A green laser at 517 nm based on intracavity frequency doubling of the diode-pumped Yb:LO laser*

LI Yong-liang (李永亮)**, **LI Xiu-fei** (李秀飞), **HU Hong-wei** (胡红伟), **HAI Xiao-quan** (海晓泉), **LIU Yang** (刘洋), **and WANG Jin-nan** (王津楠)

School of Optoelectronic Engineering, Changchun University of Science and Technology, Changchun 130022, China

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We report for the first time, to our knowledge, the diode-pumped continuous-wave (CW) thin-disk Yb^{3+}-doped Lu_2O_3 (Yb:LO) laser at 1 034 nm and the second-harmonic generation at 517 nm. With a 6.3% output coupler, the maximum output power is 1.17 W under a pump power of 18.5 W. Moreover, the intracavity second-harmonic generation (SHG) is also achieved with power of 193 mW at 517 nm by using an LiB_3O_5 (LBO) nonlinear crystal. The beam quality factor M^2 is about 1.28. The fluctuation of the output power is about 3% in 1 h.

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Coherent continuous-wave (CW) light sources in the visible spectral range have become interesting for many technical applications in medicine, lithography, communications, display and other areas. In particular, diode-pumped solid-state laser systems have been established as an efficient and compact light source for these applications. By frequency doubling the radiation from Nd^{3+} lasers, blue, green and red radiation can be obtained, and using the technique of intracavity doubling, high conversion efficiency can be achieved[1-5]. Secondary optical frequency references based on visible lasers locked on iodine hyperfine absorption lines have made a real breakthrough with the development of frequency doubled diode-pumped Nd^{3+} lasers at 532 nm[6,7]. Indeed, it combines strong and narrow hyperfine absorption lines of $^{127}I_2$ with efficient, robust and intrinsically stable compact lasers. Moreover, the natural linewidth of I_2 hyperfine transitions decreases when approaching the dissociation limit, due to the diminution of both radiative and predissociative widths[8,9]. In particular, hyperfine transition around 501.5 nm has a natural linewidth, and it is highly promising for improving the stability and the accuracy of secondary optical frequency standards. For this purpose, iodine transitions at 501.5 nm are studied since they can be addressed by an ionized argon laser. However, due to the lack of stability of argon laser, not all the potentials of this very narrow transition have been exploited yet. Recently, using an LiB_3O_5 (LBO) crystal, a cyan laser at 496 nm is obtained[10] by 914 nm and 1 085 nm from the Nd:YVO_4 laser intracavity sum-frequency mixing. The wavelength around 0.5 μm could be obtained by frequency doubling a laser source emitting at 1 μm. Xie et al[11] reported a diode-pumped passively mode-locked Nd:$CaNb_2O_6$ laser. With a single-emitter laser diode pumping, the maximum average output power of the mode-locked laser was 0.843 W, with a slope efficiency of 23%. Li et al[12] reported a diode-pumped Yb:$CaNb_2O_6$ laser at 1 038 nm. A maximum CW output power of 1.4 W with a slope efficiency of 20% is obtained.

In this paper, we report a diode-pumped CW Yb^{3+}-doped Lu_2O_3 (Yb:LO) laser at 1 034 nm. The pump module with the crystal in 16-pass pump scheme allows the realization of a Yb:LO thin-disk laser with maximum output power of 1.17 W. The slope efficiency is up to 6.3%, and the fluctuation of the output power is better than 3%. Furthermore, a CW 517 nm laser based on intracavity frequency-doubling Yb:LO-LBO is demonstrated.

The experimental setup of the fundamental laser at 1 034 nm is described in Fig.1(a). The optical pumping at 976 nm is realized with a fiber coupled diode laser (LIMO Co. td, Germany). The maximum CW output power delivered by this prototype diode is 20 W, and the width of the emission spectrum is ~ 2.5 nm. The optical fiber of diode has a diameter of 400 μm and a numerical aperture (NA) of 0.22. The laser crystals used in the experiments are 1.5% Yb:LO with thickness of 0.3 mm. The thin-disk crystal is anti-reflection (AR)-coated at the front side and high-reflection (HR)-coated at the rear side for pump and laser wavelengths. The rear side is soldered onto a water-cooled heat sink with a coolant temperature maintained at 15 °C. The parabolic mirror with focal length of 32 mm and the folding prisms lead to a 16-pass pump

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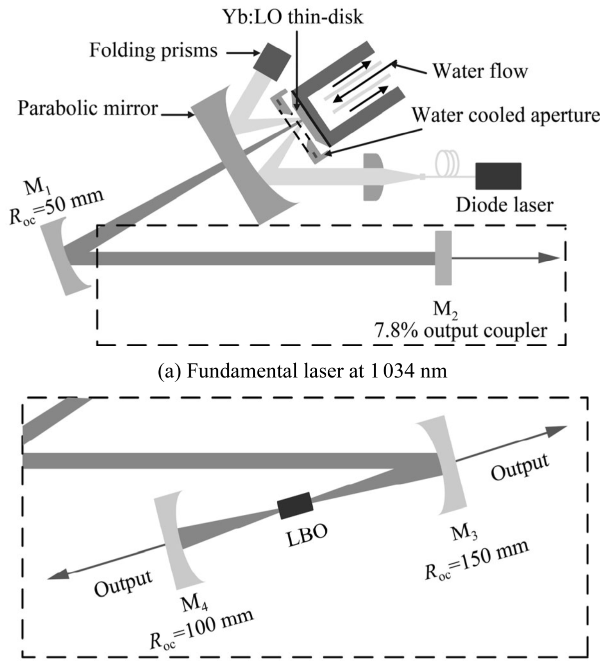
** E-mail: liyongliang@cust.edu.cn

scheme. The curvature radius of the first mirror M_1 is 50 mm, which is HR at 1 034 nm. The second mirror M_2 is an output coupler, which is with a transmission of 6.3% at 1 034 nm.



(a) Fundamental laser at 1 034 nm

(b) Frequency doubled laser at 517 nm

Fig.1 Schematic diagrams of the experimental setups

The change of the output power with the increase of the incident pump power is presented in Fig.2. The threshold is measured to be 3.8 W. With increasing the pump power, the output power at 1 034 nm is increased linearly with a slope efficiency of 7.5%. The highest output power of 1.17 W is achieved for the incident pump power of 18.5 W, corresponding to an optical conversion efficiency of 6.3%.

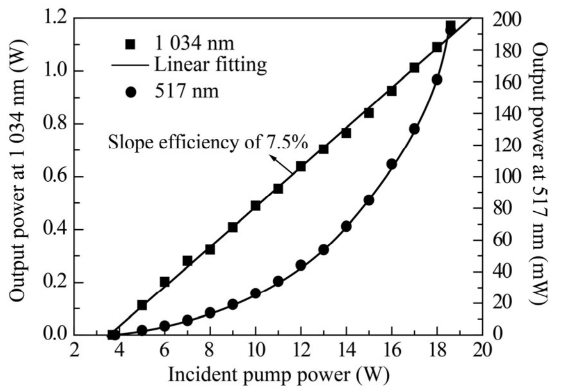
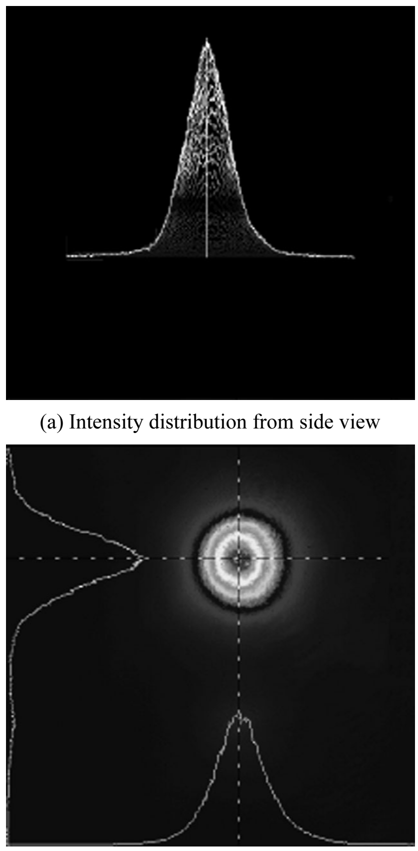


Fig.2 Output power at 1 034 nm and 517 nm versus incident pump power

As the best performance is obtained at 1 034 nm, we try the second-harmonic generation at this wavelength. We modify the cavity to reduce the cavity losses and add a second waist. All the elements are the same as the corresponding ones in the setup of fundamental 1 034 nm laser mentioned above. Two concave mirrors are added, which are M_3 coated with HR at 1 034 nm and AR at 517 nm and M_4 coated with HR at 1 034 nm and 517 nm. The experimental setup of the intracavity frequency-doubled 517 nm laser is shown in Fig.1(b). The LBO crystal, which is cut for type-I critical phase matching in the principal plane XY (θ=90°, φ=13.3° with d_{eff}=0.83 pm/V), is chosen as the nonlinear crystal due to its high anti-damage threshold of 18 GW/cm^2 and much smaller walk-off angle about 9.16 mrad. The size of the LBO crystal is 2 mm×2 mm×10 mm. The LBO is mounted in a copper block, which is also fixed on a thermoelectric controller for active temperature control. The laser performance is also presented in Fig.2. As shown in Fig.2, the threshold of the 517 nm laser is about 3.7 W, and with an incident pump power of 18.5 W, a CW second-harmonic generation output power of 193 mW at 517 nm emission is obtained.

The intensity distribution of 1 034 nm laser in Fig.3 is measured at pump power of 18.5 W using the beam profiler made by Photon Inc. The beam profile is measured to be TEM_{00}, and the ellipticity of spot is 0.99.



(a) Intensity distribution from side view

(b) Intensity distribution from cross section

Fig.3 Beam intensity distribution of 1 034 nm laser

The beam diameters versus their sample locations on z axis are shown in Fig.4. The beam quality factor M^2 can be measured by a Spiricon beam analyzer and calculated automatically from the formula as

$$M^2 = \frac{\sqrt{D^2 - D_0^2}}{Z - Z_0} D_0 \frac{\pi}{4\lambda}, \tag{1}$$

where D_0 is the waist diameter, and Z_0 is its corresponding position on z axis. The beam quality factor M^2 obtained from Fig.4 is about 1.28 in our experiment. The asymmetry of curve in Fig.4 results from the walk-off between the fundamental wave and the second harmonic in the direction of the LBO. The stability testing is carried out by monitoring the blue-green laser with a field-master-GS power meter at 10 Hz. The fluctuation of the output power is about 2.7% in 4 h. The spectrum measured by a Spectrapro-500i spectrometer is shown in Fig.5. The spectral linewidth is about 0.8 nm with the central wavelength at 517 nm.

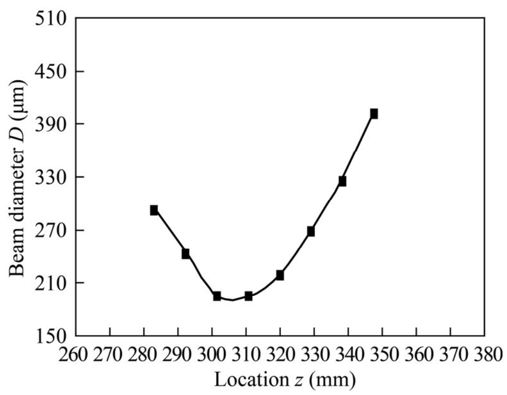


Fig.4 Measured results of the beam diameters versus their sample locations

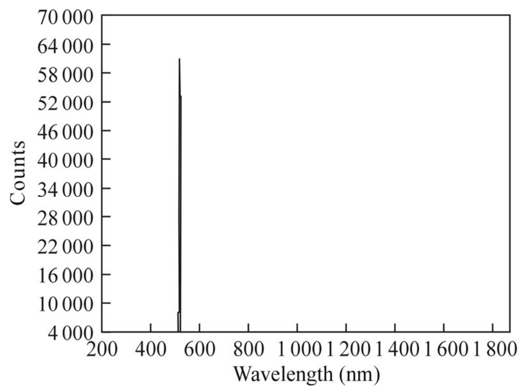


Fig.5 Output spectrum with pump power of 18.6 W

In summary, we demonstrate a laser emission at 1 034 nm in Yb:LO crystal for the first time, to the best of our knowledge. In the 1 034 nm laser, 1.5% Yb:LO with thickness of 0.3 mm is used. The CW output power of 1.17 W is achieved with the incident pump power of 18.5 W. The results show that Yb:LO is a potential 1 034 nm laser crystal for high power system. After the second-harmonic generation, a blue-green laser at 517 nm with power of 193 mW is obtained. Using more efficient nonlinear crystals, such as ppKTP or $KNbO_3$, the second-harmonic radiation power should be increased.

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