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Power scaling potential of Yb:NGW in thin disk laser configuration

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ABSTRACT We report on efficient laser operation of $Yb{:}NaGd(WO_4)_2$ (Yb:NGW) in thin disk laser configuration. Using doping concentrations of 10.7 at. % and 15.3 at. % and disk thicknesses between 0.1 mm and 0.4 mm the optimum crystal parameters have been determined. A 0.1 mm thick, 10.7 at. % Yb:NGW disk pumped at 975 nm delivered 18.2 W of output power at 43.6 W of incident pump power with a slope efficiency of 51% and a resulting optical-to-optical efficiency of 42%. Using a 2 mm thick birefringent filter, continuous tuning from 997 nm to 1075 nm has been achieved.

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1 Introduction

Ytterbium with its strong electron–phonon coupling has been demonstrated to be one of the most promising laser ions for broad band tunable laser sources around 1 µm [1, 2]. Due to the simple two-manifold structure loss processes like excited-state absorption, cross relaxation, and up-conversion do not occur. In combination with a small quantum defect this leads to a low thermal load of the system, making Yb-doped materials of particular interest for high power applications.

In the last decade the thin disk laser (TDL) concept invented in 1993 [3] has proven to be a highly efficient setup for power scaling. Thin disk lasers are successfully used for material processing or for the generation of ultrashort pulses with high average output power [4]. Due to the special design with its effective cooling mechanism an output power of more than 5 kW from one disk with an optical-to-optical efficiency of $\sim 65\%$ has been achieved [5].

Different host materials have been tested in the TDL-setup in the past. The most investigated material, Yb:YAG, combines excellent thermo-mechanical properties with high cross sections and a long fluorescence lifetime. The sesquioxides Sc_2O_3, Y_2O_3, and Lu_2O_3, which have even better thermal properties, have also been studied and recently $Yb{:}Lu_2O_3$ has surpassed Yb:YAG considerably in terms of optical-to-optical efficiency [6]. However, hosts with spectral properties like broad emission bands are of particular interest for the generation of ultrashort pulses. Unfortunately, these materials, e.g. monoclinic double tungstates or borates often have worse thermal-mechanical properties, which complicates the scaling to high output powers. However, recently two hosts of these groups, namely Yb:KYW and Yb:LSB with a thermal conductivity of $\kappa = 3.3$ W/mK and 2.8 W/mK, respectively, have been scaled to high output power [7, 8].

To study the usability of materials with an even lower thermal conductivity, the power scaling behaviour of Yb:NGW, for which a value of $\kappa = 1.1$–1.2 W/mK has been determined [9], is investigated in this work.

2 Spectroscopic and host properties

The crystal structure of NGW belongs to the tetragonal space group $I\bar{4}$ [10]. Different to the monoclinic potassium double tungstates, which have to be grown from a flux, the tetragonal double tungstates can be grown by the Czochralski-method, resulting in a higher growth rate, better optical quality, and higher purity of the crystals. In this structure the Na- and Gd-ions are randomly distributed over two lattice sites, leading to a statistical distribution of the Yb-ions, which substitute partially the Gd-ions.

Due to the disordered structure of the host, the absorption and emission bands are strongly inhomogeneously broadened (Fig. 1). The absorption bandwidth of more than 7 nm (FWHM) reduces the requirements on laser diodes for zero-phonon-line (ZL) pumping with respect to the spectral bandwidth and wavelength stability for different power levels. The absorption cross sections at 975 nm are $\sigma_{abs} = 17.8 \times 10^{-21}$ cm^2 and 13.6×10^{-21} cm^2 for π- and σ-polarisation, respectively; on average they are roughly two times higher than for Yb:YAG [10].

The emission spectra exhibit broad bands in both polarisations. The maximum emission cross section in π-polarisation is around 1000 nm with $\sigma_{em} = 18.9 \times 10^{-21}$ cm^2. In σ-polarisation a relatively flat plateau from 980 nm to 1020 nm with $\sigma_{em} \approx 8 \times 10^{-21}$ cm^2 is observed. The inhomogeneously broadened emission bands result in very broad gain profiles ranging from 1000 nm to 1080 nm, which are well suited for the generation of ultrashort pulses by mode-locking. The pulse durations are typically < 100 fs for Yb in disordered

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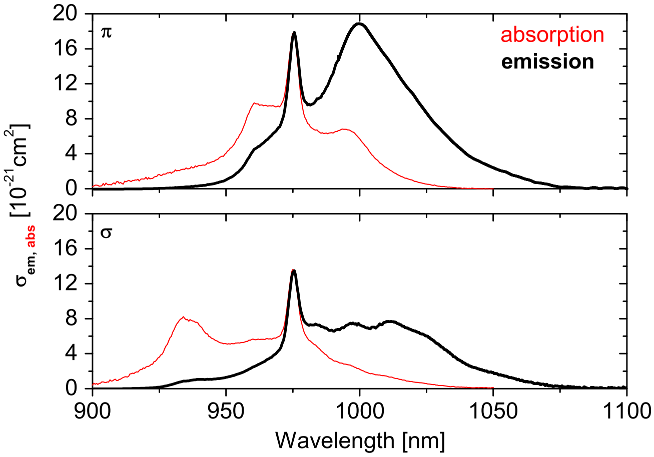

FIGURE 1 Absorption and emission cross sections of Yb:NGW

double tungstates, e.g. Yb:NGW (75 fs) or Yb:NYW (53 fs), and are in general shorter than those for ordered systems like Lu_2O_3 (220 fs), and Yb:YAG (340 fs) [11–14].

The fluorescence lifetime of Yb:NGW of 320 µs [10] is larger than that for Yb:KYW with 233 µs [15], but shorter than for Yb:YAG or Yb:Lu_2O_3 with 950 µs and 820 µs, respectively [16]. This results in a relatively high saturation intensity of $I_{sat} = 20.3\,kW/cm^2$ (average over both polarisations).

Like the monoclinic double tungstates, NGW also exhibits a strong anisotropy in thermal expansion (Table 1) resulting in strong mechanical stress in the crystal if heated. This is in particular important for the coating process and the heating of the disk during laser operation.

3 Crystal preparation and experimental setup

For the laser experiments single crystalline boules of NGW with doping concentrations of 10.7 at. % ($6.85 \times 10^{20}\,cm^{-3}$) and 15.3 at. % ($9.79 \times 10^{20}\,cm^{-3}$) (FEE GmbH, Germany) have been used to prepare samples with disk thicknesses between 0.1 mm and 0.4 mm in *a*-cut and *c*-cut orientation. The diameter of all samples was 5 mm. One side of each disk had a highly-reflective (HR) coating from 900 nm to 1150 nm, including the pump wavelength and the emission band. The opposite side of each crystal was anti-reflective (AR) coated for the same spectral range.

In a first attempt at coating *a*-cut Yb:NGW disks, 16 out of 19 samples were damaged by cleaving perpendicular to the *c*-axis. Only disks with a thickness ≥ 0.3 mm stayed crack-free. This can be attributed to strong mechanical stress in the disks during cooling down from the coating process temperature, which is about 200 °C. The coatings consist of several SiO_2 and Ta_2O_5 layers. The thermal expansion coefficients for these materials are $0.5 \times 10^{-6}\,K^{-1}$ and $5 \times 10^{-6}\,K^{-1}$ for SiO_2 and Ta_2O_5, respectively [18, 19]. These values are significantly smaller compared to NGW with a thermal expansion coefficient of $16.3 \times 10^{-6}\,K^{-1}$ ($\parallel c$), resulting in a bending along the c-axis, during cooling down to room temperature.

To reduce the mechanical stress and therefore the bending of the disks during the coating, in a second run the thinner and thus less critical AR-coating was applied first, followed by the HR-coating, which bends the disks in the opposite direction. Thereby the damage-rate of *a*-cut crystals was reduced to 1/3. Further improvement has been achieved by changing the orientation of the crystals to *c*-cut to ensure a homogeneous thermal expansion in the disk-plane. For these samples down to the minimum tested disk thickness of 0.2 mm no damage occurred during the coating process.

The HR-side of each crystal was soldered onto a watercooled copper or copper-tungsten heat-sink by using an indium-tin metallic solder.

The fiber-coupled diode pump laser (JENOPTIC Laser-Diode GmbH, Germany) delivered 50 W at 975 nm with a spectral width of 2.1–2.5 nm depending on the output power. The fiber had a diameter of 600 µm and a numerical aperture (NA) of 0.22. Efficient absorption of the pump radiation was achieved with a pump module (TGSW Stuttgart, Germany) providing 24 passes of the pump beam through the crystals. The pump spot diameter on the crystal was 1.2 mm. A plane-concave resonator of ∼ 70 mm length and outcoupling mirrors with a radius of curvature of 100 mm were used to investigate the characteristics of the laser emission.

4 Results and discussion

All crystals with a thickness of more than 0.2 mm have been damaged, if the pump power exceeded 25 W, corresponding to a pump power density of $2.2\,kW/cm^2$. Depending on the orientation of the disks, the damage occurred as cleavage perpendicular to the *c*-axis in case of *a*-cut crystals or as a partial melting without cleaving, if *c*-cut crystals were used (Fig. 2). For disk thicknesses of 0.1 mm no damage occurred up to a pump power of 43.6 W ($3.9\,kW/cm^2$). At that point a slight drop of the efficiency was observed, which is why the pump power was not further increased.

	NGW [9, 10]	KYW [7, 17]	LSB [8]	Lu_2O_3 [6, 16]	YAG [5, 16]
structure	tetragonal	monoclinic	monoclinic	cubic	cubic
heat conductivity [W/mK]					
– undoped	1.1 ($\parallel$c)	3.3	2.8	12.5	11.0
– Yb-doped				11.0 (2.7 at. %)	6.8 (5 at. %)
thermal expansion	6.7 ($\parallel a$)	2.4 ($k \parallel p$)	12.3 ($\parallel c$)	∼ 8	∼ 8
coefficient [$10^{-6}\,K^{-1}$]	16.3 ($\parallel c$)	17 ($k \parallel g$)			
$\Delta\lambda_{abs}$ FWHM [nm]	7.5 (975 nm)	3.5 (981 nm)	15 (981 nm)	2.2 (976 nm)	11 (941 nm)
max. opt.–opt. efficiency (TDL) [%]	42 (this work)	60	43	72	65

TABLE 1 Properties of Yb:NGW in comparison with other Yb-doped thin disk laser materials

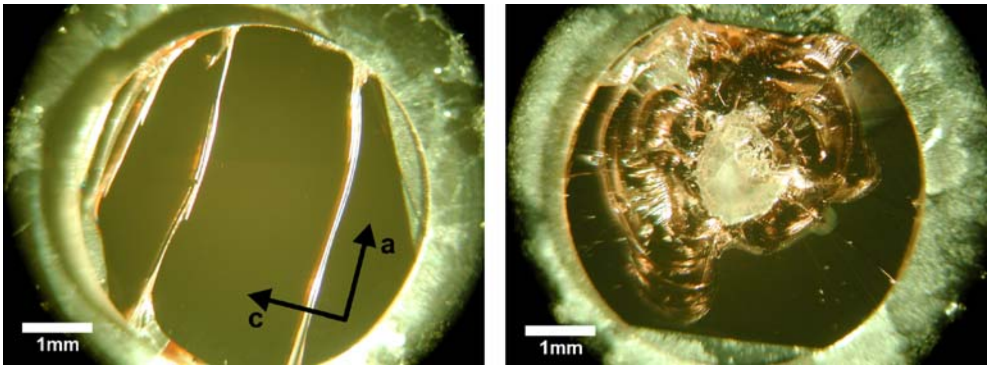

FIGURE 2 Pictures of two Yb:NGW crystals damaged during the laser experiments; 0.3 mm *a*-cut (*left*), 0.25 mm *c*-cut (*right*)

Figure 3 presents the output power versus incident pump power for the most efficient disk used in the experiments. At an outcoupling transmission of $T_{OC} = 0.8\%$ the 0.1 mm thick 10.7 at. %-doped Yb:NGW crystal (*a*-cut) delivered a maximum output power of 18.2 W at an incident pump power of 43.6 W. The slope efficiency η_s and the opt.–opt. efficiency η_{opt} were 51% and 42%, respectively, which is in good agreement with the maximum slope efficiency in case of diode pumping in [10].

The variation of the slope efficiency and laser wavelength with respect to the outcoupling losses are shown in Fig. 4. The maximum slope efficiency of 51% has been achieved with $\sim 1\%$ outcoupling. With increasing T_{OC} the laser wavelength shifted from 1033 nm to 1013 nm. This can be explained by the shift of the gain-maximum for the different inversion levels when changing the outcoupling losses, which is typical for quasi-3-level lasers.

The laser was π-polarized in case of *a*-cut crystals and randomly polarized in case of *c*-cut crystals. The beam quality factor M^2, measured with a DataRay Beamscope-P7 beam analyzer, was determined to be between 10 and 20 in the used configuration.

To compare the laser performance for the different doping concentrations the slope efficiencies of all examined crystals using an outcoupling transmission of 0.8%, which was the optimum for all disks, are shown in Fig. 5, where η_s is plotted versus the disk thickness.

Independently of the orientation and doping level of the disks, the slope efficiency decreases with increasing disk thickness. This can be attributed to an increasing thermal load of the disks for thicker samples, due to the low thermal conductivity of NGW.

The highest slope efficiencies of roughly 50% have been achieved for *a*-cut samples with disk thicknesses of $d \leq 0.2$ mm in case of 10.7 at. % and $d = 0.1$ mm for 15.3 at. % doping. With respect to the absorbed pump power a slightly higher slope efficiency of $\eta_{abs} \approx 60\%$ was achieved for the 0.1 mm, 10.7 at. %-doped *a*-cut crystal, which still absorbed between 80% and 85% of the pump light.

It can be stated that the slope efficiency η_s is strongly correlated with the disk thickness. This is in contrast to materials with a high thermal conductivity like $Yb{:}Lu_2O_3$, for which the efficiency mainly depends on the absorption and no decrease of the η_s with increasing disk thickness has been observed [6].

The tuning range of the laser emission was investigated using the most efficient disk with different outcoupling mirrors under 21 W of incident pump power (Fig. 6). The experiments were performed with a 2 mm thick birefringent filter (BF), which was inserted under Brewster's angle into the laser resonator. The resonator length was increased to 150 mm, using concave output couplers with 300 mm radius of curvature.

For $T_{OC} = 0.4\%$ laser emission could be achieved between 998 nm and 1057 nm, with a maximum of 5.1 W at 1027 nm

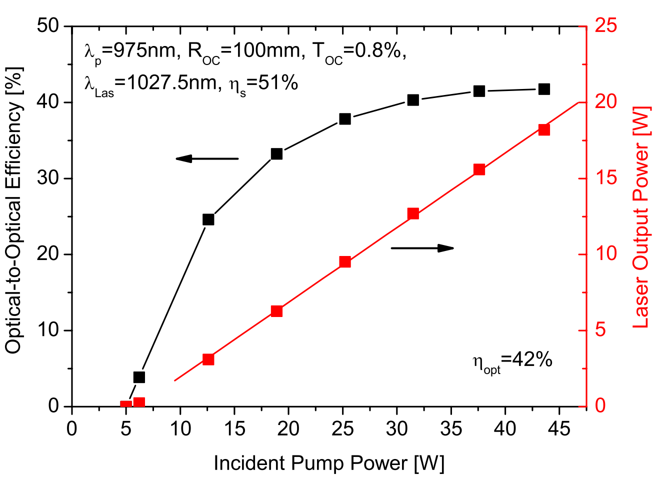

FIGURE 3 Input-Output characteristic of a 0.1 mm thick, *a*-cut 10.7 at. % Yb:NGW disk

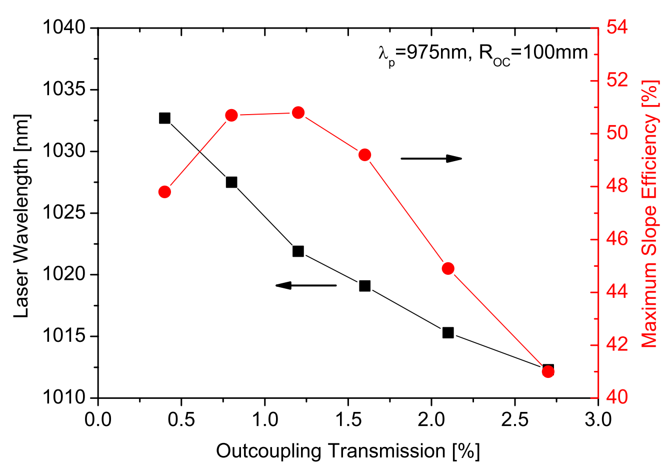

FIGURE 4 Slope efficiency and laser wavelength dependence on the outcoupling transmission of a 0.1 mm thick, *a*-cut 10.7 at. % Yb:NGW disk

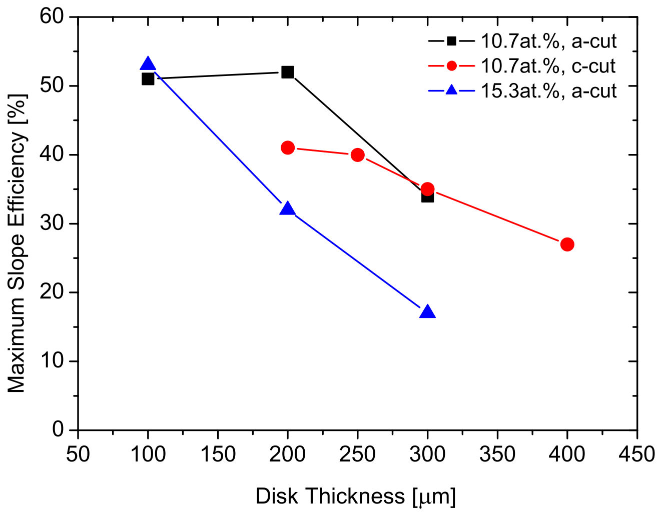

FIGURE 5 Maximum slope efficiency in dependence on the disk thickness and crystal orientation of different Yb:NGW crystals under pumping at 975 nm

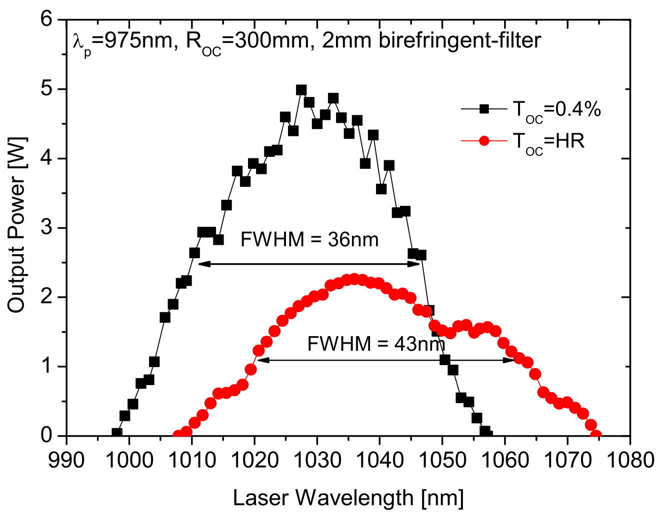

FIGURE 6 Wavelength tuning of 0.1 mm thick *a*-cut 10.7 at. % Yb:NGW under 21 W of incident pump power with T_{OC} = HR and 0.4%

(Fig. 6). Using a high reflective outcoupling mirror continuous tuning over nearly 70 nm from 1007 nm to 1075 nm with a maximum of 2.3 W at 1036 nm was possible.

5 Summary

In summary, we have demonstrated the high power laser performance of Yb:NGW. Employing the thin disk geometry with a multi-pass pumping scheme, the output power from a 10.7 at. %-doped disk of 0.1 mm thickness yielded 18.2 W at 1027.5 nm for an incident pump power of 43.6 W at 975 nm. The optical-to-optical efficiency was 42% and the laser operated with a slope efficiency of 51%. This is to the best of our knowledge, the highest output power for tetragonal double tungstates reported so far.

Using a birefringent filter, cw tuning of the laser output from 998 nm to 1075 nm was demonstrated.

Further improvement of the laser efficiency of Yb:NGW thin disk lasers might be achieved by using thinner samples (< 0.1 mm) and higher doping levels (20–25 at. %), to reduce the influence of the low thermal conductivity on the cooling efficiency. Thus, higher pump power densities could be applied.

In general, compared to other hosts with better thermal properties like YAG or Lu_2O_3, the scaling potential of NGW is relatively small, due to the low thermal conductivity and strong anisotropy of the thermal expansion coefficients.

However, one possible application could be the generation of ultrashort pulses with mode-locked Yb:NGW thin disk lasers, provided that the disk thickness is ≤ 0.1 mm.

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