Continuous wave 935 nm Nd:CNGG laser at watt-level power

Qinan Li,[1] Baohua Feng,[1,*] Zhiyi Wei,[1] Dongxiang Zhang,[1] Dehua Li,[1] Zhiguo Zhang,[1] Huaijin Zhang,[2] and Jiyang Wang[2]

[1]*Laboratory of Optical Physics, Institute of Physics, Chinese Academy of Sciences, 8 NanSanJie, Zhongguan Cun, Beijing, 100080, China*
[2]*State Key Laboratory of Crystal Material and Institute of Crystal Material, Shandong University, 27 Shanda Nanlu, Jinan, 250100, China*
*Corresponding author: bhfeng@aphy.iphy.ac.cn

An efficient continuous wave (CW) laser-diode-pumped Nd-doped $Ca_3(NbGa)_{2-x}Ga_3O_{12}$ (CNGG) laser operating at 935 nm is demonstrated by using a simple linear cavity for the first time to our knowledge. Output power up to 1.12 W is obtained, corresponding to a slope efficiency of 7.1% and an optical-to-optical efficiency of 5.7%. The laser operates with the fundamental transverse mode when the output power is as high as 800 mW. This laser provides a potential light source for differential absorption lidar in water vapor detection. © 2008 Optical Society of America

OCIS codes: 140.3530, 140.3580, 140.3380.

Nd:CNGG crystal is a typical disordered laser material and is suitable for diode laser pumping [1]. Compared with the typical ordered crystal Nd:YAG, Nd:CNGG has the following merits. First, Nd:CNGG has a melting point of 1460°C, 500°C lower than that of YAG [2,3]; therefore, it can be grown in a platinum crucible by using the Czochralski method [4]. This is an important technological advantage [2] because in growth it overcomes the difficulty of the high melting temperature of YAG crystal. Second, Nd:CNGG has a relatively broader absorption band around the diode-pumped wavelength of 808 nm, reducing the restraint on the temperature control of the diode in a Nd:CNGG laser [4]. Finally, Nd:CNGG crystal is useful for generating ultrashort pulses and in tunable mode-locked lasers [1] because of the large emission bandwidth originating from the disordered nature of the crystal. On the other hand, the weakness of Nd:CNGG is also obvious. Specifically, the thermal conductivity of Nd:CNGG is only 0.047 W/cm°C, which is nearly one-third of that of Nd:YAG (0.13 W/cm°C). This value is comparable with that of $Nd:YVO_4$ crystal (0.05 W/cm°C) [5], which has been widely used in all-solid-state lasers.

Recently, the characteristics of the spectrum and laser operated around the wavelength 1061 nm, which belongs to the four-level transition of Nd:CNGG, were reported [1–3,5–7]. However, the laser transition at 935 nm, corresponding to the quasi-three-level transition of the Nd^{3+} ion, has not been reported so far. It is well known that quasi-three-level system lasers usually have a higher threshold, lower output power, and lower slope efficiency than four-level lasers owing to the reabsorption of the lower laser state. In spite of these difficulties, research into the quasi-three-level Nd:CNGG laser is important, not only because it provides blue lasers by intracavity doubling of the 935 nm output, but also because the 935 nm wavelength overlaps the absorp-

tion peaks of water vapor and therefore can be chosen as the source for differential absorption lidar in water vapor detection [8]. Reference [9] reported a Nd:YGG CW laser that emitted lights at both 935 and 938 nm with maximum output power of about 710 mW. The more important laser wavelengths around 935 nm for water vapor absorption can be chosen by using a wavelength-selective component such as birefringent filters.

In this Letter, we report a laser-diode-pumped CW Nd:CNGG laser operated at a single wavelength, 935 nm, with a simple linear cavity. To the best of our knowledge this is the first report of a Nd:CNGG laser operated at this wavelength. Output power up to 1.12 W was obtained.

The experimental setup is shown in Fig. 1. A simple and compact linear cavity was designed, and its length was 10 mm. The pump source was a fiber-coupled CW diode laser (Unique Mode) with wavelength 808 nm. The diameter of the fiber core was 400 μm with a numerical aperture of 0.22. The 808 nm pump light was collimated and focused into the Nd:CNGG crystal with a diameter of 200 μm by two coupling lenses, which gave a coupling efficiency of 90%. The Nd:CNGG crystal used in our experiment was 6 mm in length, and the concentration of Nd^{3+} ions is 0.5 at. %. The pump facet of the crystal was coated for high transmission at 808 nm ($T > 95\%$) and high reflection at 935 nm ($R > 99.9\%$), while high transmission for the wavelength regions around 1061 and 1322 nm was specified to suppress oscillations at these transitions. The other side of the
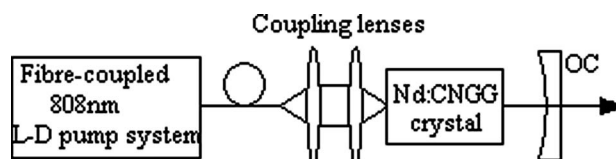

Fig. 1. Schematic of the 935 nm CW single-wavelength laser. L-D, laser diode.

© 2008 Optical Society of America

crystal was coated for high transmission at 935, 1061, and 1322 nm. The output coupler (OC) was a concave mirror with a curvature radius of 50 mm and transmission of 3% at 935 nm. For quasi-three-level lasers, unlike four-level lasers, the lower crystal working temperature is necessary to decrease the thermal population in the lower laser state as well as to remove the heat generated in the gain medium, and it is essential to overcome the reabsorption and increase the laser output power. So, in our experiment, the Nd:CNGG crystal was wrapped with indium foil and mounted in a water-cooled copper heat sink, and the water temperature was maintained at 5°C considering the air temperature and humidity of our experimental circumstances. The fluorescence spectrum of Nd:CNGG and the emission spectrum of the CW 935 nm Nd:CNGG laser were measured by a spectrometer (SpectraPro 500i). The output power of the laser was recorded by a laser powermeter, and the transverse mode of the output was recorded by a laser beam analyzer (OPHIR).

Figure 2 shows the fluorescence spectrum of Nd:CNGG crystal from 910 to 950 nm with the excitation wavelength of 808 nm. It is found that the fluorescence band around 935 nm is broad (from 930 to 940 nm), which is useful for the generation of ultrashort pulses and tunable mode-locked output. Figure 3a presents the laser emission spectrum at the wavelength 935 nm for the CW Nd:CNGG laser, where the oscillation around 1061 nm is absent. Figure 3b shows the laser emission spectrum and the water vapor absorption group at 935 nm [10,11]. Figure 4 presents the output power of the 935 nm Nd:CNGG laser as a function of the incident pump power. The maximum output power is 1.12 W when the incident pump power is 19.5 W, giving an optical-to-optical efficiency of 5.7%. The threshold pump power of the 935 nm Nd:CNGG laser is about 3.3 W, and the slope efficiency is about 7.1%.

The far-field beam spatial profile of the 935 nm laser was measured by using a laser beam analyzer
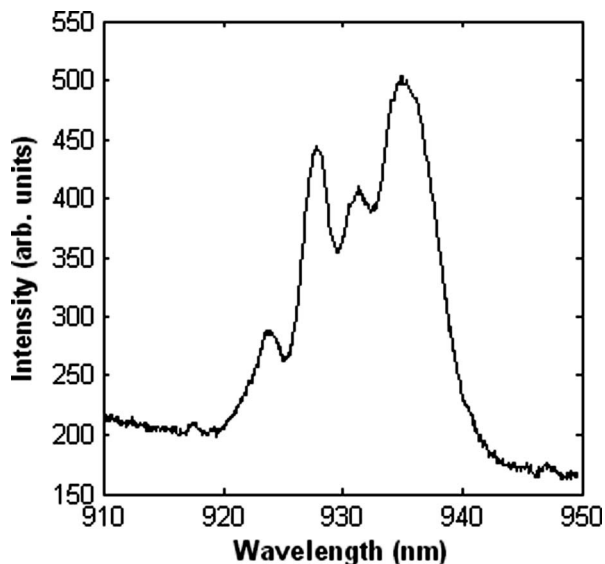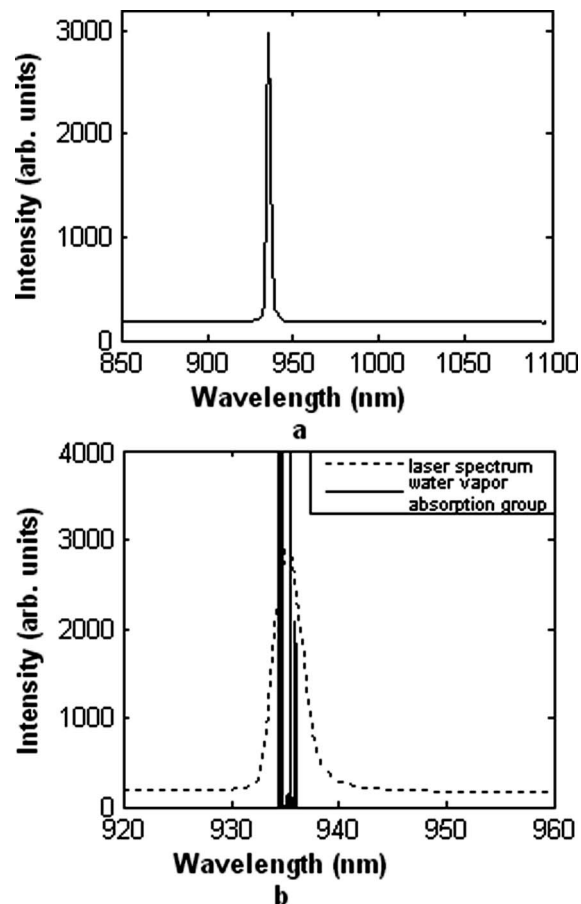

Fig. 3. a, Laser emission spectrum of the 935 nm CW Nd:CNGG laser. b, Laser emission spectrum and the water vapor absorption group around 935 nm.

(OPHIR) at a distance 20 cm behind the output coupler. The intensity distribution across the laser beam was Gaussian until the pump power was 12 W with an output power of 800 mW. When the pump power is higher than this value, the transverse mode becomes bad because the high pump power leads to oscillations of the high-order transverse modes and to a thermal-lens effect in the gain crystal. Figure 5a
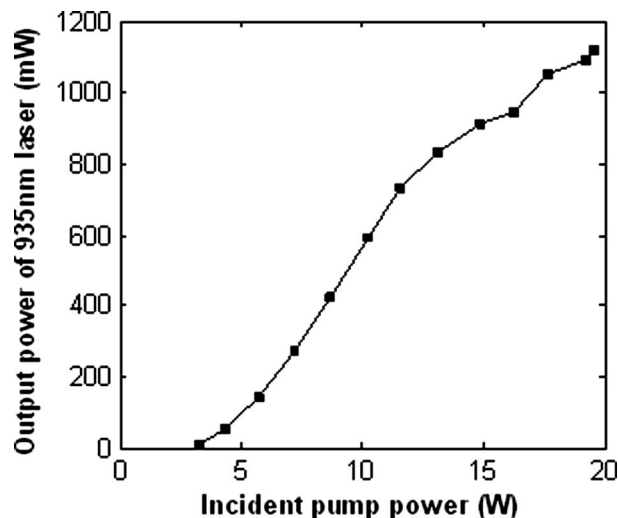

Fig. 2. Fluorescence spectrum of Nd:CNGG from 910 to 950 nm with the excitation wavelength 808 nm.

Fig. 4. Output power of the 935 nm Nd:CNGG laser as a function of the incident pump power.
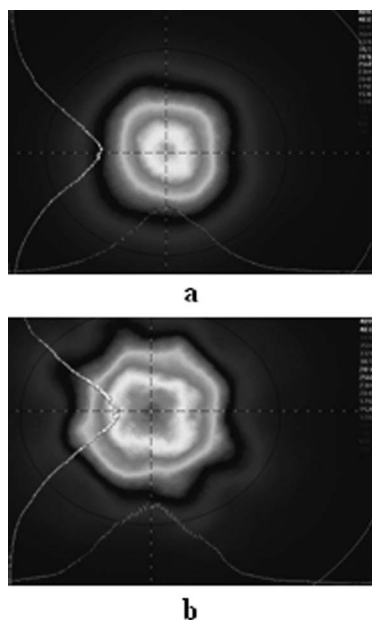
a

b

Fig. 5.   a, Typical CCD photo of the transverse mode corresponding to an output power of 467 mW at a pump power of 9 W. b, Photo of the transverse mode when the pump power is 12 W with an output power of 800 mW.

shows a typical CCD photograph of the transverse mode, corresponding to an output power of 467 mW at a pump power of 9 W. This result indicates that the laser oscillates at the fundamental transverse mode. As the pump power increases, the quality of the fundamental transverse mode declines. Figure 5b shows the photo of the transverse mode when the pump power is 12 W with an output power of 800 mW. It can be seen that the transverse mode is a little inferior to the pattern shown in Fig. 5a. However, the intensity distribution is still Gaussian, and this is the critical condition for fundamental transverse mode output. Under this circumstance (pump power of 12 W), the thermal-lens focal length of the Nd:CNGG crystal used in our experiment was measured to be about 21 mm by using a plane–plane cavity method.

In conclusion, we have reported a laser-diode-pumped, CW, 935 nm Nd:CNGG laser for the first time to the best of our knowledge. The maximum output power at a single wavelength of 935 nm is 1.12 W with the slope efficiency 7.1% and optical-to-optical efficiency 5.7%. The fundamental transverse mode is obtained when the output power at 935 nm is as high as 800 mW. The emission wavelength of 935 nm overlaps the absorption peaks of water vapor, and therefore can be chosen as the light source for differential absorption lidar in water vapor detection.

References

1. P. K. Mukhopadhyay, K. Ranganathan, J. George, S. K. Sharma, and T. P. S. Nathan, Opt. Laser Technol. **35**, 173 (2003).
2. U. Caldiño G, F. Jaque, R. Balda, J. Fernández, and A. A. Kaminskii, Opt. Mater. **4**, 713 (1995).
3. K. Naito, A. Yokotani, T. Sasaki, T. Okuyama, M. Yamanaka, M. Nakatsuka, S. Nakai, T. Fukuda, and M. I. Timoshechkin, Appl. Opt. **32**, 7387 (1993).
4. H. Zhang, J. Liu, J. Wang, J. Fan, X. Tao, X. Mateos, V. Petrov, and M. Jiang, Opt. Express **15**, 9464 (2007).
5. A. Agnesi, S. Dell'Acqua, A. Guandalini, G. Reali, F. Cornacchia, A. Toncelli, M. Tonelli, K. Shimamura, and T. Fukuda, IEEE J. Quantum Electron. **37**, 304 (2001).
6. J. Azkargorta, I. Iparraguirre, R. Balda, J. Fernández, and A. A. Kaminskii, Opt. Commun. **118**, 562 (1995).
7. T. T. Basiev, N. A. Es'kov, A. Ya. Karasik, V. V. Osiko, A. A. Sobol, S. N. Ushakov, and M. Helbig, Opt. Lett. **17**, 201 (1992).
8. B. Ileri, C. Czeranowsky, K. Petermann, and G. Huber, in *Proceedings of IEEE Conference on Lasers and Electro-Optics Europe* (IEEE, 2005), p. 10.
9. S. G. P. Strohmaier, H. J. Eichler, C. Czeranowsky, B. Ileri, K. Petermann, and G. Huber, Opt. Commun. **275**, 170 (2007).
10. "British Atmospheric Data Centre," http://badc.nerc.ac.uk/cgi-bin/data_browser/data_browser/badc/esa-wv/data.
11. HITRAN Database, http://www.cfa.Harvard.edu/HITRAN/hitrandata04/.