Characteristics of a continuous-wave Yb:$GdVO_4$ laser end pumped by a high-power diode

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An efficient and compact diode-pumped continuous-wave Yb:GdVO4 laser is demonstrated, generating an output power of 4.0 W with an optical conversion efficiency of 61% and a slope efficiency as high as 78%. With increasing pump power the polarization of the laser output changes from σ to π, while in a certain intermediate power range the two polarization states coexist with different emission wavelengths. © 2006 Optical Society of America

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As laser host media for the Yb ion emitting at ~1 μm, orthovanadate crystals including YVO_4, $GdVO_4$, and $LuVO_4$ have recently attracted much attention of the researchers working on solid-state lasers.[1–5] The major advantage of vanadate hosts in comparison with the currently popular potassium double tungstates [$KY(WO_4)_2$, $KGd(WO_4)_2$, and $KLu(WO_4)_2$] arises from their 1.5–2.5 times higher thermal conductivity (~2.5–4 W m^{-1} K^{-1} for tungstates), which is crucial to high-power solid-state lasers. In this respect, Yb:$GdVO_4$ is particularly promising among the Yb-doped vanadates; its thermal conductivity is comparable with that of Yb:YAG.[3] Despite this, however, its laser properties were studied only preliminarily by using Ti:sapphire laser pumping with an output power less than 0.5 W.[3]

In this Letter, we report the characteristics of an efficient and compact Yb:$GdVO_4$ laser end pumped by a high-power fiber-coupled diode laser. Our results indicate that, in the absence of an intracavity polarization selective element, the polarization of the laser field undergoes a transition from σ ($\parallel a$ axis) to π ($\parallel c$ axis) with increasing pump power; an intermediate region exists in which the two polarizations coexist but the corresponding oscillation wavelengths are different.

The absorption and emission spectra of Yb:$GdVO_4$ presented in Ref. 3 are quite different from those of Yb:YVO_4 and Yb:$LuVO_4$. Compared with Yb:YVO_4 and Yb:$LuVO_4$, the maximum π-polarization absorption and emission cross sections (σ_{abs} and σ_{em}) near 984 nm are much lower (roughly three and five to seven times, respectively).[1–5] More important, the σ_{em} for σ polarization is larger than for π polarization, resulting in a greater gain cross section for the entire wavelength range. This is in contradiction to the results obtained in the present work.

To clarify this, we measured the absorption spectra of Yb:$GdVO_4$ at room temperature by use of two 3 mm thick crystals with Yb concentrations of 0.9 and 3.0 at. %, and computed the σ_{em} spectra by the modified reciprocity method.[1] The radiative lifetime used in the computation was taken to be 345 μs, which is the fluorescence lifetime measured by the pinhole method with a 3.0 at. % crystal (5 at. % in melt).[2,4] As shown in Fig. 1, the major features of the σ_{abs} and σ_{em} spectra for π polarization are very similar to those of both Yb:YVO_4 and Yb:$LuVO_4$, with comparable cross section values at the peak wavelength of 985 nm.[1,2,4] It should be noted, however, that the peak of the σ_{em} spectrum at 985 nm for σ polarization is much less pronounced, giving a relatively large cross section ratio of 0.70 of the longer wavelength shoulder (at 1005 nm) to the peak, in contrast to 0.50 and 0.33 for Yb:YVO_4 and Yb:$LuVO_4$, respectively.[1,4]

The Yb:$GdVO_4$ laser was built on the basis of a compact plano–concave resonator arranged in a near hemispherical configuration. The plane mirror was

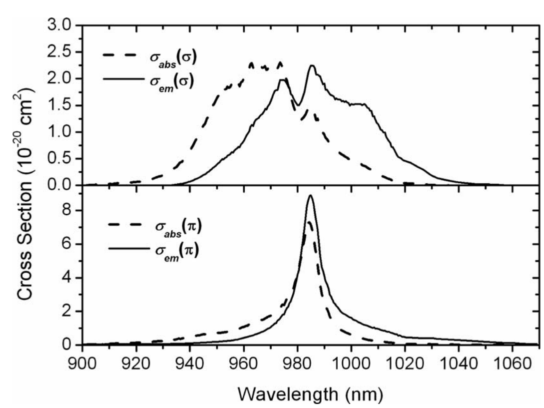

Fig. 1. Polarized absorption and emission cross sections of Yb:$GdVO_4$ at room temperature.

highly reflecting for 1015–1230 nm (>99.8%) and highly transmitting for 880–990 nm (>97%). The output coupler was a concave mirror with radius of curvature of 25 mm. The 0.9 at. %, 2 mm thick uncoated $Yb:GdVO_4$ crystal with an aperture of 3.3 mm × 3.3 mm was held in a water-cooled copper block (cooling water maintained at 12°C) and was positioned close to the plane mirror. The pump source used was a 50 W high-brightness, fiber-coupled diode laser (S50-980-2, Apollo Instruments, Incorporated) with a fiber core diameter of 200 μm and NA of 0.22. Its emission wavelength ranged from 974 to 981 nm depending on the output power level. The unpolarized pump beam was focused by a 1:1 reimaging unit and delivered onto the $Yb:GdVO_4$ crystal through the plane mirror. The cavity length was ~25 mm, yielding a 1:3 ratio of the laser mode radius to the pump spot.

Figure 2 shows the dependence of the output power on the absorbed pump power for three output transmissions ($T=0.5\%$, 1%, and 2%). Optimal operation was achieved by using a coupler with $T=1\%$, for which the output power reached 4.0 W at an absorbed pump power of 6.6 W. The optical conversion efficiency and slope efficiency in this case were 61% and 78%, respectively. Slightly lower slope efficiencies of 73% and 69% were obtained for $T=0.5\%$ and 2%, respectively. For all three coupling transmissions used, the laser output was π polarized while operating at the highest power levels, whereas the emission wavelength shifted from 1045 nm ($T=0.5\%$) to 1040 nm ($T=1\%$) and 1031 nm ($T=2\%$).

The fraction of the incident pump power absorbed in the $Yb:GdVO_4$ crystal measured under nonlasing conditions was ~20%. Such a low absorption results from the shorter than optimal pumping wavelength that changed from 974 to 979 nm for the actual pump powers used in the experiment, the relatively low Yb ion concentration in the crystal ($1.09\times10^{20}\ cm^{-3}$), and the reduction of the σ-polarization absorption cross section [$\sigma_{abs}(\sigma)$], which decreases from 2.28×10^{-20} to $1.40\times10^{-20}\ cm^2$ when the pump wavelength increases from 974 to 979 nm.

It is worthwhile to point out that the dependence of the output power on the absorbed pump power given in Fig. 2 was recorded by decreasing the pump power. In doing so, the thresholds reached for $T=0.5\%$, 1%, and 2% corresponded to absorbed pump powers of 1.5, 1.6, and 1.8 W, respectively; very close to these "down" thresholds the output power levels amounted to 0.18, 0.18, and 0.21 W, respectively. With the pump power increased from below the down threshold, however, more absorbed pump power was required for the laser to reach an "up" threshold. The absorbed pump power for reaching the up threshold in the cases of $T=0.5\%$, 1%, and 2% was, respectively, 2.2, 2.3, and 2.2 W. At these threshold pump levels, the output power immediately reached 0.68, 0.71, and 0.52 W, respectively. The laser oscillation was found in σ polarization at both the down and up thresholds. The presence of two different thresholds with finite (nonvanishing) output powers means that the $Yb:GdVO_4$ laser exhibits typical bistable behavior. Similar effects have also been encountered in $Yb:YVO_4$, $Yb:LuVO_4$, and $Yb:Lu_xGd_{1-x}VO_4$ lasers, which are under further consideration.

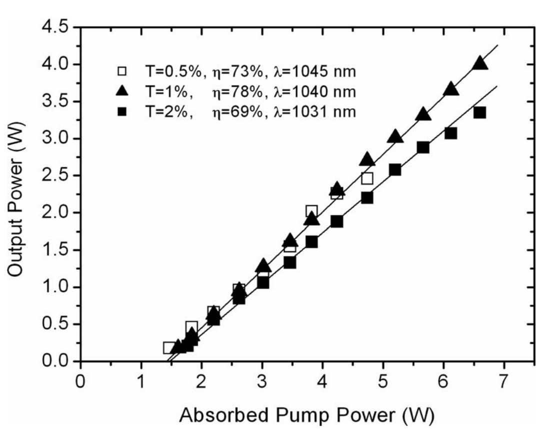

Fig. 2. Output power as a function of absorbed pump power for three output couplings.

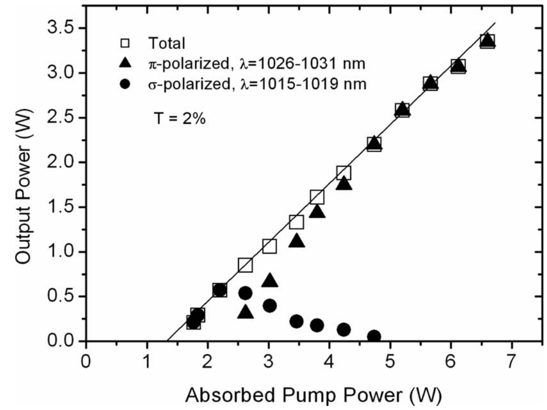

Fig. 3. Variations of σ- and π-polarized output power with the absorbed pump power for an output coupling of $T=2\%$.

One characteristic of the $Yb:GdVO_4$ laser distinguishing it from its $Yb:YVO_4$ and $Yb:LuVO_4$ counterparts is the significant competition between the σ- and π-polarization states of the oscillation. Figure 3 illustrates the dependence on the absorbed pump power of the σ- and π-polarized portions of the output in the case of $T=2\%$, obtained by increasing the pump power from above the down threshold. At low pump powers the laser oscillated in σ polarization. This state remained unchanged until the absorbed pump power reached 2.6 W; at that point, π-polarized oscillation occurred, and the laser entered a region in which the two polarization states coexisted at different oscillation wavelengths. This region extended from 2.6 to 4.7 W in terms of absorbed pump power, in which the π-polarized output increased, whereas the σ-polarized output decreased with increasing pump power. Exceeding the absorbed pump power of 4.7 W, only the π-polarized oscillation existed. Figure 4 presents typical laser emission spectra recorded in the three operational regimes, revealing the evolution of the emission wavelength with the output power. For σ-polarized oscillation the laser wavelength varied from 1015 to 1019 nm; for π-polarized oscillation, this wavelength range was 1026–1031 nm.

This polarization competition originates from the wavelength dependence of the gain cross section, which is different for σ and π polarizations. The effective gain cross section for a quasi-three-level system is given by

$$\sigma_g(\lambda) = [\beta\sigma_{\mathrm{em}}(\lambda) - (1-\beta)\sigma_{\mathrm{abs}}(\lambda)], \quad (1)$$

where β is the fraction of the Yb ions excited to the upper manifold. Figure 5 illustrates an example of the calculated $\sigma_g(\lambda)$ spectra, corresponding to $\beta = 0.12$, which is reasonable for our operational conditions. The polarization changing exhibited in the operation of the Yb:$GdVO_4$ laser can be qualitatively understood from the simple $\sigma_g(\lambda)$ spectra. As shown in Fig. 5, gain cross sections are nearly the same for both polarizations, but the maximum for σ polarization is shifted to shorter wavelength. Therefore small changes in the losses during laser operation can lead to polarization competition. Switching between the two polarization states is connected with a change in the emission wavelength. With increasing absorbed

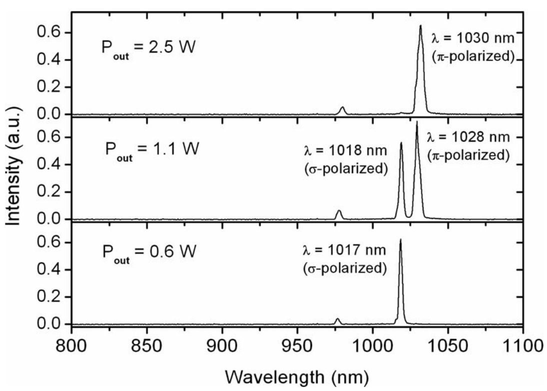

Fig. 4. Typical laser emission spectra recorded in the three operational regimes.

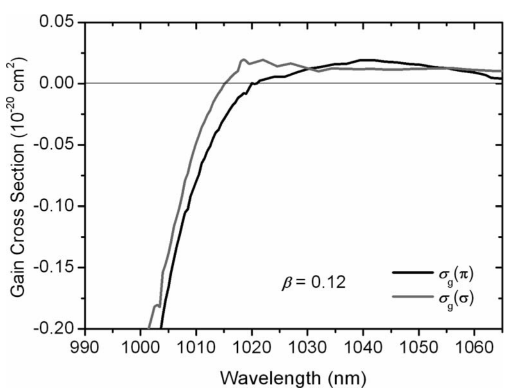

Fig. 5. Calculated gain cross section versus wavelength for $\beta = 0.12$.

pump power, the temperature rising inside the small working volume of the crystal enhanced the thermal population in the terminal laser level; as a result, the laser was forced to oscillate in longer wavelength range where the π polarization possesses higher gain, hence starting π-polarized oscillation. The coexisting region is due to the fact that the gain cross section is comparable for σ and π polarizations in a certain wavelength range.

The polarization competition and the resulting polarization state switching found in the Yb:$GdVO_4$ laser clarifies the somewhat confusing situation encountered in the previous work on Yb-doped vanadates: in Yb:$GdVO_4$, σ-polarized oscillation was obtained,[3] whereas in Yb:YVO_4 and Yb:$LuVO_4$, the laser oscillation was always found in π polarization.[1,2,4] The polarization competition effect in Yb:YVO_4 and Yb:$LuVO_4$, if it exists, must be much less significant compared with that in Yb:$GdVO_4$.

In conclusion, we have demonstrated an efficient Yb:$GdVO_4$ laser end pumped by a high-power diode laser that is capable of producing a cw output power of 4.0 W with an optical efficiency of 61% and a slope efficiency of 78%. With rising pump power the laser oscillation was found to change from σ to π polarization with an intermediate region in between where the two polarization states coexist at different emission wavelengths.

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