

Continuous-wave lasing of Yb:LuVO₄

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Abstract: We report on the crystal growth, spectroscopy and laser operation of Yb:LuVO₄ achieving an output power of 0.36 W at 1041 nm with Ti:sapphire and 2.85 W (slope efficiency of 51.3%) with diode laser pumping.

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1. Introduction

The advantages of the orthovanadate laser host crystals like YVO₄ and GdVO₄ in comparison to YAG are related to the higher absorption and emission cross sections, broader linewidths and natural polarization. Vanadate hosts possess the zircon (ZrSiO₄) structure of space group I₄/amd (D_{4h}^{19}) (point group $4/mmm$). In rare-earth doped crystals of this type, the trivalent active ions (Nd³⁺, Yb³⁺, Er³⁺, Tm³⁺, etc.) substitute the optically inert ions (Y³⁺, Gd³⁺, etc.) in lattice sites with $\bar{4}2m$ (D_{2d}) symmetry. Previous studies indicated that both Yb:YVO₄ and Yb:GdVO₄ are promising laser media for the 1- μ m spectral range [1-3]. In addition to YVO₄ and GdVO₄, there exists another relatively new member of this vanadate family, LuVO₄, for which it can be expected to benefit from the closer ionic radii of Yb and Lu in terms of crystal quality since the ion-substitution-related lattice distortion will be minimized. Moreover, the reduction of the thermal conductivity of this host with Yb-doping should be also minimum due to the smallest difference in atomic mass between Yb and Lu [4] as already observed in Yb-doped sesquioxide crystals [5]. Here we present the room-temperature spectroscopic properties and demonstrate continuous-wave (cw) laser operation of Yb:LuVO₄ pumped by both Ti-sapphire and fiber-coupled diode laser.

2. Crystal growth and spectroscopy of Yb:LuVO₄

Crystals of Yb_{0.015}Lu_{0.985}VO₄ were grown by the conventional Czochralski method with starting polycrystalline charges of LuVO₄ and YbVO₄, synthesized from high purity (99.99%) Lu₂O₃, Yb₂O₃, and V₂O₅ through the liquid-phase method. Boule sizes of about 20×20 mm were obtained for orientation along the *a*-axis. The actual Yb-concentration in the crystal was determined by optical emission spectroscopy with inductively coupled plasma and Rh as an internal standard. The 1.56±0.01 at % correspond to 204×10²⁰ cm⁻³ giving a segregation coefficient of 1.04. All samples used (1.5 and 6mm thickness for spectroscopic measurements and 2mm thickness for the laser experiments) were *a*-cut.

The “pinhole technique” [2] gave a fluorescence lifetime of $\tau=256\pm 11$ μ s for Yb:LuVO₄ which is very close to that measured for Yb:YVO₄ by using crystal powders [3].

The absorption cross section of Yb:LuVO₄ (see Fig. 1) is strongly anisotropic with higher values for the π -polarization ($E//c$) than for the σ -polarization ($E\perp c$). The main absorption band for the π -polarization centered at 985 nm has a peak cross section of 8.42×10^{-20} cm² and a FWHM of 7.3 nm. For σ -polarization, the broader band centered at 969 nm is more pronounced having a maximum absorption cross section of 1.97×10^{-20} cm² while the narrower 985-nm band has a peak cross section of 2.08×10^{-20} cm². The stimulated emission cross sections presented in Fig. 1 were computed by the modified reciprocity method [3]. The peak emission cross sections are $\sigma_{em}(\pi)=11.8\times 10^{-20}$ cm² and $\sigma_{em}(\sigma)=3.5\times 10^{-20}$ cm², for both polarizations at 985 nm. In the emission wavelength range of 1020-1055 nm, where laser oscillation can be expected, $\sigma_{em}(\pi) = 10.3\dots 1.2\times 10^{-21}$ cm². The cross-sections of Yb:LuVO₄ are also similar to those estimated for Yb:YVO₄ [2-3]. It should be outlined that the cross sections of these vanadates are rather high and approach the values for the strongly anisotropic monoclinic double tungstates.

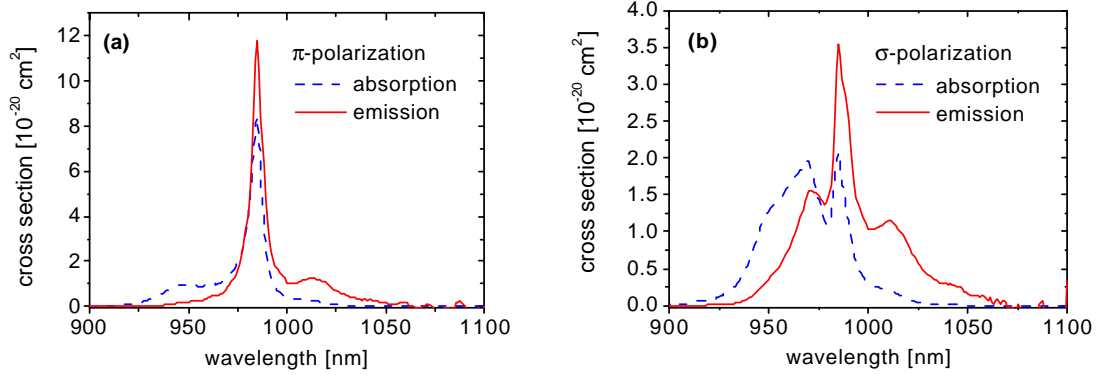


Fig.1: Polarized absorption and emission spectra of Yb:LuVO₄ at room temperature for π -polarization (a) and σ -polarization (b).

3. Experimental results

The laser performance of Yb:LuVO₄ was studied first using a tunable cw Ti-sapphire laser as a pump source (maximum applied pump power of 1.8 W at 985 nm) with a three-mirror astigmatically compensated cavity, see Fig. 2a. M₁ and M₂ were concave mirrors with radius of curvature (RC) of 50 and 100 mm, respectively, both highly reflecting (HR) from 1020 to 1240 nm and highly transmitting (HT) near 985 nm. M₃ was a flat output coupler with transmission $T=1\%$ at 1030 nm. The 2-mm-thick uncoated Yb:LuVO₄ sample was mounted on a copper holder without active cooling and placed under Brewster angle for the π -polarization at the waist position of the M₁M₂ arm. The waist radius could be varied in the range of 20-70 μm by the separation of M₁ and M₂. The π -polarized pump beam was focused by a 62.8-mm focal-length lens through M₂ to a spot with a Gaussian waist of $\approx 22 \mu\text{m}$ at the position of the crystal. The cavity length amounted to 56 cm.

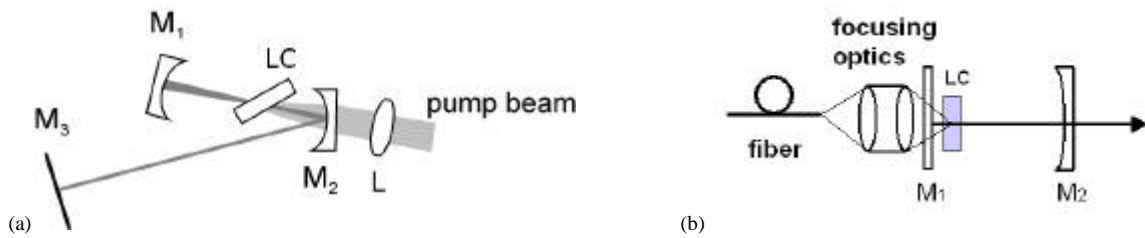


Fig.2: Schematic of the experimental laser setup using a Ti-sapphire (a) and a fiber-coupled diode laser (b) as a pump source. LC: Yb:LuVO₄.

Figure 3a shows the dependence of the output power at 1041 nm on the absorbed pump power for room temperature cw oscillation. The absorbed pump power was determined under lasing conditions by measuring the residual pump power behind M₁, taking into account both absorption bleaching and the recycling effect of the ground manifold population. The laser reached threshold at an absorbed pump power of 0.75 W. At the highest absorbed pump power of 1.5 W, a maximum output power of 0.36 W was obtained giving an optical efficiency of 24%. The slope efficiency was $\eta=47\%$. No thermal effects were encountered up to the highest pump power used. In the case of Ti:sapphire laser pumping the results in terms of efficiencies and output levels are quite similar to those obtained with Yb:GdVO₄ and Yb:YVO₄ [1,2]. The increased threshold in comparison to [2] is an indication of higher than optimum doping level in our case with 2-mm crystal thickness (the small signal absorption amounted to 97% for the π -polarization).

Diode pumping of the cw Yb:LuVO₄ laser was studied by employing a fiber-coupled diode laser (S50-980-2, Apollo Instruments, Inc., 200 μm diameter, 0.2 NA) providing a maximum unpolarized output power of 50 W at a center wavelength near 980 nm. The pump beam was focused into the crystal by a focusing optics with an imaging ratio of 1:1 and a compact nearly hemispherical (plano-concave) cavity was used, see Fig. 2b. The $4.2 \times 4.2 \times 2 \text{ mm}^3$ Yb:LuVO₄ crystal was AR-coated both for 1030 and 980 nm. It was mounted on a copper heat sink and room

temperature was maintained by water cooling. The crystal was positioned close to the 3-mm thick flat mirror M_1 (HR at 1015-1230 nm, HT near 980 nm). The output coupler M_2 was with RC=25 mm and $T=1.2\%$. The cavity length amounted to 24 mm.

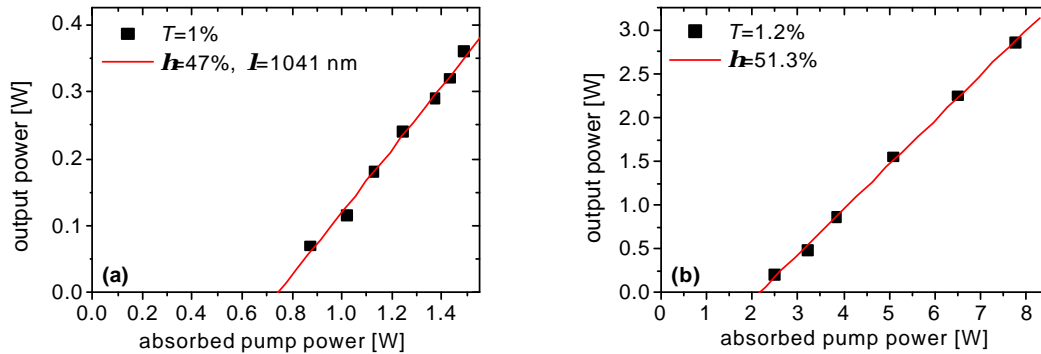


Fig.3: Output power versus absorbed pump power of the Yb:LuVO₄ laser pumped by a Ti-sapphire laser (a) and a fiber-coupled diode laser (b).

The laser beam was polarized parallel to the c -axis (π -polarization), as expected from the spectroscopic results and as observed in all laser reports on Yb:YVO₄ [2,3,6] but in contrast to the observation of higher gain for the σ -polarization in Yb:GdVO₄ [1].

The output power versus the absorbed pump power for the diode pumped Yb:LuVO₄ laser is shown in Fig. 3b. For the maximum applied incident pump power of 25 W the output power reached 2.85 W near 1045 nm. The absorbed pump power in that case amounted to 7.75 W (optical efficiency of 36.8%). This is the highest output power reported so far for an Yb-doped vanadate laser. The slope efficiency with respect to the absorbed power was 51.3% (Fig. 3b). The relatively high threshold (2.2 W) can be explained by the large pump waist and the far from optimum pump wavelength (at lower pump powers it was actually below 980 nm). The absorption at the pump wavelength of 980 nm showed weak bleaching in dependence on the incident pump power; its average value was about 35%.

4. Conclusion

In conclusion, the spectroscopic properties of Yb:LuVO₄ including absorption and emission cross sections and fluorescence lifetime were determined at room temperature and cw laser operation was demonstrated by using both Ti-sapphire and diode laser pumping. A slope efficiency of 47% was achieved with Ti-sapphire laser pumping and a slope efficiency of 51.3% was obtained with non-optimized fiber-coupled diode laser pumping. The diode-pumped Yb:LuVO₄ laser provided an output power as high as 2.85 W and showed no output saturation tendency, often resulting from thermal effects in the laser medium. This makes us confident that substantial power scaling will be possible by optimizing the crystal absorption (doping level) and by employing a diode laser emitting at the absorption peak wavelength of 985 nm. Future work will be devoted also to the passive mode-locking of the Yb:LuVO₄ laser.

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