensity, whose knowledge allows for an unambiguous definition of the slope efficiency. Finally, we have explored the tunability range of the gain medium.

2. Experimental set-up

Figure 1 shows the experimental setup. The laser cavity is V-shaped with a folding half angle of 10° and with an arm length of 78 mm between the high reflectivity end-mirror (EM) and the folding mirror (FM), while the distance between the mirror FM and the output coupler (OC) is 540 mm, setting the cavity within the stability limit. The FM curvature radius is 150 mm while several flat OC, with a transmission ranging from 1.5% to 20%, are used. To remove the heat due to pump beam, the 2-mm uncoated ceramic sample (9.8% at.) is brazed with Indium on a copper heat sink, which is cooled by a Peltier device at 18°C . The gain material is longitudinally pumped by a fiber coupled laser diode emitting at 940 nm.

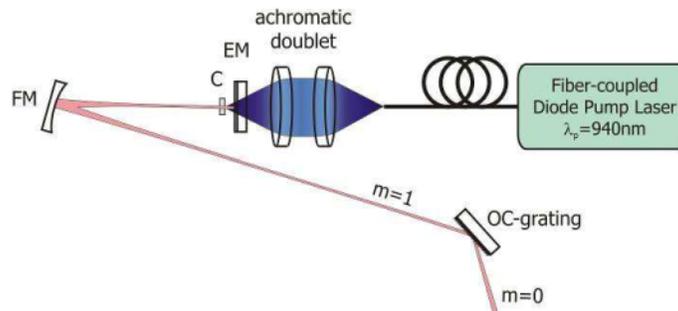


Fig. 1. Schematic view of the experimental set-up. EM: end mirror (flat); FM: folding mirror (ROC=150 mm); OC: output coupling grating at the Littrow angle; C denotes the crystal. The untunable cavity is obtained by substituting the grating with a flat output coupler mirror.

The fiber has 200 μm core diameter and a numerical aperture of 0.22. The focused pump beam inside the sample has an almost Gaussian intensity distribution with 150 μm of radius at $1/e^2$. The laser was tuned by replacing the output coupler by a gold coated ruled grating (1800 grooves/mm) used at the Littrow's angle. The zeroth-order ($m=0$) was used for the output coupling, while the first order ($m=1$) provided the feedback to the cavity. The wavelength selection action was provided by the superimposition of the diffracted beam with the pumped area in the sample, without any further limiting aperture into the cavity.

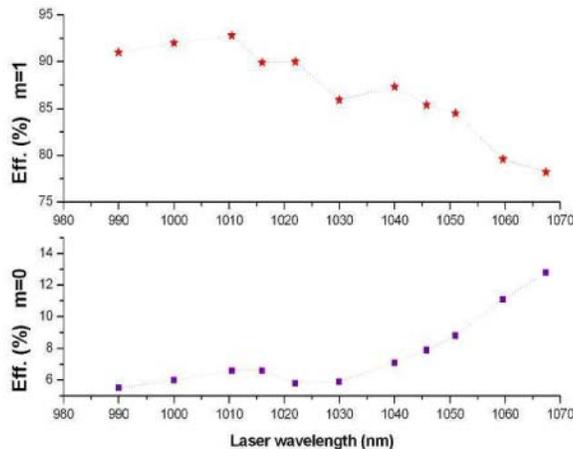


Fig. 2. Grating efficiency curve for the TM polarization. At 1030 nm the diffraction efficiency is 85.8% ($m=1$) and 5.9% ($m=0$) while at 1050 nm the efficiency is 84.5% ($m=1$) and 8.8% ($m=0$).

Figure 2 reports the measured grating efficiency for the TM polarization at the zeroth and the first-order. The measured losses due to the absorption and scattering are around 5%. The incidence angle ranges from 63.0° at 990 nm to 74.4° at 1070 nm. The emission wavelength was measured with a fiber coupled, 60 cm focal length spectrometer equipped with a multichannel detector (spectral resolution of 0.4 nm).

3. Experimental results

We have measured the output power as a function of the absorbed pump power (P_{abs}) in quasi-Continuous Wave and in Continuous Wave for three output couplers with a transmission spanning from $T=1.5\%$ to $T=20\%$, see Fig. 3(a)-(b).

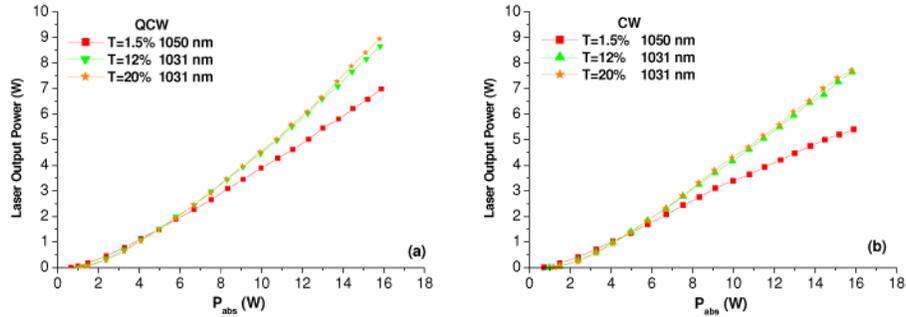


Fig. 3. Slope efficiency obtained in QCW (a) and CW (b), with different output coupler mirrors.

The maximum output peak powers of 9 W at 1030 nm, with respect a $P_{\text{abs}}=15.8$ W, has been reached in QCW (DF=20%) employing an output coupler with T=20%. The slope efficiency is 73% while the optical-to-optical efficiency is 57%; the threshold is as low as 1 W. To the our best knowledge this is the best result reported in literature in terms of slope efficiency and output power obtained with an end pumped, bulk Yb:YAG ceramic laser. A high-efficiency 1030 nm laser emission was also reached in CW with the previous output coupler, *i.e.* 7.7 W with a slope efficiency of 60% and an optical-to-optical efficiency of 49%.

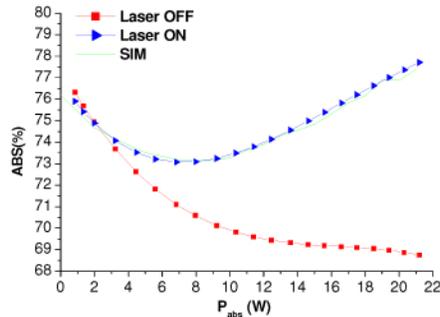


Fig. 4. Fraction of absorbed pump power from the ceramic. The output coupler is T=1.5%.

The shift of the laser wavelength, *i.e.* from 1030 nm to 1050 nm, observed when a mirror with a lower transmittance is used, independently on the pumping operation mode, is due to the Ytterbium quasi three-level system behavior. For increasing losses, the increased inversion population fraction needed to reach the lasing threshold determines a shift toward shorter wavelengths in the peak of the effective gain spectrum [18].

The slope efficiency here reported, were estimated by taking into account the absorption from the gain material under lasing condition. This was carried out by measuring the residual pump power when the laser was active or switched off. For this purpose, the cavity was rearranged by adding a flat auxiliary mirror between the FM and OC, with high reflectivity over the whole laser emission band and with high transmission around 940 nm. The residual pump emission transmitted by the auxiliary mirror was collected by a power-meter placed behind it. Figure 4 reports the fraction of the absorbed pump power (ABS) as a function of the pump power (P_p) by using the output coupler with a transmission of 1.5%. Measurements performed by employing other OC show similar trends. According to the theory [19], in non-lasing conditions the absorption of the ceramic decreases from 76% to 64% when the pump power increases from 1.4 W to 21 W, due to the saturation of the absorption at the pump wavelength. A less pronounced decrease of the absorption (about 3% with respect to the low pump power level) is expected across the same pump power interval when the laser is active, because of fast recycling of the population from the upper laser level to the lower level due to the stimulated emission. In the measurements shown here, a further increase of the absorption

(up to a level slightly higher than the unsaturated absorption) at the highest pump power levels, is due to a small shift in the emission wavelength of the pump laser (*i.e.* 4 nm in the used pump power range). Solid curve represents the theoretical result which takes into account all experimental conditions, including the pump wavelength shift.

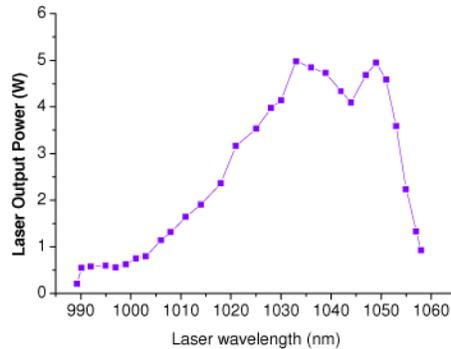


Fig. 5. Tuning curve obtained by means of a Littrow-grating-mount as output coupler.

The sample heating determined by the absorption of the pump power can significantly influence the laser performance in terms of a decrease of the output power and deterioration of the beam quality; this results from an interplay of several thermo-mechanical effects, such as a thermal lens effect into the sample, the absorption at the laser wavelength and a decrease of the thermal conductivity of the ceramic. We probed these effects by measuring the behavior of the laser output power in CW and in QCW pump condition with DF of 20%. We have found that the laser behavior, both in terms of the output power and laser threshold, is almost unaffected as it can be seen by comparing the graphs reported in Fig. 3 (a) and 3 (b). The measured threshold was 1 W.

The usefulness of a laser system in different physical applications, from spectroscopy to pollution monitoring, is strictly connected to the possibility to buildup a high-efficient and high-power tunable cavity. As described above, the tunable cavity was built up by substituting the flat output coupler by a gold coated ruled grating (1800 grooves/mm) placed at the Littrow angle (see Fig. 2). We obtained a tuning range as wide as 67 nm, see Fig. 5, with a peak output power slightly exceeding 5 W. The laser line width is about 1.4 nm across the whole tuning range. The output beam was found linearly polarized along the grating TM polarization direction.

We have further characterized the laser performance with the grating tuned cavity by measuring the output power at several wavelengths as a function of the absorbed pump power in CW and QCW (DF 20%). Figure 6(a)-(b) report the results obtained at four selected wavelengths, 1016 nm, 1030 nm, 1050 nm and 1055 nm.

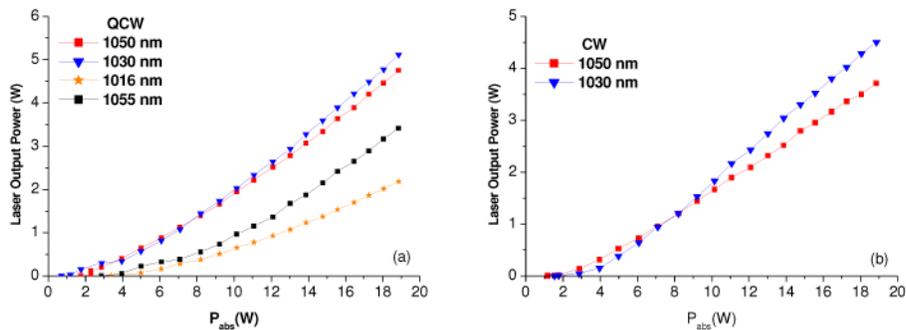


Fig. 6. Laser peak power as a function of the absorbed pump power with a Littrow-grating-mount as output coupler in QCW (a) and in CW (b) operation mode.

The maximum output power of 4.7 and 5.1 W was found in the correspondence of the two main emission peaks, *i.e.* 1030 nm and 1050 nm, in QCW. The slope efficiency is 33% and 36% respectively. A high-efficiency laser emission is also obtained in CW where output power values of 4.5 W and 3.7 W were found. Finally, output power values of 2.1 W and 3.4 W with a slope efficiency of 16% and 25% were measured at 1016 nm and 1055 nm.

4. Conclusion

We present our recent achievements in the development of a laser prototype based on a 9.8% doped ceramic Yb^{3+} :YAG pumped in QCW and CW operation mode at room temperature. The output power was investigated by using three output couplers with a transmission of $T_{oc}=1.5\%$, 12%, 20%. The maximum output power of 9 W with a slope efficiency of 73% at 1030 nm has been achieved in QCW while 7.7 W with a slope efficiency of 60% has been obtained in CW. The ceramic absorption dependence on the pump intensity, which knowledge allows for an unambiguous definition of the slope efficiency, was measured under lasing condition. Moreover, we have investigated the influence of the thermally-induced population and the thermal lens effect on the laser performance, by setting different duty factor. In CW or QCW pumping regimes, the slope efficiency results almost independent from the thermal load, while the threshold is completely independent from it. Finally, we report a systematic characterization of a low losses tunable cavity at four different laser emission, *i.e.* 1016 nm, 1030 nm, 1050 nm, 1055 nm, and the overall tunability range of the gain medium. Further improvements in laser performances can be expected by using an antireflection coated ceramic.

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