

# Efficient passively $Q$ -switched laser operation of Yb in the disordered $\text{NaGd}(\text{WO}_4)_2$ crystal host

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Efficient passively  $Q$ -switched laser operation of the disordered  $\text{Yb}:\text{NaGd}(\text{WO}_4)_2$  crystal is demonstrated for the first time to our knowledge with a  $\text{Cr}^{4+}:\text{YAG}$  saturable absorber by diode end pumping. 2.05 W of average output power at a pulse repetition frequency of 13.3 kHz was obtained at an absorbed pump power of 7.7 W, with a slope efficiency of 40%. The energy and duration of the generated laser pulse were 154  $\mu\text{J}$  and 33 ns, respectively, corresponding to a peak power of 4.67 kW. In continuous-wave operation, the  $\text{Yb}:\text{NaGd}(\text{WO}_4)_2$  laser yielded an output power of 5.5 W with an optical-optical efficiency of 51%. © 2007 Optical Society of America

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Ytterbium-doped monoclinic potassium double tungstates,  $\text{Yb}:\text{KY}(\text{WO}_4)_2$ ,  $\text{Yb}:\text{KGd}(\text{WO}_4)_2$ , and  $\text{Yb}:\text{KLu}(\text{WO}_4)_2$ , have been extensively investigated for one decade and widely used in generating continuous-wave (cw) and ultrashort pulsed laser radiation [1–5]. By contrast, however, Yb-doped sodium double tungstates,  $\text{Yb}:\text{NaT}(\text{WO}_4)_2$ , where  $T$  is a trivalent cation such as Y, Gd, or La, have received much less attention: studies of these laser crystals remain at the initial stage.

The first laser action in Yb-doped sodium double tungstates was demonstrated in 2004 with  $\text{Yb}:\text{NaGd}(\text{WO}_4)_2$  ( $\text{Yb}:\text{NaGdW}$ ) in the cw regime under Ti:sapphire laser pumping [6]. Almost simultaneously, the spectroscopic properties of  $\text{Yb}:\text{NaGdW}$  were studied and laser operation realized by diode pumping [7]. A thin-disk laser based on  $\text{Yb}:\text{NaGdW}$  was reported very recently, generating 16.5 W of cw output power [8]. A comprehensive study on  $\text{Yb}:\text{NaGdW}$  was also carried out covering its structural, spectroscopic, and tunable laser properties [9].

Unlike monoclinic  $\text{Yb}:\text{KY}(\text{WO}_4)_2$ ,  $\text{Yb}:\text{KGd}(\text{WO}_4)_2$ , and  $\text{Yb}:\text{KLu}(\text{WO}_4)_2$ ,  $\text{Yb}:\text{NaGdW}$  crystal is tetragonal, belonging to the space group  $I\bar{4}$  [9]. In this structure there are two different types of site,  $2b$  and  $2d$ , which can accommodate  $\text{Na}^+$  and  $\text{Gd}^{3+}/\text{Yb}^{3+}$  with different occupancy factors; for each type of site there are a number of environments formed by different Na–Gd/Yb ions distributions in the first cationic sphere [9]. Such a disordered character of  $\text{Yb}:\text{NaGdW}$  leads to even broader spectra of absorption and emission than the ordered Yb-doped potassium double tungstates [6]. With  $\text{Yb}:\text{NaGdW}$  crystal a tunable range of 1014–1079 nm was realized, which is expected to be capable of producing shorter than 50 fs mode-locked laser pulses [9].

In connection with the broader emission spectra, smaller cross sections can be expected for a disor-

dered structure. In  $\text{Yb}:\text{NaGdW}$ , the peak emission cross section ( $\sigma_{\text{em}}$ ) for  $\pi$  polarization at  $\sim 1000$  nm is  $1.89 \times 10^{-20}$   $\text{cm}^2$ , less than one third of that in  $\text{Yb}:\text{KY}(\text{WO}_4)_2$  and  $\text{Yb}:\text{KGd}(\text{WO}_4)_2$  [9]. Although small  $\sigma_{\text{em}}$  is a drawback for cw operation, it will favor  $Q$ -switched operation because of the enhanced energy storage capacity. The fluorescence lifetime, which is another crucial parameter affecting the  $Q$ -switched pulse energy, is about 350  $\mu\text{s}$ , which is comparable with the values for  $\text{Yb}:\text{KY}(\text{WO}_4)_2$  and  $\text{Yb}:\text{KGd}(\text{WO}_4)_2$  [8].

In this Letter we report, for the first time to our knowledge, the passively  $Q$ -switched laser operation of  $\text{Yb}:\text{NaGdW}$  crystal by use of a  $\text{Cr}^{4+}:\text{YAG}$  saturable absorber. The cw power scaling capability was also investigated by end pumping with a high-power diode laser.

To build the experimental cw and  $Q$ -switched  $\text{Yb}:\text{NaGdW}$  laser, a compact plano-concave resonator was chosen. The plane mirror was coated to be highly reflecting for 1015–1230 nm ( $>99.8\%$ ) and highly transmitting for 880–990 nm ( $>97\%$ ). A number of concave mirrors were employed as the output coupler, with radius-of-curvature (RC) of 25 and 50 mm, and transmission ( $T$ ) in the range of 0.5%–10%. The  $\text{Yb}:\text{NaGdW}$  crystal used was  $a$ -cut, uncoated, 3 mm thick, with an aperture of 3.3 mm  $\times$  3.3 mm and a Yb concentration of 4.1 at. %. It was held in a water-cooled copper block and placed close to the plane mirror inside the cavity. A 0.3 mm thick  $\text{Cr}^{4+}:\text{YAG}$  crystal with an initial transmission of  $T_0=98\%$  (at 1.06  $\mu\text{m}$ ) was used as saturable absorber. It was antireflection coated for 1.06  $\mu\text{m}$  on both faces. The pump source used was a 50 W fiber-coupled diode (S50-980-2, Apollo Instruments, Incorporated, fiber core diameter of 200  $\mu\text{m}$  and NA of 0.22) emitting infrared radiation at 974–981 nm, depending on the output level; its output beam was focused by a 1:1 re-

imaging unit and delivered onto the Yb:NaGdW crystal through the plane mirror. The physical cavity length was  $\sim 22$  mm.

The laser performance of Yb:NaGdW in the cw regime was investigated by using 25 mm RC output couplers with  $T=0.5\%$ – $10\%$ . The output characteristics are depicted in Fig. 1. It is seen that the most efficient operation was achieved by use of a low transmission coupler of  $T=1\%$  (for  $T=0.5\%$  and  $T=2\%$ , the results obtained were very similar). In this case the laser reached threshold at an absorbed pump power of  $P_{\text{abs}}=0.63$  W; the output power increased linearly with  $P_{\text{abs}}$  with a slope efficiency of 62% until  $P_{\text{abs}} \approx 7$  W, above which the laser became less efficient, with the slope efficiency reduced to  $\sim 40\%$ . At  $P_{\text{abs}}=10.8$  W, the laser yielded a maximum output power of 5.5 W, corresponding to an optical-to-optical efficiency of 51%. Exceeding this operational level, the Yb:NaGdW crystal was at risk of fracture. In the other cases, with  $T=3\%$ ,  $5\%$ ,  $10\%$ , the highest output powers achievable were lower; the slope efficiencies also decreased to 53%, 50%, and 46%, respectively. In all cases the output beam was linearly polarized along the  $c$  axis ( $\pi$  polarization), consistent with previously reported results [6,8,9].

Disordered Yb:NaGdW turns out to be inferior to its monoclinic potassium double tungstate analogs with respect to cw power scaling owing to its small  $\sigma_{\text{em}}$  and, more important, its low thermal conductivities ( $\sim 1.1$  W m $^{-1}$  K $^{-1}$  along the  $a$  axis,  $\sim 1.2$  W m $^{-1}$  K $^{-1}$  along the  $c$  axis), amounting to one third those of the latter [10]. Nevertheless, compared with the previous results obtained under similar diode pumping conditions (an output power of 1.45 W with slope efficiency of 36% [9]), the present performance represents considerable improvement, which could probably be attributed to the lower Yb doping and better quality of the sample used.

As in any quasi-three-level system, the emission wavelength of the Yb:NaGdW laser varied with the output coupling and the pump power as well. It was measured at  $P_{\text{abs}}=6.4$  W, giving results of 1048.7–1054.2 nm ( $T=1\%$ ), 1037.7–1041.4 nm ( $T=3\%$ ),

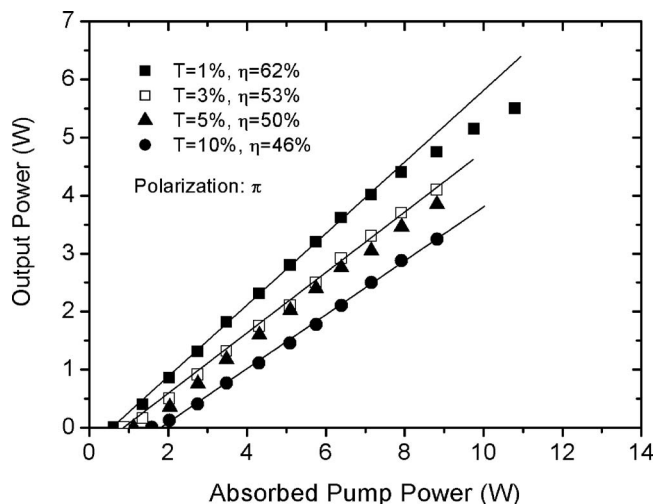


Fig. 1. Continuous-wave output power versus absorbed pump power for different output couplings.

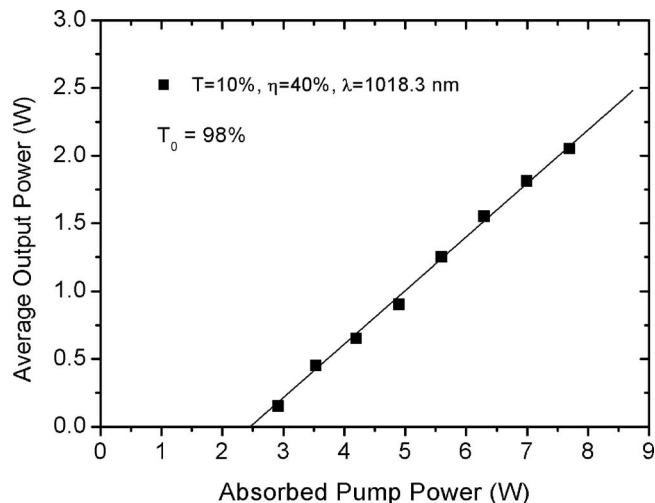


Fig. 2. Average output power in the  $Q$ -switched regime as a function of absorbed pump power for  $T=10\%$ .

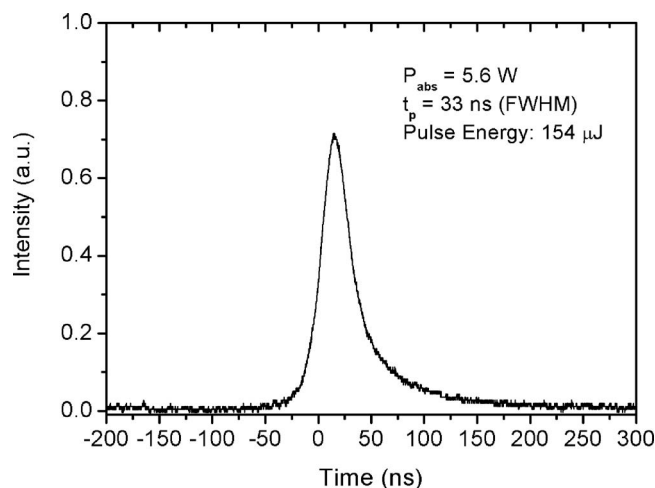


Fig. 3. Typical pulse profile of the  $Q$ -switched Yb:NaGdW laser, recorded at  $P_{\text{abs}}=5.6$  W.

1031.4–1034.7 nm ( $T=5\%$ ), and 1024.0–1029.2 nm ( $T=10\%$ ).

With the Cr $^{4+}$ :YAG absorber placed close to the laser crystal in the cavity, stable passively  $Q$ -switched operation was achieved. In this case, a 50 mm RC coupler with  $T=10\%$  was used to prevent possible damage to the intracavity elements. Figure 2 shows the generated average output power as a function of  $P_{\text{abs}}$ . The threshold for  $Q$ -switching operation corresponded to  $P_{\text{abs}}=2.5$  W. Above the threshold the average output power increased linearly with  $P_{\text{abs}}$ , giving a slope efficiency of 40%. The highest output power achievable was 2.05 W, reached at  $P_{\text{abs}}=7.7$  W, resulting in an optical-to-optical efficiency of 26%.

The pulse repetition frequency (PRF) of the  $Q$ -switched Yb:NaGdW laser was found to be linearly dependent on  $P_{\text{abs}}$ , increasing from 1.2 kHz at  $P_{\text{abs}}=2.9$  W to 13.3 kHz at  $P_{\text{abs}}=7.7$  W. The energy in a single pulse determined from the average output power and the corresponding PRF varied only slightly with  $P_{\text{abs}}$ , being  $\sim 154$   $\mu\text{J}$  for  $P_{\text{abs}} > 5$  W. Figure 3 shows a typical pulse profile detected by a fast photodiode ( $\sim 70$  ps of rise time) and recorded with a

2 GHz oscilloscope at  $P_{\text{abs}}=5.6$  W. The pulse width (FWHM) was 33 ns, nearly independent of  $P_{\text{abs}}$ . From the single-pulse energy and duration the peak power was calculated to be 4.67 kW. One sees in Fig. 3 that the generated laser pulse was asymmetric with a lengthened trailing edge, which is indicative of insufficient output coupling [11]. Increasing the output transmission of the coupler would allow symmetric pulses of somewhat shorter duration to be generated, but at the expense of reducing the average output power and the efficiency.

It is instructive to compare the emission spectra of the Yb:NaGdW laser operating in the Q-switched and cw modes. Figure 4 shows such emission spectra, recorded under identical operational conditions except the presence of the Cr<sup>4+</sup>:YAG absorber for Q switching. The Q-switched emission line was shifted to a shorter wavelength (1018.3 nm) with respect to the cw lines (1025.5–1028.7 nm). Clearly this is due to the additional losses introduced by the Cr<sup>4+</sup>:YAG absorber. Furthermore, in contrast to the multiline cw oscillation, the Q-switched emission consisted of only a single line with a width of  $\sim 0.2$  nm, which was limited by the resolution of the spectrometer. The process of absorption saturation in the Cr<sup>4+</sup>:YAG crystal also played a crucial role in the discrimination of oscillating wavelengths.

It is worth pointing out that in the Q-switched regime of the Yb:NaGdW laser no stimulated Raman scattering occurred in the laser crystal; this was confirmed by monitoring the emission spectra over a wide wavelength range of 800–1300 nm. This situation was completely distinct from a similar Yb:KLu(WO<sub>4</sub>)<sub>2</sub> laser, where stimulated Raman scattering was efficiently generated with Raman radiation energy amounting to 45% of the fundamental [12]. One possible reason for this might be the relatively small Raman gain for the strongest mode at 911 cm<sup>-1</sup> in Yb:NaGdW crystal, arising from its disordered nature. Another reason may be attributed to the low peak power density in the Yb:NaGdW crystal. Taking into account the peak power and laser mode radius, we estimated that the peak power density in the present Yb:NaGdW was  $\sim 20$  times lower than in the Yb:KLu(WO<sub>4</sub>)<sub>2</sub> crystal [12].

An effective and practical way of strengthening the pulse energy and shortening the pulse duration in a passively Q-switched laser is to utilize a saturable

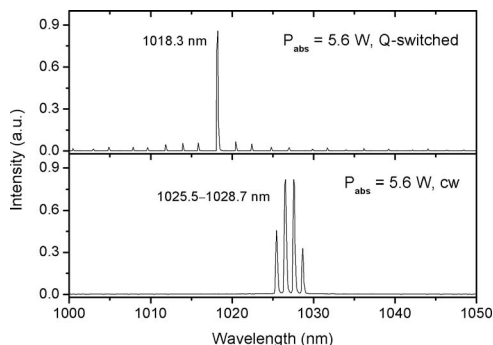


Fig. 4. Comparison of the emission spectra generated in the Q-switched and cw regimes.

absorber of lower initial transmission ( $T_0$ ). We tested this with the Yb:NaGdW laser by use of a number of Cr<sup>4+</sup>:YAG crystals with  $T_0$  in the range of 80%–95%. Unfortunately, however, even with an absorber of  $T_0$  as high as 95%, the laser produced pulses that led to damage to the absorber and/or the laser crystal. This demonstrates, on the other hand, the promising potential of the disordered Yb:NaGdW crystal in building high-energy pulsed lasers.

In conclusion, we have demonstrated an efficient diode pumped Yb:NaGdW laser operating in both cw and passively Q-switched modes by using a Cr<sup>4+</sup>:YAG saturable absorber. 5.5 W of cw output power was obtained with an optical-to-optical efficiency of 51%. The slope efficiency in the low-power range was 62%. The Q-switched operation yielded a maximum output power of 2.05 W at a PRF of 13.3 kHz with a slope efficiency of 40%. The generated pulse energy, pulse duration, and peak power were 154  $\mu$ J, 33 ns, and 4.67 kW, respectively.

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