Available online at www.sciencedirect.com
ScienceDirect
Optics Communications 270 (2007) 327–331
OPTICS COMMUNICATIONS
www.elsevier.com/locate/optcom

Single-frequency laser at 473 nm by use of twisted-mode technique

Erjuan Hao [a,b,*], Huiming Tan [a], Te Li [a,b], Longsheng Qian [a]

[a] Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, Changchun, Jilin 130033, China
[b] Graduate School of Chinese Academy of Sciences, Beijing 100039, China

Received 11 May 2006; received in revised form 30 August 2006; accepted 7 September 2006

Abstract

We experimentally demonstrate an all solid-state laser producing single-frequency output at 473 nm. Spatial gain hole-burning in the gain material has been eliminated by use of twisted-mode cavity approach. By carefully designing, a *Z*-cavity with two beam waists is chosen to provide the optimum beam radius in the gain medium Nd:YAG and second harmonic generation crystal LBO. A total output power of 85 mW was achieved, when the laser was diode-end-pumped at an incident power of 3.5 W, the light–light conversion efficiency is up to 2.4%.

Keywords: Single-frequency; Twisted-mode; Diode-end-pump

1. Introduction

The development of compact blue diode-pumped all solid-state laser sources is motivated by far-ranging application such as high-density optical data storage, display and printing technology, and replacement of argon-ion lasers [1–4]. However, stable continuous wave (CW) emission seems to be difficult to achieve, owing to the so-called blue problem, which leads to large amplitude fluctuations in the frequency-doubled emission. There are two possible ways to suppress these instabilities. The first is to force the laser to operate in single-longitudinal-mode, and the second is stabilization of multilongitudinal-mode operation. Although multimode operation is easily attained, a suitable stabilization method has to be applied. Single-mode operation can avoid the instabilities, various techniques have been tried to obtain single-longitudinal-mode laser operation [5–7]. Single-longitudinal-mode can be achieved in microchip lasers with extraordinarily thin gain materials [1,8], owing to the large frequency interval between adjacent longitudinal modes in the relevant laser cavities. Nevertheless, microchip lasers are not capable of high-power output because of the thinness of the gain material. Laser in a ring laser cavity is another known technique to obtain single-longitudinal-mode output [9]. But the ring approach with a nonreciprocal element in the laser cavity was somewhat complex, and traditional ring lasers generally consist of several mirrors, which make them hard to adjust. Another solution to obtain single-longitudinal-mode operation is to eliminate the troublesome spatial hole-burning by employing a twisted-mode cavity [10]. Compared with the normal standing-wave cavity, a twisted-mode cavity contains several polarization elements in the cavity to control the polarization state of the incavity beam. In this approach, the spatial gain hole-burning in the active material has been eliminated by use of a twisted-mode technique. The scheme has the advantages of ring laser and standing-wave cavity, which can get high power single-longitudinal-mode laser output, and has no light diode in the cavity as well. But the efficiency of second harmonic generation is sensitive to the total round-trip cavity loss, so the machine should have high stability. However, there are few papers about single-longitudinal-mode blue laser at 473 nm with twisted-mode technique.

---

[*] Corresponding author. Address: Changchun Institute of Optics, Fine Mechanics and Physics, Chinese Academy of Sciences, No. 20 Yingkou-road, Changchun, Jilin 130033, China. Tel.: +86 4316176724.
E-mail address: haoerjuan0415@sohu.com (E. Hao).

0030-4018/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.optcom.2006.09.055

In this work, we demonstrate a CW diode-end-pumped Nd:YAG/LBO laser at 473 nm with twisted-mode technique. A folded four-mirror resonator is carefully designed. We obtained 85 mW single-mode laser output at 473 nm with the incident power of 3.5 W. To the best of our knowledge, the use of twisted-mode technique to manipulate so high single-frequency 473 nm laser is reported here for the first time.

2. Theory analyze

2.1. Theory of twist-mode technology [10,11]

The sketch map of twisted-mode technique is shown in Fig. 1. The cavity consists of input mirror M1, two quarter-wave plates (P1, P2) located on each side of the gain medium, the Nd:YAG gain medium, a Brewster-plate polarizer (BP), and a output mirror M2. The two quarter-wave plates have their fast axes perpendicular to each other and the quarter-wave plate closet to the Brewster-plate polarizer has its axes oriented at 45° to the eigen-polarizations of the polarizer. The linearly polarized laser pumping through P1 can be expressed

$$E_{x1} = E\sin(\omega t - kz), \tag{1}$$

$$E_{y1} = E\sin(\omega t - kz), \tag{2}$$

where $k = 2\pi/\lambda$ (λ is the wavelength of the laser), when the linearly polarized mode across through the P1 for the first time, the linearly polarized modes at the flat cavity mirror become circularly polarized in the gain medium, expressed as follows:

$$E_{x2} = E\sin(\omega t - kz + \pi/2), \tag{3}$$

$$E_{y2} = E\sin(\omega t - kz). \tag{4}$$

Then the circularly polarized mode become linearly polarized mode, when which passed through P2, when the linearly polarized mode reflected by M2 and get across P2 for the second time, the linearly polarized modes become circularly polarized in the gain medium again, which can be expressed as

$$E_{x3} = E\sin(\omega t - 2kL + kz + \pi/2), \tag{5}$$

$$E_{y3} = E\sin(\omega t - 2kL + kz + \pi). \tag{6}$$

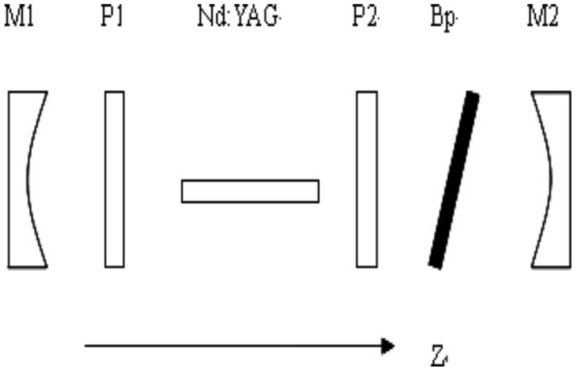

Fig. 1. The sketch map of twisted-mode technique.

So the circularly polarized modes from two directions in the gain medium would add up, which can be expressed as

$$E_x = 2E\cos(\omega t - kL)\cos k(L - z), \tag{7}$$

$$E_y = 2E\cos(\omega t - kL)\sin k(L - z). \tag{8}$$

The light intensity in the gain medium is

$$E_x^2 + E_y^2 = 2E^2\cos^2(\omega t - kL). \tag{9}$$

This gives a helical standing-wave pattern with no electric field nodes. It is evident that the light intensity is independent of the beam position z along the resonator axis. The laser beam has a spatially uniform light intensity along the resonator axis in the gain material, that is to say, there is no spatial hole-burning along the axis and the laser will oscillate in the single-longitudinal-mode.

2.2. Properties of LBO for frequency-doubling at 946 nm

Lithium triborate (LBO) crystal is chosen as second harmonic generation crystal. We calculated the double-frequency parameters of LBO at 946 nm with software SNLO, for contrasting, we list the parameters of three frequency-doubling crystals in type-I for 946 nm in Table 1, which are KN, LBO and BIBO.

From Table 1, we can get that the walk-off angle of LBO is smallest among the three crystals, and the accepted angle of LBO is the largest (4 times of BIBO's), but LBO has a small effective nonlinear coefficient. The formula for aperture length can be expressed as: [12] $l = \frac{\sqrt{\pi}\omega_0}{\rho}$, with ω_0 being beam radius and ρ the walk-off angle between the fundamental and SH wave. The formula indicates: when the walk-off angle is smaller, fundamental wave power-density through LBO in the cavity can be improved by reducing ω_0, so that efficiency of doubling frequency can be improved too. Though LBO has a smaller effective nonlinear coefficient, it has smaller walk-off angle and larger accepted angle, which made it has a long effective working area. So we can choose longer LBO and devise smaller ω_0 to obtain higher double frequency efficiency.

In our work, a Z-cavity with two beam waists is chosen to provide the optimum beam radius in the gain medium Nd:YAG and second harmonic generation crystal LBO. We can choose parameters and beam radius by ABCD matrix formalism and mode-matching criteria.

3. Experimental setup and results

In Fig. 2 the laser setup is presented. The pump laser is driven by a 4 W CW diode, whose emission center wavelength is 808.6 nm (under the room temperature) and can be tuned by changing the temperature of the heat sink to well match the peak absorption spectra of the Nd:YAG crystal to fully extract the pump energy. The multi-lens optical coupler has a transmission of about 90% at 808 nm, and can focus the pump radiation into gain medium with a spot size of about 160 μm in diameter. The res-

Table 1
Properties of KN, LBO, and BIBO for frequency-doubling 946 nm

Crystals	KN	BIBO	LBO
Phase matching (type-I)	946 (o) + 946 (o) = 473 (e)	946 (e) + 946 (e) = 473 (o)	946 (o) + 946 (o) = 473 (e)
At θ,ϕ (deg)	90.0, 60.0	18.3, 90.0	90.0, 19.4
D_{eff} (pm/v)	10.2	−2.31	0.812
Angle tolerance (mrad cm)	0.45	0.65	2.61
Accepted angle (mrad cm)	0.89, 0.89	1.29, 1.29	5.21, 5.21
Accepted bandwidth	3.67, 3.67	13.21, 13.21	45.86, 45.86
Walk-off angle (mrad)	0.00, 0.00, 46.7	40.7, 40.7, 0.00	0.00, 0.00, 11.29

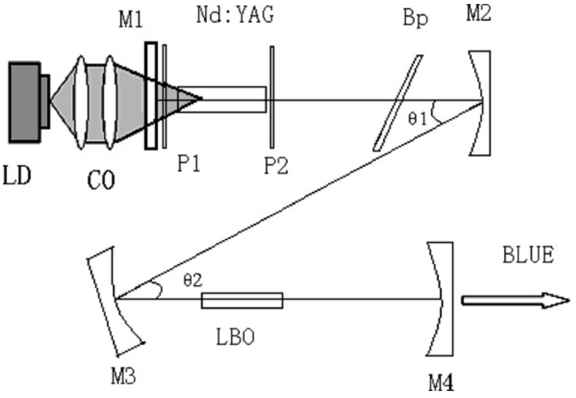

Fig. 2. The schematic configuration of the twisted-mode cavity: LD, laser diode; CO, coupling optics; M1, input mirror; M3/M4, folded mirrors; M4, output coupler; P1/P2, quarter-wave plates.

onator is composed of one flat mirror M1 and three concave mirrors M2 ($R = 100$ mm), M3 ($R = 50$ mm), and M4 ($R = 50$ mm). The gain medium is a plane-parallel polished Nd:YAG crystal (∅4 mm × 3 mm), with 1.0 at.%-doped Nd^{3+}. In order to suppress the strong 1064 nm parasitical oscillation and efficiently utilize the 808 nm pump light, a dielectric film is coated on pumping facet of the Nd:YAG crystal, which has high transmission coating (HT) at 808 nm ($T > 95\%$) and 946 nm ($T > 96\%$). The input flat mirror M1 has high reflectivity coating ($R > 99.8\%$) at both 946 nm and 473 nm, and high transmission coating (HT) at 808 nm ($T > 95\%$) and 1064 nm ($T > 96\%$) on the concave surface. The output mirror M4 has high reflectivity coating ($R > 99.8\%$) at 946 nm and high transmission coating (HT) at 473 nm ($T > 95\%$) on the concave surface. LBO crystal is chosen as second harmonic generation crystal, which is 10 mm thick, covered with an antireflection coating at 946 nm ($T > 95\%$) and 473 nm ($T > 95\%$) on both sides, and is cut for 946 nm/473 nm type-I second harmonic generation ($\theta = 90°$, $\Phi = 19.3°$, $\rho = 11.29$ mrad at 300 K), its non-linearity being sufficient for efficient frequency conversion at the anticipated intracivity fundamental power. LBO has other advantages, namely a high threshold, a large angular acceptance and type-I phase matching, so the IR beam retains the same polarization after propagation through the crystal.

A cavity with two foci is chosen to provide the optimum beam waists in the Nd:YAG and LBO second harmonic generation crystals. We can optimize the cavity parameters to get maximum power-density of pumped power and frequency-doubled efficiency. The arm lengths and relative angle are very sensitive to this cavity, so carefully calculation is needed to ensure stabilization, when driven current is added on. The beam incident angles ($\theta 1/2$, $\theta 2/2$) upon the folded mirrors are set as small as possible ($\approx 7°$) to reduce the astigmatism without optical stigmatism compensating elements. Calculated by the ABCD matrix formalism, we set the distance between M1 and M2 is 132 mm, the distance between M2 and M3 is 128 mm, the distance between M3 and M4 is 96 mm. $\omega_1 = 87$ μm (fundamental laser waist in the gain medium) and $\omega_2 = 47$ μm (fundamental laser waist in the second harmonic generation crystal), which satisfied with the mode-matching criteria, then the aperture length ($l = \frac{\sqrt{\pi}\omega_0}{\rho}$) is about 7.4 mm.

The laser crystal Nd:YAG is wrapped with indium foil, mounted in a copper holder and cooled through the resonator base plate, which is kept at a constant temperature by a thermo-electric cooler favorable to yield a small thermal population of the terminal laser level and the stability of the output power. The temperature of LD should be adjusted to make the emission accord with the absorbing of Nd:YAG. When the incidence pump power on the Nd:YAG was increased, the laser tend to operate in multimode, which caused by the mismatch between pump power and the oscillating laser modes in the Nd:YAG, and then cause the high-order transverse modes to oscillate. The other reason is the relative large gain bandwidth of Nd:YAG, many times the cavity mode spacing of about 0.58 Ghz, so there is only weak discrimination against adjacent longitudinal modes. By carefully aligning the cavity, the laser can operate at single-longitudinal-mode. We obtain 85 mw blue laser at 473 nm with the incidence power of 3.5 W. The stability of output power of 473 nm is less than 3% in the space of 2 h. The experiment has shown, the approach we chosen can select longitudinal-mode effectively and obtain single-longitudinal-mode operation at last, and has the potential to obtain higher single-longitudinal-mode blue laser.

This experiment demonstrates the potential of this route to obtain single-longitudinal-mode 473 nm laser, and improvement on many aspects is certainly possible, such as higher efficiency may be obtained by coating P1 with a HR-coated as cavity mirror this would eliminate the need

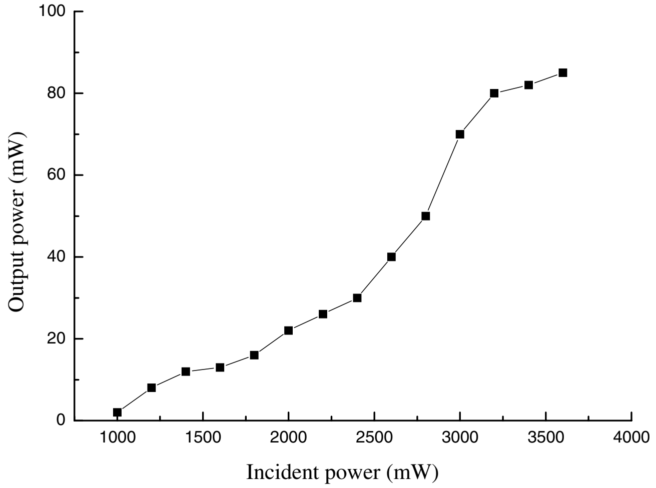

Fig. 3. Single-longitudinal-mode laser output power of the twisted-mode laser as a function of incident power.

for the input mirror M1; choose the optimum length of LBO to obtain higher output power; we also can insert an etalon to obtain tunable laser output. The M2 value of the 473 nm laser at the maximum pumping power was measured to be 1.68 with the knife-edge technique. Fig. 3 shows the single-frequency laser output power of the twisted-mode laser as a function of the incident pump power. The threshold and light–light conversion efficiency of the twisted-mode laser were 1.0 W and 2.4%, respectively. The reason for the high lasing threshold is all attribute to the saturation of re-absorption loss of the quasi-three-level for fundamental wave 946 nm. Fig. 4 shows the figure with the 3 d-intensity profile and intensity profiles along *x*-axis and *y*-axis of 473 nm blue laser. To monitor the output laser, we use a Fabry–Perot etalon in Fig. 5 shown the interference pattern of 473 nm laser, which clearly shown that the 473 nm laser is in single-longitudinal-mode operation.

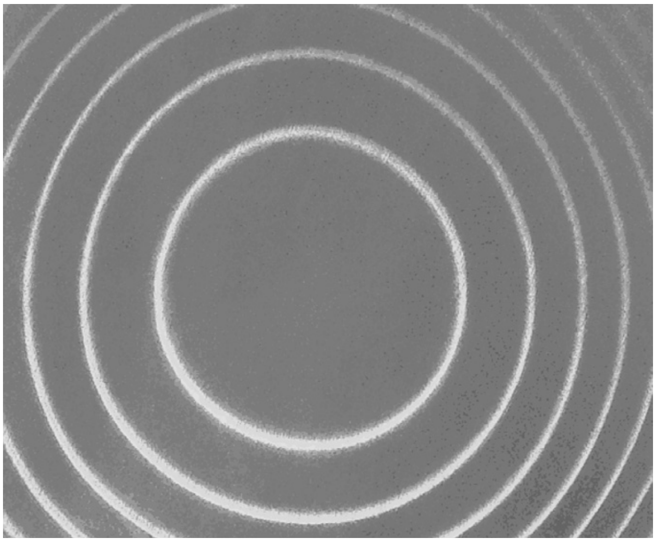

Fig. 5. Interference pattern of single-frequency blue laser by a Fabry–Perot etalon.

4. Conclusions

In summary, we have accomplished an all solid-stated laser producing single-longitudinal-mode output at 473 nm with twisted-mode technique. A total output power of 85 mW has achieved, when the laser was diode-end-pumped at an incident power of 3.5 W, indicating a

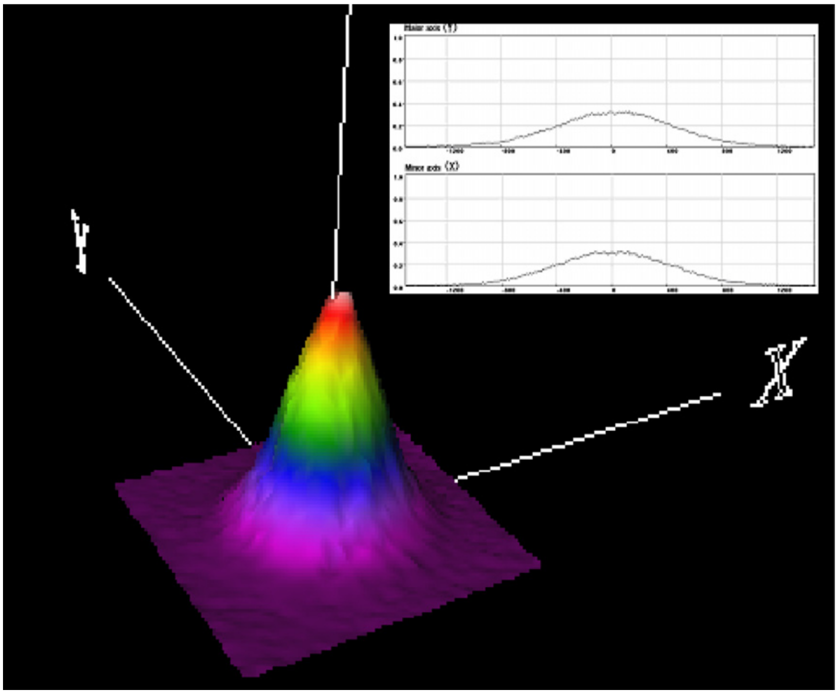

Fig. 4. The 3 d-intensity profile and intensity profiles along *x*-axis and *y*-axis of 473 nm blue laser.

light–light conversion efficiency of 2.4%, and this is to the authors knowledge, is reported here for the first time. Possible ways to improve the efficiency were discussed too.

Acknowledgements

We acknowledge the support from the Changchun New Industries Optoelectronics Co., Ltd. (CNI). This work was also supported by the national high-tech 863 plan of people's republic of China (No. 2002AA311140).

References

[1] Volker Gaebler, Baining Liu, Hans Joachim Eichler, Opt. Lett. 25 (2000) 1343.

[2] Bi Yong, Sun Zhi Pei, Ii Ruining, Zhang Hongbo, Hou Wei, Xu Zuyan, Opt. Precision Eng. 13 (2005) 16.

[3] Liu Weiren, Chen Yingxin, Qian Longsheng, Tan Huiming, Yu Jin, Opt. Precision Eng. 8 (2000) 133.

[4] Qinghua Xue, Yikun Bu, Fuqiang Jia, Quan Zheng, Opt. commun. 258 (2006) 67.

[5] W. Culshaw, J. Kannelaud, J.E. Peterson, IEEE. J. Quant. Electron. 10 (1974) 253.

[6] H. Nagai, M. Kume, I. Ohte, H. Shimizu, M. Kazumura, IEEE. J. Quant. Electron. 28 (1992) 1165.

[7] T. Taira, A. Mukai, Y. Nozawa, T. Kobayashi, Opt. Lett. 16 (1991) 1955.

[8] Yupeng Kong, Xuechun Lin, Ruining Li, Zuyan Xu, Xuekun Han, Opt. Commun. 237 (2004) 405.

[9] M. Bode, I. Freitag, A. Tunnermann, H. Welling, Opt. Lett. 22 (1997) 1220.

[10] V.E. Vtuhov, A.E. Siegman, Appl. Opt. 4 (1965) 142.

[11] Lin Yueming, He Huijuan, Lu Yutian, Acta Opt. Sin. 8 (1994) 891 (in Chinese).

[12] J.J. Zondy, M. Abed, S. Khodja, J. Opt. Soc. Am. B 11 (l2) (1994) 2368.