Continuous-wave green laser of 34 W by intracavity frequency doubling in diode-side-pumped Nd:YAG/KTP

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Continuous-wave green laser with a maximum power of 34 W has been obtained by intracavity frequency doubling with KTP in diode-side-pumped Nd:YAG. The Nd:YAG/KTP green laser has a simple three-mirror V-fold cavity structure. The optical-to-optical conversion efficiency is 9.5%. The instability of the laser is measured when the output powers are near 16, 21, 30, and 34 W after the beam is filtered. At the maximum output power, the M^2 factor is measured to be 8.

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Diode-pumped solid-state green lasers have become the mainstream of laser in applications due to their many advantages such as high efficiency, compactness, high stability, and long lifetime. During the past few years, laser diode (LD) pumped green laser has become the focus of research because of its numerous applications such as laser color display, laser medicine, pumping source of Ti:sapphire lasers, etc.[1,2] Although high average power green laser beam in excess of 100 W has been obtained in the Q-switched mode[3,4], in continuous-wave (CW) mode, stable green power generation is difficult at higher power[5]. To date, the maximum CW green power of 30.5 W under diode side pumping has been reported by Mukhopadhyay *et al.*[6] However, the M^2 factor of ~20 at the maximum operating current would limit its applications. Kojima *et al.* demonstrated a diode-side-pumped intracavity second harmonic generation (SHG) CW Nd:YAG laser in which the maximum green powers were 27 W with M^2=8 and 16 W with M^2=1.2, corresponding to optical-to-optical efficiencies of 8.2% and 4.8%, respectively[5]. While in their design, two pump heads with diffusion reflectors were used, which would make the system costly and more complex.

In this letter, highly efficient operation is achieved based on our previous work[7,8] after optimizing cavity parameters. An output power of 34 W of stable CW green laser is obtained, corresponding to an optical-to-optical conversion efficiency of 9.5%, with a beam quality of M^2≈8 at the maximum output power. The green output is very stable, and the instabilities at the output powers of 16, 21, 30, and 34 W are all less than 0.5%. To the best of our knowledge, this is the highest CW green power by intracavity frequency doubling of a diode-side-pumped Nd:YAG laser.

Figure 1 depicts the oscillator setup which consists of a pump head to couple the diode laser beam to the Nd:YAG rod, a nonlinear crystal for intracavity frequency doubling, and a V-shaped resonator. The pump head consisted of a 0.6 at.-% Nd^{3+}-doped YAG rod (diameter 3 mm; length 89 mm) with a finely ground barrel. The temperature of water for cooling the rod and diode bars was set at 22 °C. A 4×4×10 (mm) KTP crystal was cut for SHG with type-II critical phase matching (θ=90°, φ=23.5°), and both facets were anti-reflection (AR) coated at 1064 and 532 nm (R<0.2%) to reduce intracavity reflection losses. The KTP crystal was tightly wrapped in a water-cooled copper mount and an indium foil was used to improve the thermal contact between KTP crystal and the copper heat sink. The temperature of the copper mount was kept at 19±0.1 °C during the operation of the laser. The V-shaped resonator is formed between the flat rear mirror M1 with highly reflective (HR) coating at 1064 nm (R > 99.9%), flat end mirror M3 with HR coating at 1064 nm (R > 99.9%) and 532 nm (R > 99.5%), and concave mirror M2 with the radius of curvature r=−300 mm, HR coating at 1064 nm (R > 99.7%), and high transmission (HT) coating (T > 95%) at 532 nm. The folding angle was less than 20° which is small enough to let the astigmatism be as little as possible. The pump head was placed between the two mirrors M1 and M2, the KTP crystal was kept between the mirrors M2 and M3. The distance between M1 and the pump head (L_{11}) was 138 mm, and that between the pump head and M2 (L_{12}) was 145 mm. The distance between M2 and the KTP crystal (L_{21}) was 115 mm, and that between M3 and the KTP crystal (L_{22}) was 10 mm.

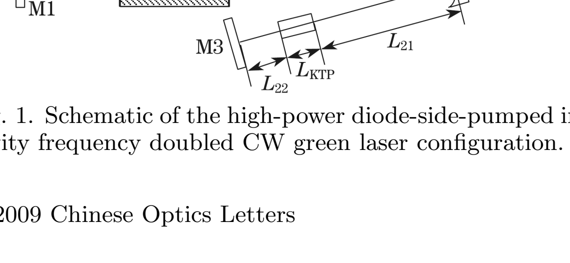

Fig. 1. Schematic of the high-power diode-side-pumped intracavity frequency doubled CW green laser configuration.

Table 1. Instantaneous Power of the CW Green Laser with the Reference Powers of 16, 21, 30, and 34 W

Time (min)	0	2	4	6	8	10	12	14	16	18	20	22	$\bar{P}$	$\Delta\bar{P}$
Power (W)	16.57	16.44	16.67	16.61	16.52	16.59	16.63	16.71	16.62	16.54	16.48	16.58	16.58	0.0736
Power (W)	21.38	21.48	21.47	21.51	21.42	21.34	21.57	21.61	21.52	21.44	21.49	21.53	21.48	0.0677
Power (W)	30.3	30.4	30.3	30.4	30.2	30.1	30.4	30.3	30.3	30.1	30.2	30.3	30.3	0.1010
Power (W)	34.2	34.1	34.2	34.2	34.1	34.3	34.3	34.2	34.1	34.1	34.3	34.2	34.2	0.0764

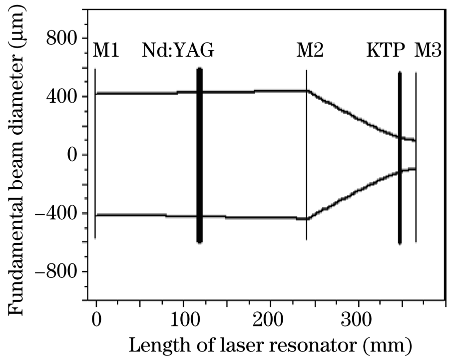

Fig. 2. Mode profile inside the resonator.

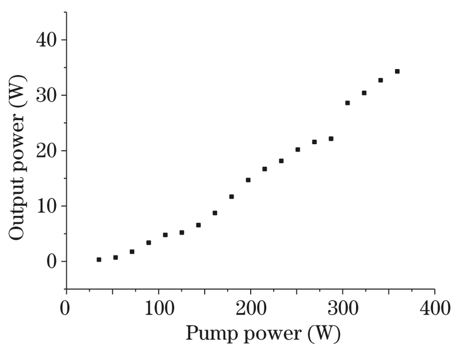

Fig. 3. Output power at 532 nm as a function of input pump power.

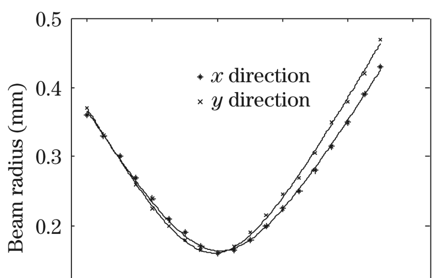

Fig. 4. Beam radii near the beam waist for both directions measured at 34-W output power. z is the position of the knife-edge along the potical axis direction.

When the thermal focal length of Nd:YAG is about 16 cm, we calculate the mode profile inside the resonator. M2 focuses the laser mode down to a waist radius of 117 μm in the KTP crystal while that of the laser mode is about 427 μm in the laser crystal, as illustrated in Fig. 2. The radius of curvature of M2 and the relative distances from M2 and M3 to the KTP crystal were optimized to achieve the desired focus size and position, while the distance from M2 to the KTP crystal was also adjusted to compensate for the astigmatism and minimize the phase mismatch between the green beams generated in the two directions. The final cavity length was experimentally optimized on this basis. The thermal focal length used in Fig. 2 is an estimated one.

The intracavity generated green laser power was coupled out through the mirror M2 and passed through a filter which was coated HR at the fundamental wavelength but HT at the SHG wavelength to block the residual fundamental power. An optical power meter (Nova II, OPHIR) was used to measure the output power. In Fig. 3, we show the measured output power as a function of the input power for the green laser. A maximum CW green power of 34 W was obtained at a total diode pump power of 360 W, corresponding to 9.5% conversion efficiency of diode pump power to CW green power. The oscillating threshold of pump current of the laser was 15.4 A.

It should also be noted that in a region where the pump power increases from 270 to 306 W, the 532-nm output power does not increase steadily, but somewhat fluctuates. This is because in this region there is one polarization or both unstable[9]. After passing this region, the laser output power increases steadily up till the highest pump power.

It is worth to mention here that though we have not placed any quarter wave plate inside the cavity to prevent the polarization coupling, the output green power is quite stable. With the Nova II power meter, the stability of the laser was measured when the output powers were near 16, 21, 30, and 34 W after the beam was filtered. The time interval measured was 2 min. The results are shown in Table 1. Using the root-mean-square (RMS) error equation $\Delta\bar{P} = \sqrt{\left[\sum_1^n (P_i - \bar{P})^2\right]/n}$, the instabilities $\Delta\bar{P}/\bar{P}$ of the green laser near 16, 21, 30, and 34 W are about 0.444%, 0.315%, 0.334%, and 0.223%, respectively.

We also performed experiments to measure the M^2 factor of this green laser using knife-edge method, and found that the beam quality was fairly good. Figure 4 shows the beam radii near the beam waist for both directions. The beam quality factor M^2 is about 8 at 34 W output power. Different from Ref. [6], the sum length of the cavity in our experimental device is longer, and the radius of the curvature of the folded concave mirror M2 is different too. We think this is the main reason that the M^2 factor is improved.

In conclusion, we have demonstrated the highly efficient CW green beam generation by intracavity frequency doubling of a diode-side-pumped Nd:YAG laser using a single pump head in a V-shaped cavity geometry. A high-power and high-stability green laser is obtained. The maximum CW output power at 532 nm is 34 W, corresponding to an optical-to-optical efficiency of 9.5%. The laser is operated with an instability of less than 0.5% and M^2 factor of about 8 at the maximum output power.

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References

1. W. Wang, X. Liu, and Y. Liu, Chinese J. Lasers (in Chinese) **34,** 646 (2007).
2. D. Xu, J. Yao, B. Zhang, S. Zhao, R. Zhou, X. Ding, W. Wen, and P. Wang, Chin. Opt. Lett. **3,** 85 (2005).
3. Z. Yao, J. Jiang, B. Tu, T. Zhou, and L. Cui, Chinese J. Lasers (in Chinese) **32,** 1459 (2005).
4. Z. Feng, C. Li, X. Li, J. Wang, and J. Bai, Acta Opt. Sin. (in Chinese) **28,** 1543 (2008).
5. T. Kojima, S. Fujikawa, and K. Yasui, IEEE J. Quantum Electron. **35,** 377 (1999).
6. P. K. Mukhopadhyay, S. K. Sharma, K. Ranganathan, P. K. Gupta, and T. P. S. Nathan, Opt. Commun. **259,** 805 (2006).
7. Y.-P. Zhang, H.-Y. Zhang, K. Zhong, X.-F. Li, P. Wang, and J.-Q. Yao, Chin. Phys. Lett. **24,** 2242 (2007).
8. H. Zhang, Y. Zhang, K. Zhong, P. Wang, X. Li, and J. Yao, Chinese J. Lasers (in Chinese) **35,** 15 (2008).
9. S. Lee, M. Yun, H. S. Kim, B. H. Cha, and S. Suk, Appl. Opt. **41,** 1082 (2002).