

All-solid-state continuous-wave frequency-doubled Nd:YAG–BiBO laser with 2.8-W output power at 473 nm

C. Czeranowsky, E. Heumann, and G. Huber

Institut für Laser-Physik, Universität Hamburg, Jungiusstrasse 9a, 20355 Hamburg, Germany

Received September 30, 2002

We report on a diode-pumped Nd:YAG laser with 4.6 W of linear polarized continuous-wave (cw) output power on the ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$ transitions at 946 nm. Three different crystals, cut for critical type I phase matching at room temperature, are used for the intracavity frequency doubling of the laser: 10-mm-long LiB_3O_5 (LBO), an 8-mm-long $\beta\text{-BaB}_2\text{O}_4$ (BBO), and a 10.4-mm-long BiB_3O_6 (BiBO) grown by FEE GmbH. Up to 2.8 W of cw output power in the blue spectral range at 473 nm has been achieved with the BiBO crystal (2.1 W with BBO and 1.5 W with LBO). © 2003 Optical Society of America

OCIS codes: 140.3480, 140.3530, 140.3580, 140.7300, 190.2620, 190.4400.

A cw all-solid-state laser system in the blue spectral region with an output power in the Watt range is an alternative for water-cooled argon-ion laser systems and a suitable light source for laser-based display technologies. The diode-pumped quasi-three-level Nd^{3+} laser, which operates on the ${}^4F_{3/2} \rightarrow {}^4I_{9/2}$ transition, was first introduced by Fan and Byer, who realized a Nd:YAG laser at 946 nm.¹

In the present work Nd:YAG is also chosen as a laser material since it is the most promising material for high output power on the ground-state transition because of its good optical quality, high thermal conductivity, and large Stark splitting (875 cm^{-1}) of the ground state; the large splitting leads to an advantageous small population of the lower laser level (0.7% at room temperature) and therefore to small reabsorption losses on the laser wavelength. However, the large Stark splitting causes a relatively long emission wavelength of 946 nm. Shorter wavelengths can be obtained with vanadate or fluoride materials; 2.1-W power at 912 nm and 840 mW of blue output power at 456 nm have been demonstrated, for example, with a Nd:GdVO₄ laser.²

In this Letter we present a Nd:YAG ground-state laser with 4.6 W of cw linear polarized output power at 946 nm. By intracavity frequency doubling of this laser, we achieved up to 2.8 W of blue output power at 473 nm. The experimental setup of the laser is shown in Fig. 1(a). The laser crystal is a 9-mm-long composite YAG rod with a 3-mm-long 1.1% Nd-doped part in the middle and two 3-mm-long undoped end caps. The crystal is glued into a copper heat sink. The doped part is water cooled. This design leads to good heat removal and minimizes the lens effect caused by bending of the crystal faces.^{3,4} The pump source is a high-brightness fiber-coupled laser diode from Albers Laser with 21 W of output power at 808 nm with a $150\text{-}\mu\text{m}$ fiber core diameter and a N.A. of 0.22. The pump light is focused by two achromatic lenses into the laser crystal, where the diameter of the focus is $300\text{ }\mu\text{m}$. The mirrors are highly reflecting for the fundamental wave at 946 nm and highly transmitting at 1064 nm for suppression of the strong four-level transition in Nd^{3+} . The plane end mirrors, M1 and

M4, and the large resonator length ($\sim 1\text{ m}$) increase the laser stability.⁵ The two curved folding mirrors, M2 (radius $R = 300\text{ mm}$) and M3 ($R = 100\text{ mm}$), determine the beam waist in the laser crystal and in the nonlinear crystal, respectively. The laser mode in the laser crystal has to match the pump mode as closely as possible if one is to avoid reabsorption losses as a result of the thermal population of the lower laser level.⁶ Although a small pump focus leads to a higher pump intensity, and thereby to a lower threshold, it also increases the temperature in the crystal, which in turn increases the threshold and strengthens the thermal lens ($f \sim w_P^2$).⁷ Therefore, the size of the pump mode is always a compromise between high pump intensity and correlated thermal problems. By determining the stable region of a plane–plane resonator, we estimate the focal length of the thermal lens in our laser crystal to be 7 cm for 21 W of pump power. When the laser crystal is placed in the focus of the laser mode close to the incoupling mirror, the resonator becomes very insensitive to thermal lensing. Figure 2 shows that the radius of the laser mode in the middle of the laser crystal is nearly constant in a broad region of the thermal-lens focal length down to 5 cm.

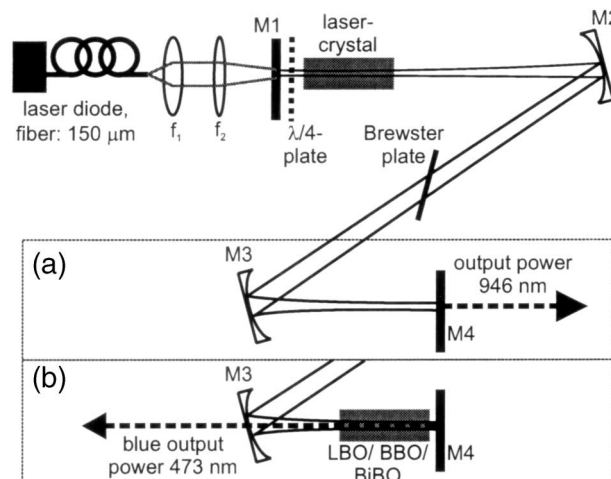


Fig. 1. Experimental setup of (a) the ground state and (b) the frequency-doubled laser.

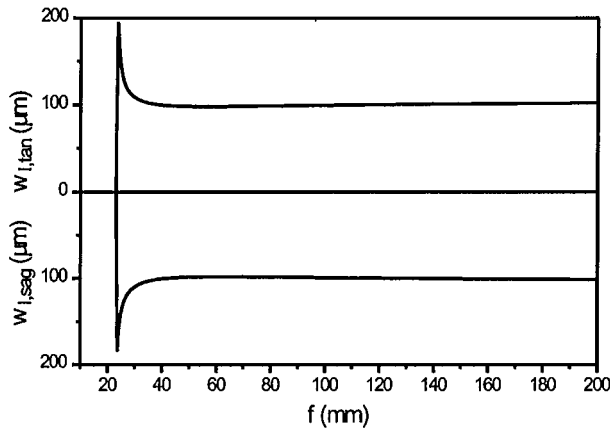


Fig. 2. Sagittal and tangential radii of laser mode w_1 in the middle of the laser crystal versus focal length of the thermal lens.

Therefore, it is not necessary to realign the cavity while increasing the pump power. The data were calculated by the *ABCD* matrix formalism with the approximation of a thin lens in the middle of the laser crystal.

Since YAG is an isotropic material and emits unpolarized radiation, we insert a Brewster plate into the cavity to fix the laser polarization, as is necessary for type I phase matching. Losses at this Brewster plate occur as a result of the depolarization of the laser beam, which is due to thermally induced birefringence in the laser crystal, and increase with the pump power. To avoid these losses Clarkson *et al.* suggested inserting a quarter-wave plate between the laser crystal and the input coupler, with one optical axis parallel to the laser polarization.⁸

The laser experiments on the ground-state transition are carried out with output coupling mirror M4 with 3.3% transmission at 946 nm. At 946 nm, 4.6 W of linear-polarized (>50:1) output power is achieved with 21 W of pump power. The crystal absorbs 58% of the pump radiation, which results in an effective absorption coefficient of $\alpha = 2.9 \text{ cm}^{-1}$ for the combination of Nd(1.1%):YAG and the diode pump that is used. The slope efficiency is 31% with respect to the incident power and 53% with respect to the absorbed power. Figure 3 shows the output power and the round-trip losses coupled out at the Brewster plate with and without a quarter-wave plate in the resonator. When the quarter-wave plate is removed from the cavity, the losses at the Brewster plate double to nearly 1 W, and the output power decreases to 3.6 W.

Three different crystals are used for intracavity frequency doubling of the laser: 10-mm-long LiB_3O_5 (LBO), 8-mm-long $\beta\text{-BaB}_2\text{O}_4$ (BBO), and 10.4-mm-long BiB_3O_6 (BiBO). BiBO is a new material and was first grown in good quality and investigated by Hellwig *et al.*⁹ and Becker *et al.*¹⁰ Compared with BBO, BiBO has a larger nonlinearity ($d_{\text{eff}} = 3.3 \text{ pm/V}$) and a smaller walk-off (40.7 mrad). The acceptance bandwidths are comparable.

The three crystals are cut for critical type I phase matching at room temperature and antireflection coated for the fundamental and the second-harmonic

waves. The crystals are inserted into the cavity very close to mirror M4 to yield a small focus ($\sim 40 \text{ }\mu\text{m}$ on the mirror) and good doubling efficiency in the crystals. Output coupler M4 is replaced by a mirror with high-reflection coating for 946 and 473 nm so the whole blue output is transmitted through mirror M3 [see Fig. 1(b)]. The maximum blue output power was 2.8 W at 21 W of pump power for BiBO, 2.1 W for BBO, and 1.52 W for LBO, as shown in Fig. 4. These results are equivalent to a coupling efficiency ($P_{\text{max}, 946 \text{ nm}}/P_{\text{max}, 473 \text{ nm}}$) of 63% for the BiBO crystal (47% for BBO and 33% for LBO). The reason for the good results with the BiBO crystal is the high value d_{eff} , resulting in high coupling efficiency K , which makes high blue output power possible, although the intracavity power is lower (163 W) than for BBO and LBO (185 W). The intracavity power was estimated by the leakage through mirror M2, which was calibrated in the setup shown in Fig. 1(a). K can be determined from the following equation (absorption in the crystal is neglected) given by Boyd and Kleinman¹¹:

$$K_{\text{Boyd}} = \frac{16\pi^2 l d_{\text{eff}}^2 h(\xi, B, \sigma, \mu)}{\epsilon_0 n_\omega n_{2\omega} c \lambda_{\text{laser}}^3}, \quad (1)$$

where l is the length of the nonlinear crystal and h is a function considering the strength of focusing (ξ), walk-off (B), phase mismatch (σ), and focal position (μ). The coupling efficiencies calculated with Eq. (2) for our measured values of the second-harmonic power and the intracavity power are lower but in the expected range (Table 1 gives an overview of the crystal data and the achieved results):

$$P_{\text{max}, 473 \text{ nm}} = K_{\text{exp}} P_{\text{max}, \text{intracavity}}^2. \quad (2)$$

The good results for the LBO crystal, reported before,¹² could not be reproduced because of the decrease of the crystal quality during the past two years as a result of the hygroscopy of LBO. At high output powers (>2 W) we also observed damage of the BiBO crystal, although the damage threshold should be comparable to that of LBO.¹³ It is not clear so far whether the

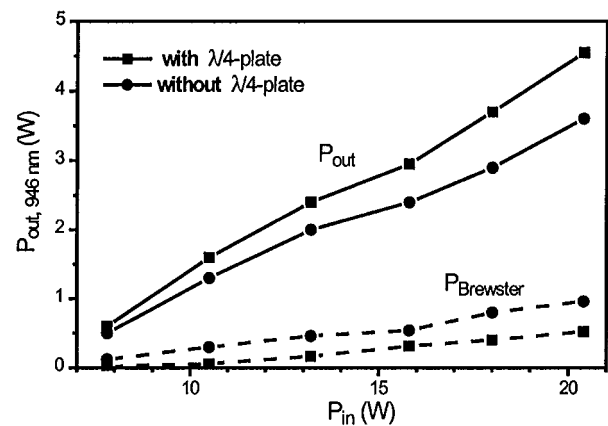


Fig. 3. Output power and losses at the Brewster plate of the ground-state laser at 946 nm with and without the quarter-wave plate in the cavity.

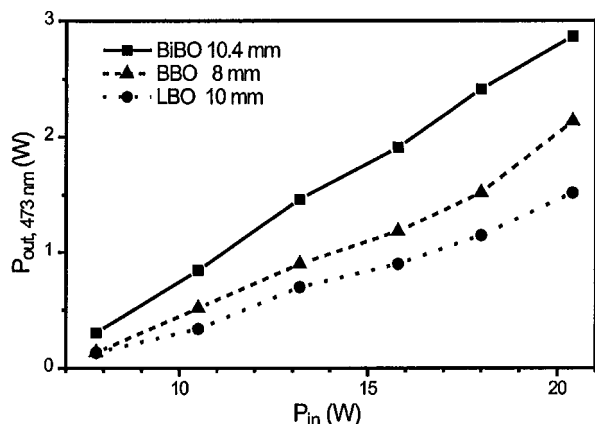


Fig. 4. Output power of the frequency-doubled laser at 473 nm.

Table 1. Data on the Nonlinear Crystals

Parameter	LBO	BBO	BiBO
Length (mm)	10	8	10.4
d_{eff} (pm/V)	0.81	2.0	3.3
Walk-off (mrad)	11.3	60.3	40.7
$\theta_{\text{phasematching}}$	90	25	161.7
$\varphi_{\text{phasematching}}$	19.3	—	90
$P_{out, max}$ at 473 nm (W)	1.52	2.1	2.8
$P_{max, 946 nm} / P_{max, 473 nm}$ (%)	33	47	63
$P_{intracavity}$ at 946 nm (W)	185	185	163
K_{Boyd} ($10^{-5} W^{-1}$)	3.5	4.2	15.5
K_{exp} ($10^{-5} W^{-1}$)	2.2	3.2	5.4
Losses at the Brewster plate (W)	0.72	1.04	1.2

crystal itself or the coating is damaged, but this effect is under investigation.

The stability of the laser was investigated with a fast photodiode and shows fluctuations of the output power, well known for intracavity-doubled lasers as the green problem.¹⁴ The appearing frequencies of the fluctuations are ~ 60 kHz, and the amplitude is $\sim 10\%$ of the signal, which is quite low for such a laser. One possible explanation for the small amplitude of the fluctuations is that the nonlinear coupling of the high

number of longitudinal mods in the nearly 1-m-long resonator results in averaging of the chaotic amplitude fluctuations.

In conclusion, we have presented a diode-pumped Nd:YAG ground-state laser with 4.6 W of linear polarized cw output power at 946 nm. By intracavity frequency doubling of this laser with a BiBO crystal, we achieved up to 2.8 W (2.1 W with BBO and 1.5 W with LBO) of blue radiation at 473 nm. This represents, to the best of our knowledge, the highest output power from a diode-pumped continuous-wave solid-state laser in the blue spectral region so far.

C. Czeranowsky's e-mail is czeranowsky@physnet.uni-hamburg.de.

References

1. T. Y. Fan and R. Byer, *Opt. Lett.* **12**, 809 (1987).
2. C. Czeranowsky, M. Schmidt, E. Heumann, G. Huber, S. Kutovoi, and Y. Zavartsev, *Opt. Commun.* **205**, 361 (2002).
3. M. P. MacDonald, Th. Graf, J. E. Balmer, and H. P. Weber, *Opt. Commun.* **178**, 383 (2000).
4. R. Weber, B. Neuenschwander, M. MacDonald, M. B. Roos, and H. P. Weber, *IEEE J. Quantum Electron.* **34**, 1046 (1998).
5. V. Magni, *J. Opt. Soc. Am. B* **4**, 1962 (1987).
6. W. P. Risk, *J. Opt. Soc. Am. B* **5**, 1412 (1988).
7. M. E. Innocenci, H. T. Yura, C. L. Fincher, and R. A. Fields, *Appl. Phys. Lett.* **56**, 1831 (1990).
8. W. A. Clarkson, N. S. Felgate, and D. C. Hanna, *Opt. Lett.* **24**, 820 (1999).
9. H. Hellwig, J. Liebertz, and L. Bohaty, *Solid State Commun.* **109**, 249 (1998).
10. P. Becker, J. Liebertz, and L. Bohaty, *J. Cryst. Growth* **203**, 149 (1999).
11. G. D. Boyd and D. A. Kleinman, *J. Appl. Phys.* **39**, 3597 (1968).
12. C. Czeranowsky, E. Heumann, T. Kellner, and G. Huber, in *Conference on Lasers and Electro-Optics (CLEO/Europe) 2000 Digest* (Optical Society of America, Washington, D.C., 2000), paper CPD1.3.
13. H. Hellwig, J. Liebertz, and L. Bohaty, *J. Appl. Phys.* **88**, 240 (2000).
14. T. Baer, *J. Opt. Soc. Am. B* **9**, 1175 (1986).