

Electro-optically Q -switched Nd:YVO₄ slab laser with a high repetition rate and a short pulse width

Keming Du

EdgeWave GmbH, Steinbachstrasse 15, 52074 Aachen, Germany

Daijun Li

Department of Physics, Tsinghua University, Beijing, China

Hengli Zhang

Fraunhofer Institut für Lasertechnik, Steinbachstrasse 15, 52074 Aachen, Germany

Peng Shi

Fraunhofer Institut für Lasertechnik, Steinbachstrasse 15, 52074 Aachen, Germany

Xiaoyu Wei

Department of Physics, Tsinghua University, Beijing, China

Robert Diart

EdgeWave GmbH, Steinbachstrasse 15, 52074 Aachen, Germany

Received July 18, 2002

We report on a compact and highly efficient diode-end-pumped TEM₀₀ Nd:YVO₄ slab laser with an output power of 103 W and beam quality $M^2 \leq 1.5$. The optical-to-optical efficiency was 41.5%. In electro-optically Q -switched operation, 83 W of average power at a pulse-repetition rate of 50 kHz with a pulse length of 11.3 ns was obtained. At a pulse-repetition rate of 10 kHz, 5.6 mJ of pulse energy, and 870 kW of peak power were measured. © 2003 Optical Society of America

OCIS codes: 140.3480, 140.3540.

Diode-end-pumped rodlike solid-state lasers have been a focus of development in the past decade because of their high efficiency, compact size, and high beam quality. Q -switched lasers at high repetition rates are important sources for a wide range of applications such as micromachining, marking, ranging, remote sensing, and microsurgery. However, power scalability in most solid-state laser media is limited by thermally induced lensing and thermal fracture damage.

Nd:YVO₄ crystals have been identified as promising materials for use in diode-pumped lasers.^{1–6} Relative to Nd:YAG and Nd:YLF, Nd:YVO₄ can produce short pulse lengths at high repetition rates in Q -switching operation because of its large gain cross section and short energy storage time.^{4,7} These properties are of essential importance for precision micromachining. Until now, for a single oscillator with Nd:YVO₄ 30-W TEM₀₀ power was reported in a continuous wave; in Q -switched operation the maximum pulse energy was below 1 mJ; even at 1 kHz, the maximum average output power was 25 W.⁴

Partially end-pumped slab lasers with hybrid resonators have proved to be favorable for power scaling at high beam quality and efficiency, as they have the properties of both the high overlapping efficiency of end-pumped rod lasers and the excellent cooling con-

ductivity of slab lasers.^{8,9} In this Letter we discuss a partially end-pumped Nd:YVO₄ slab laser oscillator that was Q switched electro-optically at a high repetition rate.

The experimental arrangement of the slab laser is shown in Fig. 1. The pumping unit consists of a stack with eight diode bars; the radiation emitted by each diode laser bar was individually collimated by a microlens. The collimated beams were first compressed in the y direction by a factor of 2 with a pair of prisms and then focused into a folded planar waveguide by

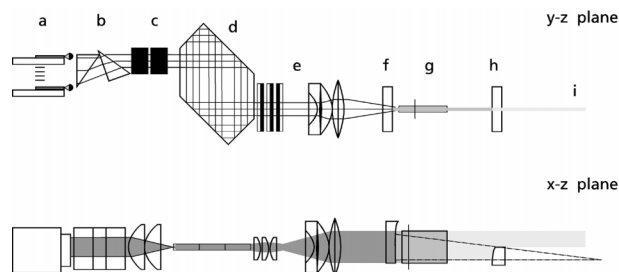


Fig. 1. Schematics of the laser: cross sections in $y-z$ and $x-z$ planes: a, diode stack; b, pair of prisms; c, two cylindrical lenses; d, planar waveguide; e, imaging group; f, rear mirror M_1 ; g, Nd:YVO₄ slab; h, output coupler M_2 ; i, output laser beam.

two $f = 25$ mm cylindrical lenses. A folded planar waveguide with a width of 3 mm was used to achieve a uniform pumping line. Using an imaging system with a magnification of $4\times$, we generated a homogeneous pumping line with dimensions of ~ 0.5 mm \times 12 mm inside the Nd:YVO₄ slab. With such a pumping unit, 88% of the diode laser power was transmitted to the Nd:YVO₄ slab. By controlling the temperature of the cooling water we fixed the central wavelength of the emission near 808 nm. The spectral width of the diode laser stacks was 3.5 nm. The Nd:YVO₄ slab had a 0.3-at. % doping concentration with a size of 1 mm \times 10 mm \times 12 mm and was a cut and with its c axis along its 12-mm edge. It was mounted between two water-cooled heat sinks with two large faces (12 mm \times 10 mm), which served as thermally conducting surfaces. Indium foils were used for effective and uniform thermal contact and cooling. Only two 1 mm \times 12 mm end faces of the slab crystal needed to be polished and coated to pass the pump radiation (808 nm) and the laser beam (1064 nm). The absorption length was estimated to be 4 mm. At the early design stage we were concerned with the maximum power load of the Nd:YVO₄ slab and selected the length 10 mm to enhance heat conduction by pumping the slab with a wavelength different from 808 nm. The experimental results show that a Nd:YVO₄ slab has quite a high thermal damage threshold and that slabs shorter than 10 mm can be used without loss of efficiency.

Two highly reflective cylindrical mirrors, M_1 ($R_1 = 350$ mm) and M_2 ($R_2 = -215$ mm), were used as resonator mirrors. The distance between the two mirrors was ~ 67.5 mm. In the plane of the pumping line a positive-branch confocal off-axis unstable resonator with $1.63\times$ magnification was formed.¹⁰ The output coupling was $1 - 1/M = 38.6\%$. Mirror M_2 was cut and polished at one edge. The laser beam was coupled out from that edge. With the line-shaped pumping geometry the heat conduction was quasi one-dimensional. The temperature gradient was perpendicular to the pumping line. Therefore there was a considerable thermal-lens effect in the direction perpendicular to the pumping line. The flat-flat cavity in the y - z plane became thermally stabilized. At a pump power of 248 W the focal length of the thermally induced lens was estimated to be 150 mm, and the beam diameter inside the laser material was ~ 0.41 mm.

Figure 2 shows the input-output characteristics for the Nd:YVO₄ slab laser without the polarizer and the Pockels cell. A maximum output power of 103 W was obtained at an incident pump power of 248 W. No saturation phenomenon was observed at this power level. The corresponding efficiency for the slab laser at the maximum output power was 41.5%, and the slope efficiency was 54.9%. The threshold was ~ 40 W. The laser beam was polarized along the unstable direction.

A birefringent polarizer and a high power β -barium borate electro-optic Pockels cell were used for Q switching. The average output power, energy per pulse, and pulse width versus the pump power at various repetition rates were studied. The results

are shown in Figs. 3 and 4. At a repetition rate of 50 kHz the energy per pulse was 1.66 mJ and the pulse width was 11.3 ns; at 10 kHz the energy of a single pulse and the pulse width were 5.6 mJ and 6.45 ns, respectively, and the maximum peak power was above 870 kW. To our knowledge, the average output power, energy per pulse at a repetition rate range of 10–50 kHz, and the peak power are the highest reported for a diode-pumped Nd:YVO₄ system. Figure 5 shows a typical pulse profile measured by a fast photodiode and a digital oscilloscope. The standard deviation of pulse-to-pulse energy is $\pm 2\%$, as the incident pump power was 248 W and the repetition rates were 10–50 kHz.

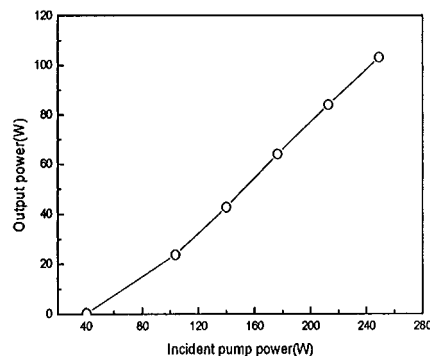


Fig. 2. Continuous-wave output power of the partially end-pumped Nd:YVO₄ slab laser versus incident pump power into the slab crystal.

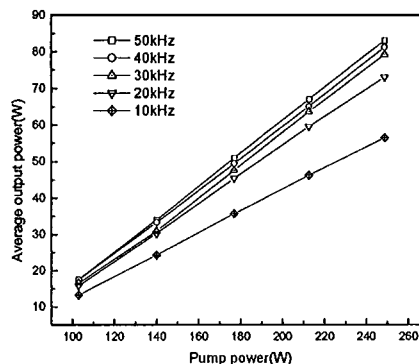


Fig. 3. Average output power versus pump power at several repetition rates.

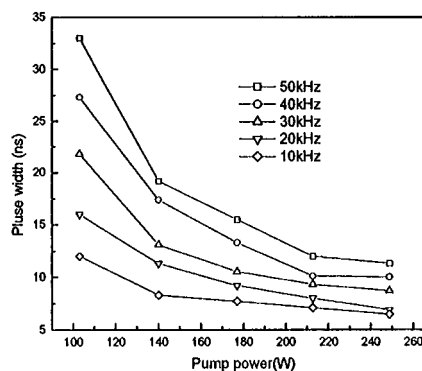


Fig. 4. Pulse width versus pump power at several repetition rates.

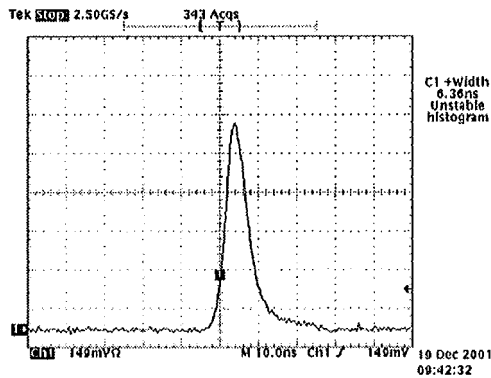


Fig. 5. Typical Q -switched pulse profile.

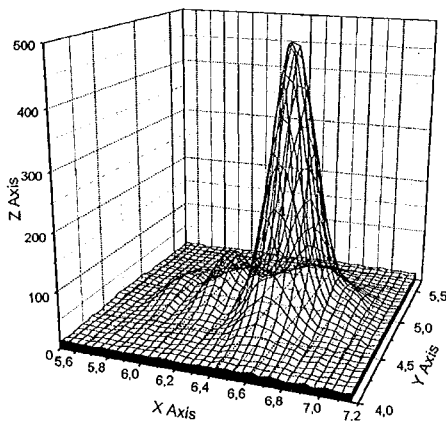


Fig. 6. Far-field intensity distribution.

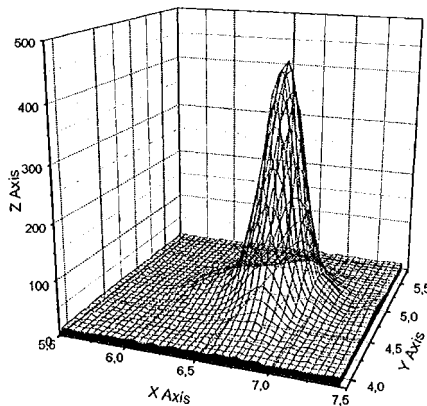


Fig. 7. Far-field intensity distribution after the spatial filter.

The output beam has a size of $\sim 0.3 \text{ mm} \times 4.6 \text{ mm}$. A group of prisms was used to expand the beam size 14 times in the y - z direction. After the prisms the output beam has a size of $4.5 \text{ mm} \times 4.6 \text{ mm}$. Figure 6 shows the intensity distribution in the far field at a

pump power of 248 W. In the stable direction it is Gaussian. As expected, in the unstable plane it shows a maximum with sidelobes of low intensity owing to diffraction on the edge of the output coupling mirror. Using a spatial filter, we cut out the sidelobes. Figure 7 shows the far-field intensity after the spatial filter. The power loss caused by the spatial filter was $\sim 10\%$.

A lens ($f = 300 \text{ mm}$) and a CCD camera (Spiricon) were used to measure the quality of a laser beam. At the 90-W output power after the spatial filter, M^2 in the stable and the unstable directions was 1.5 and 1.3, respectively. In Q -switched operation, no change in the intensity distribution was measured compared with that in cw operation. This result indicates that beam quality in the Q -switching operation should be the same as that in the cw operation.

In conclusion, we have demonstrated a high-power cw and electro-optically Q -switched Nd:YVO₄ slab laser with a hybrid resonator. We measured 103 W of power at near-diffraction-limited beam quality in the cw mode. In the Q -switched mode we achieved a 1.66-mJ pulse energy with a pulse length of 11.3 ns at 50 kHz and a 5.6-mJ pulse energy with a pulse length of 6.5 ns at 10 kHz.

H. Zhang and P. Shi thank the German Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie/Deutsche Forschungsanstalt für Luft- und Raumfahrt for support through a research fellowship at the Fraunhofer Institute für Lasertechnik in Aachen. K. Du's e-mail address is du@ilt.fhg.de.

References

1. R. A. Fields, M. Birnbaum, and C. L. Fincher, *Appl. Phys. Lett.* **51**, 1885 (1987).
2. W. L. Nighan, *Laser Focus World* **31**(5), 97 (1995).
3. J. Zhang, M. Quade, K. M. Du, Y. Liao, S. Falter, M. Baumann, P. Loosen, and R. Poprawe, *Electron. Lett.* **33**, 775 (1997).
4. Y. F. Chen, Y. P. Lan, and S. C. Wang, *Opt. Lett.* **25**, 1016 (2000).
5. M. Tsunekane, N. Taguchi, T. Kasanatsu, and H. Inaba, *IEEE J. Sel. Top. Quantum Electron.* **3**, 9 (1997).
6. M. J. Damzen, M. Trew, E. Rosas, and G. J. Crofts, *Opt. Commun.* **196**, 237 (2001).
7. J. E. Bernard and A. J. Alcock, *Opt. Lett.* **19**, 1861 (1994).
8. K. Du, N. Wu, J. Xu, J. Giesekus, P. Loosen, and R. Poprawe, *Opt. Lett.* **23**, 370 (1998).
9. C. Schnitzler, M. Höfer, J. Luttmann, D. Hoffmann, and R. Poprawe, in *Conference on Lasers and Electro-Optics*, Vol. 39 of OSA Trends in Optics and Photonics Series (Optical Society of America, Washington, D.C., 2000), paper CPD21-3.
10. A. E. Siegman, *Lasers* (University Science, Mill Valley, Calif., 1986).