Diode-pumped Tm:YAP laser performance evaluation

Diode-pumped solid-state lasers based on Tm-doped crystals have gained significant interest in the last several years. One of the most interesting crystals is Tm:$YAlO_3$ [1], which embraces several attractive features that propose it as a material of choice for development of a solid-state laser source with emission wavelength in 1.9 µm – 2 µm region. Firstly, the absorption band between $^3H_6$ and $^3H_4$ levels with a peak at 795 nm is rather easily accessible with high power AlGaAs lasers diodes, on the contrary to Tm:YAG which requires 785 nm pump. Also the 4-nm wide absorption peak of Tm:$YAlO_3$ (or Tm:YAP) is broader compared to Tm:YAG resulting in better tolerance to pump diode wavelength variations. Secondly, there is a self-quenching mechanism between $^3H_4$ and $^3F_4$ levels that produces two excitation photons in the upper laser level for one absorbed pump photon. This makes the laser potentially very efficient with quantum efficiency exceeding 100%. Most of these features are common to Tm:YLF and Tm:YAP materials. The disadvantages of using Tm:YLF include upconversion and low fracture limit, which can make development of high-power 1.9 µm laser using this material difficult.

To evaluate the laser performance of commercially available Tm:YAP laser crystals, a diode-pumped Tm:YAP laser was constructed. Fibre-coupled laser diode (Maximal output 25 W, fibre diameter 600 µm, N.A. 0.16) was used in an end-pumping scheme. The fibre tip was imaged into the laser crystal using two plano-convex lenses. The Tm:YAP crystals, which were used in this study, are listed in Table 1. All the crystals had antireflection coatings at both flat-polished parallel facets at 795 nm and 1940 nm.

Table 1. List of Tm:YAP crystal samples used for evaluation

Sample No.	Producer	Dimensions	Doping	Orientation
1	Crytur Ltd.	Ø3 mm, l=3 mm	4% at.	“a” in Pbnm
2		Ø3 mm, l=5 mm	4% at.	“a” in Pbnm

The laser crystals were clamped in a water-cooled brass block, which was kept at 10 °C. To ensure efficient heat removal, the crystals were wrapped in an Indium foil.

Absorption properties of the crystals were firstly studied. The laser diode case was kept at a constant temperature and the central wavelength of the diode radiation was monitored as a function of output power. The pump spot radius was around 300 µm in this measurement. The measured absorption as a function of pump wavelength and pump power for Samples 1 and 2 are plotted in Figure 1. The peak effective pump absorption coefficient can be calculated to be α_b=3.51 cm^{-1} for Sample 1 and α_a= 3.63 cm^{-1} for Sample 2. One should note that at higher pump

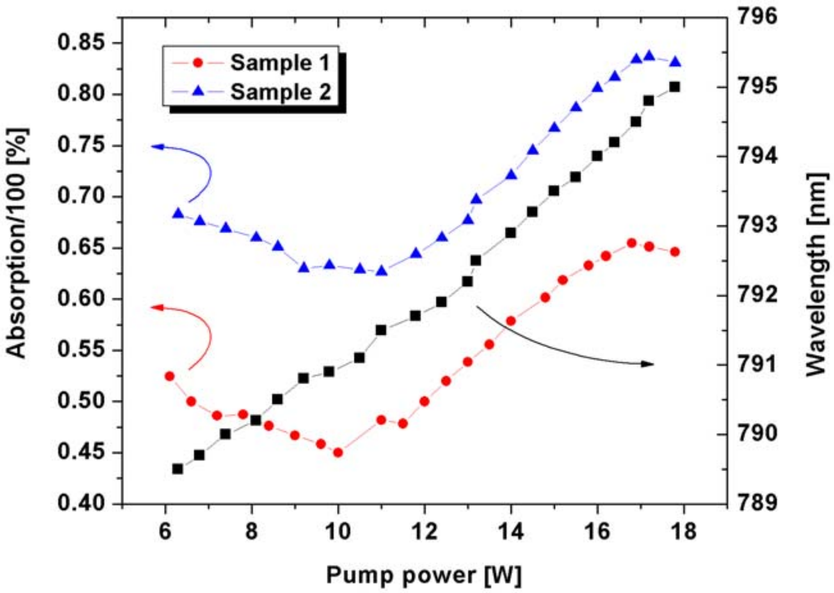


Figure 1. Absorption properties of Tm:YAP crystal Samples 1 and 2. The diode central wavelength is shown as a function of pump power for the laser diode case at 10 ^{o}C

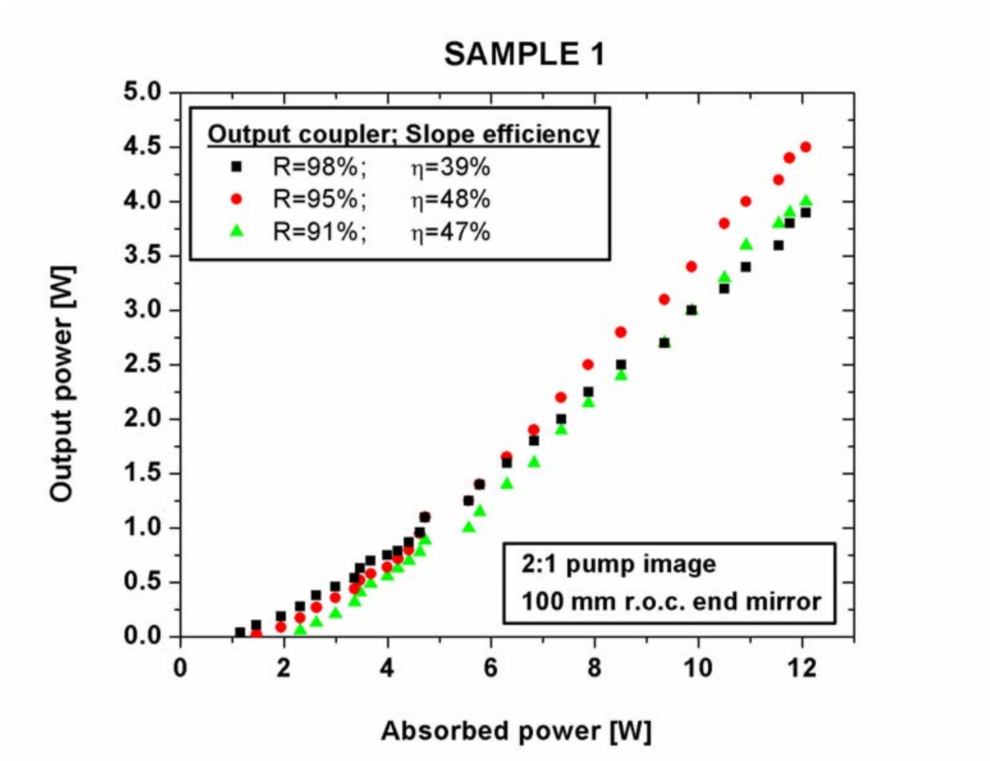
levels, the effect of pump saturation is present. The real absorption when the laser levels are depopulated during laser action can be somewhat higher than the values shown in the Figure 1. This effect was evaluated later in this study.

Next, a laser cavity was constructed in a simple two-mirror configuration consisting of a curved pump-through mirror, which was highly reflective for laser radiation and an output coupler.

For each crystal sample, an optimum pump configuration was found using different combinations of plano-convex lenses, which were used for imaging the fibre tip into the laser crystal. This way, the pump spot size and the confocal parameter could be regulated and thus the laser action threshold, overlap between the pump and cavity modes and the level of diffraction losses were influenced. The cavity length was kept at 28 mm for each measurement.

Absorption properties of crystals in lasing situation were studied. Due to the influence of pump saturation, the pump absorption was found roughly 5% higher when the crystal was placed in the laser cavity comparing to non-lasing situation. This result was taken into account in the measured absorbed power data.

The output power versus the absorbed pump power measurement was performed for each crystal. Several output couplers and curved end mirrors were used to find the most efficient configuration. In each measurement, maximum pump power from the diode fibre was 20 W. Due to different pump coupling optics and absorption properties of the crystals, the absorbed power varied from one sample to another. In order to compare the laser performance of the samples, the output power results are plotted against the absorbed power. The results are shown in Figure 2.



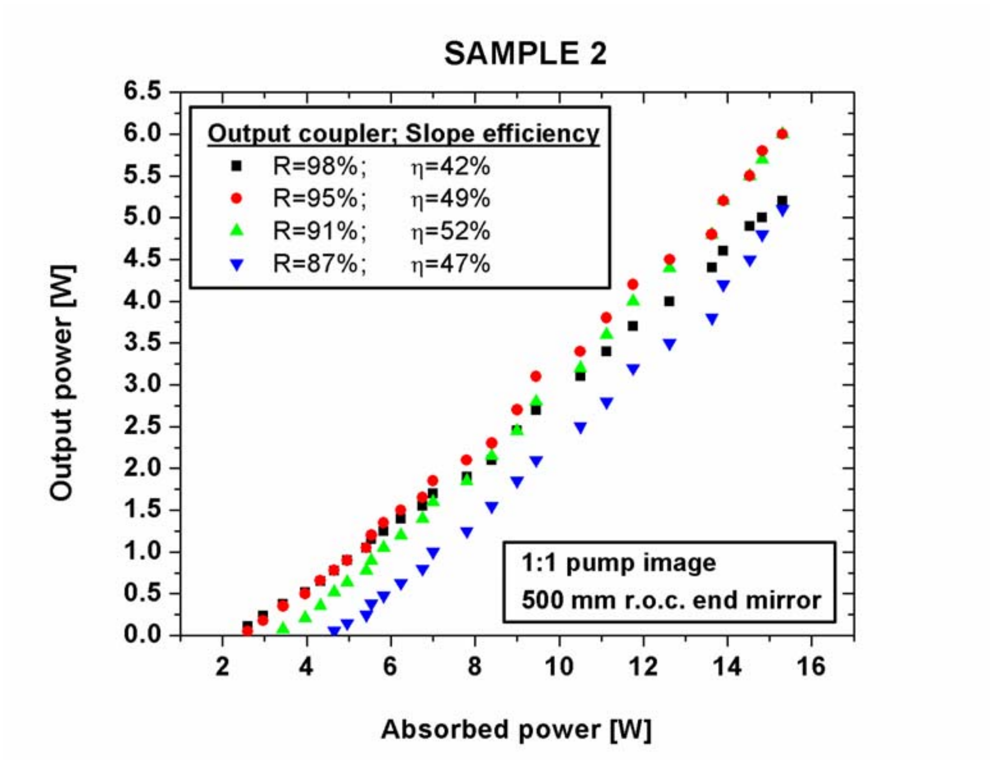


Figure 2. Output power as a function of absorbed pump power.

A lower lasing threshold was obtained for the Sample 1. The short crystal length allowed to use the 2:1 pump demagnification and thus the pump intensity was about four times higher than for the second crystal, while the pump and resonator mode overlap was still sufficient for high efficiency laser operation. This resulted in the low lasing threshold and a rather good slope efficiency of 48%.

The output power of 6W and the slope efficiency of 52% were achieved with the Sample 2. The lasing threshold was relatively low (2-5 W absorbed power), which was due to the crystal orientation ("a"-cut). Optimal pump and resonator configurations were found to ensure highly efficient laser performance. The high slope efficiency of 52% and the low threshold resulted in a good 39% optical efficiency achieved with this crystal (91% reflecting output coupler).

The output spectrum of the constructed laser was measured. The measured spectrum for the Sample 2 with different output couplers can be seen in Figure 3.

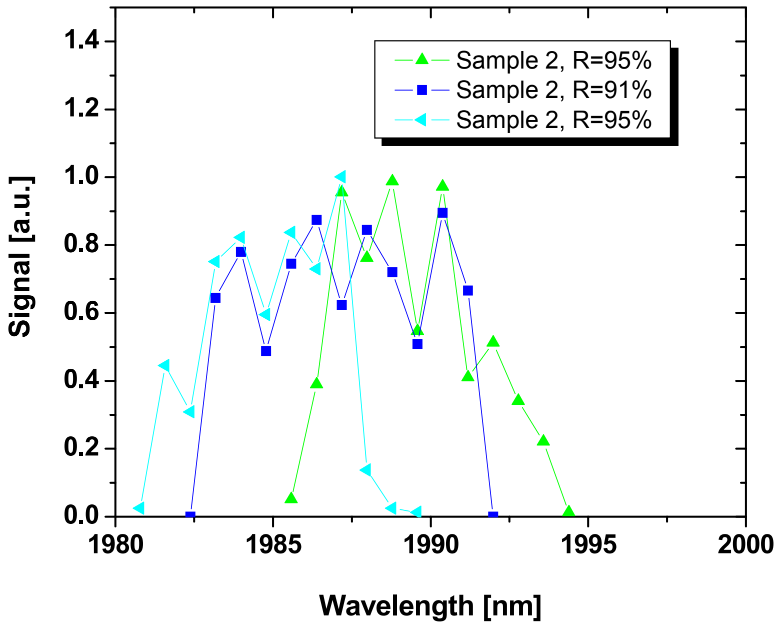


Figure 3. Tm:YAP output wavelength for different output couplers.

To quantitatively estimate the material quality of the used crystal samples, the internal losses L and the internal slope efficiency η_{int} were calculated using the measured output power curves and the formula

$$\eta_n = \eta_{\text{int}} \cdot \frac{T_n}{L + T_n}, \tag{1}$$

where η_n is the slope efficiency corresponding to the output coupling T_n [1].

The results of the least square fit using the Equation (1) are shown in the Table 2. This Table also summarises the output power and efficiency measured for each crystal. One should note the loss L also includes residual loss due to the resonator end mirror and the crystal coatings, which could be estimated to be ≤ 0.3% in total. The measured crystals thus have a material loss better than 0.5 %.

Table 2. Summary of laser performance results.

Sample No.	Output [W]	Slope eff. [%]	Optical eff. [%]	Internal slope eff. [%]	Internal losses [%]
1	4.5	48	37	51.6±3.4	0.61±0.29
2	6	52	39	55.6±0.6	0.65±0.028

In conclusion, a study of Tm:YAP laser performance was done in order to evaluate their material quality. The crystals were found to be of good quality. The highest output power of 6 W, the slope efficiency of 52% and the optical efficiency of 39% (both vs. absorbed power) were achieved with the 5-mm long "a"-cut crystal.

References

[1] R.C. Stoneman and L. Esterowitz, "Efficient 1.94-µm Tm:YAlO laser," IEEE Journal of Selected Topics in Quantum Electronics, vol. 1, No. 1, pp. 78-81, 1995.