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Highly efficient Nd:YVO₄ laser by direct in-band diode pumping at 914 nm

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A Nd:YVO₄ crystal was pumped directly into the emitting level by a laser diode at 914 nm for the first time to our knowledge. We achieved an output power of 11.5 W at 1064 nm for an absorbed pump power of 14.6 W, corresponding to an optical efficiency of 78.7%. We demonstrated that thermal effects are very weak, in agreement with the low quantum defect of only 14.1%. © 2009 Optical Society of America
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Nd:YVO₄ is a well-known laser crystal extensively studied in the past 15 years and widely used in commercial lasers. Even if it presents a high-emission cross section and a polarized emission at 1064 nm, it suffers from poor thermomechanical properties limiting the output power to a few tens of watts before beam degradation (spatial quality) and crystal fracture [1]. To push deleterious thermal effects at higher pump power levels, one can mention pumping at longer wavelengths than the classical one (808 nm) [2]. In fact, reduction of the quantum defect induced by in-band pumping around 880 nm represents one of the best methods for power scaling of Nd:YVO₄ while maintaining an excellent beam quality. First demonstrated under Ti:sapphire pumping [2], this concept has been successfully derived with high-power laser diodes in a large number of configurations [3–5]. In this way, it is possible to go further, as 880 nm is not the longest wavelength of the absorption band. Indeed, starting from the highest sublevel of the ground state manifold (see Fig. 1), Nd:YVO₄ still presents a small absorption at 914 nm that can be used for pumping. In comparison with a pumping at 880 nm, the thermal load can be reduced by 18.5%. Moreover, pumping at 914 nm opens the possibility to use InGaAs laser diodes, widely used for the pumping of Yb³⁺-doped fibers (at 915 nm) and more efficient than AlGaAs laser diodes emitting around 880 nm.

Because of the very small absorption compared with the one around 880 nm (see Fig. 2), the first (to our knowledge) demonstration of an Nd:YVO₄ laser pumped near 914 nm was realized with an intracavity setup where the pump beam is very powerful and diffraction limited, ensuring a perfect overlap between the pump and the laser beams [6]. Consequently, direct diode pumping of Nd:YVO₄ at 914 nm represents a challenge that might be taken up if extremely high-brightness laser diodes are used in combination with relatively highly doped Nd:YVO₄ crystals. In this Letter, we report on a highly efficient

1064 nm Nd:YVO₄ laser pumped at 914 nm by a laser diode for what we believe to be the first time.

The laser diode used is a high-brightness fiber-coupled device (Corvus from Spectra Physics), emitting up to 35 W at 914 nm with a 100 μm diameter core fiber (NA=0.22). The inset of Fig. 2 shows that the absorption band is broad enough (approximately 4 nm) to provide an efficient absorption of all the spectral components of the laser diode (width of 2.5 nm).

As a crystal, we chose a 1.5 at. % -doped sample (10-mm-long *a*-cut). We did not use higher concentration, because the spectroscopic properties of Nd:YVO₄ are considerably affected by doping concentration increase (for example, the lifetime is reduced to 68 μs for a 1.5 at. % [7]). As vanadate crystals present anisotropic properties, we first investigated the effect of beam polarization on the pump absorption at 914 nm. By the use of a polarizer put in our pump beam, we measured an absorption slightly higher along the *c* axis than along the *a* axis ($\alpha_c=0.65\text{ cm}^{-1}$ and $\alpha_a=0.46\text{ cm}^{-1}$, respectively). It is far from the strong difference between the two axes at 808 nm [3], and it is very similar to the absorption polarization properties at 888 nm. As mentioned in

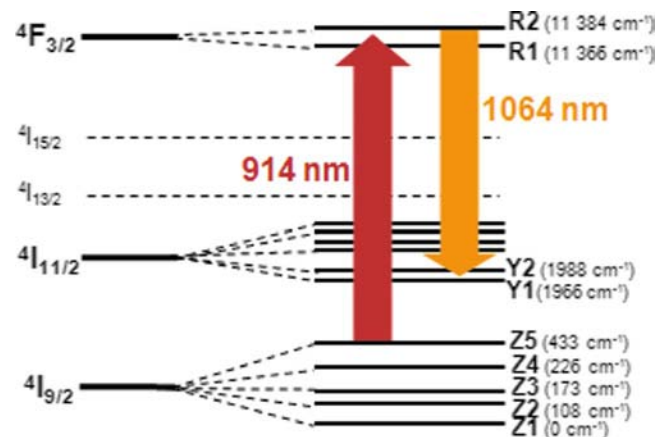


Fig. 1. (Color online) Energy levels of Nd³⁺:YVO₄.

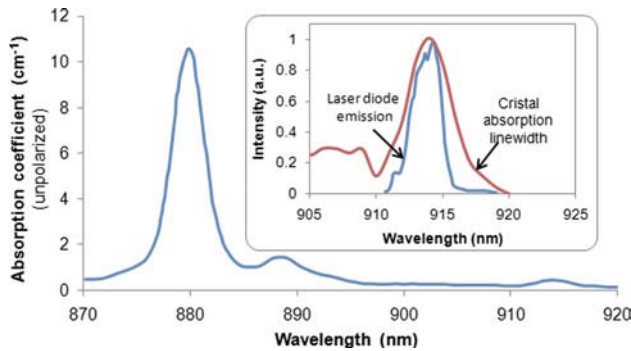


Fig. 2. (Color online) Unpolarized absorption spectrum between 870 nm and 920 nm given for a 1 at. % Nd:YVO₄ crystal (*a* cut). Inset, laser diode spectrum compared with the absorption spectrum around 914 nm.

[3], this nearly unpolarized absorption is an asset to avoid the polarization control of the pump source. For our pump beam (unpolarized), the absorption coefficient was measured to $\alpha=0.58\text{ cm}^{-1}$, close to the average between the *a* axis absorption and the *c* axis absorption. This corresponds to an overall absorption of 52%. The measurements were done at room temperature.

As the lower level of the pump transition is thermally populated (see Fig. 1), we also investigated the temperature influence on the absorption at 914 nm. We varied the crystal temperature between 20°C and 100°C by heating the crystal mount with a Peltier element. The temperature was monitored with a thermistor placed at the crystal surface. As expected, the absorption was slightly higher at 100°C with a variation of 10%. Indeed, the influence of the temperature on the absorption is much lower than that in Nd:YAG pumped at 938 nm [8], as the energy of the lower level of the pump transition is lower (433 cm^{-1} in Nd:YVO₄ versus 857 cm^{-1} in Nd:YAG). For the sake of simplicity, we realized the following experiments at room temperature.

The crystal was coated with a dichroic mirror on the pumped face: highly transmissive at 914 nm ($T=93\%$) and highly reflective at 1064 nm ($R>99.5\%$). The second face was antireflection coated at 1064 nm. It was mounted in a copper block, cooled by two sides (bottom and top) with the *c* axis in the horizontal plane. To obtain a high laser efficiency, we took care of the overlap between the pump beam and the cavity beam. To limit the pump beam divergence in the Nd:YVO₄ crystal, we used two doublets (50 mm and 250 mm, respectively) with a large magnification factor. Hence the pump beam radius was $250\text{ }\mu\text{m}$ at the focus point in the crystal and increased only to $310\text{ }\mu\text{m}$ at the crystal ends. The cavity was chosen such that the cavity beam radius in the crystal was larger than the maximum pump beam size. It was a three-mirror cavity with a plane output coupler, a concave mirror (radius of curvature 100 mm), and the mirror coated on the crystal (see Fig. 3). This design presents the advantage of controlling the beam size in the Nd:YVO₄ crystal very precisely by modifying the distance between the output coupler and the concave mirror. In our case, best performance

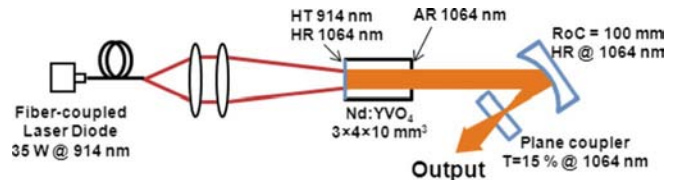


Fig. 3. (Color online) Experimental setup.

was obtained for a beam waist radius of $320\text{ }\mu\text{m}$ in the Nd:YVO₄ crystal, corresponding to a distance between the output coupler and the concave mirror of 53 mm. The best performance was obtained with an output coupler transmission of 15% at 1064 nm. Figure 4 shows the output power obtained versus the absorbed pump power. The laser threshold was reached for an absorbed pump power as low as 100 mW. The maximum output power was 11.5 W for an absorbed pump power of 14.6 W, corresponding to a slope efficiency as high as 80.7%, which is very close to the quantum efficiency (85.9%). The optical efficiency, defined by the ratio between the output power and the absorbed pump power, was 78.7%. To our best knowledge, it corresponds to the highest optical efficiency ever reported for a diode-pumped Nd:YVO₄ laser at this power level. Moreover, we measured the M^2 quality factor to be 1.1 in the horizontal plane (see Fig. 4 inset) and 1.2 in the perpendicular plane, corresponding clearly to a nearly Gaussian beam profile.

Such a high efficiency is a consequence of the excellent overlap between the pump beam and the cavity beam in all the Nd:YVO₄ crystal. Moreover, the large beam size and the small absorption coefficient limited the local population inversion density and reduced locally upper-laser-level loss mechanisms such as Auger recombination, multiphonon decay, and concentration quenching [9]. To see the contribution of these effects to the thermal load, we measured the temperature of the pumped face with or without laser action with an IR camera in a setup reported elsewhere [10] at the maximum absorbed pump power (14.6 W). With laser action, the population inversion density is very low (clamped to its value at threshold), and we can assume that the rate for upper-laser-level loss mechanisms is negligible compared with the rate of stimulated emission: we measured a tem-

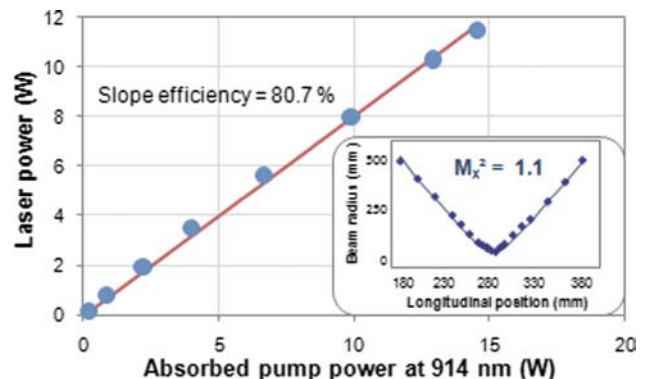


Fig. 4. (Color online) Output power versus absorbed pump power. Inset, beam radius evolution along the propagation axis, after imaging. The straight line corresponds to a fit for a beam with $M^2=1.1$.

perature increase of 15°C between the center and the edge of the pumped face. Without laser action, the population inversion density is much higher and upper-laser-level loss mechanisms can contribute significantly to the thermal load. This time, we measured a temperature increase of 20°C . Assuming that the temperature increase is proportional to the thermal load [9], the ratio α_{Th} between the thermal load with laser action and the thermal load without laser action, was equal to $\alpha_{\text{Th}}=0.75$. By thermal lens measurement, Blows *et al.* [9] found a ratio $\alpha_{\text{Th}}=0.5$ for a 2 at. %-doped Nd:YVO₄ crystal pumped with a power of only 800 mW at 808 nm. This demonstrates the low contribution of upper-laser-level loss mechanisms to the thermal load in our setup. As the temperature gradient is very low compared with other experiments realized under pumping at 808 nm [10], we expected to have a very weak thermal lens in the crystal. To carry out this measurement, we took advantage of the sensitivity of our cavity to the thermal lens. As the crystal was placed in a collimated arm with a large beam size, even a weak thermal lens induced a variation of the beam size on the output coupler. Hence, we measured the beam size on the output coupler versus the absorbed pump power. We found a beam size variation lower than 10% from oscillation threshold to maximum pump power. Next we calculated the corresponding thermal lens thanks to *ABCD* matrices (assuming that the beam remained Gaussian, as it was clearly the case). We found a value of 0.6 m^{-1} at maximum pump power. This is 1 order of magnitude lower than the thermal lens measured under hardly 800 mW of absorbed pump power at 808 nm [9].

In conclusion, we demonstrated what we believe to be the first Nd:YVO₄ laser under in-band diode pumping at 914 nm. The optical efficiency of 78.7%

(with respect to the absorbed pump power) is the highest ever reported for a diode-pumped Nd:YVO₄ laser and is close to the quantum efficiency of 85.9%. Moreover, both thermal mapping and thermal focal lens measurement have clearly demonstrated very low-heat generation under in-band pumping at 914 nm. The thermal effects are so low that the laser can be used in the full range of the available pump power without any additional optimization. This represents a great improvement for the versatility of Nd:YVO₄ sources, generally optimized at fixed pump power and an asset for power scaling of such systems. To go further, longer crystals and a double-pass pumping scheme can be used to increase the absorption and much higher pump power can be considered, as the thermal load are strongly reduced.

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