High-power laser performance of *a*-cut and *c*-cut $Yb:LuVO_4$ crystals

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We report high-power laser operation that was achieved with a-cut and c-cut $Yb:LuVO_4$ crystals. Up to 8.3 W of π-polarized output power was generated from an a-cut, 2 mm uncoated crystal with an optical conversion efficiency of 59%. The highest slope efficiency was 80%. Laser oscillation obtained with c-cut crystal was also linearly polarized, with two orthogonal polarization components along [110] and $[\bar{1}10]$ directions. The highest output power achieved was 4.5 W, with an optical conversion efficiency of 33% and a slope efficiency of 40%.

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The crystal of $LuVO_4$ is a relatively new member of the orthovanadates family, which have become widely used host media for trivalent rare-earth laser ions like Nd^{3+}, Tm^{3+}, and Yb^{3+}. Among all Nd-doped vanadates, $Nd:LuVO_4$ possesses the largest absorption and emission cross sections (σ_a and σ_{em}), high-power laser operation has been demonstrated in both cw and pulsed regimes.[1,2] As host crystal for Yb ion, $LuVO_4$ might be more advantageous over YVO_4 and $GdVO_4$, because the Lu ion is the closest to the dopant Yb ion in respect of ionic radius and mass, which is likely to lead to less lattice distortion and less reduction in thermal conductivity caused by ion substitution process. Previous spectroscopic studies on the three Yb-doped vanadates indicate a similar tendency of the largest σ_a and σ_{em} in $Yb:LuVO_4$,[3–7] this is particularly true for the σ_{em} of σ polarization ($E \perp c$ axis), with a peak value at 985 nm equal to $3.5 \times 10^{-20}\ cm^2$, compared to $\sim 2.2 \times 10^{-20}\ cm^2$ for both $Yb:YVO_4$ and $Yb:GdVO_4$.[6,7]

In this Letter, we report the high-power laser performance of both a-cut and c-cut $Yb:LuVO_4$ crystals achieved through end pumping by a high-power diode laser. In addition to highly efficient high-power operation, our study revealed interesting polarization properties of the laser beam generated from the c-cut crystal.

The 1.5 at. % $Yb:LuVO_4$ utilized in the experiment was grown along the c axis by the conventional Czochralski method. From the grown boule both a-cut and c-cut crystal samples were prepared with thickness of 2 mm and cross section of 3.3 mm × 3.3 mm.

The laser performance was investigated by employing a plano–concave resonator arranged in a near hemispherical configuration. The plane mirror had a dielectric coating highly reflecting for 1015–1230 nm (>99.8%) and highly transmitting for 880–990 nm (>97%). As the output coupler, several concave mirrors of radius of curvature of 50 mm with transmissions of 0.5%–10% for 1030 nm were used. The uncoated $Yb:LuVO_4$ sample was fixed into a copper holder that was water cooled. The cooling water was maintained at temperature of 12 °C. The pump source used was a 50 W high-brightness fiber-coupled diode (S50-980-2, Apollo Instruments, Inc., fiber core diameter of 200 μm and NA of 0.22) emitting infrared radiation at 974–981 nm depending on the output level, its output beam was focused by a 1:1 reimaging unit and delivered onto the laser crystal that was positioned close to the plane mirror.

Figure 1 shows the dependence of the output power on the absorbed pump power (P_{abs}) for three output couplings of $T=2\%$, 5%, and 10%, obtained with the 2 mm a-cut $Yb:LuVO_4$ crystal. The P_{abs} required for reaching threshold, measured with decreasing pump power, was 1.9, 2.6, and 3.2 W for $T=2\%$, 5%, and 10%, respectively. With increasing pump power from below threshold, more pump power had to be absorbed for the laser to get oscillating, due to the bistable nature in laser operation of Yb-doped vanadates.[7] For $P_{abs} < 6$ W, the most efficient operation was attained with a coupling of $T=2\%$; exceed-

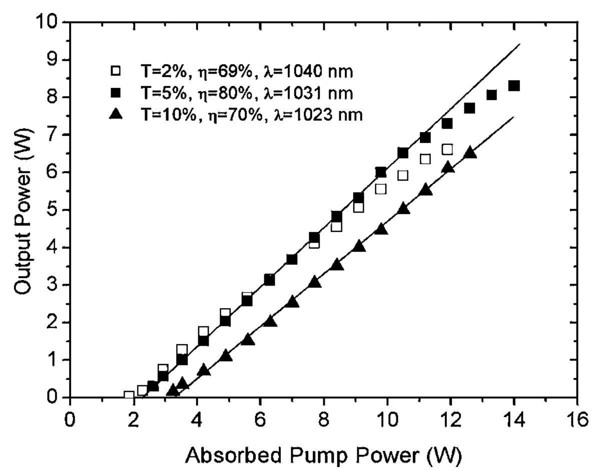

Fig. 1. Output power versus P_{abs} for the a-cut $Yb:LuVO_4$ crystal.

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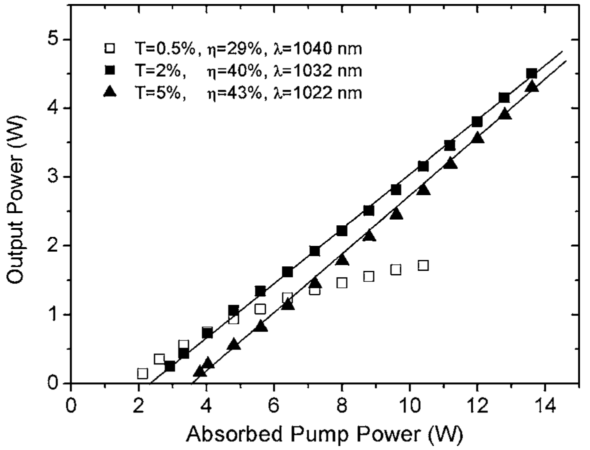

Fig. 2. Output power versus P_{abs} for the c-cut Yb:LuVO$_4$ crystal.

ing this level; however, the optimal coupling changed to $T=5\%$, a slope efficiency as high as 80% was reached for $P_{abs}<11$ W. When P_{abs} was further increased, the laser became less efficient; the slope efficiency reduced to ~50%. This is due to the insufficient cooling of the laser crystal that led to increased reabsorption losses arising from the more populated terminal laser level. Before the output power started to roll off; however, a maximum of 8.3 W was reached at 1031 nm for $P_{abs}=14$ W, resulting in an optical conversion efficiency of 59%. The slope efficiency in the cases of $T=2\%$ and 10% was determined to be 69% and 70%, respectively. The highest attainable output power in these two cases was also lower than that for $T=5\%$. The emission wavelength, which usually consisted of several lines, depended on the pump power. The wavelengths given in Fig. 1 correspond to the highest pump power levels utilized. The generated laser output was always linearly polarized along the c axis (π polarized), independent of power level and output coupling used, which is in accordance with the previous results obtained with a-cut Yb:LuVO$_4$ crystal.[6]

Figure 2 shows the relations between the output power and the absorbed pump power for $T=0.5\%$, 2%, and 5%, obtained with the 2 mm c-cut crystal employed. The pump power absorbed at threshold for $T=0.5\%$, 2%, and 5% was measured by decreasing the pump power: it was 2.1, 2.9, and 3.8 W, respectively. The higher thresholds in comparison with the a-cut crystal originated from the smaller σ_{em}. As in the case of a-cut crystal, bistable operational behavior also existed. From Fig. 2 one can see that the output power exhibited an early roll-off in the case of $T=0.5\%$. The optimal operation was achieved with an output coupling of $T=2\%$, yielding a maximum output power of 4.5 W at $P_{abs}=13.6$ W, leading to an optical conversion efficiency of 33%; the slope efficiency was 40%. The emission wavelength at this power level was 1032 nm. With an even larger output coupling of $T=5\%$, the slope efficiency was slightly higher (43%), but the highest output power reached was 4.3 W, slightly lower than that obtained in the case of $T=2\%$. The emission wavelength shifted to a shorter value of 1022 nm, owing to the requirement for higher gain that increases with wavelength shortening in the range of lasing wavelength of Yb:LuVO$_4$.

Yb:LuVO$_4$ is a uniaxial crystal belonging to the point group $4/mmm$. Its optic axis, the c axis, is a unique fourfold symmetry axis. As a result, the a and b axes are indistinguishable; accordingly, the plane determined by a and b is optically isotropic. Considering these facts, one might expect an unpolarized output beam generated with the c-cut crystal. However, this is not the case. Instead of being unpolarized, the laser oscillation was actually linearly polarized along [110] direction; under sufficiently strong pumping, the second polarization component parallel to $[\bar{1}10]$ direction would start oscillating, and the laser entered a region in which the two orthogonal polarization components oscillated simultaneously. Figure 3 illustrates the variation of the output power ratio between the two polarizations, $\xi=P_{[\bar{1}10]}/P_{[110]}$, measured in the case of $T=2\%$. Under relatively weak pumping ($P_{abs}<4.8$ W), ξ remained zero, the laser oscillation was linearly polarized along the [110] direction, with a maximum output power up to ~1 W. In the high pump power range of $P_{abs}>4.8$ W, the variation of ξ was not monotonic with the absorbed pump power, it exhibited some sort of oscillating feature. With increasing pump power, ξ increased first to a maximum of ~0.24, then reduced gradually to a minimum of ~0.11; after that, it increased again, reaching a value of 0.43 at the highest absorbed pump power utilized of 13.6 W, the output powers polarized in the [110] and $[\bar{1}10]$ directions being 3.15 and 1.35 W, respectively.

It was found that the laser emission spectra were distinct for the two orthogonal polarizations. Figure 4 gives the emission spectra recorded at two different pump powers; the output coupling used was $T=2\%$. For $P_{abs}=4.8$ W, at which the $[\bar{1}10]$ polarization component just started oscillating with an output power of 0.02 W, its emission spectra consisted of two lines centered at 1024.3 and 1025.5 nm, whereas for the

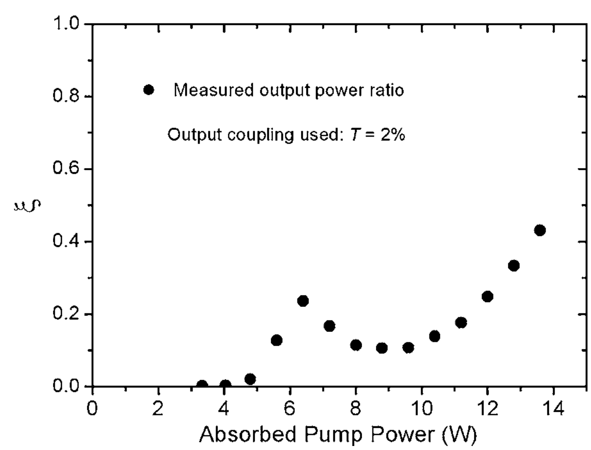

Fig. 3. Variation with P_{abs} of the output power ratio (ξ) between the two orthogonal polarizations along the $[\bar{1}10]$ and [110] directions.

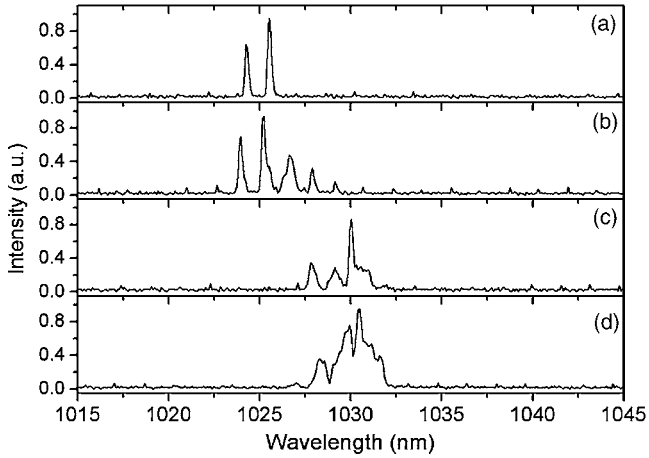

Fig. 4. Laser emission spectra of the two orthogonal polarization components recorded with output coupling $T=2\%$: (a) $[\bar{1}10]$, $P_{abs}=4.8$ W, $P_{out}=0.02$ W; (b) [110], $P_{abs}=4.8$ W, $P_{out}=1.04$ W; (c) $[\bar{1}10]$, $P_{abs}=7.2$ W, $P_{out}=0.28$ W; (d) [110], $P_{abs}=7.2$ W, $P_{out}=1.64$ W.

[110] polarization the spectra were made up of five discrete lines located at 1023.9, 1025.2, 1026.6, 1027.9, and 1029.1 nm. For an intermediate pumping level of $P_{abs}=7.2$ W, the individual emission lines became overlapped, with the peak wavelength shifted to 1030 and 1030.5 nm for $[\bar{1}10]$ and [110] polarization components, respectively. The emission lines observed were determined mainly by the intracavity air etalon formed by the plane mirror and one of the uncoated crystal surfaces (~0.4 mm thick, leading to a free spectra range of ~1.25 nm).

The linearly polarized laser oscillation achieved with the *c*-cut $Yb:LuVO_4$ crystal is attributed to the existence of some degree of birefringence in the crystal. Similar situations have been encountered in some Nd:YAG microchip lasers, in which the stress-induced birefringence in the optically isotropic crystal led to linearly polarized oscillation.[8,9] However, the *c*-cut $Yb:LuVO_4$ laser differs significantly from those Nd:YAG lasers: The polarization directions in those Nd:YAG lasers were determined by the stress exerted on the crystal, whereas the lasing polarizations retained parallel to [110] and $[\bar{1}10]$ directions in the case of *c*-cut $Yb:LuVO_4$, regardless of the direction alteration of the stress applied through the copper holder. Therefore the birefringence present in the *c*-cut $Yb:LuVO_4$ crystal might be induced through the elasto-optic effect, by the residual strain formed during crystal growing, and/or by the process of sample preparing (only the crystal boule was annealed after its growth).

Placing the crystal between two orthogonal polarizers and using a He–Ne laser as a probe beam, we examined the anisotropy of the *c*-cut $Yb:LuVO_4$ crystal under conditions of no pumping. Just as expected, the crystal did exhibit weak birefringence, with the induced principal axes parallel to [110] and $[\bar{1}10]$ directions, which represent the two orthogonal eigenpolarization directions. This means the $Yb:LuVO_4$ has become, in some sense, a biaxial crystal owing to the residual strain. As in a real biaxial laser crystal, laser oscillation is usually generated with its polarizations parallel to these two directions. Because of the similar gain cross sections for the two polarizations, strong polarization competition is predicted in the resultant laser operation; this has been demonstrated in our experiment by the substantial variation of the output power ratio between the two polarization components.

From a practical point of view, the *a*-cut $Yb:LuVO_4$ crystal is more advantageous, not only because of the more efficient laser operation with higher attainable output power, but also because of its simple linear polarization nature as well. On the other hand, however, the *c*-cut $Yb:LuVO_4$ laser oscillating in two orthogonal polarizations simultaneously, may also find some practical applications.

In conclusion, high-power laser performance of both *a*-cut and *c*-cut $Yb:LuVO_4$ crystals was investigated by diode end pumping based on a simple plano–concave resonator. With an uncoated 2 mm *a*-cut crystal, a maximum output power of 8.3 W in π polarization was generated with an optical conversion efficiency of 59%. The slope efficiency reached prior to the appearance of output saturation was as high as 80%. Linearly polarized laser operation was also achieved with a *c*-cut crystal, for the first time to our knowledge in vanadates lasers, in which two orthogonal polarization components were present simultaneously with their polarizations parallel to [110] and $[\bar{1}10]$ directions. The maximum output power attained in this case was 4.5 W, with an optical efficiency of 33% and a slope efficiency of 40%.

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