

Single-Frequency Laser at 473 nm by Twisted-Mode Technique¹

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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 V-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 105 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 3%.

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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 [1–6]. 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 [7–9]. Single-longitudinal-mode can be achieved in microchip lasers with extraordinarily thin gain materials [1, 10], 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 [11]. 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 [12]. 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. There are some papers about single-longitudinal-mode blue laser at 473 nm with twisted-mode technique before [13].

In this work, we demonstrate a CW diode-end-pumped Nd:YAG/LBO laser at 473 nm with twisted-mode technique. A folded three-mirror resonator is carefully designed. We obtained 105 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. 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, which are KN, LBO, and BIBO.

From table, 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

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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 $\theta, \phi/\text{deg}$	90.0	60.0		18.3	90.0		90.0	19.4	
$D_{\text{eff}}, \text{pm/V}$	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

expressed as [14]: $l = \frac{\sqrt{\pi}\omega_0}{\rho}$, 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 V-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. 1 the laser setup is presented. The pump laser is driven by a 4 W CW diode, whose emission

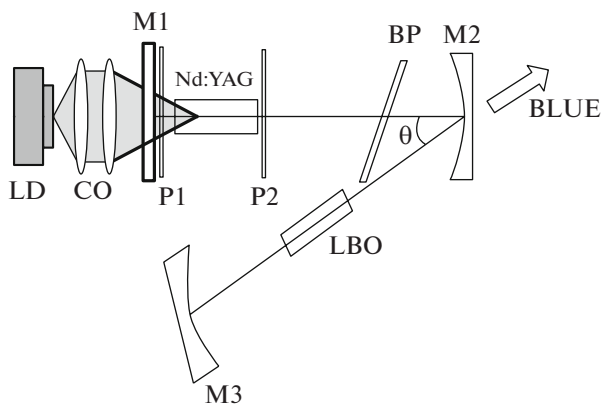


Fig. 1. The Schematic configuration of the twisted-mode cavity: (LD) laser diode; (CO) coupling optics; (M1) input mirror; (M2 and M3) folded mirrors, where M2—output coupler; (P1 and P2) quarter-wave plates.

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 resonator is composed of one flat mirror M1 and two concave mirrors M2 ($R = 50$ mm), M3 ($R = 100$ mm). The gain medium is a plane-parallel polished Nd:YAG crystal ($\varnothing 4 \times 3$ 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 and 473 nm on the side near the cavity, and high transmission coating (HT) at 808 nm ($T > 95\%$) and 1064 nm ($T > 96\%$) on the other flat surface. The output mirror M2 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 946/473 nm type I second-harmonic generation ($\theta = 90^\circ$, $\Phi = 19.3^\circ$, $\rho = 11.29$ mrad at 300 K), its non-linearity being sufficient for efficient frequency conversion at the anticipated intracavity 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 ($\theta/2$) upon the folded mirrors are set as

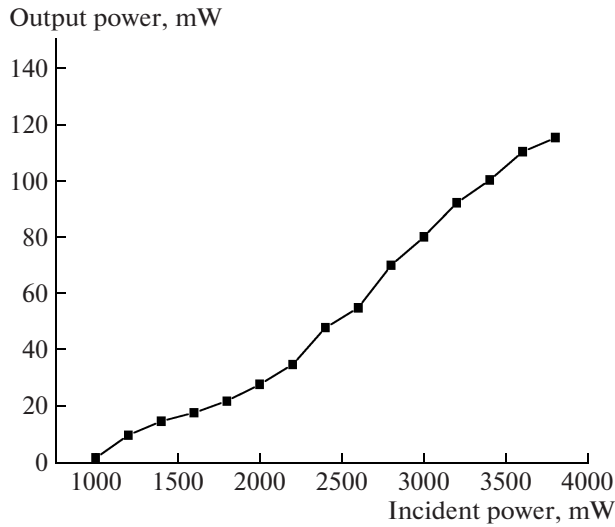


Fig. 2. Single-longitudinal-mode laser output power of the twisted-mode laser as a function of incident power.

small as possible ($\approx 7^\circ$) to reduce the astigmatism without optical stigmatism compensating elements. Calculated by the ABCD matrix formalism, we set the distance between M1 and M2 is 58 mm, the distance between M2 and M3 is 39 mm. $\omega_1 = 81 \mu\text{m}$ (fundamental laser waist in the gain medium) and $\omega_2 = 52 \mu\text{m}$ (fundamental laser waist in the second harmonic generation crystal) which satisfied with the mode-matching criteria, then the aperture length ($l = \sqrt{\pi\omega_0/\rho}$) is about 8.2 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, 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 105 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 two hours. The experiment has shown, the approach we chosen can select longitudinal—mode effectively and obtain single-longitudinal—mode

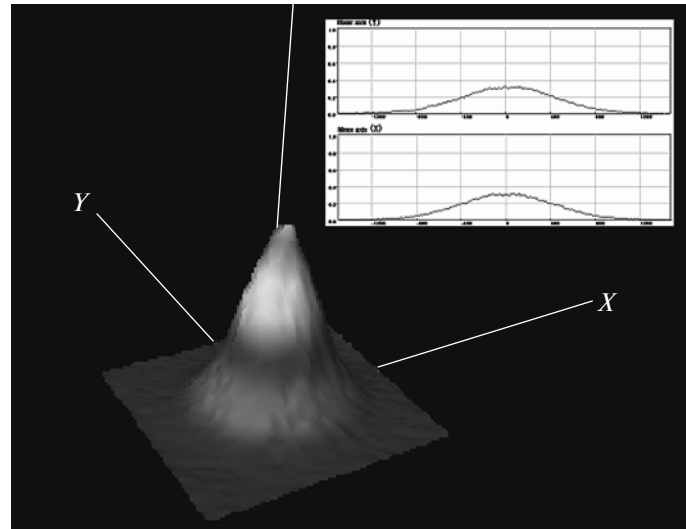


Fig. 3. The 3D-intensity profile and intensity profiles along x-axis and y-axis of 473 nm blue laser.

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 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 M^2 value of the 473 nm laser at the maximum pumping power was measured to be 1.47 with the knife-edge technique. Figure 2 shows the single frequency laser output power of the twisted-mode laser as a function of the incident pump power.

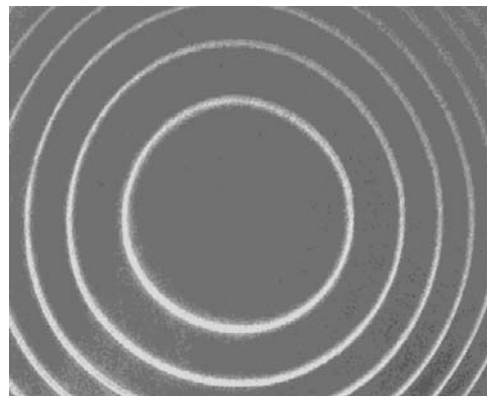


Fig. 4. Interference pattern of single-frequency blue laser by a Fabry—Perot etalon.

The threshold and light-light conversion efficiency of the twisted-mode laser were 1.0 W and 3%, 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. Figure 3 shows the figure with the 3D-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. Figure 4 shown the interference pattern of 473 nm laser, which clearly shown that the 473 nm laser is in single-longitudinal—mode operation.

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 105 mW has achieved when the laser was diode-end-pumped at an incident power of 3.5 W, indicating a light-light conversion efficiency of 3%, and this is to the authors knowledge, is reported here for the first time. Possible ways to improve the efficiency were discussed too.

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