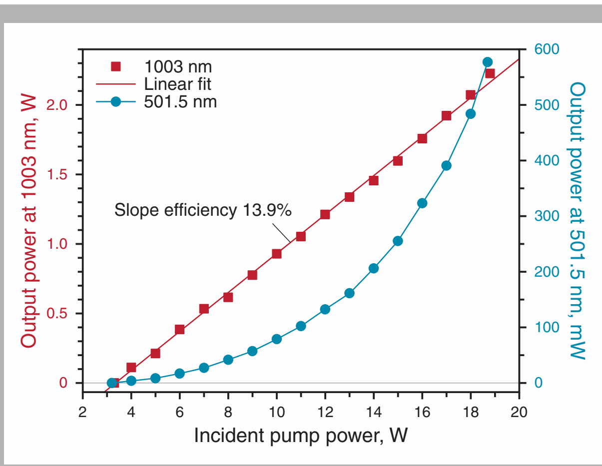
Abstract: Thanks to its high emission cross section around 1 μm, Yb:$CaNb_2O_6$ is a good candidate for laser operation near 1 μm as shown in our figure of merit. We demonstrated, for the first time to our knowledge, laser operation of Yb:$CaNb_2O_6$ at 1003 nm. More than 2.23 W at 1003 nm and 577 mW at 501.5 nm were produced simultaneously. This visible wavelength corresponds to an iodine transition previously studied with argon ionized lasers for metrological applications.



Output power *versus* incident pump power

Efficient diode-end-pumped Yb:$CaNb_2O_6$ thin-disk laser at 1003 nm and second-harmonic generation for an emission at 501.5 nm

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1. Introduction

Coherent continuous-wave 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, one can generate blue, green, and red radiation, and by implementing the technique of intracavity doubling, one can achieve high conversion efficiencies [1–15]. 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 [16–32]. 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 ($\approx$ 500 nm), due to the diminution of both radiative and predissociative widths [33,34]. In particular, hyperfine transitions around 501.5 nm exhibit a natural linewidth in the order of 11 kHz [35], highly promising for the im-

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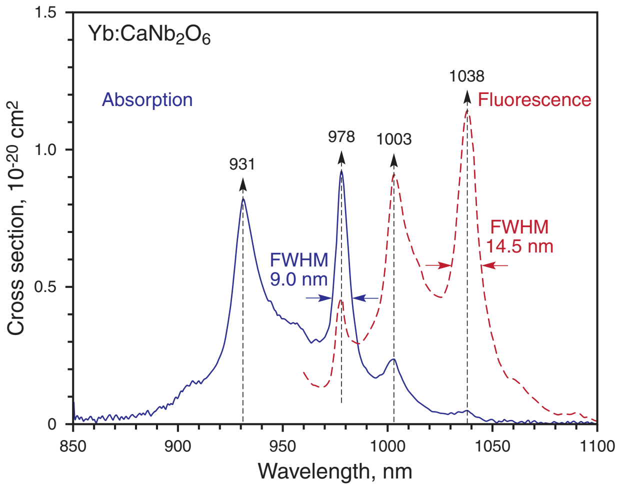

Figure 1 (online color at www.lphys.org) Room temperature optical spectra of $Yb:CaNb_2O_6$ crystal [41]

provement of the stability and of the accuracy of secondary optical frequency standards. For this purpose, iodine transitions at 501.5 nm were studied since it can be addressed by an ionized argon laser. However, due to the lack of stability of argon laser, not all the potential of this very narrow transition has been exploited yet [33]. Our goal is then to replace the argon ionized laser by a diode-pumped solid-state laser emitting at 501.5 nm. In 2005, M. Jacquemet et al., the laser emission reported at 1003.4 nm was done with an $Yb^{3+}:Y_2SiO_5$ crystal leading to a power of about 350 mW [36]. By intracavity frequency doubling this fundamental infrared laser emission, a visible output power of 55 mW at 501.7 nm had also been obtained [37]. In 2006, M. Jacquemet et al. proposed a figure of merit showing the Yb:KYW crystal suitable for laser operation at 1003.4 nm. More than 500 mW at 1003.4 nm and 35 mW at 501.7 nm were produced simultaneously [38]. Quite recently, a new way to reach around 501 nm is to use the first Nd:YAG laser emitting at 1064 nm intracavity pumped at 946 nm by the second Nd:YAG laser, intracavity sum frequency mixing at 1064 and 946 nm was then realized in a nonlinear crystal to reach the this range [39]. The wavelength around 0.5 μm could be reached by frequency doubling a laser source emitting at 1 μm. As Yb-doped materials have a broad emission spectrum around 1 μm, they are good candidates for this kind of source. In 2010, G.Q. Xie et al. reported a diode-pumped passively mode-locked $Nd:CaNb_2O_6$ laser for the first time. With a singe-emitter laser diode pumping, the maximum average output power of the mode-locked laser was 0.843 W, with a slope efficiency of 23% [40]. Recently, D.Z. Li et al. reported a diode-pumped $Yb:CaNb_2O_6$ laser at 1038 nm for the first time [41]. A maximum continuous-wave output power of 1.4 W with a slope efficiency of 20% is obtained. However, the fluorescence spectrum shows that there are three central emission wavelengths (978 and 1003 nm) besides 1038 nm (see Fig. 1). Until now, no lasers at 978 and 1003 nm of the $Yb:CaNb_2O_6$ has been reported.

In this letter, we report on a continuous wave (CW) $Yb:CaNb_2O_6$ laser at 1003 nm by a laser diode for what we believe to be the first time. The use of a pump module with 16 passes through the crystal allowed the realization of a $Yb:CaNb_2O_6$ thin-disk laser with 2.23 W of CW output power. The slope efficiency is up to 13.9%, and the fluctuation of the output power was better than 3.55%. Furthermore, a continuous-wave 501.5 nm laser based on intracavity frequency-doubling $Yb:CaNb_2O_6$-LiB_3O_5 (LBO) is demonstrated.

2. Experimental setups

The experimental setup of the fundamental 1003 nm laser used is described in Fig. 2a. The optical pumping at 978 nm was realized with a fiber coupled diode laser of LIMO Co., Germany. The maximum CW output power delivered by this prototype diode was 20 W and the width of the emission spectrum was $\sim$2.5 nm. The optical fiber of diode had a diameter of 400 μm and a numerical aperture of NA = 0.22. The laser crystals used in the experiments were 1.5 at.% $Yb:CaNb_2O_6$. The crystals' thickness was 0.3 mm. The thin-disk crystal was 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 was soldered onto a water-cooled heat sink with a coolant temperature maintained at 15°C. The parabolic mirror (32 mm focal length) and the folding prisms lead to a 16-pass pump scheme. The radii of curvature of the first mirror M1 was 50 mm. The M1 of the cavity is HR at 1003 nm and AR at 1038 nm to suppress the strong parasitical oscillation at this transition. The second M2 is an output coupler, which was coated with a transmission of 3.8% at 1003 nm.

3. Experimental results

The change of the output power with the increase of the incident pump power is presented in Fig. 3. The threshold was measured to be 3.4 W. Augmenting the pump power, its output power increased linearly with a slope efficiency of 13.9%. Increasing the pump power, the highest output power of 2.23 W was achieved for an incident pump power of 18.8 W, corresponding to an optical conversion efficiency of 11.9%. Under the maximum output power, the beam quality factor M^2 was measured by a laser beam propagation analyzer (M2-200s-FW, Ophir-Spiricon, Inc.). A typical CCD photograph of the transverse mode at its waist is shown in Fig. 4.

Fig. 5 shows the measurements of beam radius versus position of the CCD, which corresponds to a beam quality factor M^2 of 1.11 and 1.13 for tangential direction and

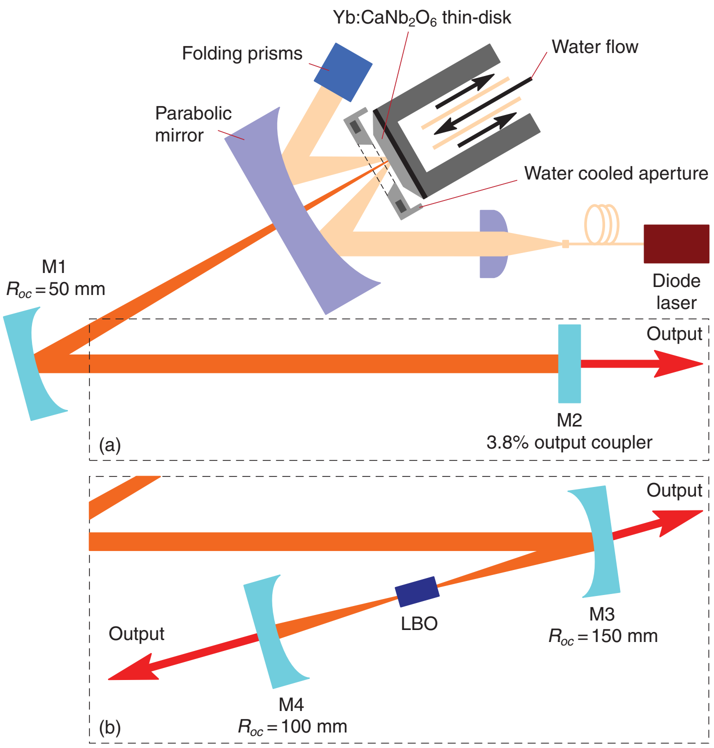

Figure 2 (online color at www.lphys.org) Schematic diagrams of the experimental setup. (a) is for fundamental 1003 nm laser and (b) is for the frequency doubled 501.5 nm laser

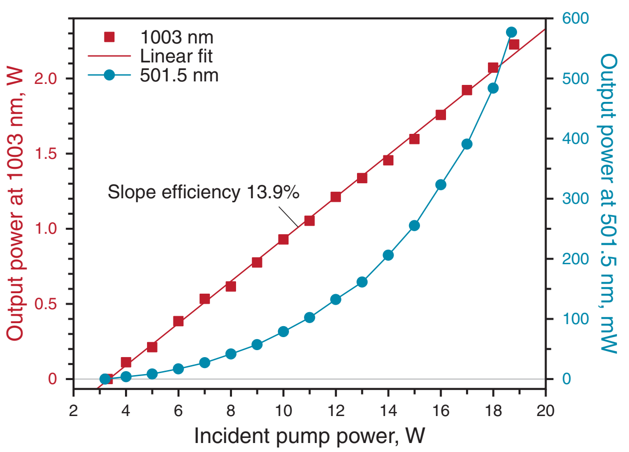

Figure 3 (online color at www.lphys.org) Output power *versus* incident pump power

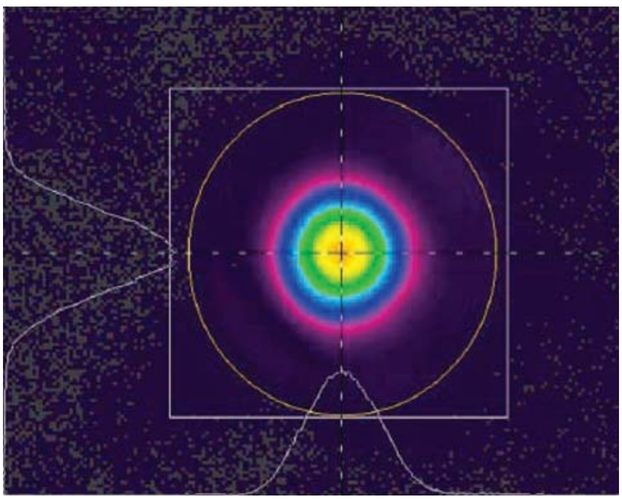

Figure 4 (online color at www.lphys.org) Typical CCD photo of the transverse mode corresponding to an output power of 2.23 W

sagittal direction, respectively. Fig. 6 shows the spectra of 501.5 nm emission which was detected using the grating spectrometer.

As the best performance was obtained at 1003 nm, we tried second-harmonic generation at this wavelength. We modified the cavity to reduce the cavity losses and to add a second waist. All the elements were the same as the corresponding ones in the setup of fundamental 1003 nm laser mentioned above. A concave mirror M3 was coated with HR at 1003 nm and AR at 501.5 and 1038 nm. A concave

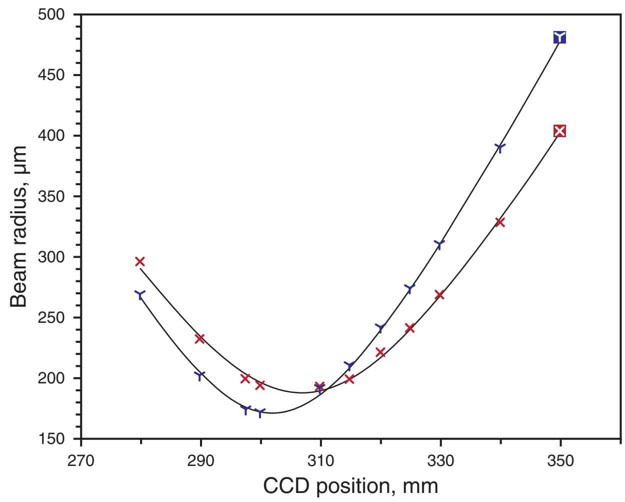

Figure 5 (online color at www.lphys.org) Measured beam quality factor (M^2) of Yb:$CaNb_2O_6$ laser by the laser beam propagation analyzer M2-200s-FW

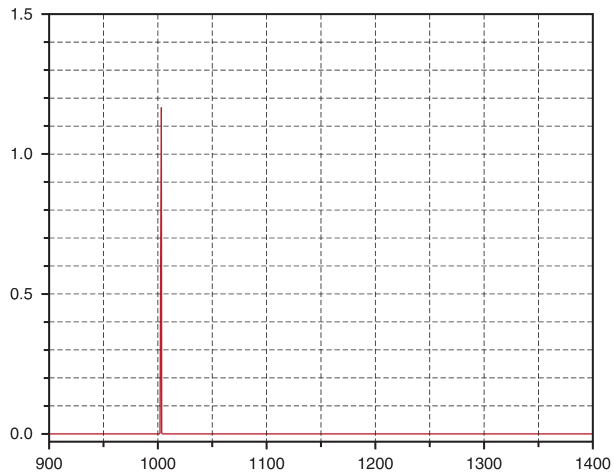

Figure 6 (online color at www.lphys.org) Output spectrum when the pump power was 18.8 W

mirror M4 was coated with HR at 1003 and 501.5 nm. The experimental setup of the intracavity frequency-doubled 501.5 nm laser is described in Fig. 2b. The LBO crystal cut for type-I critical phase matching in the principal plane XY ($\theta = 90°$, $\phi = 15.4°$ with $d_{eff} = 0.83$ pm/V) was chosen as the nonlinear crystal due to its high anti-damage threshold (18 GW/cm^2) and much smaller walk-off angle (about 9.16 mrad). The size of the LBO crystal is $2\times2\times10$ mm^3 and both end facets of the LBO crystal. 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. 3. The threshold of the 501.5 nm laser is about 3.3 W. With an incident pump power of 18.8 W, a CW second-harmonic generation output power of 577 mW at 501.5 nm emission has been obtained, corresponding to an optical conversion efficiency of 3.1% with respect to the incident pump power. The M^2 factors are about 1.14 and 1.28 in X and Y directions respectively measured by knife-edge technique. The asymmetry of the M_2 factor in two directions is result of the walk-off between the fundamental wave and the second in the direction of the LBO. The stability testing was carried out by monitoring the blue-green laser with a Field-Master-GS powermeter at 10 Hz. The fluctuation of the output power is about 3.28% in 4 h.

4. Conclusions

In summary, we have demonstrated for the first time, to the best of our knowledge, laser emission at 1003 nm in Yb:$CaNb_2O_6$ crystal. For the 1003 nm emission, with a 0.3 mm long, 1.5 at.% doped crystal, a CW output power of 2.23 W was achieved for 18.8 W of incident pump power. These results show that Yb:$CaNb_2O_6$ is a potential 1003 nm laser crystal for high power systems. After the second-harmonic generation, blue-green power of 577 mW at 501.5 nm was obtained. The use of more efficient nonlinear crystals, such as ppKTP or $KNbO_3$, should increase the second harmonic radiation power.

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