Continuous-wave laser at 440 nm based on frequency-doubled diode pumped Nd:GdVO4 crystal

Marc Castaing, François Balembois, Patrick Georges

Continuous-wave laser at 440 nm based on frequency-doubled diode-pumped $Nd:GdVO_4$ crystal

Marc Castaing,[1,2,*] François Balembois,[1] and Patrick Georges[1]

[1]*Laboratoire Charles Fabry de l'Institut d'Optique, du CNRS et de l'Université Paris-Sud, Campus Polytechnique, RD 128, F-91127 Palaiseau, France*

[2]*Oxxius, Lannion, France*

**Correspoding author: marc.castaing@institutoptique.fr*

Received June 2, 2008; revised July 21, 2008; accepted July 22, 2008; posted July 29, 2008 (Doc. ID 96958); published August 22, 2008

We present for the first time, to the best of our knowledge, a frequency-doubled $Nd:GdVO_4$ laser operating in a cw on the pure three-level laser line at 880 nm. We obtained 300 mW at 440 nm for 23 W of incident pump power at 808 nm. Moreover, with a 25% output coupler we obtained a cw power of 1.9 W at the fundamental wavelength at 880 nm. © 2008 Optical Society of America

OCIS codes: 140.3530, 140.3480, 140.7300.

HeCd lasers emitting at 442 nm are particularly useful for many applications such as optical data storage, flow visualization, holography, or Raman spectroscopy. However, the main problems relative to gas lasers are their size, their very restrictive maintenance, and their low efficiency. Diode-pumped solid-state (DPSS) lasers have been developed to overcome these problems with the use of the quasi-three-level transition of neodymium-doped crystals. After second-harmonic generation (SHG), classical wavelengths achieved using these architectures are 456–457 nm ($Nd:GdVO_4/Nd:YVO_4$) [1,2] or 473 nm (Nd:YAG) [3,4]. These lasers are efficient and powerful; nevertheless their wavelengths are too high compared to the 442 nm HeCd laser emission. Other possibilities, e.g., GaN laser diodes emitting a few hundreds of milliwatts [5], or DPSS lasers based on $Cr^{3+}:LiSrAlF_6$ (Cr:LiSAF) crystals intracavity doubled [6], could be considered. However, the first solution is limited by poor spatial beam quality, and the second one is not easily power scalable owing to the bad thermal behavior of the crystal, and to the lack of high brightness of the red laser diode in the absorption band of Cr:LiSAF.

Neodymium-doped crystals such as $Nd:GdVO_4$ oscillating on the pure three-level laser transition $^4F_{3/2}-^4I_{3/2}$ offer an alternative for an emission around 880 nm and at 440 nm after SHG. Demonstration of laser action at 879 nm was done by Herault *et al.* [7]. However, the intracavity power obtained was only of a few watts, making efficient intracavity SHG impossible in cw operation. Indeed, intracavity SHG is very challenging on this pure three-level transition compared to a quasi-three-level laser; the population inversion is much lower and the saturation intensity is much weaker. Indeed, simulations [8,9] (parameters in Table 1) show that the intracavity power is strongly dependent on losses at 880 nm compared to laser emission at 912 nm (Fig. 1). Hence for standard passive losses (around 3%), more than 100 W could be easily achievable at 912 nm in a $Nd:GdVO_4$ crystal, whereas only a few tens of watts could be achieved in the case of 880 nm emission.

In this Letter we present a way to achieve high intracavity power at 880 nm and efficient cw SHG at 440 nm for what we believe to be the first time with a three-level $Nd:GdVO_4$ laser. Efficient laser action on the three-level line is also investigated.

We computed intracavity power at 880 nm versus different parameters such as the M^2 of the pump diode, the crystal length, and the doping concentration. Figure 2 reveals that the M^2 factor is a key parameter to improve intracavity power. We notice that the brighter the pump source, the higher the intracavity power at 880 nm. In the case of a three-level laser, if the pump beam has a too strong divergence (high M^2 factor), the pump intensity does not reach the pump transparency intensity (defined in [7,9]) everywhere in the crystal, so that the medium exhibits absorption in some areas. This explains why three-level lasers are very sensitive to pump brightness.

Moreover, particular care must be taken to choose the right crystal (doping concentration and length). Figure 2 predicts that much better results could be achieved with a 5 mm 0.1% doped crystal compared

Table 1. Theoretical Values Used for the Computations Corresponding to the Experimental Setup

σ_P (10^{-20} cm^2)	$\sigma_{em\ laser}$ (10^{-20} cm^2)	$\sigma_{abs\ laser}$ (10^{-20} cm^2)	Lifetime (μs)	Pump Waist (μm)	Laser Waist (μm)
53.6 (π) 12.3 (σ)	19	28	100	115	60

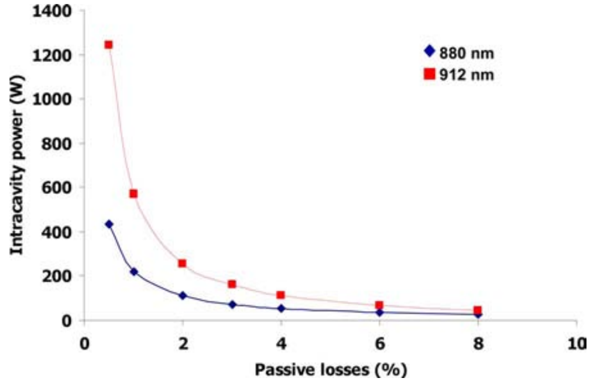

Fig. 1. (Color online) Simulation of the influence of passive losses on the intracavity power achievable at 880 and 912 nm (4-mm-long, 0.2% doped crystal under 20 W incident pump power).

to a 4 mm 0.2% one (the crystal used in [7]). This can be explained by Fig. 3, presenting the evolution of the small signal gain through the whole crystal length in the lasing operation. The 4 mm 0.2% doped crystal presents a strong reabsorbing zone owing to the lack of pump power at the end of the crystal. With a lower absorbing crystal (5 mm 0.1% doped) this effect is significantly reduced, which allows higher intracavity power operation.

In our setup we chose a 25 W laser diode with M^2 around 40 and a 5-mm-long, 0.1% doped $Nd:GdVO_4$ crystal. Simulations (Fig. 2) show that this setup should allow a 2.5 times higher intracavity power than in the setup published in [7]. Despite this optimization, Fig. 2 also points out that the intracavity power remains below 100 W. That is why we decided to use a highly nonlinear crystal, $KNbO_3$. Our crystal is 10 mm long, in type 1 noncritical phase matching (NCPM) at 80°C. This crystal has a nonlinear coefficient 16 times higher than LiB_3O_5 and 3.7 times than BiB_3O_6, which are the most commonly used nonlinear crystals in the blue range. Moreover, as the $KNbO_3$ is in NCPM at this wavelength the angular acceptance and walk-off do not limit the conversion efficiency.

The experimental setup is presented in Fig. 4. The pump source is a laser diode emitting at 808 nm (coupled into a 100 μm core diameter fiber with a nu-

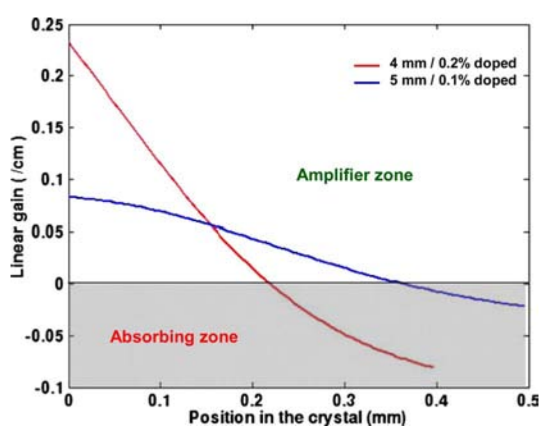

Fig. 2. (Color online) Simulation of the evolution of the linear gain at 880 nm along the crystal.

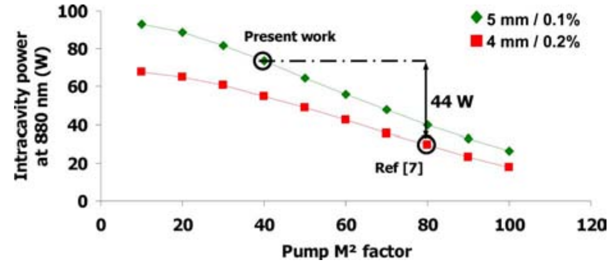

Fig. 3. (Color online) Simulation of the intracavity power at 880 nm versus M^2 factor of the pump beam (for 20 W of incident pump power and cavity round trip losses of 3%).

merical aperture of 0.22). The fiber output is imaged with two doublets through a dichroic mirror [HR (highly transmittive) 880 nm, HT (highly reflective) 808 nm] into the $Nd:GdVO_4$ crystal with a measured waist radius of 115 μm inside. We designed a four-mirror high-finesse cavity that allows a second waist, of 35 μm radius, where the nonlinear crystal is inserted.

The last experimental key point consists in the spectral selection of the three-level laser line. Indeed, in previous work [7] this element was a true limitation involving the blue generation in pulsed mode. In our case we designed dichroic mirrors especially dedicated to this application (M_3 and M_4), with a stiff transmission curve varying from 0.12% at 880 nm to 72% at 912 nm. These mirrors avoid laser operation on the high gain quasi-three-level transition at 912 nm. Moreover, mirrors M_2, M_3, and M_4 are highly transparent at 1063 nm to suppress any parasitic oscillation of the four-level line.

We obtained a maximum cw $TEM_{0,0}$ (inset in Fig. 4) output power of 300 mW at 440 nm horizontally polarized, on three output beams (mirrors not optimized in the blue range). The beam quality of the fundamental was quite good with an M^2 factor inferior to 1.5.

This result was obtained for one optimized point. Indeed, we measured a thermal focal length of 25 mm (via a beam diameter measure at the output of the cavity and *ABCD* matrix computations). By reducing the incident pump power, the thermal focal length increases, which implies a change in the cavity geometry, making it difficult to record an efficiency curve.

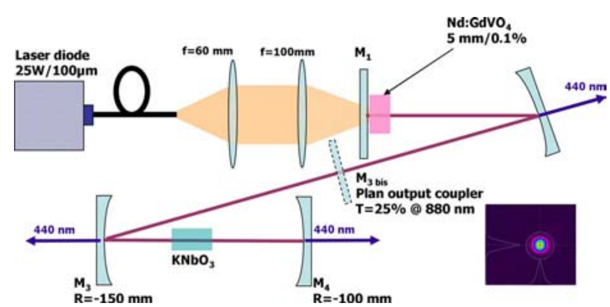

Fig. 4. (Color online) Experimental setup. M_1, HT 808 nm and HR 850–900 nm; M_2, HR 850–900 nm and HT 1064 nm; M_3 and M_4 filter mirrors, HR 880 nm and T =72% at 912 nm. $M_{3\ \mathrm{Bis}}$ corresponds to the 25% output coupler used for the 880 nm extraction.

By replacing the two last mirrors by a plane output coupler having a transmission of 25% at 880 nm (mirror $M_{3\ bis}$ in Fig. 4) we obtained a maximum output power of 1.9 W at 880 nm for 23 W of incident pump power at 808 nm (Fig. 5). The laser emission was $TEM_{0,0}$ and was vertically polarized. Above 16 W pump power no parasitic wavelengths (1063 or 912 nm) have been observed. However, below this level we recorded a slight emission at 1063 nm due to parasitic oscillation between the first mirror and the second facet of the crystal (in spite of the antireflection coating having a reflection inferior to 0.5% at 1063 nm), and also a breaking in the slope efficiency, with a higher threshold than expected. Indeed, this competition reduces the population inversion and increases the 880 nm oscillation threshold.

In conclusion, we succeeded in the realization of what we believe to be the first diode-pumped cw SHG three-level laser at 440 nm based on a neodymium-doped crystal. Key points are pump brightness, crystal length, and doping level, and the use of a highly nonlinear crystal. We achieved a power of 300 mW at 440 nm with a good spatial beam quality. Moreover, 1.9 W has been obtained at 880 nm with a 25% output coupler. This corresponds to a 2.3 times higher output power than in previous work [7]. Further improvements will consider the use of volume Bragg gratings to enhance the spectral selectivity and the possibility of compact architectures will be assessed.

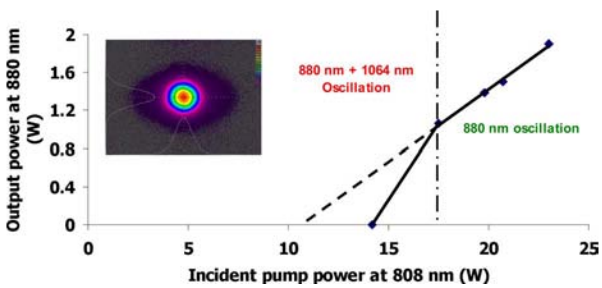

Fig. 5. (Color online) Laser performances in cw operation with a 25% output coupler at 880 nm.

References

1. F. Jia, Q. Xue, Q. Zheng, Y. Bu, and L. Qian, Appl. Phys. B **83**, 245 (2006).
2. C. Czeranowsky, M. Schmidt, E. Heumann, G. Huber, S. Kutovoi, and Y. Zavartsev, Opt. Commun. **205**, 361 (2002).
3. T. Y. Fan and R. L. Byer, Opt. Lett. **12**, 809 (1987).
4. S. Bjurshagen, D. Evekull, and R. Koch, Appl. Phys. B **76**, 135 (2003).
5. www.nichia.com.
6. S. Makio, T. Miyai, M. Sato, and T. Sasaki, Jpn. J. Appl. Phys. Part 1 **39**, 6539 (2000).
7. E. Herault, F. Balembois, and P. Georges, Opt. Lett. **31**, 2731 (2006).
8. W. P. Risk, J. Opt. Soc. Am. B **5**, 1412 (1988).
9. S. Yiou, F. Balembois, and P. Georges, J. Opt. Soc. Am. B **22**, 572 (2005).