

# Continuous-wave and tunable laser operation of Tm:LuVO<sub>4</sub> near 1.9 μm under Ti:sapphire and diode laser pumping

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We demonstrate for the first time to our knowledge laser oscillation of Tm:LuVO<sub>4</sub> at room temperature with both Ti:sapphire and diode laser pumping, and tunable operation

from 1839 to 1952 nm. Spectroscopic studies indicate higher gain cross section for the σ-polarization as observed in the laser experiments.

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The orthovanadates with the general formula TVO<sub>4</sub> (T: trivalent lanthanide ion Ln, Y or Sc) are oxide compounds which crystallize in the zircon (ZrSiO<sub>4</sub>) structure with space group I4<sub>1</sub>/amd (D<sub>4h</sub><sup>19</sup>), point group 4/mmm [1]. They are interesting for laser technology because they exhibit thermal conductivity comparable to that of YAG but the cross sections and the spectral bandwidths of the “active” rare-earth dopants (Nd<sup>3+</sup>, Yb<sup>3+</sup>, Tm<sup>3+</sup>, etc.) are larger. In addition, their uniaxial character ensures natural polarization of the output laser beam. These properties make them attractive for diode-pumped, high-power, as well as mode-locked laser operation. In the case of Tm-doping the absorption transition that can be used for diode pumping is more suitable for commercially available AlGaAs laser diodes in comparison with YAG. Tm-laser operation has been demonstrated so far only with the YVO<sub>4</sub> and GdVO<sub>4</sub> “passive” hosts: while YVO<sub>4</sub> was studied with Tm-doping as early as 1992 [2], GdVO<sub>4</sub> was introduced later believing that its thermal conductivity is higher (most of the literature on this Tm-host can be found in the recent work [3]) an issue which is at present still controversial. The successful growth of Tm:LuVO<sub>4</sub> was reported only recently [4] and these authors established that the absorption cross section for the <sup>3</sup>H<sub>6</sub> → <sup>3</sup>H<sub>4</sub> transition near 800 nm is substantially larger than for Tm:GdVO<sub>4</sub> (only π-spectra were presented in [4]). Here we report the basic spectroscopic pro-

perties of Tm:LuVO<sub>4</sub> relevant for laser operation on the <sup>3</sup>F<sub>4</sub> → <sup>3</sup>H<sub>6</sub> transition near 1.9 μm and, for the first time to our knowledge, room temperature laser operation of Tm:LuVO<sub>4</sub> both under Ti:sapphire and diode laser pumping, including tunability with a Lyot filter.

The Tm:LuVO<sub>4</sub> crystal with 3 at% Tm in the melt was grown in the *a*-direction by the conventional Czochralski technique. The size of the grown boule was about Ø20 mm × 20 mm. The distribution coefficient of Tm in the grown crystal determined by X-ray fluorescence analysis was 1.09 (*N* = 4.11 × 10<sup>20</sup> cm<sup>-3</sup>). Several *a*-cut plates with an aperture of 3.3 × 3.3 mm<sup>2</sup> and thickness 1.5, 2, and 3 mm

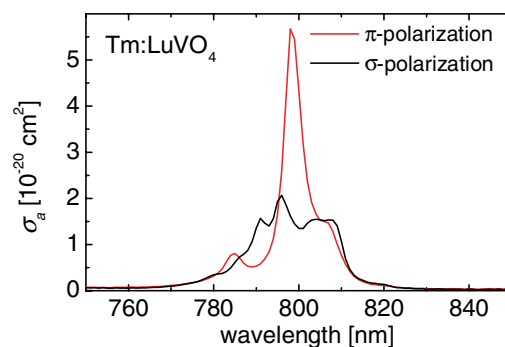
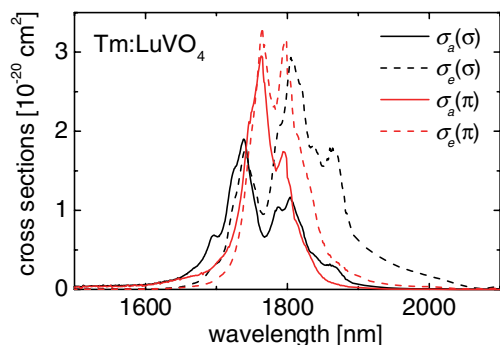


Figure 1 Absorption cross section  $\sigma_a$  near 800 nm (<sup>3</sup>H<sub>6</sub> → <sup>3</sup>H<sub>4</sub>).

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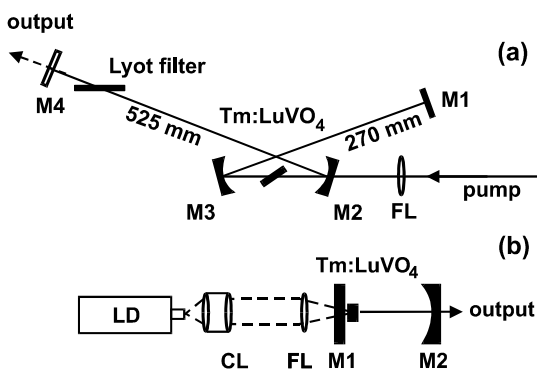


**Figure 2** Measured absorption ( $\sigma_a$ ) and calculated emission ( $\sigma_e$ ) cross sections of Tm:LuVO<sub>4</sub> near 1800 nm (<sup>3</sup>F<sub>4</sub> ↔ <sup>3</sup>H<sub>6</sub>).

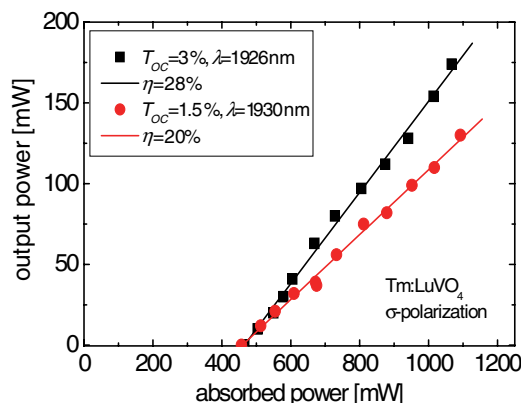
were polished for the spectroscopic measurements and the laser experiments. Figure 1 shows the measured absorption cross sections for the two polarizations near 800 nm. The FWHM for  $\pi$ -polarization is roughly 5.5 nm while the lisheshape for  $\sigma$ -polarization is very broadband.

Figure 2 shows the measured absorption and the calculated by the modified reciprocity method [5] emission cross sections in the 1800 nm spectral range. The latter required the knowledge of the radiative lifetime assumed normally to be equal to the fluorescence lifetime [5]. The pinhole method was used to eliminate the radiation trapping effect in the quasi three-level Tm-system when measuring this decay time and the result was  $0.57 \pm 0.04$  ms.

At first we studied Ti:sapphire laser pumping placing a 2 mm thick uncoated Tm:LuVO<sub>4</sub> sample under Brewster angle into the astigmatically compensated X-type cavity depicted in Fig. 3a (same laser and pump polarization), see [6]. The mirrors M1, M2 and M3 were highly reflecting (HR > 99.9%) from 1800 to 2075 nm and AR-coated on the rear side for high transmission from 780 to 1020 nm. Two output couplers (M4) with transmission  $T_{OC} = 1.5$  and 3% were used. The tunable CW Ti:sapphire laser (three-



**Figure 3** (a) Cavity setup for Ti:sapphire laser pumping. FL: AR-coated focusing lens with  $f = 70$  mm; M1: plane total reflector; M2–M3: RC =  $-100$  mm mirrors; M4: plane output coupler. Cavity length: 90 cm. (b) Cavity setup for laser diode (LD) pumping. CL: collimating lens system with  $f = 34$  mm and 80% transmission; FL: focusing lens with  $f = 20$  mm and 88% transmission; M1: plane total reflector; M2: output coupler with RC =  $-50$  mm.



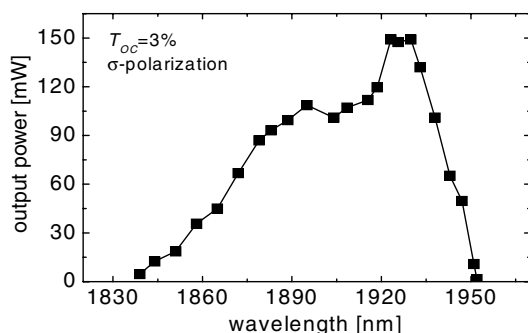
**Figure 4** Output power versus absorbed pump power for the Ti:sapphire laser pumped Tm:LuVO<sub>4</sub> laser and  $\sigma$ -polarization (symbols), and slope efficiency  $\eta$  fits (lines).

plate intracavity Lyot filter) delivered a maximum output power of 3.5 W near 800 nm when pumped with 20 W of an all-lines Ar-ion laser. The output linewidth was normally 0.2 nm or even less. The pump laser was tuned to 796.7 nm. Without active cooling we limited the maximum power incident on the crystal to 1.5 W. In the position of the Tm-crystal, the pump spot had a Gaussian waist of 37  $\mu$ m.

The input–output characteristics recorded for the  $\sigma$ -polarization are shown in Fig. 4. The maximum output power of 174 mW obtained for  $T_{OC} = 3\%$  corresponds to an optical efficiency of 16.3%. The relatively high thresholds measured (around 460 mW for both output couplers) indicate predominant effect of the reabsorption losses and higher than optimum dopant concentration. This is confirmed by the fact that it was possible to obtain stable oscillation only for the  $\sigma$ -polarization where the crystal absorption under lasing conditions was roughly 70% (independent of the pump level). This absorption was only slightly reduced (by about 5%) at maximum pump power when lasing was interrupted and the bleaching was more efficient due to the reduced saturation intensity in the three level Tm-system. The pump absorption for the  $\pi$ -polarization was higher (see Fig. 1) but the output power was lower and in the absence of cooling slowly decayed with time.

Tunable operation was studied for  $T_{OC} = 3\%$  by inserting a 3 mm thick quartz plate with its optical axis at 60° to the surface (described in [7]) into the long cavity arm in Fig. 3a, which acted as a Lyot filter. To the best of our knowledge this is the first report of tuning with any of the vanadate Tm-hosts. The FWHM of roughly 70 nm (Fig. 5) is very promising for mode-locking and it is expected that the tuning range will be broader at lower doping levels.

The diode laser module used for pumping contained a single 50 W commercial bar with 19 emitters and 30% fill factor, mounted in a conduction cooled packaging. Only simple adapted beam shaping optics was used for the pump beam which was unpolarized. The nearly collimated beam had a size of several millimeters. The emission wavelength

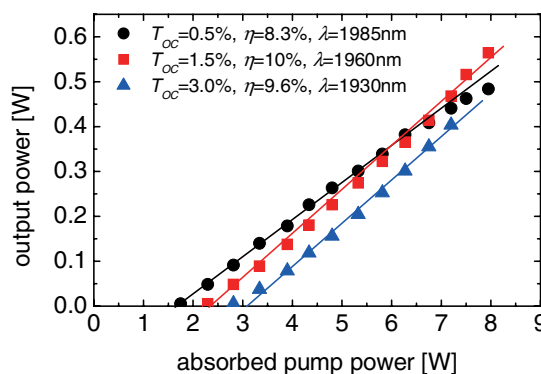


**Figure 5** Tuning of the Tm:LuVO<sub>4</sub> laser with an intracavity Lyot filter. The absorbed pump power is 1.05 W.

depended on the operating current and changed with the output power. At the maximum output power used for the present experiment the wavelength was 800 nm. The single-peaked pump spectrum had a FWHM of 2 nm. The nearly circular spot achieved in the position of the Tm:LuVO<sub>4</sub> sample had a cross section with a diameter of about 125  $\mu\text{m}$ . The pump beam focus was close to the front surface of the crystal. The same uncoated 2 mm thick Tm:LuVO<sub>4</sub> sample was placed into a nearly hemispherical 50 mm long cavity close to the plane mirror through which it was pumped (Fig. 3b). The Cu-holder was provided with water cooling to maintain room temperature. The actual absorption of the crystal was only weakly dependent on the pump power and amounted to 75%. The three curved output couplers used had  $T_{OC} = 0.5, 1.5,$  and 3%.

The reabsorption effect was even stronger in the case of diode pumping which is clear from the longer oscillation wavelengths (Fig. 6). Independent of this, however, the fact that the laser naturally selected the  $\sigma$ -polarization for an unpolarized pump beam confirms the higher gain for this polarization (see Fig. 2). The maximum output power of 564 mW achieved with  $T_{OC} = 1.5\%$  (Fig. 6) corresponds to an optical efficiency of 7%. Notwithstanding the relatively low slope efficiencies (Fig. 6) the output power achieved with diode laser pumping is, to the best of our knowledge, the highest for any CW Tm-doped vanadate laser [3].

In conclusion Tm:LuVO<sub>4</sub> with 3 at% doping in the melt was grown by the Czochralski method and tunable laser oscillation near 1900 nm in the CW regime has been obtained reaching output powers more than 500 mW with diode pumping.



**Figure 6** Output power versus absorbed pump power for the diode laser pumped Tm:LuVO<sub>4</sub> laser and three output couplers. The slope efficiencies ( $\eta$ ) and the oscillation wavelengths ( $\lambda$ ) are indicated in the figure. The oscillating polarization is  $\sigma$ .

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