

# Diode-pumped Yb:TVO<sub>4</sub> (T=Y, Gd, and Lu) lasers provide output powers exceeding 4 W in the continuous-wave regime

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**Abstract:** We demonstrate output powers exceeding 4 W with continuous-wave, diode-pumped Yb:TVO<sub>4</sub> (T=Y, Gd, and Lu) lasers operated at room temperature. The three orthovanadate hosts are compared in longitudinal and thin-disk pump geometries.

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## 1. Introduction

Ytterbium (Yb) solid-state lasers exhibit small quantum defect and long storage time which ensures high efficiency and low heat generation. In addition, the relatively simple two-manifold electronic structure of the Yb<sup>3+</sup>-ion prevents excited-state absorption and upconversion. The advantages of the uniaxial (point group *4/mmm*) orthovanadate (TVO<sub>4</sub>, T=Y, Gd, Lu) Yb-host crystals in comparison to YAG are related to the higher absorption and emission cross sections, broader linewidths and natural polarization at almost the same thermal conductivity. Although previous studies indicated that all three hosts are promising for Yb-laser operation in the 1- $\mu$ m spectral range, the maximum powers achieved were 1 W or less [1-5].

We investigated in this work the power limits achievable with these three Yb-hosts under diode laser pumping using longitudinal and thin-disk pump geometries. With all three of them, output powers exceeding 4 W could be obtained in the continuous-wave (cw) regime. The maximum slope efficiency achieved with a simple short cavity was above 80%. Thin disk laser operation is demonstrated for the first time with an Yb-doped vanadate crystal.

## 2. Experimental results and discussion

Single crystals of Yb:TVO<sub>4</sub> (T=Y, Gd, Lu) were grown by the conventional Czochralski technique using *a*-oriented seeds. The starting compositions corresponded to 2 at. % Yb (YVO<sub>4</sub>) and 1.5 at. % Yb (GdVO<sub>4</sub> and LuVO<sub>4</sub>). The measured Yb doping levels in the grown crystals were  $1.95 \times 10^{20} \text{ cm}^{-3}$  (YVO<sub>4</sub>),  $1.09 \times 10^{20} \text{ cm}^{-3}$  (GdVO<sub>4</sub>), and  $2.04 \times 10^{20} \text{ cm}^{-3}$  (LuVO<sub>4</sub>). All-samples used were *a*-cut so that natural selection of the polarization was possible.

Optimum operation of Yb:GdVO<sub>4</sub> which was compared directly with Yb:LuVO<sub>4</sub> required lower doping levels. These two samples (Yb:GdVO<sub>4</sub> and Yb:LuVO<sub>4</sub>) were 2 mm thick and uncoated. They were placed in a hemispherical (plano-concave) cavity, near the plane total reflector through which the laser was pumped. The output coupler had a radius of curvature (RC) equal to 25 mm. The fiber-coupled pump diode laser (diameter: 200  $\mu$ m, NA=0.2) provided a maximum unpolarized output power of 50 W but at the somewhat lower pump powers used here the pump wavelength (975-981 nm) was not optimum for the studied vanadates where the peak Yb absorption for  $\pi$ -polarization occurs near 985 nm [1-5]. The pump beam was focused to a spot of about 200  $\mu$ m (diameter) at the position of the crystals by a focusing optics with an imaging ratio of 1:1. The 0.25-mm thick Yb:YVO<sub>4</sub> sample was studied in a standard thin disk laser design with 16 pump passes and was correspondingly HR/AR coated. Both the plano-concave cavity (length: 65 mm, output coupler with RC=100 mm) and the pump source (collimated, unpolarized 50 W fiber-coupled diode laser with an upper limit of 981.5 nm) were similar. The cavity length was optimized in order to match the relatively large pump spot diameter ( $\approx 2.5$  mm). In both geometries used the crystals were maintained at room temperature by water cooling.

The maximum absorption/emission cross sections for the  $\pi$ -polarization near 985 nm are similar for the three vanadate hosts:  $6.74 \times 10^{-20} \text{ cm}^2/8.30 \times 10^{-20} \text{ cm}^2$  in  $\text{YVO}_4$  [1],  $7.2 \times 10^{-20} \text{ cm}^2/9.0 \times 10^{-20} \text{ cm}^2$  in  $\text{GdVO}_4$  (remeasured here), and  $8.42 \times 10^{-20} \text{ cm}^2/11.8 \times 10^{-20} \text{ cm}^2$  in  $\text{LuVO}_4$  [5]. The fluorescence decay times measured for the three hosts by the pinhole or powder methods range roughly from 250 to 350  $\mu\text{s}$  [5].

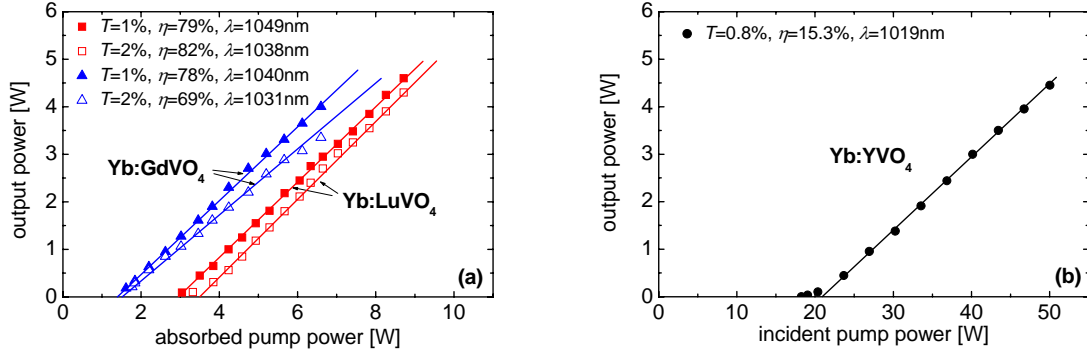


Fig. 1. Output power versus absorbed/incident pump power (symbols) and linear fits for calculation of the slope efficiencies  $\eta$  for different output couplers ( $T$ ): Yb:GdVO<sub>4</sub> (triangles) and Yb:LuVO<sub>4</sub> (squares) with longitudinal (a) and Yb:YVO<sub>4</sub> (circles) with thin-disk (b) pump geometries.

The main results are summarized in Fig. 1 in terms of slope efficiencies and oscillation wavelengths. The maximum incident pump powers applied depended on the absorption, the pump beam size, and the thermal management: they were 50 W (Yb:YVO<sub>4</sub>), 33 W (Yb:GdVO<sub>4</sub>), and 25 W (Yb:LuVO<sub>4</sub>). In the case of longitudinal pumping we measured the actual absorption only up to  $\approx 70\%$  of the maximum incident pump power applied in order to avoid crystal damage since heat generation is increased in the absence of lasing. Although some weak bleaching occurred with increasing pump power, it was neglected assuming compensation by the recycling effect in the lasing state (note that this assumption can result in only underestimation of the slope efficiency). The Fresnel reflections were taken into account and the absorbed power was corrected for a second pass after  $\approx 11\%$  reflection at the rear crystal face assuming the same absorption. In the case of the thin-disk pump geometry it was impossible to measure directly the absorbed pump power but calculations indicate that the total absorption for the 16 passes is about 95%.

For all three hosts the oscillating Yb-laser polarization at high powers was  $\pi$ . Only for Yb:GdVO<sub>4</sub> the polarization changed to  $\sigma$  for absorbed powers less than 2.6 W. This explains the fact that previously only in this material the observed laser polarization was  $\sigma$  [2]. The maximum output powers obtained with Yb:GdVO<sub>4</sub> and Yb:LuVO<sub>4</sub> for  $T=1\%$  were 4.0 and 4.6 W, respectively. The corresponding laser thresholds were roughly 1.6 and 3 W of absorbed pump power. The Yb:YVO<sub>4</sub> laser was the first attempt to test an Yb-doped vanadate crystal in the thin-disk laser design. For the  $T=0.8\%$  (optimum output coupling) this laser had a threshold of about 18.3 W (incident pump power) and produced a maximum output of 4.45 W. The power limits for all three crystals were set by bulk damage as a result of imperfect heat management related to the transversal crystal dimensions in the case of longitudinal pumping and caused by the presence of some inclusions in the case of Yb:YVO<sub>4</sub>.

### 3. Conclusion

In conclusion, we increased the output power from Yb-vanadate lasers to above 4 W and compared the three hosts. At present it seems that GdVO<sub>4</sub> which exhibits lower segregation coefficient is also less suitable for practical applications due to the dependence of the output polarization for maximum gain on the inversion level. LuVO<sub>4</sub> is definitely a better host and since, in addition, improved thermal conductivity can be expected in this novel material we plan to test its feasibility also in the thin disk laser design for achieving of yet higher output powers.

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