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Abstract. An efficient and compact all-solid-state continuous wave 67-nm red laser is generated by intracavity frequency doubling of a diode pumped Nd:YVO_4 laser at 1342 nm while suppressing the higher gain transition near 1064 nm. With the incident pump power of 40 W and a frequency doubling crystal lithium triborate, as high as 10.5-W output power at 671 nm is achieved. The optical-to-optical conversion efficiency is 26.3% and the output power stability during 8 h of operation is better than 2.3%. To the best of our knowledge, this is the highest conversion efficiency of watt-level laser at 671 nm generated by intracavity frequency doubling of a diode pumped Nd:YVO_4 laser at 1342 nm. [DOI: 10.1117/1.OE.51.6.064202]

Subject terms: diode-pumped solid-state laser; 671 nm; intracavity frequency doubling; Nd:YVO_4.

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1 Introduction

Diode pumped all-solid-state lasers have facilitated considerable advances in various fields of science and technology.[1–5] High power red lasers have been prosperous in medical therapy, colorful display, and scientific research. Generally, there are several main methods by which people can obtain continuous-wave (CW) red laser output, such as red laser diode (LD), and frequency doubling of laser at 1.3 μm from Nd ion doped laser crystal, etc. Although the output power of red LD has increased, the red LD has bad beam quality and a wide spectral output of several nanometers. The red laser can also be generated by frequency doubling of the fundamental wave at 1.342 μm from Nd:YVO_4. In addition, it is necessary to suppress the oscillation at 1064 nm. After Zhou et al.[6] demonstrated a CW red laser at 660 nm of 1.2 W with a side pump (Nd:YAG) and a type II phase match potassium titanyl phosphate (KTP) crystal, the output power at 660 nm laser was enhanced to 2 W in 2005 using a KTP crystal and an acoustic-optic Q-switch.[7] However, no high power CW watt-level red laser at 671 nm with Nd:YVO_4 crystal has been previously reported.

In this letter, a high power and efficient CW 671-nm red laser based on fiber-coupled LD end pumped intracavity frequency doubling Nd:YVO_4/lithium triborate (LBO) is demonstrated. With an incident pump power of 40 W, low doped bulk Nd:YVO_4, a long type I phase-matching LBO crystal, and a compact three-mirror-fold cavity, up to 10.5 W of red laser emission at 671 nm was achieved. The optical to optical conversion efficiency was greater than 26.3%, and the stability of the output power was better than 2.3% for 8 h.

2 Theoretical Analysis

We compare the performance of main laser transition lines in the Nd:YVO_4. To obtain laser oscillation at 1342 nm, which has a relatively low gain cross section compared with other main laser lines, the 1064-nm oscillation must be suppressed. Generally, the pumped end of the Nd:YVO_4 is coated at 1064-nm antireflection (AR) to suppress the oscillation of the 1064-nm laser, and the output coupler is also coated at 1064 nm AR to restrain the oscillation at 1064 nm. This method brings inconvenience to the coating progress and is not advantageous to commercial production. In our experiment, the output coupler was AR coated at 1064 nm, high reflection (HR) coated at 1342 nm, and the suppression of the 1064-nm laser line was accomplished by a one-cavity mirror.

The pump end of the Nd:YVO_4 was AR coated at 808 nm and HR coated at 1342 nm and 1064 nm. The output coupler was AR coated at 1064 nm and 671 nm but highly reflected at 1342 nm. Figures 1 and 2 show the coating curves of the pump face of the Nd:YVO_4 crystal and the concave surface of the output coupler.

A nonlinear crystal such as KTP and LBO was used in the second harmonic generation (SHG) field. Comparison of the characteristics of the two crystals are shown Table 1, although the effective nonlinear optical coefficient of KTP is 3.07 pm/V, which is much larger than that of LBO at 0.81 pm/V, the walk-off angle of LBO is 3.31 mrad, which is much smaller than that of KTP at 44.30 mrad. An LBO crystal with a longer length could be used to obtain higher

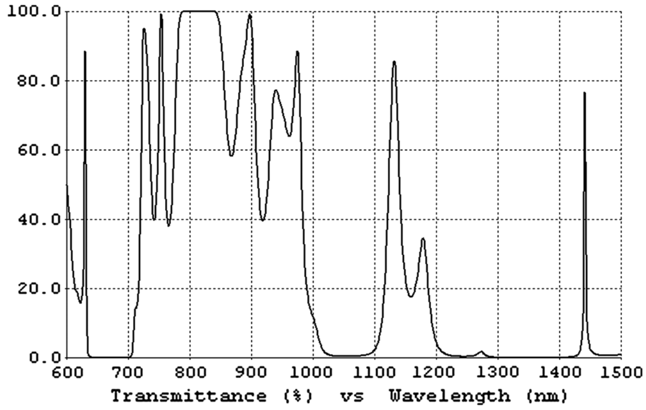

Fig. 1 Transmittance of the pump end of the $Nd:YVO_4$ crystal.

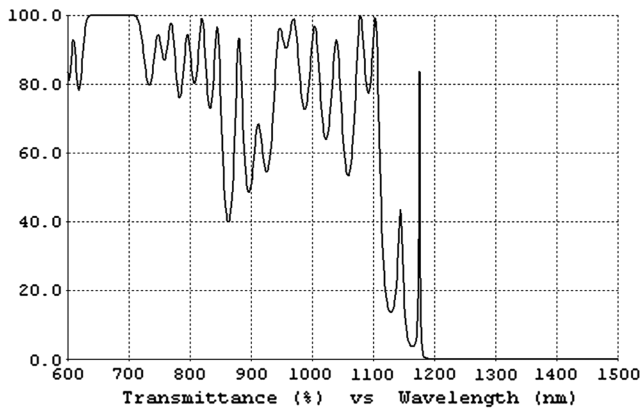

Fig. 2 Transmittance of the output coupler of the 671-nm red laser.

SHG efficiency. Owing to the characteristic of KTP, high intracavity power will incur a gray trace that makes the output power of the harmonic wave unstable or even decrease over a long time. Therefore LBO was selected to be the frequency doubling crystal.

3 Experimental Setup

The experimental setup is shown in Fig. 3. The pump source was a 40-W fiber-coupled LD array with an emission wavelength of 807.5 nm. The core diameter of the coupling fiber was 400 μm, and its numerical aperture was 0.22. The emission central wavelength of the pump source can be tuned by changing the temperature of the heat sink to match the best absorption of the laser crystal. The optics coupling system was composed of two plano-convex lenses that were AR coated at 807.5 ± 10 nm. The pump beam was imaged into the crystal at a ratio of 1:1. The laser crystal was a 0.5% at $\%Nd^{3+}$ doped, $3 \times 3 \times 5$ mm^3 $Nd:YVO_4$ crystal that was wrapped with indium foil and mounted on a thermal electronic cooled copper block to keep the temperature at 22.5°C.

The relative performance of the 1342-nm line was one-half that of the 1064-nm line, and its emission cross-section was much smaller than the main spectral line of $Nd:YVO_4$ at 1064 nm. To obtain the oscillation at 1342 nm, the chief line at 1064 nm was suppressed. M_1 is a 50-mm radius-of-curvature plano-concave output mirror. The concave facet plano AR coated at 1064 nm and 671 nm, and HR coated at 1342 nm. The plano facet of M_1 plano AR coated at 671 nm. The end mirror M_2 is a 200-mm radius-of-curvature concave mirror HR coated at 1342 nm and 671 nm. LBO is a frequency doubler with dimensions $2 \times 2 \times 10$ mm^3, cut for critical type I phase matching ($\theta = 86.3$ deg, $\varphi = 0$ deg) and AR coated at 1342 nm and 671 nm on both sides to reduce the intracavity loss of the fundamental laser and the red laser. The intracavity frequency doubling method

Table 1 Comparison of the frequency doubling parameters of KTP and LBO.

Crystal	Phase-matching type	Deff (pm/V)	Accept angle	Walk-off-angle
KTP	1342(o) + 1342(e) = 671(o)	3.07	1.69 mrad × cm	44.30 mrad
LBO	1342(e) + 1342(e) = 671(o)	0.818	12.67 mrad × cm	3.31 mrad

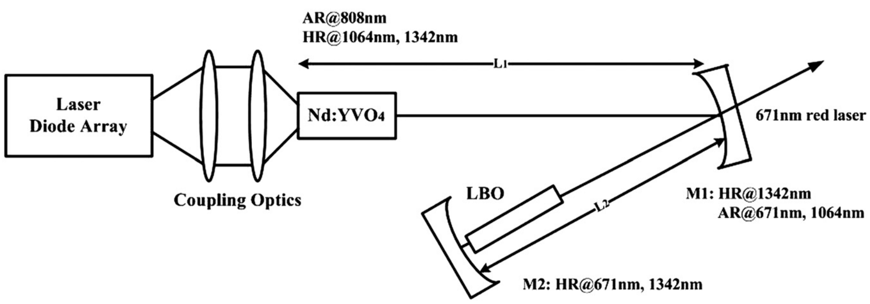

Fig. 3 Setup for the intracavity frequency doubling $Nd:YVO_4$/LBO red laser at 671 nm.

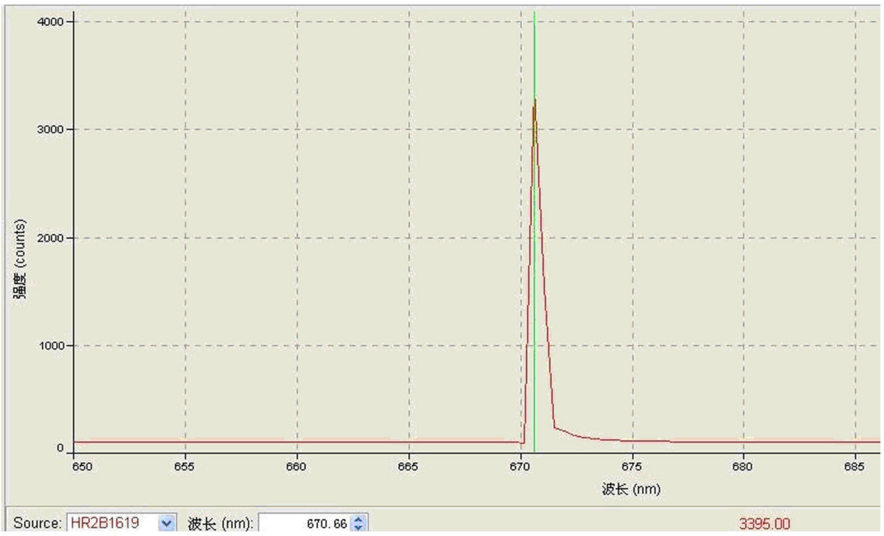

Fig. 4 Spectral of the 671-nm red laser.

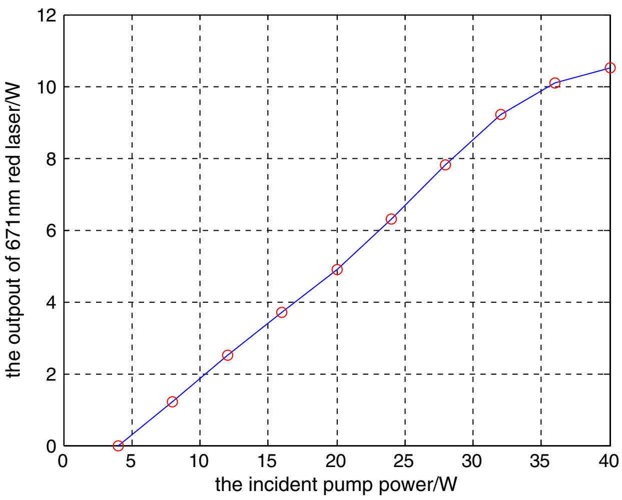

Fig. 5 Output power at 671 nm versus incident pump power.

was adopted in our experiment. All photons with fundamental wavelength oscillates were in the cavity to achieve high photon density, which is beneficial for the generation of second harmonic wave. The resonator is a three-mirror folded cavity with two separate waists; one is near the left side of $Nd:YVO_4$ to satisfy the mode-matching condition, and the other is near the surface of M_2, which could enhance the efficiency of SHG. The lengths of cavity arms L_1 and L_2 are about 76 mm and 45 mm, respectively. After numerical calculation, the radii of the beam waists were 142 μm and 53 μm which satisfy the design requirement.

4 Results and Discussion

Although the $Nd:YVO_4$ crystal is anisotropic, the frequency-doubling LBO crystal and the LD with high polarization ratio increase the high polarization characteristic of the fundamental wave, and it is not necessary to insert a polarizer, such as a Brewster plate into the cavity. When the LBO was inserted into the cavity close to the end mirror M_2 and the aligning angle of the LBO was tuned, the maximum output power of 10.5 W at 671 nm was achieved. Using the LABRAM-UV spectrum analyzer to scan the SHG laser and dealing with the data by software, the spectrum of the SHG laser is shown in Fig. 4. The dependence of the output power at 671 nm on the incident pump power is shown in Fig. 5. We measured the power of the 671-nm red laser at five different pump power levels, and used the average value to demonstrate the power increase with the incident pump power.

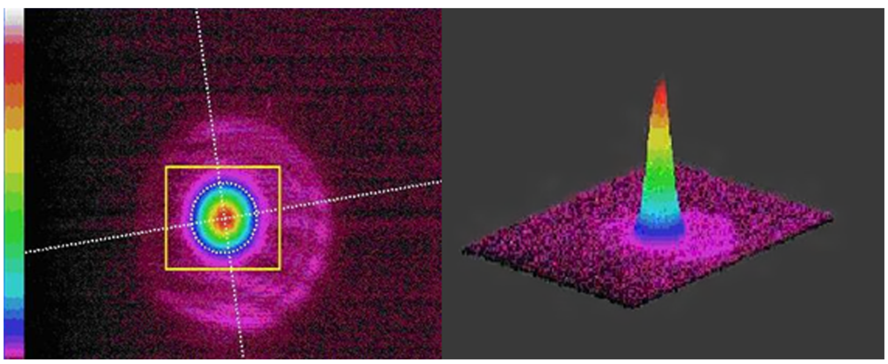

Fig. 6 Beam profile of the 671-nm red laser with 2-D and 3-D views.

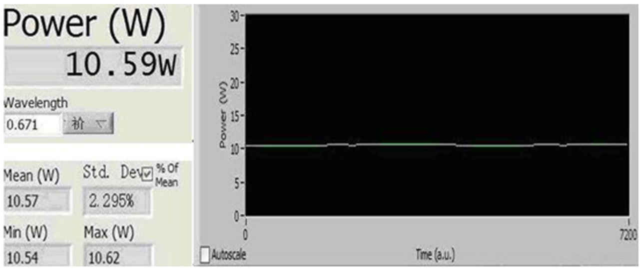

Fig. 7 Power stability of the 671-nm red laser.

The output power was 10.5 W at 671 nm with 40-W incident pump power. The output power fluctuation was due to the spectral line competition between the 1342-nm line and the 1386-nm line. When inserting an LBO cut for a 1342-nm SHG laser into the cavity, the output at 671 nm could be considered as the loss of the 1342-nm fundamental wave. The loss of the 1342-nm line increased the net gain of the 1386-nm line, which lead to an increase of the intracavity power at 1386 nm. This competition progress decreased the loss of the 1342-nm line, which was equal to the net gain at 1342 nm. Thus, the power of the second harmonic wave increased. Figure 6 is the beam quality testing result at a two-dimensional (2-D) and three-dimensional (3-D) view, which shows that the 671-nm laser was operating near TEM_{00} mode and the far-field intensity distribution was near Gaussian distribution. The M-square factor was about 1.45 measured by the knife-edge method with a Spiricon Beam star FX. Figure 7 demonstrates the long time of 8 h power stability measured by power meter at intervals of 4 sec. The power stability was 2.29% and the mean power was 10.57 W, whereas the minimum and maximum power was 10.62 W and 10.54 W, respectively.

5 Conclusions

In this paper, an efficient and compact all-solid-state continuous wave 671-nm red laser was generated by intracavity frequency doubling of a diode pumped $Nd:YVO_4$ laser at 1342 nm while suppressing the higher gain transition near 1064 nm. With the incident pump power of 40 W and a frequency doubling crystal LBO, as high as 10.5-W output power at 671 nm was achieved. The optical-to-optical conversion efficiency was 26.3% and the output power stability over 8 hours was better than 2.3%. To the best of our knowledge, this is the highest conversion efficiency of watt-level laser at 671 nm generated by intracavity frequency doubling of a diode pumped $Nd:YVO_4$ laser at 1342 nm.

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Biographies and photographs of the authors are not available.