

# A comparison of the laser performance of $\text{Yb}^{3+}$ :LuAG crystals with different doping levels

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**Abstract:** We present a study and a comparison of the laser performance achieved by using 10at.%, 15at.% at. and 20at.%  $\text{Yb}^{3+}$ :LuAG crystals longitudinally pumped at 936 nm in quasi-continuous wave.

## 1. Introduction

$\text{Yb}$ :LuAG [1-4] is one of the most attractive gain materials due to several reasons. First, it has similar optical properties of YAG as well as a well-defined absorbed peak around 940 nm, which allows it to be used in a laser system without specific adaptations of commercially available pump diodes. Second, it has a high thermal conductivity [5-6] which is independent on the concentration of dopant. In fact, the similar atomic masses of  $\text{Yb}^{3+}$  and  $\text{Lu}^{3+}$  (173 and 175 g/mol [7], respectively) reduces the scattering at the mass defect of the phonons responsible of the heat transportation. Finally, this material has a broad and high emission cross section spectrum making it appealing for the generation of short pulses [8-9].

In this paper we reported a comparative investigation of the laser performances achieved by using three crystals with 10at.%, 15at.% and 20at.% concentration of  $\text{Yb}^{3+}$ . Longitudinally pumped in *quasi*-Continuous Wave at 936 nm, the crystals have shown different behavior in terms of laser output power and efficiency. Excellent performances are achieved by the 10at.%. Emitting at 1046 nm it delivers  $P_{\text{out}}=11.8$  W with a slope efficiency of  $\mu_s=82\%$ . In the case of 15at.% doping, two different regimes are observed. At high ion excitation density, we measured a dramatic decrease of the output power due to the appearance of a non-linear and non-radiative loss mechanism [10-13]. Conversely, at low excitation density, the crystal releases the maximum output power at 1030 nm, *i.e.*  $P_{\text{out}}=9.7$  W with a corresponding slope efficiency as high as  $\mu_s=59\%$ . Low laser performance are achieved with the 20at.%. Also for this sample two different regimes are observed, which, however, depend on the

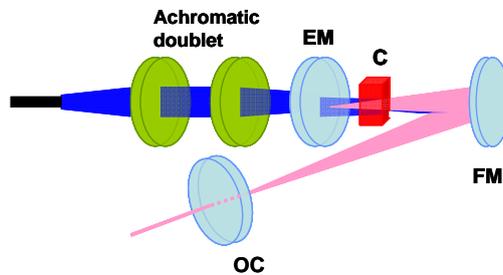
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pumping level and not on the excitation density as the decrease of the delivered power occur with all OC mirrors. The maximum output power of  $P_{\text{out}}=5.3$  W is reached by  $T=9\%$ . The cause of the reduced performance is addressed to thermal lensing effects [10].

## 2. Experimental set up

The experimental setup used to test the laser performance of the crystals is depicted in Fig. 1. The resonator is constituted by three mirrors placed in a V-shaped configuration. EM is a flat mirror with a dichroic coating with high transmission around the pump wavelength and high reflectivity in the laser emission band. The folding mirror, FM, has a curvature radius of 100 mm with high transmission at the pump wavelengths. The OC is the output coupler mirror. The uncoated 10at.%, 15at.% and 20at.% Yb:LuAG crystals have a thickness of 2 mm, 1 mm and 2 mm, respectively, while both face are flat and perpendicular of  $5 \times 5$  mm<sup>2</sup>. They are soldered with indium on a copper heat sink which in turn is water cooled at 18 °C; the crystals are placed as near as possible to the flat EM. A very carefully orientation of the facets perpendicular to the cavity axis allowed the re-injection of the Fresnel reflection, which are estimated around 8.5%.



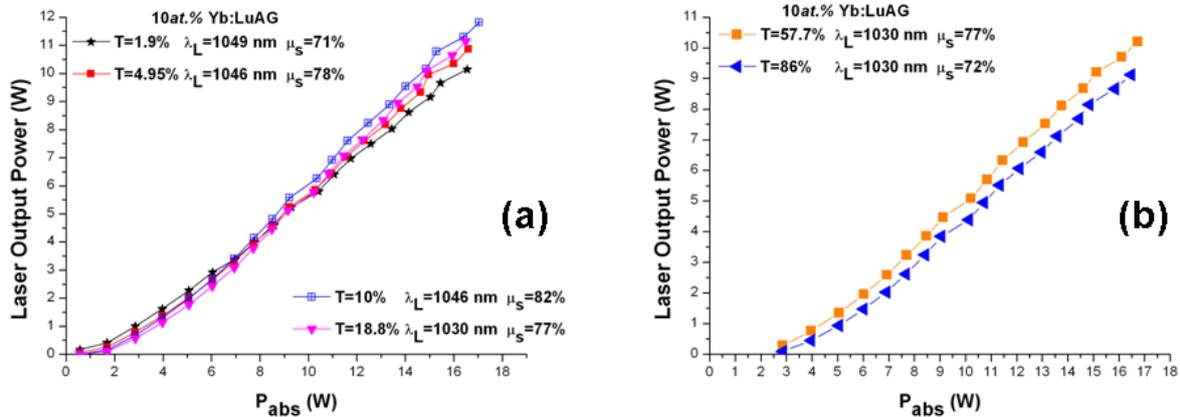
**Figure 1.** Experimental set up to test the laser performance of the samples. EM: End Mirror (flat); FM: Folding Mirror; OC: Output Coupler (flat).

For the pumping of these samples, a fibre-coupled laser diode is used. The emission from the fibre is refocused and injected into the sample by a pair of achromatic doublets with a magnification of 1:1. The pump emits at 936 nm (fiber core diameter  $\Phi=200$   $\mu\text{m}$ , numerical aperture N.A.=0.22, maximum output power  $P_p=25$  W) and it has an almost Gaussian intensity distribution in the focal plane of the doublets with 150  $\mu\text{m}$  of radius at  $1/e^2$ . In the experiment Duty Factor, DF, of 20% and 40% are employed.

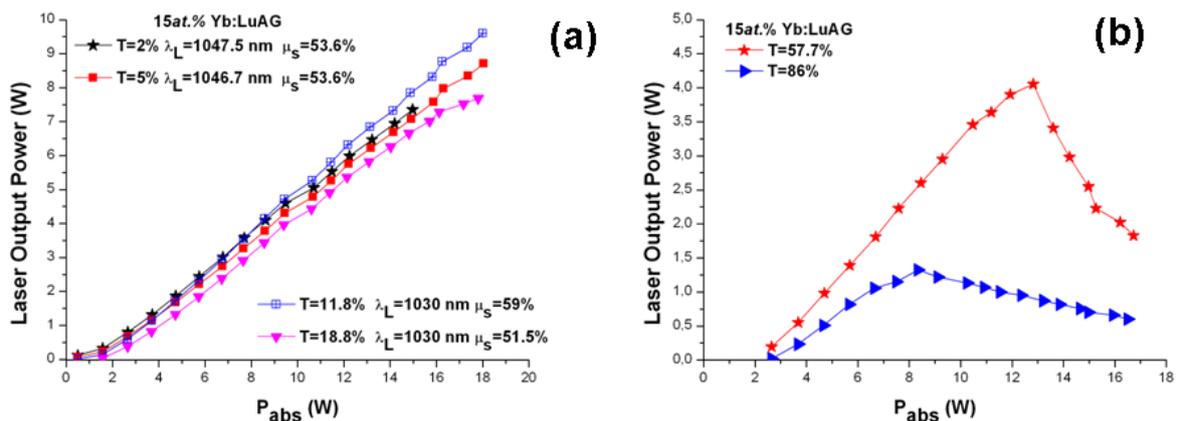
## 3. Experimental results and comments

Excellent performances, *i.e.* output power and slope efficiency, are achieved by the 10at.% Figure 2 (a)-(b) reports the experimental results obtained with several OCs (from  $T=1.9\%$  to  $T=86\%$ ). The maximum powers,  $P_{\text{out}}=11.8$  W, is delivered at 1046 nm with a corresponding slope efficiency of  $\mu_s=82\%$ . The lowest laser threshold is  $P_{\text{th}}=0.5$  W. The shift of the emitted wavelength from 1049 nm with  $T\sim 2\%$  to 1030 nm measured with the other OC is ascribed to the behavior of the  $\text{Yb}^{3+}$ , which is a quasi three-level system. As a matter of fact, for increasing losses the increasing inversion population fraction needed to reach the lasing threshold determines a shift toward shorter wavelengths in the peak of the effective gain spectrum.

From the comparison of the performance obtained with 15at.% doping, see Fig. 3 (a)-(b) it is immediately evident that the sample has two different behavior depending on the ion excitation density involved in the laser action.



**Figure 2.** 10at.% LuAG laser output power as a function of the absorbed pump power. T: output coupler transmission;  $\lambda_L$ : laser wavelength;  $\mu_S$ : slope efficiency. The crystals are pumped at 936 nm in quasi-CW (DF=20%, 10 Hz).



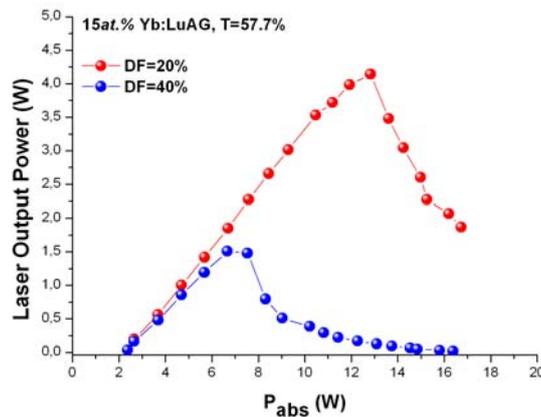
**Figure 3.** 15at.% LuAG laser output power versus the absorbed pump power. T: output coupler transmission;  $\lambda_L$ : laser wavelength;  $\mu_S$ : slope efficiency. The crystals are pumped at 936 nm in quasi-CW (DF=20%, 10 Hz).

Good performances are achieved by the 15at.% sample with low ion excitation densities, *i.e.* with OC transmission ranging from 2% to 18.8%. At 1030 nm it releases a maximum output power of  $P_{out}=9.7$  W with a corresponding slope efficiency of  $\mu_S=59\%$ . The threshold is  $P_{th}=0.57$  W which is quite similar to the one obtained with the 10at.% in the same experimental conditions. Contrary, see Fig. 3 (b), when higher Yb-ion excitation densities in the laser action are involved (*i.e.* with T=86% and T=57.7%), the performance is dramatically reduced. The observed shift of the onset of the roll-over in the curves toward lower value of the absorbed pump power (from  $P_{abs}\sim 13$  W with T=57.7% to  $P_{abs}\sim 8$  W by T=86%) demonstrates that it starts at a well-defined threshold of the excitation levels and its rate is enhanced by increasing the ions excitation density. According to our calculation based on the equation rates, we estimated a threshold of the density of  $4.5 \times 10^{20}$  exc. ion/cm<sup>3</sup>.

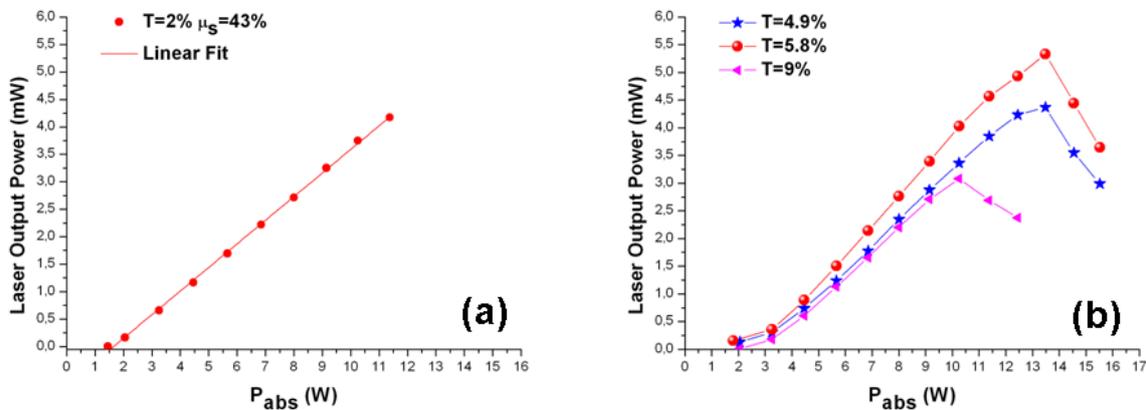
The role played by the temperature on this effect is studied by increasing the DF from 20% to 40% and closing the cavity with T=57.7%, see Fig. 4. Also in this case, two different regimes can be easily observed. At lower absorption levels, *i.e.*  $P_{abs}\sim 13$  W by T=57.7% and  $P_{abs}\sim 7.5$  W by T=86%, the increase of the temperature inside of the crystal does not affect the laser performance as the output power linearly increases with the pump power. The scenario totally changes as the  $P_{abs}$  exceeds the

mentioned threshold with a dramatic decrease of the  $P_{out}$ . We point out that, at the maximum level of the absorption used in the experiment ( $P_{abs} \sim 16$  W), the laser cavity still emits 2 W when the crystal is pumped with DF=20%, whereas the laser action is practically hampered with DF=40%.

The experimental data are explained by the appearance of non-radiative channels which take place when higher ion excitation densities are involved in the laser action. The origin of these channels is still under investigation [10].



**Figure 4.:** Laser output power versus absorbed pump power at higher ion excitation density with two Duty Factor (20% and 40%).



**Figure 5.:** 20at.% laser output power versus absorbed pump power. T: output coupler transmission;  $\lambda_L$ : laser wavelength;  $\mu_s$ : slope efficiency. The crystals are pumped at 936 nm in quasi-CW (DF=20%, 10 Hz).

Low laser performance are achieved with the 20at.% doping as reported in Fig 5. Also for this sample two different behaviors are observed, which, however, depend on the pumping level and not on the excitation density as the decrease of the delivered powers occur with all OC mirrors. The maximum output power of  $P_{out}=5.3$  W is reached by  $T=5.8\%$ . The cause of the reduced performance is addressed to thermal lensing effects as reported in [10]. In other words, the thermal lens was so strong to drive the resonator out of the stability region, thus preventing the laser action.

#### 4. Conclusions

In this paper we reported the laser performance achieved with a longitudinally diode-pumped laser based on 10at.%, 15at.% at. and 20at.% Yb<sup>3+</sup>:LuAG crystals. In particular, we measured with the 10at.% doping an output power of 11.8 W with a slope efficiency as high as  $\mu_s=82\%$  at 1046 nm, which confirms the full potential of the Yb:LuAG to be employed in the development of diode-pumped solid state laser sources, at least for reasonable doping levels. A heavy doping of the matrix can trigger loss mechanisms which degrade the laser performance.

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