Low quantum defect laser oscillation of a new mixed $Yb_{0.009}:Y_{0.575}Gd_{0.416}VO_4$ crystal

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Abstract: Spectroscopic properties and continuous-wave laser performance of a new $Yb_{0.009}:Y_{0.575}Gd_{0.416}VO_4$ mixed vanadate crystal are reported. Purely σ-polarized laser oscillation at 1013–1009.5 nm, with quantum defect lower than 3%, is demonstrated at room temperature in free running mode under diode pumping, producing an output power of 1.55 W with optical-to-optical and slope efficiencies of 19% and 32%, respectively. At longer wavelengths where the π-polarized oscillation exhibited higher gain, the output power reached 2.5 W, with a slope efficiency of 41%.

OCIS codes: (140.3615) Lasers, ytterbium; (140.3580) Lasers, solid-state; (140.3480) Lasers, diode-pumped.

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1. Introduction

In the past decade, significant progress has been made in the development of ytterbium (Yb) ion solid-state lasers based on a wide variety of host crystals. Compared with conventional Nd ion lasers operating near 1 μm, the Yb laser has a major advantage: The quantum defect for the emission process is considerably lower, resulting from the in-band pumping inherent to the two-manifold energy level scheme of the Yb ion. Among the various Yb laser materials developed so far, the orthovanadates, including Yb:YVO_4, Yb:$GdVO_4$, and Yb:$LuVO_4$, seem one class of the most advantageous in achieving low quantum defect laser oscillation, owing to their main absorption band centered at ~985 nm which is longer than in other Yb crystals [1–4], providing the potential of reducing the quantum defect to a small value under conditions of ordinary diode pumping. In combination with their relatively high thermal conductivities, this character may make Yb doped vanadates even more attractive for applications in high power or high repetition rate lasers. This is particularly true for Yb:$GdVO_4$, which is capable of oscillating in the σ-polarization at wavelengths as short as 1015 nm [3,5]. In the diode-pumped Yb:$GdVO_4$ laser, however, the short-wavelength oscillation is usually suppressed under higher pumping levels by the π-polarized one which exhibits higher gain at longer wavelengths [3], making it impractical to scale the output of a Yb:$GdVO_4$ laser to high powers while maintaining the short-wavelength oscillation in σ polarization.

It was found from our previous work that the Yb-doped yttrium gadolinium mixed vanadates, Yb:$Y_xGd_{1-x}VO_4$, possess partly the features of Yb:$GdVO_4$, being capable of sustaining σ-polarized laser oscillation at short wavelengths. In this paper, we report on the spectroscopic properties and continuous-wave (cw) laser performance of a new $Yb_{0.009}$:$Y_{0.575}Gd_{0.416}VO_4$ crystal, one such mixed vanadate with compositional local disorder. Purely σ-polarized cw laser oscillation was realized in free running mode with a low quantum defect.

2. Description of the experiment

The $Yb_{0.009}$:$Y_{0.575}Gd_{0.416}VO_4$ crystal was grown by the Czochralski method. The exact content of Y and Gd in the crystal was determined by the x-ray fluorescence analysis method. The Yb concentration in the crystal, 0.92 at. %, corresponding to 1.13×10^{20} cm^{-3}, was measured also using this technique. Two crystal samples with a thickness of 1.5 and 6 mm, were prepared for spectroscopic measurements; another 2 mm thick sample was available for the laser experiments. All the crystals were *a*-cut, with an aperture of 3.3 mm × 3.3 mm.

The laser was built on a plano-concave resonator arranged in a near hemispherical configuration. The plane mirror was coated 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 were used, with output coupling (T) in the range of 0.5%–5%. The 2 mm thick uncoated crystal was fixed in a water-cooled copper holder and placed close to the plane mirror inside the cavity. The pump source was a 50 W fiber-coupled diode laser (S50-980-2, Apollo Instruments, Inc.) with a fiber core diameter of 200 μm and NA of 0.22, its emission wavelength, depending on the operational level, was tuned to ~ 985 nm through adjusting the temperature of the cooling water at an output power of 32 W, which was the highest incident pump power applied in the experiment. The unpolarized pump radiation was first focused by a 1:1 reimaging unit and then delivered onto the laser crystal through the plane mirror.

3. Results and discussion

The polarized absorption spectra of $Yb_{0.009}$:$Y_{0.575}Gd_{0.416}VO_4$ were measured at room temperature for both **E**//*c* (π polarization) and **E**⊥*c* (σ polarization). The results are represented in terms of absorption cross section (σ_{abs}) in Fig. 1. Also shown in this figure are

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the polarized emission cross section (σ_{em}) spectra, which were calculated according to the reciprocity method [6]. As in the cases of Yb:YVO_4 and Yb:$GdVO_4$ [1,3], the absorption for π polarization is much stronger than for σ polarization, with a peak cross section of σ_{abs} = 4.8×10^{-20} cm^2 at 985 nm, the bandwidth (FWHM) being 9.5 nm. For σ polarization, the very broad band around 964 nm could be in principle also utilized for pumping. One notes from Fig. 1 that, for both polarizations, the emission peak appearing at 985 (π) and 986 nm (σ) corresponds to the zero-phonon transition, with a maximum cross sections of σ_{em} = 5.8×10^{-20} cm^2 (π) and 1.6×10^{-20} cm^2 (σ).

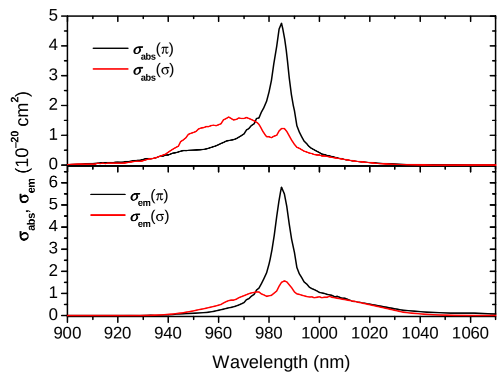

Fig. 1. Polarized absorption and emission spectra of $Yb_{0.009}$:$Y_{0.575}Gd_{0.416}VO_4$ at room temperature.

In general, the π-polarized absorption or emission spectrum looks very similar for all the vanadates, as only a single, strong band is present around ~985 nm [1–4]. It is more instructive to compare the σ-polarized absorption and emission spectra of the mixed crystal with those of Yb:YVO_4 and Yb:$GdVO_4$ [1,3]. As discussed in more detail on the spectroscopic properties of $Yb_{0.007}$:$Y_{0.407}Gd_{0.586}VO_4$ and $Yb_{0.015}$:$Lu_{0.52}Gd_{0.465}VO_4$ [7], the mixed $Yb_{0.009}$:$Y_{0.575}Gd_{0.416}VO_4$ possesses the spectroscopic features of both Yb:YVO_4 and Yb:$GdVO_4$.

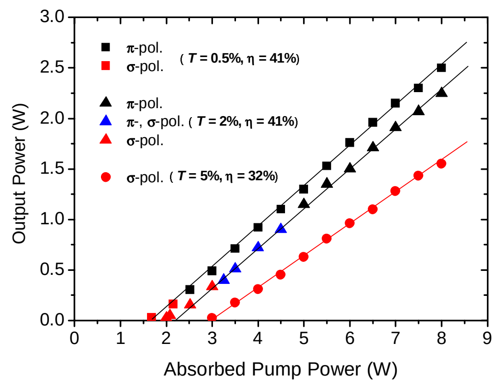

Fig. 2. Output power versus P_{abs} for different output couplings of T = 0.5%, 2%, and 5%, measured with decreasing pump power.

Utilizing the simple plano-concave resonator in a nearly hemispherical configuration, we achieved cw laser operation at room temperature with the 2 mm thick, *a*-cut, uncoated

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$Yb_{0.009}$:$Y_{0.575}Gd_{0.416}VO_4$ crystal. The laser performance was found to depend critically on the output coupling. Figure 2 shows the output power versus absorbed pump power (P_{abs}) for T = 0.5%, 2%, and 5%, respectively, measured with decreasing pump power. Due to the bistable nature of laser operation that seems common to all of the Yb doped vanadate crystals [3,8,9], the laser oscillation at low power levels near threshold was quite different with increasing pump power. As illustrated in Fig. 2, with a coupler of T = 0.5% the laser oscillated in π polarization, producing a maximum output power of 2.5 W at P_{abs} = 8.0 W, with optical to optical and slope efficiencies determined to be 31% and 41%, respectively. Reducing the pump power down to a certain level corresponding to P_{abs} = 2.15 W, the laser oscillation switched its polarization state from π to σ, accompanied by an emission wavelength hopping from 1033.5 to 1021, 1024 nm. This process is illustrated by the evolution of the laser emission spectrum shown in Fig. 3. The σ-polarized oscillation was maintained for P_{abs}< 2.15 W, until the threshold was reached at P_{abs} = 1.7 W.

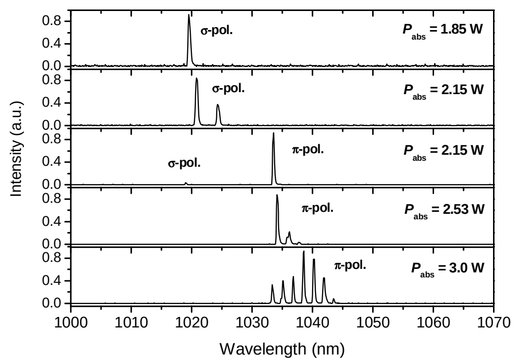

Fig. 3. Evolution of the laser emission spectrum with decreasing P_{abs} recorded for T = 0.5%. The polarization state switching occurs at P_{abs} = 2.15 W.

The σ to π polarization state switching, upon increasing pump power from just above threshold, occurred at a slightly higher pump level of P_{abs} = 2.25 W, owing to the presence of optical bistability in the laser operation, with an emission wavelength shifting from 1019 to 1033 nm.

As summarized in Ref. 8, the laser systems of different types exhibiting optical bistability such as the CO_2 laser, the semiconductor laser, and the Er doped fiber laser, are common in having an internal effective saturable absorber that is the physical reason leading to such behavior. In fact, before its experimental demonstration the optical bistability was predicted theoretically in a laser system having a saturable absorbing medium [10]. In the present case of mixed vanadate, the crystal region near the unpumped end in which the inversion was not established acted as an effective saturable absorber, just as in other Yb vanadate lasers [8,9].

The operational range of purely π-polarized oscillation narrowed with a higher output coupling of T = 2%. The σ-polarized component appeared at P_{abs} = 4.5 W with decreasing pump power and the laser entered a region in which the σ, π polarization states coexisted. Reducing the pump power further within this coexistence region, the σ-polarized oscillation became strengthened while the π-polarized diminished; at P_{abs} = 3.2 W, the π-polarized oscillation was completely suppressed, leaving only the σ polarization state oscillating. Figure 4 presents the evolution of the laser emission spectrum in this process, showing the coexistence and changing of the σ, π polarization states, along with emission wavelength shifting.

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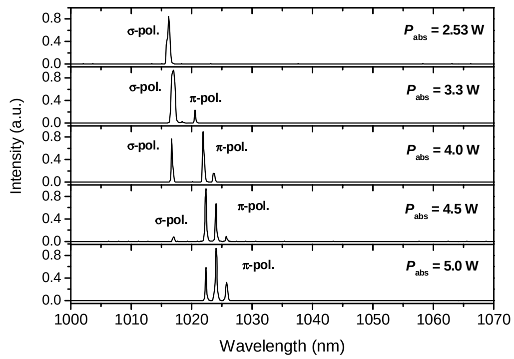

Fig. 4. Evolution of the laser emission spectrum with decreasing P_{abs} recorded for T = 2%. The σ, π polarization states coexist in the range of P_{abs} = 4.5–3.2 W.

The presence of switching and coexistence of different polarization states in the laser operation is due to the different wavelength dependence of the gain cross section for σ and π polarizations. This is exactly the same as in the Yb:$GdVO_4$ laser [3]. A similar situation occurred also in a Yb:$YCa_4O(BO_3)_3$ laser [11]. The curves of gain cross section, $\sigma_g(\lambda) = \beta\sigma_{em}(\lambda) - (1-\beta)\sigma_{abs}(\lambda)$ with β being the fraction of inversion, can provide a basis for understanding the polarization state changing with pump level, as presented in the case of Yb:$GdVO_4$ laser [3]. Unfortunately, we failed in plotting accurate $\sigma_g(\lambda)$ curves based on the spectroscopic data given in Fig. 1. As a result of weak absorption in the wavelength range longer than ~ 1020 nm, the signal-to-noise ratio of $\sigma_{abs}(\lambda)$ is considerably low, leading to a large uncertainty in the calculated $\sigma_{em}(\lambda)$ of the long wavelength region. A possible way of avoiding this difficulty is to calculate the $\sigma_{em}(\lambda)$ of long wavelengths by the so-called β–τ method, as performed in the case of Yb:YLF [12], provided that the emission spectra and fluorescence lifetime are measured.

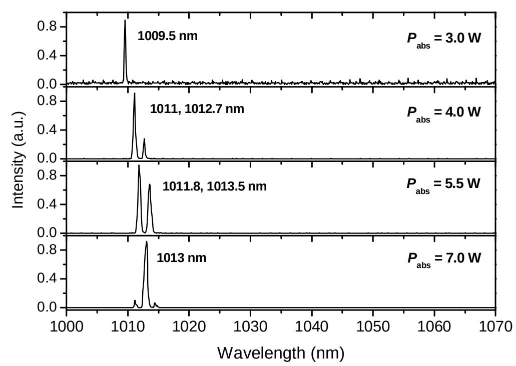

Fig. 5. Evolution of the laser emission spectrum with decreasing P_{abs} recorded for T = 5%. The laser oscillation maintains the σ polarization state.

With a coupler of T = 5%, purely σ-polarized laser oscillation was achieved in the entire operational range. A highest output power of 1.55 W was obtained at P_{abs} = 8.0 W, resulting in an optical to optical efficiency of 19%, while the slope efficiency was 32%. With decreasing pump power, the lasing threshold was reached at P_{abs} = 3.0 W. Figure 5 depicts a series of laser emission spectra for T = 5%, measured at different pump powers. The lasing wavelength shifted with decreasing pump power, from 1013 nm at P_{abs} = 7.0 W, to 1009.5 nm

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approaching the threshold. Such a laser wavelength, 1013–1009.5 nm, represents the shortest ever realized in vanadate lasers under free running conditions. With respect to the pump wavelength of 985 nm, the resulting quantum defect is 2.8%–2.4%.

It is noted from Fig. 2 that the laser efficiency is only slightly reduced at P_{abs} = 8.0 W, the highest absorbed pump power applied in the experiment, indicating the potential of further power scaling. With P_{abs} increased further, however, a crystal fracture was very likely to occur, making the power scaling not feasible. Nevertheless, more output power is expected to generate with low quantum defect from the mixed $Yb_{0.009}$:$Y_{0.575}Gd_{0.416}VO_4$ crystal by improving the crystal quality, choosing properly the crystal thickness and/or the Yb doping level, and optimizing the resonator configuration and pump geometry.

4. Conclusions

In summary, we have studied the spectroscopic properties and cw laser performance of a new mixed $Yb_{0.009}$:$Y_{0.575}Gd_{0.416}VO_4$ crystal with compositional disorder. Purely σ-polarized laser oscillation was achieved at room temperature, generating a maximum output power of 1.55 W with optical to optical and slope efficiencies of 19% and 32%, respectively. Upon decreasing the pump power, the laser emission wavelength shifted from 1013 to 1009.5 nm, giving a low quantum defect of less than 3%. The highest output power generated in π-polarized oscillation amounted to 2.5 W, with a slope efficiency of 41%.

Acknowledgments

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