Continuous-wave laser operation of Yb:LuVO_4

Junhai Liu and Xavier Mateos

Max-Born-Institute for Nonlinear Optics and Ultrafast Spectroscopy, 2A Max-Born-Strasse, D-12489 Berlin, Germany

Huaijin Zhang, Jiyang Wang, and Minhua Jiang

National Laboratory of Crystal Materials, Shandong University, Jinan 250100, China

Uwe Griebner and Valentin Petrov

Max-Born-Institute for Nonlinear Optics and Ultrafast Spectroscopy, 2A Max-Born-Strasse,
D-12489 Berlin, Germany

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We report on the room-temperature spectroscopic properties and continuous-wave laser operation of a new Yb:LuVO_4 crystal. The peak absorption cross section for the π-polarization is 8.42×10^{-20} cm^2 at 985 nm, and the stimulated emission cross section at 1020 nm is 1.03×10^{-20} cm^2. An output power of 0.36 W at 1041 nm was obtained with a slope efficiency of 47% by use of Ti:sapphire laser pumping. With diode pumping the output power reached 1.05 W at the highest available incident pump power of 6.8 W. © 2005 Optical Society of America

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As well-known host materials for the neodymium (Nd) ion, the orthovanadate crystal YVO_4 and later GdVO_4 have found wide applications in diode-pumped solid-state lasers operating at low-to-medium power levels. Their advantages in comparison with YAG are related to their higher absorption and emission cross sections, broader bandwidths, and natural polarization. Recent studies indicated that both ytterbium (Yb)-doped GdVO_4 and YVO_4 are also promising laser media for the 1 μm spectral range.[1–3] In comparison with the biaxial monoclinic potassium double tungstates, which along with YAG are currently the most popular hosts for the Yb ion, the uniaxial vanadate crystals are advantageous in terms of thermal load management because their thermal conductivity is 1.5–2.5 times higher and, in the case of Yb-doping, comparable with that of YAG.[1] LuVO_4 is another relatively new member of this vanadate family, in which the absorption and emission cross sections of Nd^{3+} were found to be larger than in both YVO_4 and GdVO_4.[4] Both continuous-wave (cw) and pulsed laser operation has been already demonstrated with Nd:LuVO_4.[4,5]

Vanadate crystals possess the zircon (ZrSiO_4) structure of space group $I4_1/amd$ (point group $4/mmm$). In rare-earth-doped crystals of this type, the trivalent active ions (Nd^{3+}, Yb^{3+}, Er^{3+}, Tm^{3+}, etc.) substitute for the optically inert trivalent cations (Y^{3+},Gd^{3+},Lu^{3+}) at lattice sites with $\bar{4}2m$ symmetry. It can be expected that Yb:LuVO_4 will benefit from the closer ionic radii and masses of Yb and Lu in terms of crystal quality and thermal conductivity. In this Letter, we report the room-temperature spectroscopic properties and demonstrate cw laser operation of Yb:LuVO_4 pumped by both Ti:sapphire and fiber-coupled diode lasers.

By the conventional Czochralski method, the a-axis-grown Yb:LuVO_4 crystal was obtained with boule sizes of about ⌀20×20 mm from a melt with a chemical formula of $Yb_{0.015}Lu_{0.985}VO_4$. The Yb concentration in the crystal was determined, by optical emission spectroscopy with inductively coupled plasma and Rh as an internal standard, to be 1.56 ± 0.01 at. %, corresponding to 2.04×10^{20} cm^{-3}. The pinhole technique,[2] which helps to avoid reabsorption and radiation trapping, gave a fluorescence lifetime of $\tau=256\pm11$ μs for Yb:LuVO_4, which is very close to that measured for Yb:YVO_4 by use of crystal powders (see Table 1).

The absorption cross section of Yb:LuVO_4 (see Fig. 1) exhibits strong anisotropy: as with other dopants, it is much higher for π polarization ($E\parallel c$) than for σ polarization ($E\perp c$). The main absorption band for π polarization is centered at 985 nm with a peak cross section of 8.42×10^{-20} cm^2 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} cm^2, while the narrower 985 nm band has a peak cross section of 2.08×10^{-20} cm^2. Figure 1 also presents the stimulated emission cross sections, computed by use of the modified reciprocity method.[3] The peak emission cross sections are $\sigma_{em}(\pi)=11.8\times10^{-20}$ cm^2 and $\sigma_{em}(\sigma)=3.5\times10^{-20}$ cm^2 for both polarizations at 985 nm. In the emission wavelength range of 1020–1055 nm, where laser oscillation can be expected, $\sigma_{em}(\pi)$ ranges from 10.3×10^{-21} to 2.0×10^{-21} cm^2.

As can be seen from Table 1, the cross sections of Yb:LuVO_4 are closer to those measured for Yb:YVO_4 in Refs. 2 and 3. The trend of increasing Yb^{3+} cross sections from GdVO_4 to YVO_4 and finally to LuVO_4, as observed[4] for Nd^{3+}, has yet to be confirmed. The emission cross sections depend in addition on the method of calculation, and precise comparison of the results requires knowledge of the energy level schemes. Nevertheless, it should be noted that the rather large cross sections for Yb:LuVO_4 are very

Table 1. Spectroscopic Parameters of Yb-doped Vanadates

Host	τ (μs)	σ_a (10^{-20} cm^2)	σ_{em} (10^{-20} cm^2)	$\Delta\lambda_a(\pi)$ (nm)
$GdVO_4$[a]	320	2.40 at 984 nm (π)	1.60 at 984 nm (π)	15
	345[b]	1.26 at 969 nm (σ)	1.80 at 984 nm (σ)	
YVO_4[c]	318	6.74 at 984.5 nm (π)	4.28 at 985.5 nm (π),	8.0[d]
		1.92 at 969.6 nm (σ)	8.30 at 985.5 nm (π)[d]	
			1.73 at 986 nm (σ),	
			2.10 at 986 nm (σ)[d]	
YVO_4[e]	247	7.40 at 985.4 nm (π)	9.50 at 985.4 nm (π)	5, 9[f]
		2.00 at 970 nm (σ)	2.25 at 985.4 nm (σ)	
YVO_4[g]	255	2.20 at 982 nm (π)	1.90 at 1010 nm (π)	26
		1.60 at 965 nm (σ)	1.70 at 1010 nm (σ)	
$LuVO_4$[h]	256	8.42 at 985 nm (π)	11.8 at 985 nm (π)	7.3
		1.97 at 969 nm (σ)	3.50 at 985 nm (σ)	

[a] Ref. 1, Yb doping 2%, τ measured by the powder method.

[b] Yb doping 5%, τ measured by the pinhole technique.

[c] Ref. 2, Yb doping 1.6 at. %, τ measured by the pinhole technique.

[d] Updated by the same group.

[e] Ref. 3, Yb doping 1.62 at. %, τ measured by the powder method.

[f] Updated by the same group in Ref. 6.

[g] Ref. 7, Yb doping 10 at. %, τ measured by the powder method; cross sections obviously exchanged in Ref. 7, here corrected.

[h] This work, Yb doping 1.56 at. %, τ measured by the pinhole technique.

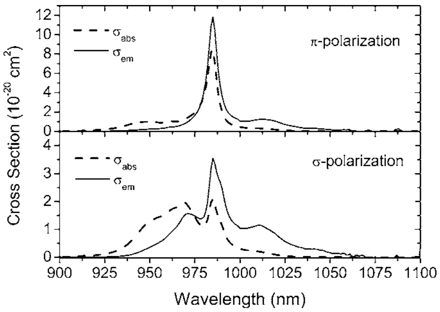

Fig. 1. Polarized absorption and emission spectra of Yb:$LuVO_4$.

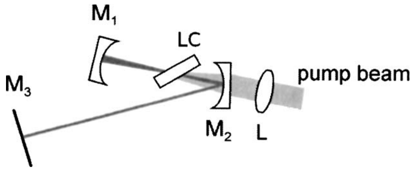

Fig. 2. Experimental laser setup for Ti-sapphire laser pumping. LC, Yb:$LuVO_4$ crystal; cavity length 56 cm.

close to those for the strongly anisotropic monoclinic double tungstates.

To study the laser performance of Yb:$LuVO_4$, we first used a tunable cw Ti:sapphire laser (maximum power of 1.8 W at 985 nm) as a pump source and a three-mirror astigmatically compensated cavity (Fig. 2). M_1 and M_2 were concave mirrors with radii of curvature (RC) of 50 and 100 mm, respectively, both highly reflecting from 1020 to 1240 nm and highly transmitting near 985 nm. M_3 was a flat output coupler with transmission $T=1\%$ at 1030 nm. The 2 mm thick uncoated a-cut Yb:$LuVO_4$ sample was mounted on a copper holder without active cooling and placed at the Brewster angle for π polarization at the waist position of the M_1M_2 arm. The π-polarized pump beam was focused by a 62.8 mm focal length lens through M_2 to a spot with a Gaussian waist of ~22 μm at the position of the crystal.

Figure 3(a) shows the dependence of the cw output power at 1041 nm on the absorbed pump power, measured under lasing conditions. 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 47%. No thermal effects were encountered compared with the performance with average pump power reduced by a chopper, although no special measures were taken to cool the crystal. 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:$GdVO_4$ and Yb:YVO_4.[1,2] The increased threshold compared with Ref. 2 is an indication of a higher than optimum doping level in our 2 mm thick crystal (the small signal absorption amounted to 97% for π-polarization).

Diode pumping of the cw Yb:$LuVO_4$ laser was studied by employing a fiber-coupled diode laser with a maximum output of 7 W at 981 nm (116 μm core diameter, 0.22 NA). A compact hemispherical cavity was used, in which the same uncoated 2 mm thick Yb:$LuVO_4$ crystal mounted on a passive copper heat sink was positioned close to the flat mirror (highly reflecting at 1015–1230 nm, highly transmitting near

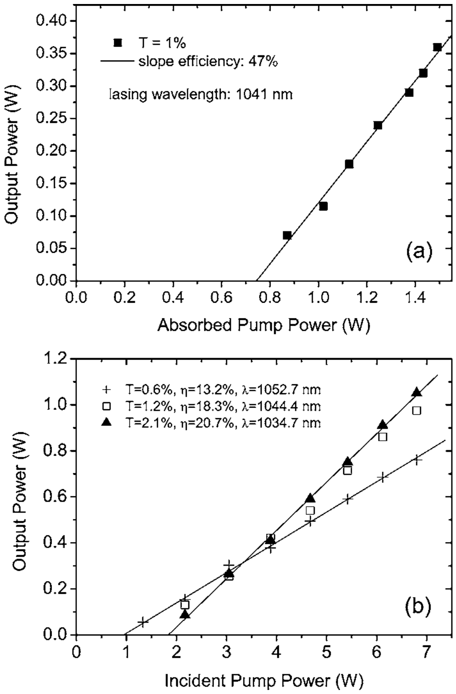

Fig. 3. Output power versus pump power of the Yb:$LuVO_4$ laser pumped by (a) a Ti:sapphire laser and (b) a diode laser.

981 nm). The pump beam was focused through the flat mirror by special micro-optics to a spot of waist of $\approx 40\ \mu m$ at the crystal position. The RC=25 mm output couplers had $T=0.6\%$, 1.2%, 2.1%.

The output power versus the incident pump power is shown in Fig. 3(b). It reached a maximum of 1.05 W at the highest available incident pump power of 6.8 W, resulting in an optical efficiency of 15.4%, whereas the slope efficiency was 20.7%. For $T=0.6\%$ and $T=1.2\%$, the maximum output power was 0.76 and 0.98 W, with slope efficiencies of 13.2% and 18.3%, respectively. In all cases, the laser beam was polarized parallel to the c axis (π polarization), as expected from the spectroscopic results and as observed in Yb:YVO_4 lasers[2,3,8] but in contrast to the observation of higher gain for the σ polarization in Yb:$GdVO_4$.[1] Since the highly divergent pump beam precluded the estimation of the absorbed pump power under lasing conditions, the above efficiencies refer to the incident pump power and are correspondingly lower. Nevertheless, it is possible to compare the maximum output power obtained with that for cw diode-pumped Yb:YVO_4 lasers using very similar cavities and pump sources.[2,3,8] The most efficient operation was achieved in our case with $T=2.1\%$, and the output power is the highest reported so far to our knowledge for Yb-doped vanadate lasers. The only comparable result of 0.98 W was achieved with an antireflection coated and actively cooled Yb:YVO_4 crystal.[8] It was possible to determine the absorbed pump power at threshold by removing the output coupler, since then lasing had no effect on the actual absorption: it was 0.52, 0.69, and 0.90 W, for $T=0.6\%$, 1.2%, 2.1%, respectively. The increased threshold and the longer lasing wavelengths (from 1052.7 nm for $T=0.6\%$ to 1034.7 nm for $T=2.1\%$) are indications of higher than optimum Yb-doping level for the chosen crystal thickness.

As can be seen from Fig. 3(b) the diode-pumped Yb:$LuVO_4$ laser showed no output saturation tendency, often resulting from thermal effects in the laser medium, although the crystal was not cooled actively. It is expected that substantial power scaling will be possible by optimizing the crystal absorption and applying antireflection coatings and active cooling in order to reduce the thermal population in the terminal laser level and by employing a diode laser emitting at the absorption peak wavelength of 985 nm.

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J. Liu's e-mail address is jhliu@mbi-berlin.de.

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