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3.8 W of cw blue light generated by intracavity frequency doubling of a 946-nm Nd:YAG laser with LBO

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ABSTRACT Efficient cw intracavity frequency doubling of a diode-end-pumped Nd:YAG laser operating on $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transitions at 946 nm has been demonstrated. A symmetrical cavity with two composite laser rods was designed, which divides the pump power between the two composite laser rods, allowing for greater power scalability. A 30-mm-long LiB_3O_5 (LBO) crystal, cut for critical type I phase matching at 57 °C, was used for the intracavity frequency doubling of the laser. A maximum output power of 3.8 W in the blue spectral range at 473 nm has been achieved at 39 W of pump power. The beam quality M^2 value is 2.3 in both horizontal and vertical dimensions.

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1 Introduction

An all-solid-state laser in the blue spectral region is of special interest for high-density optical storage, laser-based display devices and Raman spectroscopy. Fan and Byer first introduced a diode-end-pumped Nd:YAG laser operating on $^4F_{3/2} \rightarrow {}^4I_{9/2}$ transitions at 946 nm at room temperature in 1987 [1]. Then, the 473-nm blue light produced by intracavity frequency doubling was extensively studied [2, 3].

However, blue lasers at 473 nm are still limited in output power in contrast with all-solid-state green lasers. The problems are the quasi-three-level nature of the 946-nm transition, which results in a very small stimulated emission cross section and a significant reabsorption loss at room temperature [1, 4]. Such a laser requires high pump intensities for efficient laser operation. Hence, power scaling of diode-end-pumped Nd:YAG lasers has been problematic due to the high heat loading on the laser rod, which leads to a strong thermal lens effect and depolarization loss. There are two ways to reduce the thermal effect and to shift the stability range to higher power: different cooling schemes [5] and designing a novel cavity including a variable configuration resonator [6]. Composite rods (rods with undoped end caps) were used to remove the part of the thermal lens formed by the bending of the pump face of the rod [7, 8].

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Various nonlinear crystals, such as KNO_3, $LiJO_3$, BaB_2O_4, BiBO or LiB_3O_5 (LBO), were used for intracavity frequency doubling of the 946-nm laser line of Nd:YAG [9–11]. Recently, an output power as high as 2.8 W at 473 nm has been achieved for an intracavity frequency doubled Nd:YAG laser with BiBO. However, BiBO was damaged at high output power (> 2 W) [12]. With respect to the high damage threshold, the small walk-off angle and the wide spectral and angular acceptance bandwidths, LBO seems to be the most promising candidate for high-power output of blue light [10]. However, LBO has a low nonlinear coefficient. It is possible to obtain a high doubling efficiency by using a longer LBO crystal.

In this paper, a symmetrical cavity with two composite Nd:YAG rods was designed to increase the pump power scalability, with the advantage of dividing the pump power between the two rods. Moreover, optimum mode matching and high doubling efficiency can be realized at the same time in this symmetrical cavity. An output power of over 3.8 W at 473 nm has been achieved by intracavity frequency doubling of the 946-nm Nd:YAG laser with a 30-mm-long LBO crystal at 39 W of pump power. The fluctuation of the blue output power was better than 5.0% around the 3.5-W operating point. The beam quality M^2 value is 2.3 in both horizontal and vertical dimensions.

2 Experimental setup

The experimental setup is schematically shown in Fig. 1, and is a symmetrical cavity with two composite Nd:YAG crystals. This design could shift the stability range to higher pump power, with the advantage of dividing the pump power between the two Nd:YAG rods. The composite crystal has two flat, undoped end caps, each 3-mm long, diffusion bonded to a 3-mm-long 1.1% Nd-doped inner part. The sides of the laser crystal were coated for high transmission at 946 nm and the pump wavelength. High transmission at 1064 and 1319 nm was also specified to prevent parasitic oscillations on these Nd:YAG transitions. In order to decrease the influence of the thermal effects, the laser crystal was water cooled and the water temperature was maintained at 18 °C. The high-brightness fiber-coupled laser diode served as the pump. It delivered a maximum output power of 25 W at 808 nm from the end of a fiber with 200-μm core diameter and a N.A. of 0.22. The pump light is focused by four achromatic

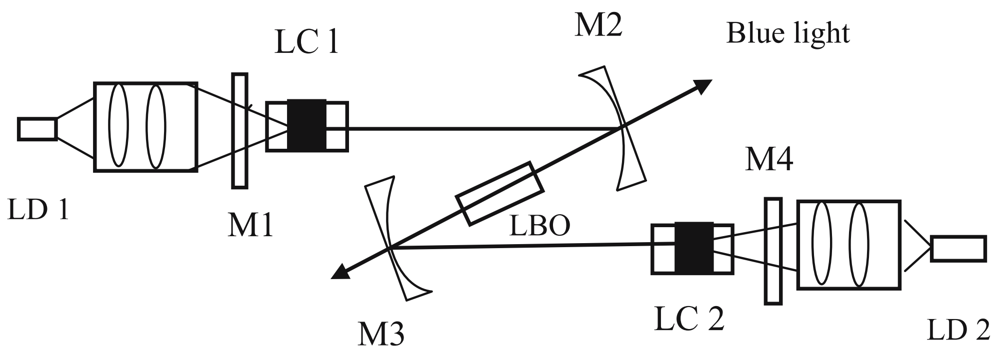

FIGURE 1 The experimental setup for blue light generation by intracavity frequency doubling. LD: laser diode, LC: laser crystal

lenses into the laser crystal, where the diameter at the focus is 300 μm. The plane input mirrors, M1 and M4, had antireflection coatings at the pump wavelength and high-reflection coatings at the operating wavelength. In addition, the mirrors had sufficient transmission at 1064 nm and 1319 nm. Two curved folding mirrors ($R = 100$ mm) M2 and M3 with high-reflection coatings at the laser wavelength and antireflection coatings at the doubling frequency wavelength determine the beam waist in the laser crystal and in the nonlinear crystal, respectively. A 30-mm-long LBO crystal, cut for critical type I phase matching at 57 °C, was used as the frequency doubling crystal, which had an antireflection coating at the laser wavelength and the doubling frequency wavelength. In our experiment, we easily controlled the phase matching temperature by heating the LBO crystal using an oven with controlled temperature accuracy of ±0.1 °C. The arrows in Fig. 1 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.

Figure 2 shows the radius of the laser mode in the middle of the laser crystal and the frequency doubling crystal. The radius in the laser crystal is about 109 μm and matched the pump mode in a region of the thermal lens focal length from 25 to 130 mm. Therefore, such a laser can stably operate with high pump power. The LBO crystal is placed in the focus of the laser mode between the curved mirrors M2 and M3 to yield a small focus (about 35 μm in the center of the LBO crystal) and good doubling efficiency. Moreover, it is not necessary to adjust the location of the frequency doubling crystal 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.

3 The experimental results

Nd:YAG is an isotropic material and emits unpolarized radiation. However, it was found that the fundamental light is partially polarized in our experiment. The polarization ratio is 15 : 1 at the pump power of 11 W and it decreases when increasing the pump power. The polarized characteristic of the laser mainly results from the different reflectivities of the folded mirrors for the differently polarized light. Figure 3 shows the blue output power versus the pump power (the summed values given by the two diode lasers). A maximum blue output power of 3.8 W was obtained at 39 W of pump power, corresponding to an optical conversion efficiency of 9.7%. To the best of our knowledge, this experimental result is the highest power reported for an all-solid-state cw blue laser at 473 nm. At an input power level higher than 39 W, although the intracavity power further increased, the output power of the blue light was not increased and became unstable. We think that the main reason is the depolarization loss of the laser beam, which is due to thermally induced birefrin-

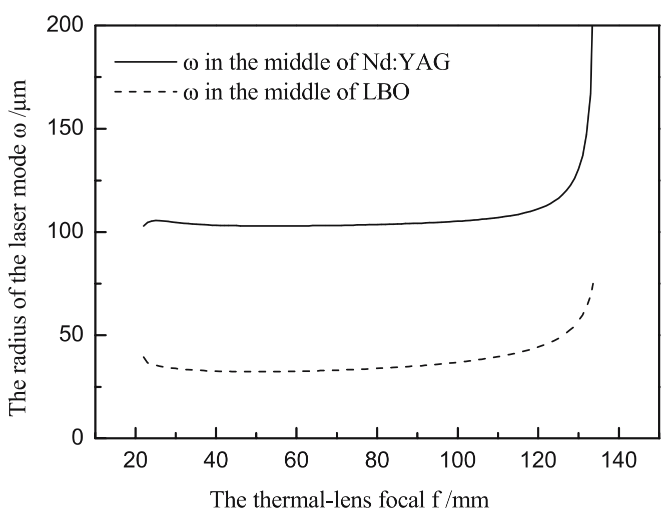

FIGURE 2 The radius of the laser mode in the middle of the laser crystal and the frequency doubling crystal via the thermal lens focal length

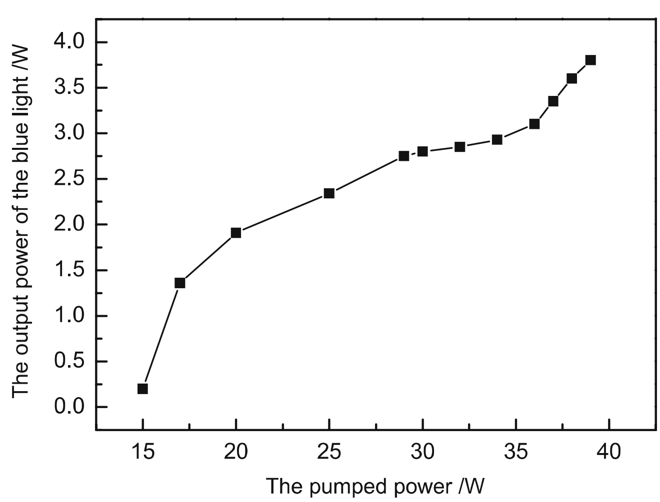

FIGURE 3 The output power of the blue light at 473 nm as a function of the pump power

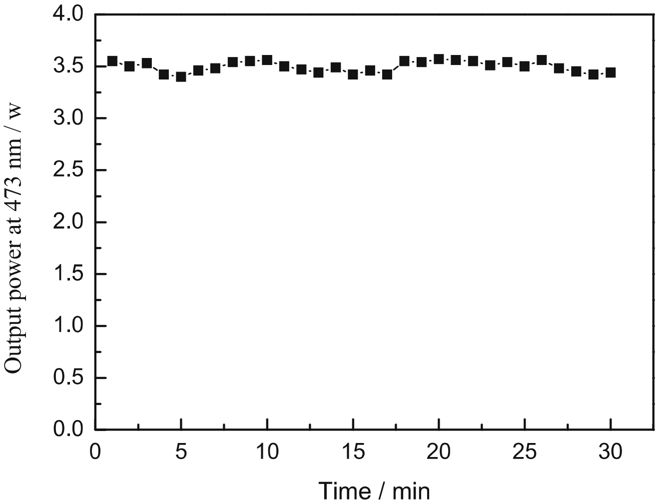

FIGURE 4 Stability of the blue output power around the 3.5-W operation point

gence in the laser crystal. If a Brewster plate is inserted into the cavity to fix the laser polarization and a quarter-wave plate is simultaneously inserted between the laser crystal and the input coupler, with one optical axis parallel to the laser polarization, the depolarization loss could be reduced [13]. In order to improve the output power, further investigations are under way and a higher output is expected. The intracavity power was estimated by the leakage through mirror M2 and the maximum value was 230 W when the pump power was 39 W. For the measured values of the second-harmonic power and the intracavity power, the coupling efficiency K_{exp} was calculated with (1), which was $3.6 \times 10^{-5}\,\text{W}^{-1}$. The value is about 63% greater than that obtained with a 10-mm-long LBO crystal reported by Czeranowsky et al. [12].

$$P_{\text{max},473} = K_{\text{exp}} P^2_{\text{max,intracavity}}. \tag{1}$$

The stability of the laser was investigated with a fast photodiode and recorded with a digital storage oscilloscope. The output light showed a quite stable behavior and did not show any large-amplitude fluctuation on the very short time scale (‘green problem’) [14]. The maximum amplitude of the fluctuation was less than 10%. The average stability of the blue laser was also investigated and the time trace of the average output power around the 3.5-W operating point is shown in Fig. 4. The fluctuation of the blue output power was better than 5.0% in the given 30 min. The small fluctuation is attributed to the precise control of the LBO crystal temperature. Moreover, the LBO crystal has not been damaged, which certified that the LBO crystal was suited to high-power intracavity frequency doubling.

The beam intensity distribution and beam propagation characteristics are very important for many high-precision laser-based applications. However, the beam characteristics were less investigated in the diode-end-pumped blue laser at 473 nm. An output power of 1.5 W at 473 nm with a beam quality parameter M^2 of less than 2.5 were reported in [15]. In our experiment, the M^2 value was measured by a Spiricon beam analyzer. The X and Y beam widths plotted against their

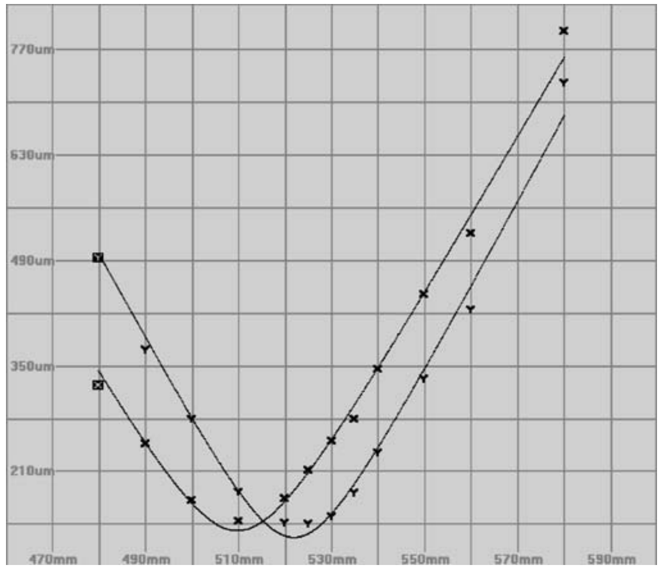

FIGURE 5 The X and Y beam widths as a function of their Z-axis sample locations

Z-axis sample locations are shown in Fig. 5. The beam widths are plotted in mm, the Z values in mm. The M^2 value was equal to 2.3 in both transverse directions at the maximum output power. The good beam quality was attributed to the good mode match.

4 Conclusion

In conclusion, a diode-pumped cw blue laser at 473 nm has been demonstrated with the maximum output power of 3.8 W by using a symmetrical cavity with two composite Nd:YAG crystals. To the best of our knowledge, this experimental result is the highest power reported for an all-solid-state cw blue laser at 473 nm. At the output power level of 3.5 W, the output stability is better than 5%. The beam quality M^2 value was equal to 2.3 in both transverse directions at the maximum output power.

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