Nd:GdVO4 as a three level laser at 879 nm

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We present what we believe to be the first true three-level laser based on a Nd-doped crystal. From the $^4F_{3/2}-^4I_{9/2}$ laser transition, the lower laser level being the ground state, emission at 879 nm in $NdGdVO_4$ has been obtained with diode pumping. Up to 0.8 W of power has been achieved in cw operation and 24 μJ per pulse (35 ns) in the Q-switched regime. Intracavity second-harmonic generation in the pulsed regime is also demonstrated with 178 mW of average output power at 439.5 nm, corresponding to an energy of 17 μJ per pulse. © 2006 Optical Society of America

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Visible lasers are useful in many applications, such as full-color displays, astronomy, or biology. These past few years there has been research to reach wavelengths deeper in the blue.[1] For diode-pumped solid-state lasers there are two ways to reach this range. One way is to design lasers with crystals doped with ions directly emitting in the blue, such as Dy^{3+} (Ref. 2) or Pr^{3+} (Ref. 3). The other way is to develop lasers emitting at the lowest wavelength possible in the near infrared[4] and to perform nonlinear conversion. In neodymium-doped crystals the transition offering the lowest wavelengths is the $^4F_{3/2}-^4I_{9/2}$. This transition is usually used to design lasers around 910 nm in vanadate crystals[5] or at 946 nm in YAG crystal.[6] In these cases the laser system is a quasi-three-level one, the lower laser level of the transition being the highest sublevel of the fundamental manifold. However, the fluorescence spectra also show emission at 879 or 880 nm in vanadate crystals or 869 nm in Nd:YAG, corresponding to a true three-level laser system as shown in Fig. 1 for $Nd:GdVO_4$. This zero-line transition has been previously used to diode pump $Nd:GdVO_4$ crystal,[7] $Nd:YVO_4$,[8] or Nd:YAG,[9] as these crystals are also highly absorbing at these wavelengths. However, a laser emitting at this transition has not been demonstrated so far. The first laser demonstrated by Maiman[10] was in fact a true three-level laser based on Cr-doped ruby emitting at 693 nm under flashlamp pumping. Since then there have been three-level lasers in Yb-doped crystals, such as in S-FAP (strontium fluorapatite) emitting at 985 nm under Ti:sapphire pumping[11] and diode pumping[12] or in Yb-doped fibers emitting around 976 nm under solid-state $Nd:YVO_4$ pumping[13] and diode pumping.[14]

The lower laser level being the ground state, it is naturally populated (see Table 1), making the population inversion difficult to reach. An important parameter is then the pump intensity at the transparency, i.e., the pump intensity for which the gain is null. The calculated transparency intensities for $Nd:GdVO_4$, $Nd:YVO_4$, and Nd:YAG are presented in Table 1. It should be possible for the three crystals to reach this intensity with high-brightness laser diodes. As the transparency intensity is lower for vanadate crystals, we investigated three-laser operation with $Nd:GdVO_4$ and $Nd:YVO_4$ crystals.

In this Letter we demonstrate laser emission around 880 nm in cw and Q-switched operation. Intracavity second-harmonic generation was obtained in pulsed operation by using a nonlinear BiBO crystal to reach blue emission around 440 nm.

The experimental setup used in cw operation is presented in Fig. 2. The pump source was a laser diode emitting at 808 nm, coupled into a 0.22 aperture fiber with a 200 μm diameter core, providing up to 20 W of power. The pump beam was relay imaged into the crystal by two doublets such that the pump waist in the crystal had a radius of 100 μm. At the fiber output the beam was linearly polarized. The

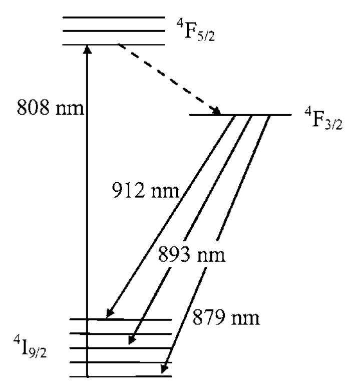

Fig. 1. Energy structure of a $Nd:GdVO_4$ crystal.

Table 1. Spectroscopic Data for $Nd:GdVO_4$, $Nd:YVO_4$, and Nd:YAG

Data	$Nd:GdVO_4$	$Nd:YVO_4$	Nd:YAG
$\lambda_{emission}$ (nm)	879	880	869
Fraction of $^4I_{9/2}$ population in lower laser level at 300 K (%)	40.8	40.1	46.2
Effective emission cross section at $\lambda_{emission}$ (10^{-23} m^2)	2.5	3.7	0.2
Transparency intensity (kW/cm^2)	7.9	5.0	17.2

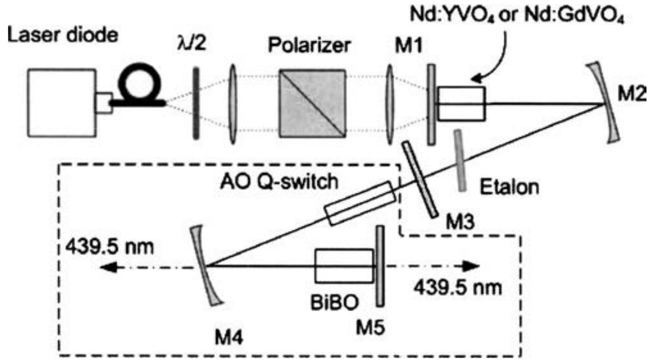

Fig. 2. Experimental setup for cw operation and pulsed operation (inset). Ml, HT at 808 nm, HR at 879 nm; M2, HR at 879 nm, HT at 1064 nm, radius of curvature (RoC) 200 mm; M3, output coupler (transmission 25% or 3% at 879 nm); M4, HR at 879 nm, HT at 1064 nm, RoC 200 mm; M5, HR at 879 nm.

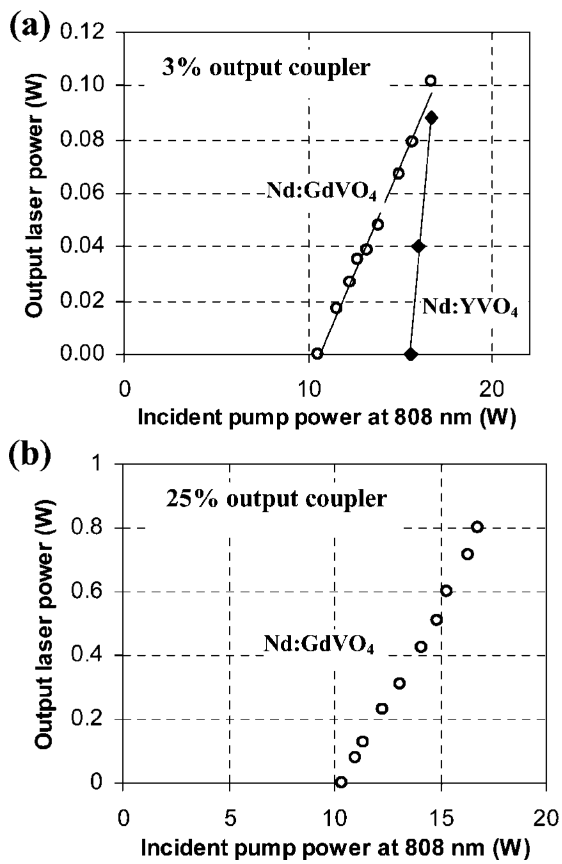

Fig. 3. Three-level laser emission at 880 nm with (a) a 3% output coupler in $Nd:YVO_4$ and $Nd:GdVO_4$ or (b) with a 25% output coupler in $Nd:GdVO_4$.

pump power incident on the crystal was tuned from 0 to 17 W via a half-wave plate and a polarizer. To prevent lasing oscillations at 1063 nm, all the mirrors were highly transmitting (HT) at 1063 nm. The output coupler transmitted 3% from 879 to 914 nm. To select the lasing wavelength, we inserted a 25 μm etalon into the cavity. We tested two laser crystals, a $Nd:YVO_4$ and a $Nd:GdVO_4$. Both crystals had 0.2% Nd doping and were 4 mm long, and their faces were antireflection coated. They were orientated so that the absorption at 808 nm and the laser emission were Π polarized.

We first used a $Nd:YVO_4$ crystal as gain medium, as its transparency intensity is the lowest (see Table 1). We obtained a maximum output power of 88 mW at 880 nm and a pump power at threshold of 15.6 W [see Fig. 3(a)]. Below this pump power we observed laser emission at 1064 nm despite the HT coating of all the mirrors at this wavelength. With the $Nd:GdVO_4$ crystal, we achieved a maximum cw output power of 100 mW and a pump threshold of 10.5 W [see Fig. 3(a)]. No laser emission at 1063 nm was observed, as the emission cross section at 1063 nm is lower in this crystal.[15] $Nd:YVO_4$ offered a better laser efficiency because of its greater effective emission cross section at 880 nm (see Table 1). However, it presented a higher pump threshold, probably due to the emission observed at 1064 nm. We then decided to use the $Nd:GdVO_4$ crystal for the next experiments.

In $Nd:GdVO_4$, by rotating the etalon, we have been able to select a lasing wavelength at 912.0, 893.5, or 879.4 nm, coming from the de-excitation of the $^4F_{3/2}$ energy level to the first, third, and fifth sublevel of the $^4I_{9/2}$ energy level, as shown by Fig. 1. No emission was observed at 900 or 887 nm (corresponding to the other sublevels of the $^4I_{9/2}$ energy level). As can be seen in the emission spectrum of $Nd:GdVO_4$,[5] the emission cross sections at these wavelengths are weaker. Laser performances are presented in Table 2. The transition at 912 nm was the most efficient, with a maximum cw output power of 1.7 W, and offered the lowest threshold at 3.8 W of incident pump power. In contrast, the transition at 879 nm was less efficient, with a higher pump threshold. This can be explained by the energy of the lower level of the laser transition: the closer to the ground state, the lower the laser level, and the harder to reach the population inversion and the higher the reabsorption at this lasing wavelength.

With the output coupling increased to 25%, only emission at 879.4 nm was observed in $Nd:GdVO_4$ without the need for an intracavity spectral selection (Lyot filter or thin etalon). Indeed, at increasing losses, higher population inversion is required. The balance between emission and absorption processes results in a blueshift of the lasing wavelength. This effect has already been observed in Yb- or Er-doped crystals for the emission around 1.5 μm.[16] A HT coupler then favors the 879 nm transition. The output power at 879 nm versus incident pump power is shown in Fig. 3(b). For 18 W of incident pump power, we achieved a cw output power of 800 mW at 879 nm.

Table 2. Laser Performance in $Nd:GdVO_4$ for the $^4F_{3/2}$–$^4I_{9/2}$ Laser Transition

	λ (nm)		
Measure	912	893	879
Pump threshold (W)	3.8	7.5	10.5
Maximum output power (W)	1.69	0.55	0.10

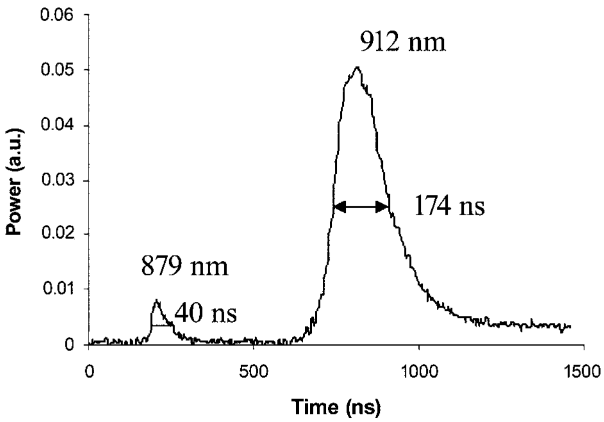

Fig. 4. Q-switched pulses at 912 and 879 nm.

To achieve efficient blue emission by second-harmonic generation, we replaced the output coupler with a highly reflecting (HR) mirror. A 25 μm etalon was inserted into the cavity to select the 879 nm emission. We evaluated the intracavity power at 879 nm to be only 5 W: it was not enough for efficient nonlinear conversion. For this laser transition at 879 nm, it is particularly difficult to realize the population inversion, since the lower laser level corresponds to the ground state, leading to a high oscillation threshold. Moreover, the laser saturation intensity is weak (50 kW/cm^2 for an incident pump power of 17 W), half that of a four-level laser with the same spectroscopic parameters. It is then not possible to operate the laser with a high intracavity intensity. To reach the blue range at 439.5 nm, a pulsed regime is then required.

For the Q-switched regime, we used an antireflection-coated acousto-optic deflector (Intra-Action Corporation), as illustrated by Fig. 2. With an output coupler transmitting 3% from 879 to 912 nm, we observed pulses emitted at both 879 and 912 nm, as shown in Fig. 4. The buildup time and the pulse duration were shorter for the pulse at 879 nm, owing to a greater emission cross section at this wavelength. However, the 912 nm transition offered the highest energy.

With the 25% transmitting output coupler at 879 nm and as observed in cw operation, only pulses at 879 nm were observed without the need for an intracavity spectral selection. For a pump power of 17 W and a repetition rate of 10.4 kHz, we obtained an average output power of 250 mW at 879 nm and an energy of 24 μJ. The pulse duration was 35 ns.

Second-harmonic generation was achieved in Q-switched regime by inserting a BiBO nonlinear crystal into the cavity and by replacing the output coupler with a HR-coated mirror. In this configuration, we again observed laser pulses at 879 and 912 nm. To suppress the emission at 912 nm, a 25 μm etalon was inserted into the cavity. The BiBO crystal was 10 mm long, and both sides were antireflection-coated at 879 nm. The crystal was cut for room temperature type I phase matching ($\theta = 157.4°$, $\varphi = 90°$). For a 10.4 kHz repetition rate, we demonstrated a total output blue average power of 178 mW in two output beams, corresponding to an energy of 17 μJ. The pulse duration was 40 ns, leading to a peak power of 428 W.

In conclusion, we have demonstrated for the first time to our knowledge a true three-level laser based on an Nd-doped crystal. Although such a laser transition is theoretically difficult to achieve, especially under diode pumping, we have been able to reach it. The best results were obtained with $Nd:GdVO_4$ both in cw operation with 0.8 W output power for 17 W incident diode pump power and in the pulsed regime with 24 μJ per pulse for a 10.4 kHz repetition rate. Pulsed intracavity second-harmonic generation was also realized. We obtained 178 mW of average blue power in two output beams, corresponding to an energy per pulse of 17 μJ.

A key point for laser emission at 879 nm is the wavelength selection. Losses introduced by our intracavity etalon could be avoided with highly selective mirror. More efficient nonlinear conversion could also be obtained by using a more efficient nonlinear crystal, like $KNbO_3$. This demonstration opens a new way to achieve 440 nm emission that is much simpler than 1320 nm Nd:YAG frequency tripling.[17]

References

1. L. Marshall, Laser Focus World, October 2004, p. 79.
2. J. Limpert, H. Zellmer, P. Riedel, G. Maze, and A. Tunnermann, “Laser oscillation in yellow and blue spectral range in Dy^{3+}:ZBLAN,” Electron. Lett. **36**, 1386 (1991).
3. H. Zellmer, P. Riedel, and A. Tunnermann, Appl. Phys. B **69**, 417 (1999).
4. G. Aka, E. Reino, D. Vivien, F. Balembois, P. Georges, and B. Ferrand, in *Advanced Solid State Lasers*, Vol. 68 of OSA Trends in Optics and Photonics, M. E. Fermann and L. R. Marshall, eds. (Optical Society of America, 2002), p. 329.
5. C. Czeranowsky, M. Schmidt, E. Heumann, G. Huber, S. Kutovoi, and Y. Zavartsev, Opt. Commun. **205**, 361 (2002).
6. S. Bjurshagen, D. Evekull, and R. Koch, Appl. Phys. B **76**, 135 (2003).
7. V. Lupei, N. Pavel, Y. Sato, and T. Taira, Opt. Lett. **28**, 2366 (2003).
8. L. Mc Donagh, R. Knappe, A. Nebel, and R. Wallenstein, in *Conference on Lasers and Electro-Optics* (Optical Society of America, 2005), paper CMS5.
9. S. Bjurshagen, R. Koch, and F. Laurell, Opt. Commun. **261**, 109 (2006).
10. T. H. Maiman, Nature **187**, 493 (1960).
11. S. Yiou, F. Balembois, K. Schaffers, and P. Georges, Appl. Opt. **42**, 4883 (2003).
12. B. Jeffries and D. W. Coutts, “Three-level operation of a diode-bar-pumped Yb:S-FAP laser,” Opt. Commun. (to be published).
13. A. Bouchier, G. Lucas-Leclin, and P. Georges, Opt. Express **13**, 6974 (2005).
14. R. Selvas, J. K. Sahu, L. B. Fu, J. N. Jang, J. Nilsson, A. B. Grudinin, K. H. Yla-Jarkko, S. A. Alam, P. W. Turner, and J. Moore, Opt. Lett. **28**, 1093 (2003).
15. Y. Sato and T. Taira, IEEE J. Quantum Electron. **11**, 613 (2005).
16. S. Taccheo, P. Laporta, and C. Svelto, Appl. Phys. Lett. **68**, 2621 (1996).
17. X. Mu and Y. J. Ding, Opt. Lett. **30**, 1372 (2005).