Available online at www.sciencedirect.com

SCIENCE DIRECT®

Optics Communications 215 (2003) 159–162

OPTICS COMMUNICATIONS

www.elsevier.com/locate/optcom

Diode-pumped high-power cw blue laser at 473 nm with a compact three-element cavity

Pingxue Li[a,*], Dehua Li[a], Zhiguo Zhang[a], Shiwen Zhang[b]

[a] *Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences, P.O. Box 603, Beijing 100080, China*
[b] *North China Research Institute of Electro-Optics, Beijing 100015, China*

Received 24 September 2002; received in revised form 14 November 2002; accepted 18 November 2002

Abstract

We report on a diode-pumped cw Nd:YAG laser operating at 946 nm with a maximum output power of 3.3 W and a slope efficiency of 22% with respect to the incident pump power of 17.5 W. Intracavity frequency doubling with nonlinear crystal LBO yielded a single-ended blue output power of 590 mW with optical conversion efficiency of 3.4%. A very simple, compact three-element cavity of 35 mm long was used. The power fluctuation of the blue laser was 4.3% (rms) at output power level of 400 mW. Transverse mode hopping was observed at higher output power.

PACS: 42.55.Rz; 42.55.Xi; 42.65.Ky; 42.70.Hj

Keywords: Blue light; Nd:YAG; Intracavity doubling; Diode-pumped laser

1. Introduction

During the past few years blue lasers have attracted much attention for applications such as high-density data storage, color display, underwater communication, high-resolution printing, Raman spectroscopy and medical diagnostics. Frequency doubling of the ground-state laser transition $^4F_{3/2}$–$^4I_{9/2}$ of neodymium-doped laser hosts is a practical option to obtain high-power cw laser in the blue spectral region [1–5]. However, obtaining efficient operation of Nd:YAG laser at 946 nm ($^4F_{3/2}$–$^4I_{9/2}$) is very difficult. Because the laser is a quasi-three level system, it results in a considerable reabsorption loss due to thermal population at the lower level. In addition, the effective emission cross-section is quite smaller than that of the $^4F_{3/2}$–$^4F_{11/2}$ transition (1.06 μm). In order to overcome these difficulties, laser diode with high power density is needed for pump source. However, it brings on serious heating and thermal lensing in gain medium. To obtain efficient operation of 946 nm laser, heat effects must be minimized. Recently, not only the water-cooled system but also a diffusion bonded composite laser rod instead of the conventional crystal was used. It is reliable for heat transfer from both faces of the

---

[*] Corresponding author. Tel.: +86-108-264-9074; fax: +86-108-264-9451.
E-mail address: pxli@aphy.iphy.ac.cn (P. Li).

PII: S0030-4018(02)02202-2

Nd:YAG crystal through two undoped YAG caps when the Nd:YAG laser was operating at high pump power. By using the composite laser rod, high-power Nd:YAG blue lasers were achieved with multi-element folded cavities by some researchers. As much as 1.5 W of 473 nm radiation was obtained with a five-element cavity at a pump power of 21 W [6]. By using a folded cavity of six elements, a blue output power of 740 mW was reported with nonlinear crystal PPKTP [7]. Although the doubling efficiency can be enhanced by employing multi-element-cavity, a linear cavity system with reasonable conversion efficiency seems more desirable in some applications, as it makes this kind of blue solid-state source compact, simple and easier to produce. In this paper we demonstrate a blue laser employing a simple linear resonator with cavity length of 35 mm. The whole cavity consisted of only three elements, a composite Nd:YAG laser rod, a LBO crystal and an output mirror. As much as 590 mW of output power at 473 nm was achieved by intracavity frequency doubling of 946 nm Nd:YAG laser at incident pump power of 17.5 W.

2. Experiments and results

The experimental arrangement with a linear cavity was shown in Fig. 1. A high-brightness fiber-coupled diode laser with center wavelength of 808 nm was used in an end-pumping geometry. The pump power from a fiber with a core diameter of 400 μm and a NA of 0.22 was coupled into the gain medium with spot size of 300 μm diameter via a multi-lens system. The laser medium was a plane-parallel polished composite laser rod, two sides of a 1.0-at.% 3-mm thick Nd:YAG crystal were diffusion bonded with 2-mm thick undoped YAG crystals. The length of the Nd:YAG crystal was chosen to be 3 mm, to balance the needs of decreasing the reabsorption losses, which is essential for this quasi-three level laser, and absorbing reasonable fraction of the pump power. The diameter of the crystal was 3 mm, so as to achieve efficient heat transfer. The laser rod was bonded in a flowing box with adhesive. So the laser rod was cooled directly with water ($T = 17$ °C). The pumping facet of the laser rod was coated with high transmission (HT) for the pump light at 808 nm, high reflection (HR) at 946 nm. High transmission at 1064 and 1320 nm was also specified to prevent oscillating on these Nd:YAG transitions. The other side of the rod was coated with antireflection (AR) at 946, 1064 and 1320 nm.

We first measured the behavior of fundamental frequency at 946 nm without the nonlinear crystal in the cavity. A concave mirror with curvature radius of 50 mm and 5% transmission at 946 nm was used as output coupler. The output power of 946 nm as a function of the pump power was shown in Fig. 2. The laser threshold was 2.5 W. A maximum output power of 3.3 W was generated with slope efficiency of 22% at incident pump power of 17.5 W. The stability of output power was better than 1% and no degradation was observed during the operation of 1 h.

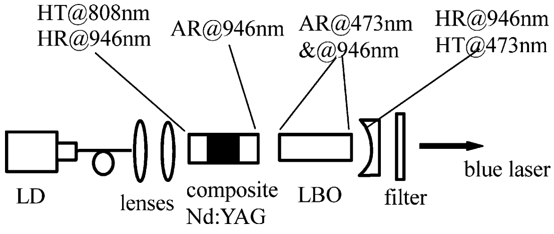

Fig. 1. Experimental setup of intracavity frequency doubled Nd:YAG laser.

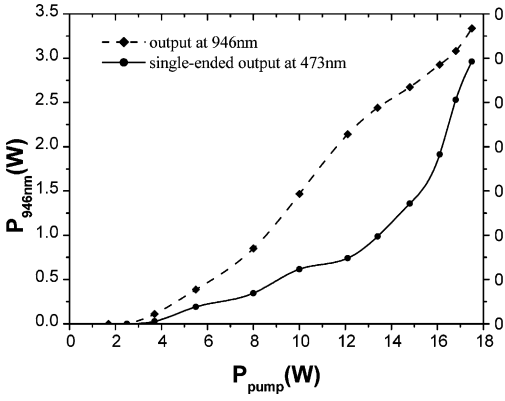

Fig. 2. Output power at 946 and 473 nm versus incident pump power.

$KNbO_3$ is the most commonly used nonlinear material for intracavity frequency doubling the 946 nm laser line of Nd:YAG mainly because of its high nonlinearity. However, it has some disadvantages such as a very small temperature and spectral acceptance bandwidth, the possibility of domain reversal and photorefractivity, and the difficulty in producing. LBO was selected as the doubling material in our experiment, due to its small walk-off angle and large spectral- and angular acceptance bandwidth. Blue laser at 473 nm was obtained by using a 10-mm-long LBO crystal with an aperture of 3×3 mm^2 (type I phase matching, $\Theta = 90°$, $\Phi = 19.37°$) for intracavity frequency doubling. Both facets of the LBO crystal were coated for antireflection at 473 and 946 nm to reduce the reflection losses in the cavity. It was wrapped with indium foil for reliable heat transfer and mounted in a copper block, which was fixed on a thermoelectric cooler for an active temperature control with stability of ± 0.1 °C. The output mirror was replaced by the one with curvature radius of 100 mm, which was coated with high reflection at 946 nm ($R > 99.8\%$) and high transmission at 473 nm ($T > 90\%$). To characterize the nonlinear crystal LBO, we measured the blue output power as a function of the crystal LBO heat-sink temperature and the result was shown in Fig. 3. The optimum LBO temperature, which maximized the blue output power at incident pump power of 9 W, was measured to be 22 °C. The FWHM bandwidth was 12 °C with the temperature bandwidth (ΔTL) of 12 (°C cm). Due to the limit of temperature control system, zero blue output power cannot be reached in our experiment.

The output power of blue laser at 473 nm as a function of the incident pump power was measured at the optimum LBO temperature of 22 °C and the result was also shown in Fig. 2. The threshold of the blue laser was 1.7 W. At the pump power of 14 W, corresponding to an output power of 230 mW, the laser emitted nearly TEM_{00} radiation with $M^2 \sim 1.4$, where M^2 is the beam-quality parameter. When the pump power was increased to 17.5 W, a single-ended output power of 590 mW was obtained with optical conversion efficiency of 3.4%, while M^2 increased to 2.1.

We carried out some stability testing of the blue laser by monitoring the blue output power with power-meter. At the output power level of 400 mW, the output noise was 4.3% (rms) and the temporal behavior of the blue output power for 22 min was shown in Fig. 4(a). At the pump power of 16.8 W, corresponding to a single-ended output power of 520 mW, transverse mode hopping accompanied with abrupt changes in output power was observed in 2 h of operation. The temporal behavior of the blue output power at

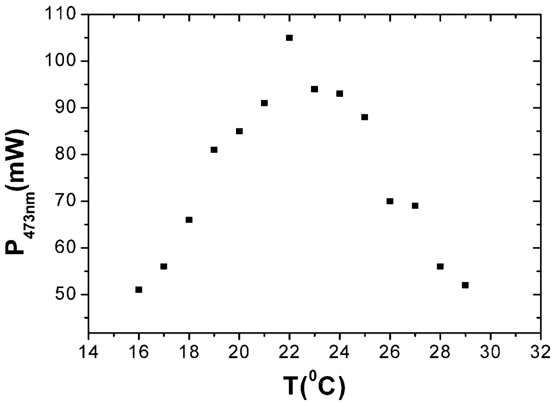

Fig. 3. Dependence of the blue output power on the LBO crystal temperature.

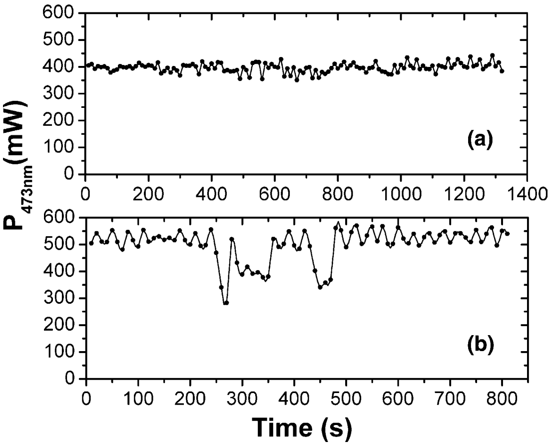

Fig. 4. Temporal behaviors of the blue output power at output power levels of (a) 400 mW, and (b) 520 mW.

this power level for 14 min was shown in Fig. 4(b). We found that the mode hopping usually appears after 10–40 min of relative stable operation during which the fluctuation of the output power was less than 5% (rms), and the blue output power gets back to nearly the original power level after 10–100 s of continued running. Possible reasons for these behaviors are analyzed as follows. First, since the spot size of pump light in composite laser rod is larger than that of fundamental laser, it tends to multi-transverse mode operation at high pump power. The competition between TEM_{00} mode and high transverse mode may be one of possible reasons that led to fluctuation and abrupt changes of output power at high pump power. Therefore, if we decrease the spot size of pump light to overlap with that of laser, the output stability and laser beam quality may be improved. Second, heating and thermal lensing of the nonlinear crystal LBO induced by the absorption of the fundamental and doubled frequency laser were generated seriously at high pump power, which would make the system unstable [7,8]. Finally, no special vibration isolation was used for the whole configuration, which also brought on instability to the cavity. Similar behavior of power dropping or fluctuation at high power was ever observed by other researchers [7,9]. Further investigations about these behaviors are carrying on. The high-frequency noise was detected with a fast photodiode and recorded with a digital storage oscilloscope. Output fluctuations were present indicating "blue problem". This kind of fluctuation is usually presented in intracavity frequency doubled laser system due to longitudinal mode coupling [10]. Our experimental arrangement was not optimized for low-noise operation, the noise should be reduced by improvements in crystal temperature control, vibration isolation and using two crossed doubling crystals [11]. How to suppress the high-frequency noise of blue laser for high pump power is also our next task. In addition, for practical applications, the blue light emitted from pumping side could be coupled out by coating the laser crystal with high reflection at 473 nm.

3. Conclusion

We have demonstrated a diode-pumped cw Nd:YAG laser operating at 946 nm, for which an output power of 3.3 W and a slope efficiency of 22% were achieved at incident pump power of 17.5 W. By intracavity frequency doubling with a LBO crystal, a single-ended blue output power of 590 mW at 473 nm was generated. The whole cavity consisted of three elements was only 35 mm long. Our experiments have shown that high-power blue laser with reasonable efficiency is possible by intracavity doubling with LBO in a compact linear cavity. Transverse mode hopping was observed in 2 h of operation at single-ended output power of 520 mW. Possible reasons about these behaviors can be attributed to transverse mode competition, heat effects and the "blue problem".

Acknowledgements

This work was supported by the Foundation of Laboratory of Optical Physics at Institute of Physics, Chinese Academy of Sciences.

References

[1] V. Pruneri, R. Koch, P.G. Kazansky, W.A. Clarkson, P.St.J. Russell, D.C. Hanna, Opt. Lett. 19 (1995) 2375.

[2] D.G. Matthews, R.S. Conroy, B.D. Sinclair, Opt. Lett. 21 (1996) 198.

[3] C.Q. Wang, L. Reekie, Y.T. Chow, W.A. Gambling, Opt. Commun. 167 (1999) 155.

[4] T. Kellner, F. Heine, G. Huber, Appl. Phys. B 65 (1997) 789.

[5] C. Czeranowsky, M. Schmidt, E. Heumann, G. Huber, S. Kutovoi, Y. Zavartsev, Opt. Commun. 205 (2002) 361.

[6] P. Zeller, P. Peuser, Opt. Lett. 25 (2000) 34.

[7] M. Pierrou, F. Laurell, H. Karlsson, T. Kellner, C. Czeranowsky, G. Huber, Opt. Lett. 24 (1999) 205.

[8] T. Kojima, S. Fujikawa, K. Yasui, IEEE. J. Quantum Electron. 35 (1999) 377.

[9] W.R. Bosenberg, J.I. Alexander, L.E. Myers, R.W. Wallace, Opt. Lett. 23 (1998) 207.

[10] T. Baer, J. Opt. Soc. Am. B 3 (1986) 1175.

[11] V. Gaebler, B. Liu, H.J. Eichler, Z. Zhang, D. Shen, Opt. Lett. 25 (2000) 1343.