phys. stat. sol. (a) **202**, No. 3, R19–R21 (2005) / **DOI** 10.1002/pssa.200409088

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Efficient room temperature continuous-wave operation of an $Yb^{3+}:Sc_2O_3$ crystal laser at 1041.6 and 1094.6 nm

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Received 14 December 2004, revised 11 January 2005, accepted 12 January 2005
Published online 14 January 2005

PACS 42.55.Rz, 42.60.Jf, 42.60.Lh, 42.70.Hj

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An Yb-doped Sc_2O_3 crystal grown by the heat exchanger method provided extremely high pump (62.2%) and slope (72.7%) efficiencies in a continuous-wave (cw) laser operating either at 1041.6 or 1094.6 nm depending on the output coupling. Maximum powers of 1.55 and 1.35 W, respectively, were achieved by Ti:sapphire laser pumping without special cooling.

Among the rare earth laser hosts the sesquioxides Sc_2O_3, Y_2O_3, Gd_2O_3, and Lu_2O_3 are known for their superior thermo-mechanical properties [1]. Their thermal conductivity, e.g., considerably exceeds that of $Y_3Al_5O_{12}$ (YAG). Their low phonon energy ensures large energy storage times by minimizing non-radiative relaxation processes. Yb-doped sesquioxides exhibit somewhat broader absorption and emission bandwidths than Yb:YAG which is advantageous for uncritical diode laser pumping and femtosecond pulse generation [1, 2]. The splitting of the lower Yb^{3+} manifold in Sc_2O_3, Y_2O_3 and Lu_2O_3 is larger than in YAG which is important in the quasi-four-level operation scheme. These three sesquioxides with cubic bixbyite structure (space group $Ia\bar{3}$ or T_h^7) are isotropic and thus attractive for ceramic lasers. Solid solutions of cubic structure can be expected with the isostructural Yb_2O_3 but the observed strong lifetime quenching [2] makes them more suitable for laser geometries that profit from relatively low Yb concentrations.

The slope efficiency in the initial laser experiments with single crystals of Yb-doped Sc_2O_3, Y_2O_3, and Lu_2O_3 in simple two-mirror longitudinally pumped cavities ranged from 37% to 58% [1, 3]. So far the most efficient sesquioxide crystal laser has been $Yb:Sc_2O_3$ which possesses the largest ground-state splitting and emission cross section, and exhibits the highest thermal conductivity at low doping levels [4]. A slope efficiency of 49% was demonstrated with this material also employing the thin-disk laser design [5], and a similar slope efficiency of 47% was obtained in the picosecond regime with a cavity designed for mode-locked operation [4]. An $Yb:Sc_2O_3$ ceramic laser exhibited a slope efficiency of 9% with diode pumping [6].

In spite of these very promising initial results the progress in Yb-doped sesquioxide crystal lasers remains still quite limited because of the difficulties in crystal growth by the Czochralski method caused by the very high melting points which exceed 2400 °C [1, 2]. Here we present our recent results obtained with an $Yb:Sc_2O_3$ single crystal grown by the heat exchanger method. In order to assess the limits achievable in terms of efficiency we studied Ti:sapphire laser pumping in a simplified three mirror cavity facilitating optimum mode matching. We established that extremely high efficiencies can be obtained with this crystal at either 1041.6 nm or 1094.6 nm, depending on the output coupling used. The crystal absorption was carefully measured under lasing and non-lasing conditions, showing distinctly different behaviour.

The 0.7% Yb-doped Sc_2O_3 crystal used (2.3×10^{20} Yb^{3+} ions/cm^3) was grown by the heat exchanger method with a 44 mm crucible [7]. Crystals of sizes as large as 1 cm^3 can be produced now by this technique at a rate of several mm/h. Using the pinhole method we measured a fluorescence decay time of 826 µs. The slightly increased value in

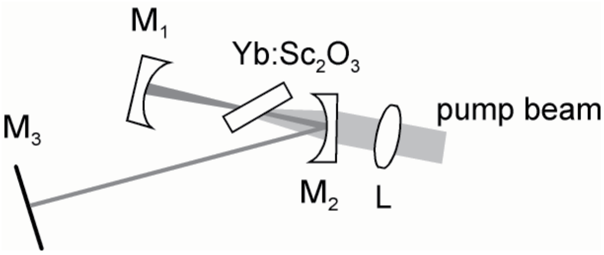

Figure 1 Schematic of the $Yb:Sc_2O_3$ laser formed with a three-mirror astigmatically compensated folded cavity. The concave mirrors M_1 and M_2 (both with RC = –100 mm) are highly reflecting from 1020 to 1240 nm and highly transmitting at the pump wavelength of 976 nm. M_3 is a flat output coupler. L is an f = 62.8 mm antireflection coated lens.

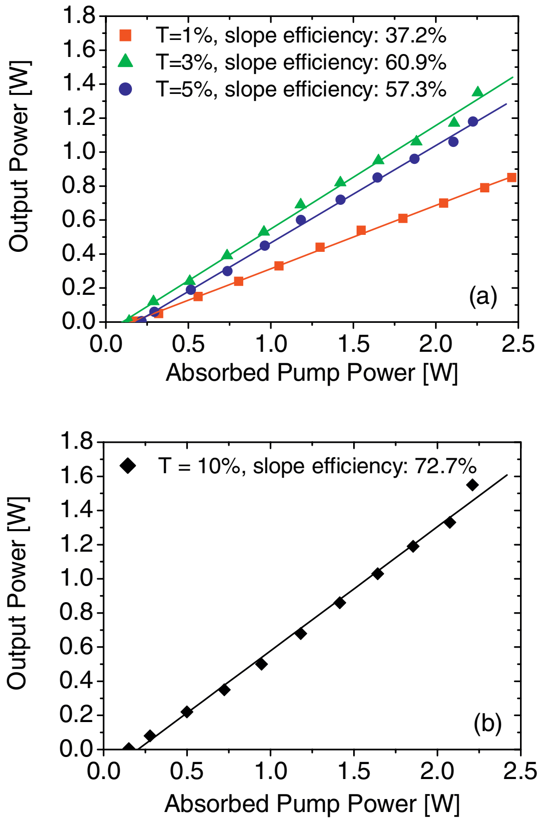

Figure 2 (online colour at: www.pss-rapid.com) Output power at 1094.6 nm (a) and 1041.6 nm (b) versus absorbed pump power for different output couplers.

comparison to the previously published one [4] is considered to reflect the better crystal quality.

The continuous-wave (cw) Ti:sapphire pump laser provided as much as 3 W at 976 nm. The pump beam was focused to a spot of about 22 µm (Gaussian waist). The uncoated $Yb:Sc_2O_3$ sample of 2.7 mm thickness was placed at Brewster angle in the waist position of the M_1M_2 arm (Fig. 1). This waist could be varied in the range from 20 to 70 µm by changing the separation between M_1 and M_2, allowing an optimization of the mode matching. The calculated low-signal absorption under Brewster angle was ≈95%. The actual absorption was estimated by measuring the residual pump power behind M_1. The cw laser performance was studied at room temperature without special cooling of the sample.

Depending on the output coupler used, the $Yb:Sc_2O_3$ laser oscillated at two different wavelengths, i.e. at 1041.6 nm or at 1094.6 nm (Fig. 2). These two wavelengths correspond to different transitions from the lowest Stark component of the upper $^2F_{5/2}$ manifold to the two highest Stark components of the lower $^2F_{7/2}$ manifold [4]. The oscillation wavelength at the net gain maximum is determined by the wavelength dependent cross sections, the nonsaturable loss, the inversion rate, and the bleaching. In our case the transmission of all output couplers used was the same for the two oscillation wavelengths given above.

Numerical considerations of similar wavelength hops in a ceramic $Yb:Y_2O_3$ laser can be found in [8]. Our observations are in agreement with Figs. 7–9 in [8] where the threshold for short wavelength operation is computed to be lower than for long wavelength operation only at increased transmission T of the output coupler. This behaviour can be fully accounted for within a rate equation model by calculating the threshold pump rate as a function of the cavity losses with the relevant emission cross sections and fractional populations corresponding to the two transitions mentioned [8]. Although relatively small, the different thermal population of the two highest Stark components of the lower $^2F_{7/2}$ manifold is essential for this effect. For $T \leq 5\%$ the laser oscillated only at the longer wavelength of 1094.6 nm. Figure 2a shows the output power as a function of the absorbed pump power. In the whole pump power range studied, the laser operated most efficiently with the 3% output coupler. The maximum output power was 1.35 W, obtained at an absorbed pump power of 2.25 W which leads to an optical conversion efficiency of 60%. The threshold absorbed pump power with this output coupler was 142 mW.

For T = 10% the laser oscillated at 1041.6 nm and the threshold absorbed power was 195 mW (Fig. 2b). A maximum output power of 1.55 W was achieved for an absorbed pump power of 2.49 W. The optical conversion efficiency reached in this case 62.2% while the slope efficiency was as high as 72.7%. The measured absorption (the ratio of the absorbed to the incident pump power) is plotted in Fig. 3. It can be seen that the actual absorption is greatly influenced by the recycling effect [9] while in the absence of this effect (non-lasing) bleaching from the small-signal value of 0.88 (measured) down to 0.60 can be observed. The recycling effect totally eliminated the pump power dependence of the ground state absorption in the presence of lasing and resulted in almost constant values at higher powers which were maximum for T = 1% when the intracavity power was also maximized.

Summarizing, efficient cw laser operation of $Yb:Sc_2O_3$ at two oscillation wavelengths, 1094.6 and 1041.6 nm, was obtained employing a Ti:sapphire laser for pumping. Output power of 1.55 W was achieved at 1041.6 nm with an

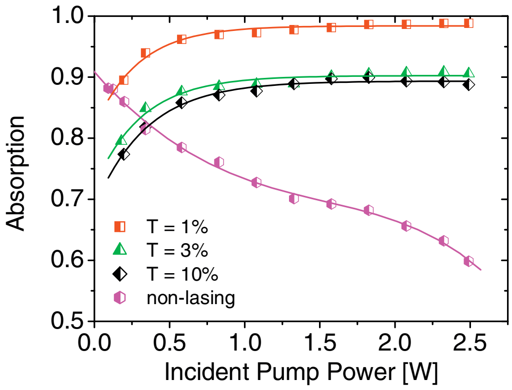

Figure 3 (online colour at: www.pss-rapid.com) Crystal absorption versus incident pump power for different output couplers in the lasing state, and with lasing interrupted.

optical conversion efficiency of 62.2% and a slope efficiency of 72.7%. When operating at 1094.6 nm, the output power reached 1.35 W corresponding to an optical conversion efficiency of 60% and a slope efficiency of 60.9%. These efficiencies are comparable to the highest previously demonstrated with Ti:sapphire laser pumped monoclinic double tungstates which are strongly anisotropic and have much larger cross sections [10], and also with the most advanced (Y_2O_3) sesquioxide ceramics [11]. It was also found that the Yb:Sc_2O_3 crystal exhibits quite different absorption behavior under lasing and non-lasing conditions. All results reported were obtained without active cooling of the crystal. We conclude that Yb^{3+}-doped sesquioxide crystals, similarly to the corresponding ceramics [11], have great potential for highly efficient, high-power, diode-pumped, all-solid-state lasers.

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