$Yb:NaGd(WO_4)_2$ tunable solid-state laser operation with Ti:sapphire and diode laser pumping

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Abstract: Room temperature laser operation near 1030 nm of Yb^{3+} in the disordered crystal $NaGd(WO_4)_2$ with slope efficiencies exceeding 30%, output powers more than 300 mW, and tuning from 1016 to 1049 nm are demonstrated.

OCIS Codes: (140.5680) Rare earth and transition metal solid-state lasers; (140.3070) Infrared and far-infrared lasers; (140.3480) Lasers, diode-pumped; (160.5690) Rare earth doped materials

1. Introduction

Ytterbium (Yb) solid-state lasers exhibit some important advantages over those based on the neodymium ion. Due to the small quantum defect and long storage time, high efficiency in combination with low heat generation is possible. Because of the relatively simple two-manifold electronic structure of the Yb^{3+}-ion, Yb-doped crystals do not suffer from excited-state absorption, upconversion and self-quenching of fluorescence through cross-relaxation. In addition, Yb provides broad absorption and emission bands, which are attractive for diode pumping as well as for tunable and mode-locked laser operation. All in all this ion seems predestined for high-power laser operation. Nowadays, one of the most promising scalable concepts for high-power diode pumped lasers is based on the thin disk design [1]. The required high doping concentration makes hosts with increased separation between the activating ions preferable since energy migration between the Yb-ions can be minimized in that case. It is well known that the monoclinic potassium double tungstates $KGd(WO_4)_2$ and $KY(WO_4)_2$ possess this property and can accommodate very high doping levels of Yb reaching the stoichiometric structure $KYb(WO_4)_2$ [2]. Unfortunately, these materials can be grown only by unfavourable flux methods. In contrast, the related $NaGd(WO_4)_2$, hereafter NaGdW, can be grown in large sizes by the Czochralski method.

The uniaxial NaGdW belongs to a more general class of sodium double tungstates $NaR(WO_4)_2$ where R=Y, La, Bi and Ln (Ln=Ce…Lu). Its crystalline structure originates from the tetragonal scheelite structure of $CaWO_4$ (space group $I4_1/a$) where the Ca^{2+} ion is substituted by a pair of Na^+ and R^{3+} ions. In these tetragonal double tungstates Na^+ and R^{3+} ions are almost randomly distributed in the same cationic sublattice. This distribution holds also for the active laser dopant. As a consequence, a locally variable crystal field around the dopant ion is present (inhomogeneous broadening) and the linewidths of the electronic transitions for the rare earth elements are found to be broader than in ordered crystals. Room temperature laser operation is known up to now only for neodymium doped sodium double tungstate crystals. We present here our cw laser studies of Yb:NaGdW with special emphasis on cavity configurations, possible pumping sources and polarizations, and tuning behaviour.

2. Experimental

Single crystals of $(NaGd)_{1-x}Yb_x(WO_4)_2$ with x=0.05 and 0.1 in the melt were grown by the Czochralski method. The segregation coefficient varied from 0.72 to 0.8. The laser samples prepared were uncoated polished plates of thickness 0.75 mm (x=0.05) and 3.273 mm (x=0.1) allowing polarization either parallel or perpendicular to the optical axis c to be used.

The resonant transition of Yb^{3+} is actually also magnetic-dipole allowed and three spectra have to be measured for a complete description in an uniaxial crystal: α (E⊥c, H⊥c), π (E//c) and σ (H//c). In the case of Yb:NaGdW, however, we recorded very similar optical densities for the α and σ polarizations (Fig. 1). The maximum absorption cross sections near 974 nm calculated for the π and σ polarizations are 1.51 and 1.21×10^{-20} cm^2, respectively. Currently, measurements are under way in order to distinguish both sites where the Yb-ion replaces Na and Gd ions. A complete energy scheme of Yb:NaGdW for both sites and low temperature spectra will be presented elsewhere.

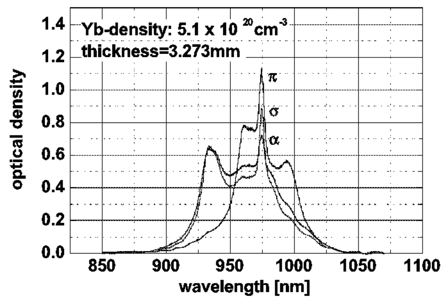

Fig. 1. Polarized optical density of Yb:NaGdW at room temperature for E//c (π), H//c (σ), E⊥c, H⊥c (α), and x=0.1 in the melt.

The Yb segregation coefficient, crystal lattice parameters and optical absorption properties agree rather well with those previously reported [3]. According to [3] the maximum emission cross sections calculated near 996 nm amount to $\approx2\times10^{-20}$ cm^2 for the π polarization and $\approx1.5\times10^{-20}$ cm^2 for the σ polarization and the fluorescence decay time equals 320 μs at low (<5%) Yb-doping levels which is comparable or even longer than in the monoclinic potassium double tungstates [4]. The calculated pump saturation intensity is equal to 42.3 kW/cm^2 (π) and 52.7 kW/cm^2 (σ), respectively. Note that both the emission and the absorption cross sections of Yb:NaGdW are almost an order of magnitude lower than the cross sections observed for the E//N_m polarization in the Yb-doped monoclinic double tungstates. That is why it is normal to expect lower efficiencies and higher laser thresholds for Yb:NaGdW than those found with the ordered double tungstates.

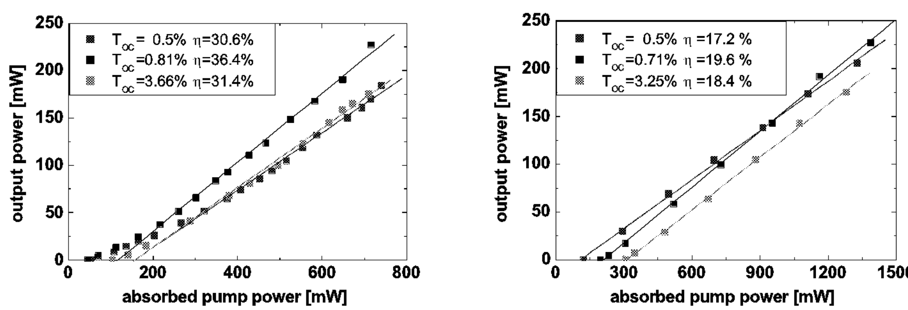

Fig. 2. Output power versus absorbed pump power (symbols) of the Yb:NaGdW laser obtained for E//c and Ti:sapphire (left) and diode (right) laser pumping. The linear fits give the slope efficiencies η for three different output couplers (T_{OC}).

A simple concentric cavity with two mirrors having RC=5 cm was used to study the 0.75 mm thick sample of $(NaGd)_{1-x}Yb_x(WO_4)_2$ with x=0.05. The pump beam, in this case from a Ti:sapphire laser at 975 nm in π-polarization, was focused by an f=5 cm lens onto the crystal. Different output couplers with transmission (T_{OC}) ranging from 0.5 to 3.6 % were used. Their reflectivity at the pump wavelength was 95 to 99.5 % which ensured pumping in a second pass since the absorption of this sample was only about 35% (π-polarization). The Yb:NaGdW laser operated at 1023 nm with a maximum output power of 230 mW and its emission was also π-polarized. Using different output couplers maximum slope efficiency of 36% and minimum threshold of 43 mW could be achieved.

The same sample could be pumped also by a 975 nm InGaAs laser diode using a modified hemispherical cavity of 5 cm length, an f=3 cm pump lens and the same output mirrors. A maximum output power of 227 mW at 1033 nm was obtained, again in the π polarization. The longer laser wavelength can be explained by the larger laser mode required for matching to the increased pump mode of the diode resulting in less bleaching and increased reabsorption in comparison to the Ti:sapphire laser pumping. The minimum laser threshold was 123 mW.

In order to study tunable laser operation we used an astigmatically compensated three-mirror cavity of 73 cm length consisting of an end mirror with RC=5 cm, totally reflecting only the laser radiation, a folding mirror with

RC=10 cm through which the pump beam was focused by an f=6.28 cm lens, and a plane output coupler with T_{OC}=3, 5 and 10%. The Ti:sapphire pump laser operated at 974 nm. The single pass pumping geometry was compatible with the higher absorption (calculated small signal values under Brewster angle of 94.4% and 89.4% for the π and σ polarizations, respectively) of the 3.273 mm thick $(NaGd)_{1-x}Yb_x(WO_4)_2$ sample with x=0.1.

We studied with this sample the π and σ polarizations and established that in both cases the absorption depletion effect is partially compensated at high pump levels by the recycling effect. Both the thresholds (at $P_{abs}\approx0.5$ W) and the slope efficiencies obtained with the three different output couplers were essentially the same for the two polarizations. For T_{OC}=10% the slope efficiency reached 33% and 30% for the π and the σ polarizations, respectively. The lasing wavelength was between 1027 and 1031.5 nm. Pump efficiencies as high as 20% with respect to the absorbed power resulted in maximum output powers exceeding 300 mW. The similar performance for E//c and H//c can be attributed to the comparable emission cross sections at the actual laser wavelengths which are far from the corresponding fluorescence maxima. Thermal effects were not observed up to incident powers of 2 W although no special cooling was provided to the crystal.

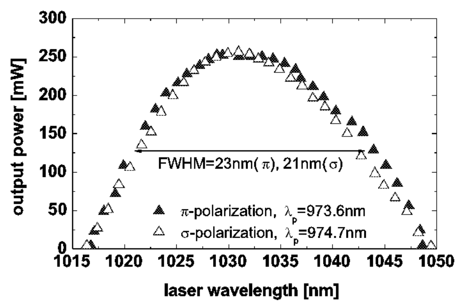

Fig. 3. Output power versus laser wavelength for an incident pump power of 2 W and T_{OC} = 5% near 1030 nm. The tuning performance by a Lyot filter for both the π (filled triangles) and σ (empty triangles) polarizations is shown.

The tuning operation of the laser was investigated inserting a two-plate Lyot filter under Brewster angle close to the output coupler. Under optimum alignment the power reduction with the filter inside the cavity did not exceed 10%. The tuning curve obtained for the π-polarization is slightly broader than for the σ-polarization (Fig. 3). Tunability extending from 1016 to 1049 nm at the zero-level was obtained. The FWHM for the π-polarization corresponds to $\Delta\nu=6.5\times10^{12}$ Hz. For a $sech^2$-shaped mode-locked pulse this means that sub-50-fs pulses can be expected from this laser in the mode-locking regime. This is about two times less than the shortest pulses typically achieved nowadays with femtosecond lasers based on the monoclinic double tungstates for similar T_{OC} values [5].

3. Conclusion

In conclusion cw and tunable room temperature laser operation of Yb:NaGdW under Ti:sapphire and diode laser pumping is demonstrated. The performance for the two possible polarizations is very similar achieving an output power of about 300 mW for 1.5 W of absorbed pump radiation. Initial tuning experiments indicate interesting potential for mode-locking with this disordered Yb-host. We note that in comparison to the recent laser demonstration of $Yb:CaF_2$ [6] the disorder and the inhomogeneous line broadening in NaGdW are rather due to occupation with some probability of two possible sites (each with multiple environments) than to lattice defects.

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