

Efficient, multiwatt, continuous-wave laser operation on the ${}^4F_{3/2}$ - ${}^4I_{9/2}$ transitions of Nd:YVO₄ and Nd:YAG

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We report multiwatt, diode-pumped cw operation on the ${}^4F_{3/2}$ - ${}^4I_{9/2}$ laser transition at 914.5 nm in Nd:YVO₄, for which an output power of 3.0 W and a slope of efficiency of 22.8% were achieved. For the corresponding laser transition of Nd:YAG at 946 nm an output power of 5.35 W and a slope efficiency of 40.2% were measured. By intracavity frequency doubling, an output power of 1.5 W at 473 nm was generated. © 2000 Optical Society of America

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During the past few years the ${}^4F_{3/2}$ - ${}^4I_{9/2}$ laser transition near 900 nm of the neodymium ion has attracted much attention for applications especially in display technologies, as it opens the way for efficient generation of continuous blue laser radiation in the watt range by means of a compact, all-solid-state frequency-doubling laser. The main basis for such a laser is provided by novel high-power diode-laser sources that offer high beam brightness for longitudinal pumping because the quasi-three-level nature of this laser transition requires high pump intensities for efficient laser operation. Most publications in this field have concentrated on Nd:YAG.¹⁻⁴ This is so mainly because of the large Stark splitting in this laser material, which leads to a relatively high terminal laser level at 846 cm⁻¹ and thus to a low fractional thermal population; the good overall properties of this crystal are also important. Consequently, the highest blue second-harmonic cw output was produced with Nd:YAG at 473 nm, in the range of several hundred milliwatts.²⁻⁴

To find a basis for generating laser radiation with the deep blue color that is important for laser display technologies, we investigated Nd:YVO₄. In fluorescence measurements this crystal exhibited a strong signal from the ${}^4F_{3/2}$ - ${}^4I_{9/2}$ transition near 914 nm. The stimulated-emission cross section σ (914 nm) was determined relative to the main transition at 1064 nm as $0.1 (\pm 0.01) \times \sigma(1064 \text{ nm})$, for which high values of $>10^{-18} \text{ cm}^2$ can be found in the literature.⁵ However, the ${}^4I_{9/2}$ level is only 433 cm⁻¹ above the ground state⁶ and results in a high thermal population of 5% at room temperature. This means difficult conditions for efficient laser operation, as high reabsorption losses have to be overcome. Furthermore, the thermal properties of this crystal are inferior to those of Nd:YAG. Here we demonstrate efficient diode-pumped cw-laser operation on the ${}^4F_{3/2}$ - ${}^4I_{9/2}$ transition in Nd:YVO₄ with 3.0 W of output power. For comparison, we have also investigated a similar Nd:YAG laser, which was used for studies on intracavity frequency doubling by which a second-harmonic output power of 1.5 W was achieved in the blue spectral range.

As has been extensively discussed in several theoretical and experimental papers dealing with the

performance of quasi-three-level lasers,⁷⁻¹⁰ a few parameters have special importance for the laser design. To achieve a low absorbed pump power at threshold, $P_{a,\text{th}}$, one must choose the length L of the active material as short as possible so the reabsorption losses will be minimal; these losses are described by the last term in parentheses on the right-hand side of Eq. (1):

$$P_{a,\text{th}} = \frac{\pi h \nu_p (w_p^2 + w_m^2)}{4\sigma \eta_q (f_l + f_u) \tau} (T + 2\alpha_{\text{int}} L + 2\sigma f_l N_{\text{ion}} L), \quad (1)$$

where $h \nu_p$ is the energy of a pump photon, w_p and w_m are the radii of the pump beam and the laser mode, respectively, σ is the stimulated-emission cross section, η_q is the pump quantum efficiency, f_l and f_u are the fractional populations of the lower and the upper laser levels, respectively, τ is the fluorescence decay time, T is the transmission of the resonator outcoupling mirror, α_{int} describes the residual internal resonator losses without reabsorption, and N_{ion} is the concentration of doping ions. To maximize the slope efficiency, however, a high absorption efficiency for the pump radiation is necessary, which requires a sufficiently large crystal length. Also, the crystal temperature should be as low as possible to yield a small thermal population of the terminal laser level. A high pump intensity has to be applied to reach threshold, as a considerable fraction β_{min} of the population needs to be in the upper manifold for population inversion to be achieved. According to Fan,⁹

$$\beta_{\text{min}} = \frac{f_l/f_u}{1 + f_l/f_u}, \quad (2)$$

which is valid for an ideal lossless resonator, we get $\beta_{\text{min}} = 8.8\%$ at 300 K for Nd:YVO₄, whereas in the case of Nd:YAG the corresponding value is only 1.3%. Special attention is required to the ratio of the radius of the pump beam and the laser mode. It can be seen from Eq. (1) that w_p should approximate zero

for a low lasing threshold, but this is contradictory to the condition that unpumped regions over the cross section of the laser mode should be avoided because reabsorption losses would then increase. The pump intensity must be scalable for high gain to be obtained for laser operation well above threshold, as the term for δ_{sat} that describes the saturation of the reabsorption loss approaches zero for high circulating intensities I according to⁷

$$\delta_{\text{sat}} = \frac{\sigma f_l N_{\text{ion}} L I_{\text{sat}}}{I} \ln\left(1 + \frac{2I}{I_{\text{sat}}}\right), \quad (3)$$

where I_{sat} is the saturation intensity given by $I_{\text{sat}} = \hbar\nu/[(f_l + f_u)\sigma\tau]$ with an energy $\hbar\nu$ of a laser photon.

We used a composite Nd:YVO₄ crystal (Onyx Optics, Inc.) that had flat, undoped end pieces, each 3 mm long, diffusion bonded to a 1-mm-thick doped inner part. The crystal was *a* cut, and the Nd concentration was 0.5 at. %. Special care was taken to ensure high-quality coatings of the resonator mirrors, which, in addition to having resonator coatings at 914 nm, were antireflecting at 1064 and 1340 nm, to prevent lasing on these strong Nd:YVO₄ transitions. The highly reflecting mirror was directly coated onto the crystal front end, with an additional highly transmitting coating for the pump radiation at 807 nm. The other end had three antireflecting coatings, at 914, 1064, and 1340 nm. For reliable heat transfer the crystal was wrapped in indium foils and fixed by water-cooled copper mountings. A high-brightness fiber-coupled diode laser (Fraunhofer-Institut für Lasertechnik, Aachen, Germany) was used in an end-pumped geometry. The pump power from a fiber with a core diameter of 200 μm and a numerical aperture of 0.2 was coupled into the active medium via a compact multilens system by which imaging of the fiber end to the laser crystal was possible at different ratios. By applying these coupling optics we studied the lasing behavior in short, plano-concave resonators of only ~ 10 -mm length while strong thermal lensing was present. At pump powers of ~ 10 W, corresponding to an output power of ~ 1 W, the laser emitted nearly TEM₀₀ radiation with $M^2 < 1.2$, where M^2 is the beam-quality parameter. The focusing length of the thermal lens was determined at an input power of 9.5 W to be 45 (± 10) mm. When the pump power was increased to 20 W the output power was scaled up to 3.0 W, while M^2 increased to 2.9. The transmission of the outcoupling mirror was $T = 3\%$, and the radius was 500 mm. We recorded the lasing spectrum at maximum output power to make sure that no other laser line was present. The best performance of the laser was achieved when we applied a 1:1 imaging ratio of the pump optics, from which a value of 1.28 resulted for w_p/w_m , where w_m was calculated as 78 μm . The slope efficiency, related to the pump power at the fiber output, was determined by the linear part of the laser characteristics and yielded a value of 22.8% (Fig. 1). There is a significant non-linear increase in output power up to ~ 300 mW after the lasing threshold is reached. This increase is attributed to the saturation of the reabsorption loss

for which at the lasing threshold a very high value of 9.4% is calculated by the corresponding term in Eq. (1) with the following values: $\sigma = 15 \times 10^{-20} \text{ cm}^2$, $f_l(300 \text{ K}) = 0.05$, $N_{\text{ion}}(0.5 \text{ at. \%}) = 0.623 \times 10^{20} \text{ cm}^{-3}$, and $L = 1 \text{ mm}$. By using Eq. (3) we can now calculate how the increase of circulating intensity I influences the decrease of the reabsorption loss. For a measured output power of $P = 300 \text{ mW}$, which corresponds to $I = 52.3 \text{ kW cm}^{-2}$, we get a value of 0.004 for the reduction factor $R = I_{\text{sat}} \ln(1 + 2I/I_{\text{sat}})/I$, whereas close to the lasing threshold, at $P = 1 \text{ mW}$, we have $I = 157 \text{ W cm}^{-2}$ and $R = 0.448$. A Findlay-Clay analysis confirmed the large value of the initial reabsorption loss, showing that the remaining internal losses were $< 1\%$ and providing an extrapolated absorbed power at a threshold of $\sim 1.3 \text{ W}$ for $T = 0$. With this extrapolated value we can estimate the fraction β_{min}^* of the population in the upper manifold at laser threshold, which can be described by

$$\beta_{\text{min}}^* = \frac{I_{\text{min}}}{I_{p,\text{sat}}} = \frac{P_{a,\text{th}}(T=0)\sigma_a\tau}{\pi w_p^2 \hbar\nu_p}, \quad (4)$$

with $I_{\text{min}} = P_{a,\text{th}}/(\pi w_p^2)$ for the minimum pump intensity to reach laser threshold and $I_{p,\text{sat}} = \hbar\nu_p/(\sigma_a\tau)$ for the pump saturation intensity.¹¹ With $\sigma_a = 27 \times 10^{-20} \text{ cm}^2$ for the absorption cross section at the pump wavelength, $\tau = 100 \mu\text{s}$ for the fluorescence decay time, $\hbar\nu_p = 2.46 \times 10^{-19} \text{ W s}$ for the energy of a pump photon, and $w_p = 100 \mu\text{m}$, we get $\beta_{\text{min}}^* = 0.45$. This is nearly five times the value of β_{min} from Eq. (2), which reflects the large initial reabsorption losses. The slowing down of the slope at pump powers above about 17 W is assumed to be caused mainly by the strong thermal-lens buildup in the laser crystal and by the bleaching of the pump absorption; however, the causes of this buildup deserve further investigations.

In the course of these experiments we have seen that the resonator had to be very short for optimum performance. By using convex input mirrors it would be possible to increase the resonator length to a value that would permit a folded configuration, which is

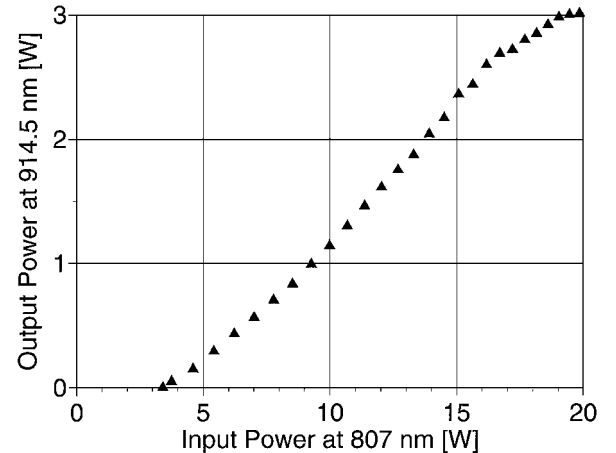


Fig. 1. Output power of the Nd:YVO₄ laser at 914.5 nm as a function of the pump diode power at the fiber end.

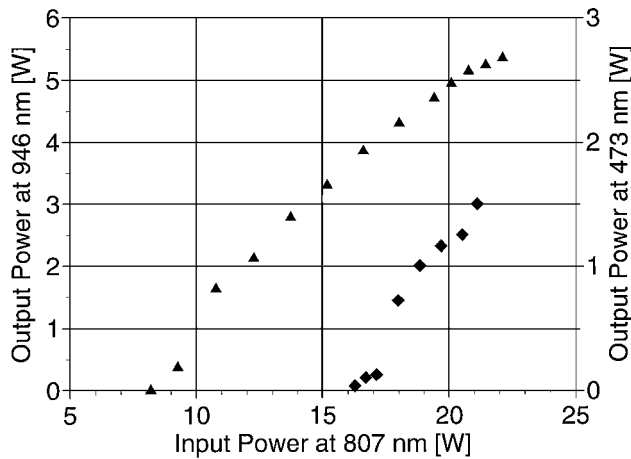


Fig. 2. Output power of the Nd:YAG laser at 946 nm (triangles) and at the second harmonic (diamonds), plotted as a function of the pump diode power at the fiber end.

advantageous for optimum intracavity second-harmonic generation. As this would require another laser crystal that was not yet available, we used a laser with a similar, composite Nd:YAG crystal for preliminary studies of second-harmonic generation with a V-shaped, folded resonator. The 0.9-at. % doped Nd:YAG had a length of 3 mm with two diffusion bonded ends of 3 mm each. The coatings corresponded to those of the Nd:YVO₄ crystal. The resonator configuration was similar to that described by Kellner *et al.*² By using the same setup for pumping and cooling as in our experiments with Nd:YVO₄, we measured an output power of 5.35 W with $M^2 = 3$ for a pump power of 22 W and $T = 3\%$, which resulted in a slope efficiency of 40.2% (Fig. 2).

Several nonlinear crystals such as β -BaB₂O₄, LiIO₃, KNbO₃, and LiB₃O₅ were used for the intracavity frequency-doubling experiments. The best result, 1.5 W of 473-nm radiation coupled out through the folding mirror of the V resonator, was achieved with a 10-mm-long LiB₃O₅ crystal, which is characterized by high optical quality that provides a low loss, a small walk-off angle, and a nonlinear coefficient $d_{\text{eff}} = 1.085$ pm/V. The crystal was cut for type I frequency doubling with $\Theta = 90^\circ$ and $\Phi = 19.5^\circ$ and had antireflection coatings at 946 nm. In Fig. 2 the output power at 473 nm is plotted as a function of the power from the pump diode laser. One can discriminate between a threshold region and an intermediate power region up to a pump power of 20.5 W. Whereas these values were recorded without changing the adjustment of the resonator, the highest

output power at a diode power of 21 W was measured after extensive readjustment of the resonator, which resulted in an overall optical-to-optical efficiency of 7.1%. Beam quality parameter M^2 was less than 2.5, and the average power stability was better than 3% in 12 h. However, output fluctuations caused by nonlinear coupling of the longitudinal modes were present, indicating a blue problem.

To summarize our research on $^4F_{3/2} - ^4I_{9/2}$ Nd-lasers, we have demonstrated that multiwatt cw-laser power can be generated with Nd:YVO₄ at room temperature in a compact diode-pumped laser device. The experiments with Nd:YAG have shown that high efficiency is possible for a high-power blue laser by intracavity second-harmonic generation with LiB₃O₅ in a V-shaped resonator. It should be possible to extrapolate these results to Nd:YVO₄ in a next step to produce laser radiation at 457 nm.

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