Efficient room temperature cw laser oscillation of crystalline $Yb:Sc_2O_3$ at 1041.6 and 1094.6 nm

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Abstract: Extremely high pump (62.2%) and slope (72.7%) efficiencies are obtained with a cw $Yb:Sc_2O_3$ crystal laser operating at 1041.6 and 1094.6 nm and delivering maximum powers of 1.55 and 1.35 W, respectively, without special cooling.

OCIS Codes: (140.5680) Rare earth and transition metal solid-state lasers; (140.3070) Infrared and far-infrared lasers; (160.5690) Rare earth doped materials.

1. Introduction

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., exceeds that of $Y_3Al_5O_{12}$ (YAG). Their low phonon energy ensures large energy storage time by minimizing non-radiative relaxation processes. The chemical relation to the "active" rare-earths used as dopants facilitates the substitution and similarly to the monoclinic double tungstates, Yb-doped sesquioxides exhibit broader absorption end emission bandwidths than Yb:YAG which is advantageous for uncritical diode laser pumping and operation in extended spectral ranges including femtosecond pulse generation by various mode-locking techniques [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 for the three level operation scheme of ytterbium lasers. These three sesquioxides with cubic bixbyite structure (space group $Ia\bar{3}$ or T_h^7) are isotropic which makes them very suitable for ceramic lasers [3]. Although total solid solutions of cubic structure can be expected in the diagram with the isostructural Yb_2O_3 the strong lifetime quenching with Yb-concentration observed [2] makes them more suitable for laser geometries that profit from relatively low dopant levels. Thus in fact the cubic sesquioxide hosts can be considered in many aspects complementary to the monoclinic double tungstates and most adequate for high power laser applications.

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 resulted in slope efficiencies ranging from 37% to 58% [1,4] while with polycrystalline $Yb:Y_2O_3$ slope efficiencies as high as 29% could be achieved [3]. So far the highest slope efficiencies were obtained with $Yb:Sc_2O_3$ which possesses the largest ground state splitting and emission cross section and exhibits the highest thermal conductivity at low doping levels [5]. A slope efficiency of 49% was demonstrated with this material also employing the thin disk laser design, at an output power as high as 124 W [6], and a similar slope efficiency of 47% was obtained in the picosecond regime with a cavity designed for mode-locked operation [5].

In spite of these very promising initial results the progress in Yb-doped sesquioxide 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 exchange method. In order to assess the limits achievable in terms of efficiency we studied Ti:sapphire laser pumping of crystalline $Yb:Sc_2O_3$ in a simplified three mirror cavity facilitating optimum mode matching. We established that extremely high efficiencies can be obtained at either 1041.6 nm or 1094.6 nm, depending on the output coupling used. The pump power absorption in the crystal was carefully measured under lasing and non-lasing conditions, showing distinctly different behaviour.

2. Experimental set-up

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 (HEM) with a 44 mm crucible [7]. Crystals of sizes as large as 1 cm^3 can be grown now by this technique with a rate of several mm/h. Using the pinhole method we measured a fluorescence decay time of 826 μm. The slightly increased value in comparison to the previously published one [5] is considered to reflect the better crystal quality.

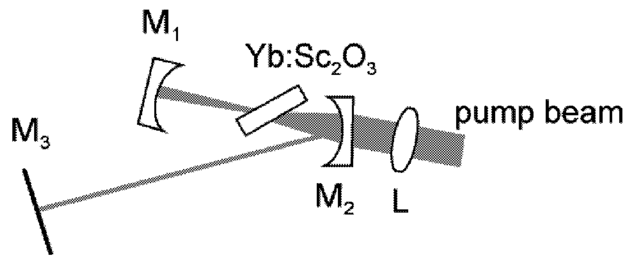

Fig. 1 Schematic of the Ti-sapphire laser pumped $Yb:Sc_2O_3$ laser formed with a three-mirror folded cavity.

The three mirror astigmatically compensated cavity of the cw $Yb:Sc_2O_3$ laser is shown in Fig. 1. The concave mirrors M_1 and M_2 (both with radius of curvature equal to 100 mm) were highly reflecting from 1020 to 1240 nm and highly transmitting at the pump wavelength of 976 nm. M_3 was a flat output coupler. The cw Ti-sapphire laser used for pumping provided as much as 3 W at 976 nm. The pump beam was focused onto the laser crystal by a f=62.8-mm antireflection coated lens 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. 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 to get efficient and stable operation. The calculated maximum 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.

3. Results and discussion

Depending on the output coupler used the $Yb:Sc_2O_3$ laser oscillated at two different wavelengths, 1041.6 and 1094.6 nm. These two wavelengths belong to two separate emission lines which correspond to the transitions from the lowest Stark component of the upper $^2F_{5/2}$ manifold to the top two Stark components of the lower $^2F_{7/2}$ manifold. The resulting oscillation wavelength corresponds to the net gain minima which are determined not only by the wavelength dependent cross sections and the nonsaturable losses but also by 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 of the output coupler.

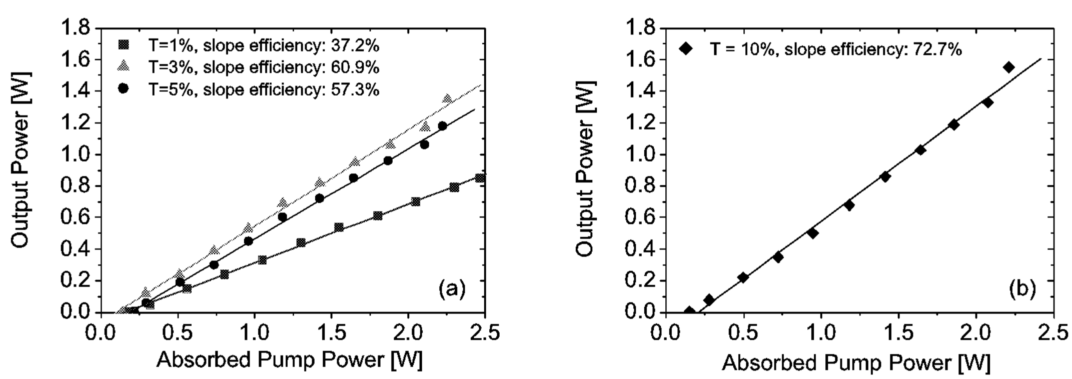

Fig. 2 Output power at 1094.6 nm (a) and 1041.6 nm (b) versus absorbed pump power for different output coupler transmissions (T).

When the output coupling did not exceed 5% the laser oscillated at the longer wavelength of 1094.6 nm. Fig. 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.

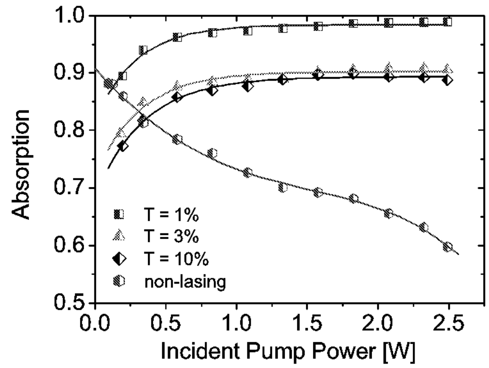

Fig. 3 Crystal absorption versus incident pump power for different output couplers, and with lasing interrupted.

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 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.

3. Conclusion

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. 1.55 W of output power at 1041.6 nm was achieved with an 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 [9]. 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.

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