

*Rapid communication***Efficient laser performance of Nd:YAG at 946 nm and intracavity frequency doubling with  $\text{LiJO}_3$ ,  $\beta\text{-BaB}_2\text{O}_4$ , and  $\text{LiB}_3\text{O}_5$** 

T. Kellner, F. Heine, G. Huber

Institut für Laser-Physik, Universität Hamburg, Jungiusstr. 9a, 20355 Hamburg, (Fax: +49-40/4123-6281, E-mail: kellner@physnet.uni-hamburg.de)

Received: 15 September 1997

**Abstract.** Efficient cw room temperature laser performance at 946 nm and frequency doubling into the blue spectral region has been achieved by using a composite Nd:YAG laser rod end pumped by two coupled beamshaped 20 W laser diode bars. An output power of 5.7 W at the fundamental wavelength was obtained. Intracavity frequency doubling with  $\text{LiJO}_3$ ,  $\beta\text{-BaB}_2\text{O}_4$ , and  $\text{LiB}_3\text{O}_5$  yielded a maximum output power of 550 mW at 473 nm with  $\beta\text{-BaB}_2\text{O}_4$  as the nonlinear crystal.

PACS: 42.44R; 42.65

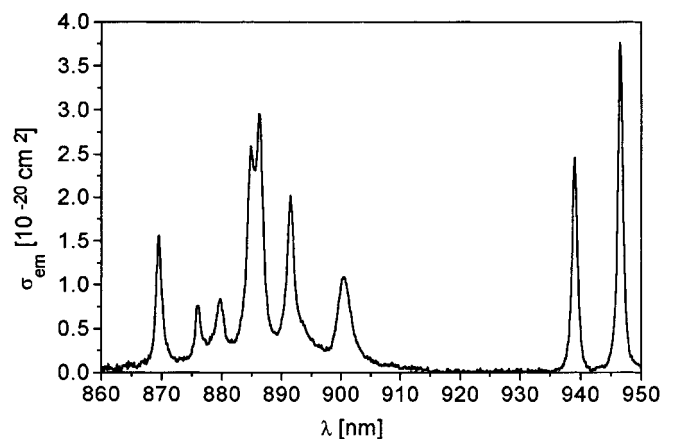
Frequency doubling of the ground-state laser transition of neodymium-doped laser hosts is a promising possibility to obtain high cw output power in the blue spectral region. A compact blue laser source is attractive for argon-ion laser replacement, high resolution printing, Raman spectroscopy, and laser based display devices. Other approaches to generate coherent cw blue light such as direct frequency doubling or sum frequency mixing of diode lasers [1], single pass frequency doubling in periodically poled lithium niobate [2], sum frequency mixing of the pump diode and the  $1.05\ \mu\text{m}$  transition in Nd:YLF [3], and Tm fibre lasers [4, 5] exhibit output powers below 250 mW up to now. Recently, frequency doubling the 946 nm transition of Nd:YAG in an external cavity yielded an output power up to 500 mW [6]. However, the latter technique is limited to certain applications because of the necessity of an active stabilization scheme for the external cavity. Intracavity frequency doubling the ground-state laser transition of Nd:YAG with  $\text{KNbO}_3$  as the nonlinear crystal yielded an output power up to 100 mW [7] in a cw mode and up to 366 mW [8] in a pulsed mode.

In this paper we report on the improved laser performance of a composite Nd:YAG laser rod in comparison to a conventional Nd:YAG crystal. Furthermore we report on intracavity frequency doubling with  $\text{LiJO}_3$ ,  $\beta\text{-BaB}_2\text{O}_4$ , and  $\text{LiB}_3\text{O}_5$  and compare the results with the achievable theoretical output power at a given intracavity power.

**1 Laser experiments**

Internally frequency doubled cw laser systems of the  ${}^4\text{F}_{3/2} \rightarrow {}^4\text{I}_{11/2}$  transition in different Nd-doped laser hosts are already commercially available with maximum green output power of up to 10 W. However, there are some difficulties concerning the frequency doubling of the  ${}^4\text{F}_{3/2} \rightarrow {}^4\text{I}_{9/2}$  transition due to the low effective emission cross section of  $\sigma_{\text{em}} = 3.7 \times 10^{-20}\ \text{cm}^2$  (see Fig. 1) and the quasi-three level nature of this laser transition, which exhibits a significant thermal population of the lower laser level. The requirements for a low laser threshold are short gain elements and a high pump brightness. This was achieved by using an end-pumped configuration.

The pump source was a 40 W laser diode module composed by two 20 W diode bars with a center wavelength of 804 nm at  $T = 15\ ^\circ\text{C}$ . Each diode bar was beam shaped, which allows focusing by a  $f = 14\ \text{mm}$  lens to an elliptical pump spot of  $80\ \mu\text{m} \times 200\ \mu\text{m}$  (diameter at  $1/e^2$ ,  $\text{NA} = 0.4$ ). Nd:YAG is the most suitable material for efficient laser operation on the ground-state transition because of its high



**Fig. 1.** Effective emission cross section of the  ${}^4\text{F}_{3/2} \rightarrow {}^4\text{I}_{9/2}$  transition in Nd:YAG

thermal conductivity ( $13 \text{ W m}^{-1} \text{ K}^{-1}$ ) and its large ground-state splitting. The thermal population of the terminal laser level in Nd:YAG at room temperature is 0.7% in comparison to 1.8% in Nd:YAlO<sub>3</sub> and 3.2% in Nd:YLF. The calculated reabsorption loss per round trip just above threshold for a 3 mm long crystal is 2.8% for a doping concentration of  $N = 4.6 \times 10^{19} \text{ cm}^{-3}$  (corresponding to a Nd-concentration of 1%). The measured absorption coefficient at the pump wavelength is  $\alpha = 2.4 \text{ cm}^{-1}$  because the pump wavelength does not match the peak absorption of Nd:YAG at 808 nm. The calculated optimum laser crystal length according to the theory given by Risk [9] for a total loss of 6% (including reabsorption losses, mirror transmission, and crystal losses) is approximately 3 mm. Two different laser crystals were used for the laser experiments. The first crystal was a halfmonolithic 3 mm long laser crystal with a diameter of 3 mm. The entrance facet of the laser crystal was coated for high reflection at 946 nm, for high transmission at the pump wavelength, and also for high transmission at  $1.06 \mu\text{m}$  ( $R < 5\%$ ) to avoid laser oscillation on the  ${}^4\text{F}_{3/2} \rightarrow {}^4\text{I}_{11/2}$  transition. The second facet was only antireflection coated for 946 nm. The second crystal was a composite laser rod consisting of a 3 mm long neodymium-doped YAG crystal with two diffusion bonded 3 mm long undoped YAG end caps (see Fig. 3). This crystal had no laser coatings at all. The conventional laser crystal was transversally cooled by placing the crystal between two water-cooled copper heatsinks. The thermal contact was improved by use of an indium foil. The composite laser rod was directly cooled with water ( $T = 15^\circ\text{C}$ ) in a flow tube.

The laser output power as a function of the incident pump power was measured in a plane parallel cavity with a 3.1% output coupler. With the conventional laser crystal a maximum laser output power of 4.57 W corresponding to a slope efficiency of 19% was achieved at an input power of 33.2 W. At an input power level higher than 26 W the slope efficiency decreased because of the increasing thermal load in the laser crystal. Figure 2 shows the cw laser performance of the two different laser crystals versus the incident pump power. The curve depicting the output power versus incident pump power of the composite laser rod shows a significant better laser performance. The higher threshold is due to the uncoated sur-

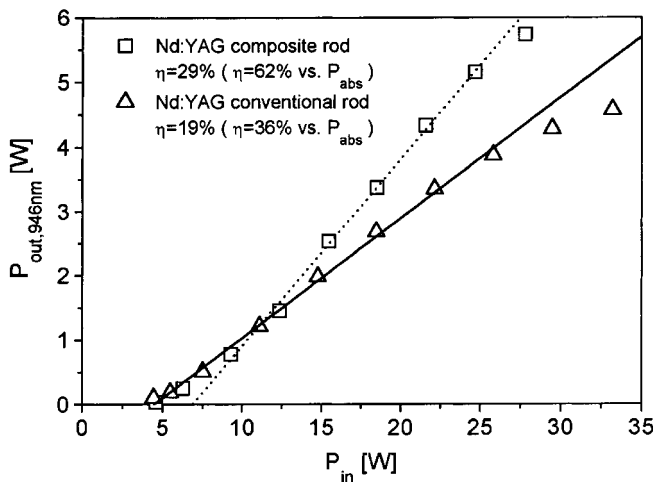


Fig. 2. Output power and slope efficiencies of Nd:YAG at 946 nm in a plane-parallel cavity ( $T_{oc} = 3.1\%$ )

faces of the crystal which introduces additional losses. An input power of 27.8 W results in an output power of 5.74 W corresponding to a slope efficiency of 29%. The slope efficiency was 62% with respect to the measured absorbed pump power. This improved laser performance is mainly due to the more efficient heat removal which was attained by the direct cooling of the laser rod. The beam quality factor  $M^2$  was measured to be  $M^2 = 4$  in the sagittal plane and  $M^2 = 5.4$  in the tangential plane at an output power of 4.7 W. For lower output powers up to 0.8 W the laser beam is nearly diffraction limited.

## 2 Frequency doubling

KNbO<sub>3</sub> is the most commonly used nonlinear material for intracavity frequency doubling the 946 nm laser line of Nd:YAG. The high nonlinearity and the possibility of non-critical phasematching (NCPM) as well as the small walk-off angle for critical phasematching makes this material very attractive for frequency doubling. However, KNbO<sub>3</sub> has also some disadvantages such as a very small temperature and spectral acceptance bandwidth, photorefractivity, and the possibility of domain reversal (particularly for NCPM, where heating of the crystal up to  $180^\circ\text{C}$  is necessary). So we decided to investigate the performance of LiJO<sub>3</sub>,  $\beta$ -BaB<sub>2</sub>O<sub>4</sub> (BBO), and LiB<sub>3</sub>O<sub>5</sub> (LBO) for intracavity frequency doubling. The relevant data for frequency doubling at 946 nm for these nonlinear crystals are listed in Table 1. The angular and spectral acceptance bandwidth were calculated by using the formulae [13]

$$\Delta\theta L = \frac{0.886\lambda_\omega}{n_{o,\omega}^3 \left| n_{o,2\omega}^{-2} - n_{e,2\omega}^{-2} \right| \sin(2\theta)} \quad (1)$$

and

$$\Delta\lambda L = \frac{0.443\lambda_\omega}{\frac{\partial n_{o,\omega}}{\partial \lambda_\omega} - \frac{\partial n_{e,2\omega}}{\partial \lambda_{2\omega}}}, \quad (2)$$

where the phasematching angle is given by  $\theta$ . The acceptance bandwidths are defined as the FWHM of the  $\text{sinc}^2(\Delta k \cdot L/2)$ -function in the plane wave approximation. LiJO<sub>3</sub> and BBO are negative uniaxial crystals and the type of phase-matching is ooe. LBO is a negative biaxial crystal. The assignment of the crystallographic axes to the usually used coordinate system for calculating the phasematching properties is  $(X, Y, Z) \rightarrow (a, c, b)$  [18]. The beam propagation

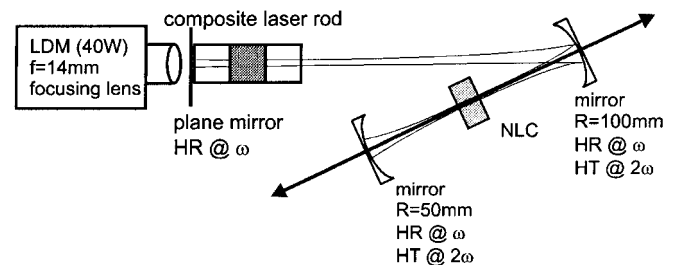


Fig. 3. Schematic of the experimental setup for blue light generation by intracavity frequency doubling. The arrows indicate the generated blue light output

**Table 1.** Properties of BBO, LBO and LiJO<sub>3</sub> for frequency doubling at 946 nm

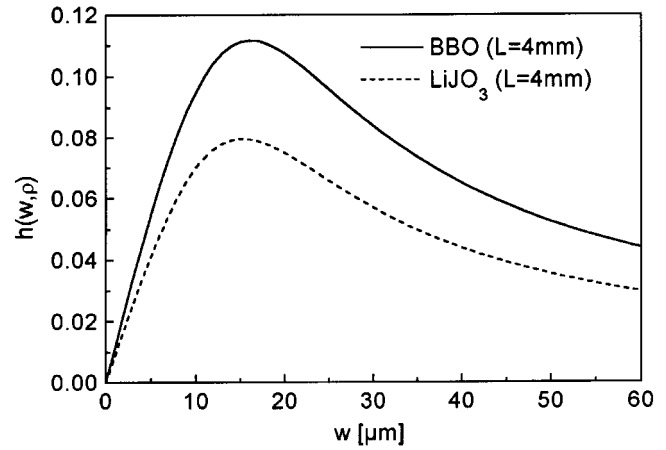
	BBO	LBO	LiJO <sub>3</sub>
phasematching	type I ooe	type I	type I ooe
phasematching-angle	$\theta = 24.9^\circ$	$\phi = 19.5^\circ$	$\theta = 34.3^\circ$
$d_{\text{eff}} [10^{-12} \text{ m/V}]$	2.08 [10]	0.92 [11]	4.0 [12]
walk-off angle	$3.5^\circ$	$0.7^\circ$	$4.6^\circ$
$n_\omega$	1.658 [13]	$n_z = 1.6077$ [14]	1.861 [15]
$\Delta\theta L [\text{mrad cm}]$	0.42	2.29	0.28
$\Delta\lambda L [\text{nm cm}]$	0.43	0.63	0.16
$\Delta TL [\text{K cm}]$	23 [13]	8 [16]	20 [17]

is within the *XY*-plane. The fundamental wave is polarized parallel to the *Z*-axis and the second harmonic wave is polarized in the *XY*-plane. LiJO<sub>3</sub> is the nonlinear crystal with the highest nonlinear coefficient ( $d_{\text{eff}}$ ), however, it has also the smallest spectral acceptance bandwidth. BBO and LiJO<sub>3</sub> exhibit a large temperature bandwidth so there is no need for an active temperature control. The main restrictions of these crystals are the small angular acceptance bandwidth and the large walk-off angle which reduces the effective coupling constant about an order of magnitude (see discussion below). LBO seems to be the most promising candidate with respect to the walk-off angle and the spectral- and angular acceptance bandwidth. However, LBO's nonlinear coefficient is less than that of BBO and LiJO<sub>3</sub> which limits the frequency doubling efficiency.

We used a folded cavity for the intracavity frequency doubling experiments with a plane input coupler, a folding mirror with a radius of curvature of 10 cm, and a curved end mirror with  $R = 5$  cm. A schematic of the experimental setup is shown in Fig. 3. The mirrors were high reflection coated at 946 nm ( $T = 1.5 \times 10^{-4}$ ) and coated for high transmission at the second harmonic wavelength. The nonlinear crystal (NLC) was placed in the focus of the laser mode between the curved mirrors. The radius of the laser mode inside the nonlinear crystal was calculated by ABCD matrix calculations to be 30  $\mu\text{m}$ . For this calculation a TEM<sub>00</sub> mode and a thermal lens of 7 cm at a pump power level of 26 W were taken into account. The thermal lens was determined in a plane parallel cavity by varying the length of the cavity. The cavity becomes unstable at a length of 7 cm.

The arrows in Fig. 3 indicate the generated blue light output by the two counterpropagating fundamental waves inside the cavity. The output power given in this paper are summed values of the two blue light beams. A maximum output power of 550 mW with BBO and of 520 mW with LiJO<sub>3</sub>, respectively, was generated. The input pump power was 25.8 W and 24 W, respectively. Using LBO the blue output power was slightly lower. An output power of 372 mW at an input power of 24 W was obtained. We observed chaotic output power fluctuations in the order of 20–30% for the three different nonlinear crystals due to longitudinal mode coupling [19].

A theoretical estimation of the achievable blue output power was made following the treatment of Boyd and Kleinman [20]. The formula for the second harmonic output power

**Fig. 4.** Dependence of the nonlinear coupling function  $h$  on the fundamental beam waist for LiJO<sub>3</sub> and BBO (length of both crystals  $L = 4$  mm)**Table 2.** Theoretical and experimental values for the generated second harmonic output power

	LiJO <sub>3</sub>	BBO	LBO
$P_{\text{intra}} [\text{W}]$	55	65	63
$P_{2\omega, \text{calc.}} [\text{mW}]$	880	620	430
$P_{2\omega, \text{exp.}} [\text{mW}]$	520	550	372

is given by

$$P_{2\omega} = \frac{2\omega^2 d_{\text{eff}}^2 L h k_\omega}{\varepsilon_0 c^3 \pi n_\omega^3} M^2 P_\omega^2. \quad (3)$$

This formula is valid in the undepleted pump approximation which is fulfilled for intracavity frequency doubling. The effective nonlinear coefficient is given by  $d_{\text{eff}}$ , the frequency of the fundamental wave by  $\omega$ , the length of the nonlinear crystal by  $L$ , the wavevector of the fundamental wave inside the nonlinear crystal by  $k_\omega$ , and the refractive index at the fundamental wavelength by  $n_\omega$ . The factor  $M$  takes into account the multimode character of the laser. For a multimode laser  $M$  is approximately 2. The factor 2 accounts for the two counterpropagating fundamental waves inside the cavity and  $P_\omega$  is the intracavity fundamental power. The nonlinear coupling function  $h$  depends on the walk-off angle ( $\rho$ ), on the length of the nonlinear crystal, and on the radius of the fundamental mode ( $w_0$ ) inside the nonlinear crystal. For noncritical phase-matching under optimum focusing conditions  $h$  is equal to 1. For critical phase-matching it was shown by Boyd and Kleinman that an analytical solution for the function  $h$  exists if the condition:  $\lambda/\rho\pi n_\omega < w_0 < \rho L/(24)^{1/2}$  is fulfilled. The formula for the nonlinear coupling function  $h$  is given by

$$h = \frac{\sqrt{\pi}}{2B\sqrt{\zeta}} \arctan(\zeta). \quad (4)$$

$B$  is the walk-off parameter ( $B = \rho/2(\pi n L/2\lambda)^{1/2}$ ) and  $\zeta$  is the focusing parameter ( $\zeta = L\lambda/2\pi w_0 n_\omega$ ). The analytical solution for the function  $h$  is given in Fig. 4 for LiJO<sub>3</sub> and BBO (length of both crystals 4 mm). Equation (4) is valid for beam radii less than 50  $\mu\text{m}$  for BBO and beam radii less than 67  $\mu\text{m}$

for  $\text{LiJO}_3$ , respectively. The lower limit is below  $10\ \mu\text{m}$ . It is obvious from Fig. 3 that the strong walk-off angle of these nonlinear crystals limits the effective nonlinear coupling constant about an order of magnitude. There exists no analytical solution for LBO. From [19] the value of the function  $h$  for LBO was determined to be 0.3 for a fundamental mode radius of  $30\ \mu\text{m}$ .

The total calculated output power, the intracavity power, and the experimentally observed output power are listed in Table 2. The theoretical results for BBO and for LBO are in good agreement with the experimentally measured output power levels. However, to explain the difference between the experimental and theoretical results for the second harmonic output power with  $\text{LiJO}_3$  as the nonlinear crystal we have investigated the spectral behaviour of the fundamental wavelength. We observed spectral fluctuations of the fundamental wavelength with a bandwidth of  $0.15\ \text{nm}$ . Occasionally the spectrum broadens to approximately  $0.5\ \text{nm}$  and at the same time the second harmonic output power decreases. The laser can decrease the nonlinear loss by detuning the lasing wavelength out of the acceptance bandwidth of the nonlinear crystal due to the fact that the gain bandwidth of  $1.5\ \text{nm}$  is much broader than the spectral acceptance bandwidth of the  $\text{LiJO}_3$ -crystal. This behaviour decreases the nonlinear conversion efficiency. In contrast to this the spectral acceptance bandwidth of LBO and BBO is broad enough to frequency double the whole bandwidth of the fundamental laser.

### 3 Conclusion

In conclusion, we have demonstrated high power frequency doubling on the  ${}^4\text{F}_{3/2} \rightarrow {}^4\text{I}_{9/2}$  laser transition of Nd:YAG with  $\text{LiJO}_3$ , BBO and LBO. An maximum output power up to  $550\ \text{mW}$  was achieved with BBO as the nonlinear crystal. We observed that the small spectral acceptance bandwidth of  $\text{LiJO}_3$  limits the nonlinear conversion efficiency. To avoid

this problem a birefringent filter has to be inserted in the laser cavity to reduce the bandwidth of the fundamental laser. The frequency doubling efficiency with LBO could be improved by using longer crystals to increase the effective nonlinear coefficient.

*Acknowledgements.* This work was supported by the German Ministry for Education and Research (BMBF project 16SV094/3).

### References

1. D. Fluck, P. Günter: *Opt. Commun.* **136**, 257 (1997)
2. V. Pruneri, R. Koch, P.G. Kazansky, W.A. Clarkson, P.St.J. Russell, D.C. Hanna: *Opt. Lett.* **20**, 2375 (1995)
3. P.G. Wigley, Q. Zhang, E. Miesak, G.J. Dixon: *Opt. Lett.* **20**, 2496 (1995)
4. S. Sanders, R.G. Waarts, D.G. Mehuys, D.F. Welch: *Appl. Phys. Lett.* **67**, 1815 (1995)
5. R. Paschotta, N. Moore, W.A. Clarkson, A.C. Tropper, D.C. Hanna, G. Mazé: *Conference on Lasers and Electro Optics* **11**, 1997 OSA Technical Digest Series (Optical Society of America, Washington, DC 1997) paper CTuG3
6. M. Bode, I. Freitag, A. Tünnermann, H. Welling: *Opt. Lett.* **22**, 1220 (1997)
7. G. Hollemann, E. Peik, H. Walther: *Opt. Lett.* **19**, 192 (1994)
8. F. Hanson: *Appl. Phys. Lett.* **66**, 3549 (1995)
9. W.P. Risk: *J. Opt. Soc. Am. B* **5**, 1412 (1988)
10. Y.X. Fan, R.C. Eckardt, R.L. Byer, C. Chen, A.D. Jiang: *IEEE J. QE-* **25**, 1196 (1986)
11. S. Lin, Z. Sun, B. Wu, C. Chen: *J. Appl. Phys.* **67**, 634 (1990)
12. M.M. Choy, R.L. Byer: *Phys. Rev. B* **14**, 1693 (1976)
13. D. Eimerl, L. Davies, S. Velsko, E.K. Graham, A. Zalkin: *J. Appl. Phys.* **62**, 1968 (1987)
14. K. Kato: *IEEE J. QE-* **30**, 2950 (1994)
15. K. Kato: *IEEE J. QE-* **21**, 119 (1985)
16. D. Chen, J.T. Lin: *IEEE J. QE-* **29**, 307 (1993)
17. M.S. Webb, S.P. Velsko: *IEEE J. QE-* **26**, 1394 (1990)
18. V.G. Dmitriev, G.G. Gurzadyan, D.N. Nikogosyan: *Handbook of Non-linear Optical Crystals* Springer Series in Optical Sciences **64**, 1st edn. (Springer, Berlin, Heidelberg 1991)
19. T. Baer: *J. Opt. Soc. Am. B* **3**, 1175 (1986)
20. G.D. Boyd, D.A. Kleinman: *J. Appl. Phys.* **39**, 1312 (1966)