Highly efficient mode-locked Yb:Sc_2O_3 laser

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Passive mode locking of the Yb:Sc_2O_3 laser is demonstrated. We investigate the laser performance with Ti:sapphire and diode-laser pumping. The laser is mode locked by use of a semiconductor saturable-absorber mirror and emits as much as 0.8 W of power in the picosecond range with a pump efficiency as high as 47%. With dispersion compensation, pulses as short as 230 fs for an average power of 0.54 W are obtained at 1044 nm. This is, to our knowledge, the first femtosecond oscillator based on an Yb-doped sesquioxide crystal.

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Yb-doped materials are well suited for building simple and robust diode-pumped ultrashort-pulse lasers near 1 μm. Femtosecond laser operation has been demonstrated successfully in a number of Yb-doped hosts,[1–5] and mode-locked output powers in the watt range were achieved.[6] The attractions of Yb-doped materials are their small quantum defects, which reduce the thermal load, and the absence of excited-state absorption, upconversion, cross relaxation, and concentration quenching.

The spectroscopic and the thermomechanical properties and the doping level of the material depend strongly on the host and its anisotropy. Comparative studies of 13 available hosts in which the output yield and the slope efficiency were evaluated on the basis of the host's spectroscopic characteristics predicted that scandia (Sc_2O_3) and the monoclinic double tungstates $KGd(WO_4)_2$ and $KY(WO_4)_2$ doped with Yb^{3+} would be the three most efficient representatives of this class of material for end-pumped cw lasers.[7] The tungstates stand out because of their large absorption and emission cross sections.[3] The isotropic sesquioxides[8] Sc_2O_3, Y_2O_3, and Lu_2O_3 are, however, more promising for high-power applications because the strong anisotropy of the thermomechanical properties of $KGd(WO_4)_2$ and $KY(WO_4)_2$ is a serious limitation. The thermal conductivity of the sesquioxides is better and the splitting of the ground state is larger than in the tungstates or in YAG, which makes them destined for highly efficient ultrashort-pulse laser sources. Among the sesquioxides, which are also interesting as ceramic-based laser materials,[9] Sc_2O_3 seems to hold the greatest promise because of its larger emission cross section, higher thermal conductivity at low Yb-doping levels, and larger splitting of the ground state (Table 1). These advantages have already been evidenced in terms of slope efficiency in cw laser experiments.[8] The absorption and emission cross sections and an energy-level diagram of Yb:Sc_2O_3 are shown in Fig. 1.

In this Letter we demonstrate, for the first time to our knowledge, mode-locked operation of the Yb:Sc_2O_3 laser with high pump efficiency and present results obtained in both the picosecond and the femtosecond regimes.

Initial experiments were performed with a Ti:sapphire (Ti:Sa) laser as a pump source, which emitted 2 W of output power at 976 nm. For diode-pumped operation a tapered diode laser[3] (TDL) was used that delivered 2 W of power at $M^2 < 4$ for the slow axis emission. The emission of the TDL with a spectral bandwidth of only 1 nm was stabilized at 976 nm by feedback with a reflection grating of a small amount of radiation (<0.02%). Because of the excellent beam quality of the TDL, relatively simple beam shaping optics were required.[3]

For the experiments a 2.75-mm-thick 0.7% Yb–Sc site (2.3×10^{20} Yb^{3+} ions/cm^3) Sc_2O_3 crystal with an aperture of 4 mm × 5.8 mm was used at the Brewster angle. Approximately 97% of the incident pump radiation was absorbed by the crystal.

We studied a Z-shaped resonator with two folding mirrors [radius of curvature (RC), 10 cm] in the middle to form a 30-μm cavity waist at the position of the Yb:Sc_2O_3 crystal (Fig. 2). One arm contained an additional focusing mirror, M_1, to increase the intensity on the semiconductor saturable absorber mirror (SESAM), which terminated the resonator. The other arm contained a plane output coupler, and in this arm two dispersion-compensating prisms could be included. The SESAM (BATOP GmbH, Weimar, Germany) was designed for a central wavelength of 1045 nm, with 2% saturable absorption and a saturation fluence of 70 $\mu J/cm^2$. The nonsaturable loss was specified to be less than 0.3%, and the relaxation time to be equal to 20 ps.

In the first part of the experiments the Ti:Sa pump source was applied with an estimated 30-μm pump beam waist at the Yb:Sc_2O_3 crystal. With a 9.6% output coupler and the SESAM replaced by a plane total reflector on which an additional cavity waist of

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Table 1. Comparison of Properties of Yb^{3+}-Doped Sesquioxides with YAG and the Monoclinic Double Tungstates

	Yb-Doped Crystal					
Property[a]	YAG	KYW	KGW	Y_2O_3	Lu_2O_3	Sc_2O_3
λ_{laser} (nm)	1030	1025[b]	1026[b]	1031	1032	1041
$\sigma_{emission}$ (10^{-21} cm^2)	19	30[b]	28[b]	10.6	12.8	14.4
$\sigma_{reabsorp}$ (10^{-21} cm^2)	1.2	3[b]	2.9[b]	0.8	0.7	0.7
$\Delta\lambda$ (nm)	8.5	16[b]	20[b]	14.5	13	11.6
$^2F_{5/2}$ lifetime (μs)	950	300	300	850	820	800
$^2F_{7/2}$ splitting (cm^{-1})	785	568	535	874	903	1017
κ (W m^{-1} K^{-1})	11	3.3[c]	3.3[c]	≥13.6	≥12.5	≥16.5

[a] κ, thermal conductivity (Yb^{3+}-doping level <1%; for Yb-doping dependence, see Ref. 10); $\Delta\lambda$, emission bandwidth.
[b] N_m polarization.
[c] Values averaged over the polarizations.

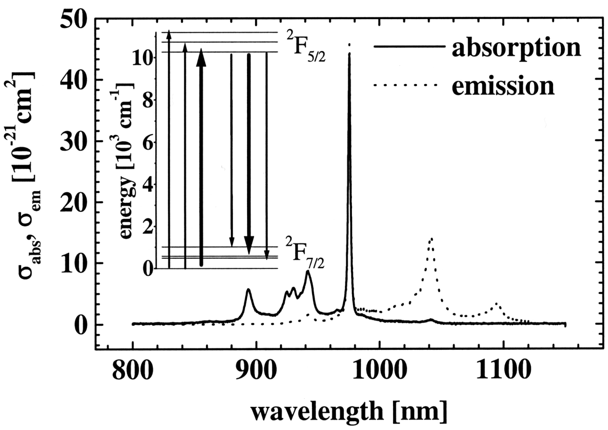

Fig. 1. Absorption and emission spectra of Yb:Sc_2O_3 and energy-level diagram with the relevant transitions (inset).

~100 μm was produced by the mirror with a RC of 10 cm (M_1, Fig. 2), the laser generated a maximum cw output power of 1 W, with a slope efficiency of 65%.

Although the Yb:Sc_2O_3 crystal was not actively cooled, thermal problems did not occur. When the SESAM was inserted in the same configuration, still without intracavity prisms, the laser operated in the picosecond regime with a cavity round-trip time of 9.2 ns. The measured cw lasing threshold amounted to 250 mW of absorbed power [Fig. 3(a)]. In the mode-locked regime the maximum pump efficiency reached 47%. We believe that this value represents the highest reported optical-to-optical pump efficiency with respect to the absorbed power of any mode-locked laser including those based on the thin disk concept.[1,6] The small jump in output power that is apparent in Fig. 3(a) in the transition from the cw to the mode-locked regime is due to a slight reduction in resonator losses associated with saturation of the SESAM loss. Pulses as short as 1.33 ps (with a spectral bandwidth ~5 times above the Fourier limit) at 1041.5 nm were achieved at a maximum output power of 0.8 W. At lower output powers the pulse duration remained unchanged but the pulse spectral width decreased from 4.6 to ~2 nm.

For femtosecond operation, mirror M_1 with a RC of 15 cm was applied to optimize the pulse fluence on the SESAM. Additionally, two 60° SF6 prisms with a tip-to-tip separation of 64 cm were inserted into the arm containing a 5.5% output coupler, M_4 (Fig. 2). The prisms compensate for the positive group-velocity dispersion inside the cavity and balance the self-phase modulation introduced by the Kerr nonlinearity of the laser crystal. The resultant cavity round-trip time is 11.7 ns. Mode-locked operation was obtained with a maximum output power of 540 mW, corresponding to a pulse energy of 6.3 nJ, or 27.6-kW peak power. From these experimental data we deduce a pump efficiency of 30%. The lower efficiencies compared with the picosecond results [Fig. 3(a)] are due to insertion losses of the prisms in connection with the lower transmission of the output coupler. The measured autocorrelation trace could be fitted well when sech^2 pulse shapes were assumed and is shown in Fig. 3(b) together with the emission spectrum at maximum output power. The deconvolved FWHM of the pulse is 230 fs and the central wavelength is 1044.5 nm. The time–bandwidth product amounts to 0.33, which is close to the Fourier limit (0.315).

Using the setup of Fig. 2 (M_1: +RC = 10 cm), the TDL as the pump source, and the prisms inserted into the cavity, we achieved stable mode locking for output coupler transmissions of 1.5–3.5%. With 1-W pump power incident upon the crystal, the maximum mode-locked output power was 120 mW for a 2.8% output coupler. The laser threshold (cw) was obtained at an absorbed pump power of 250 mW. Although the available power of the TDL and that of the Ti:Sa laser were roughly the same in front of focusing lens

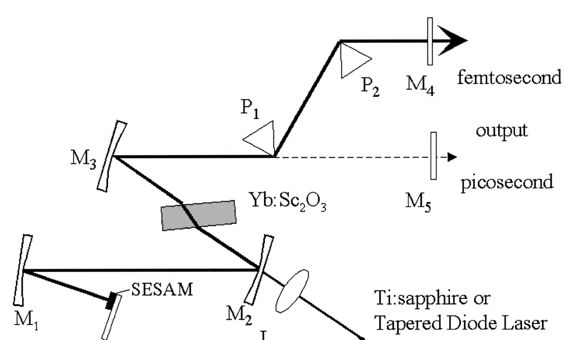

Fig. 2. Schematic of the mode-locked Yb:Sc_2O_3 laser: M_1, focusing mirror (RC, 10–15 cm); M_2, M_3, folding mirrors (RC, 10 cm); P_1, P_2, SF6 prisms; M_4, M_5, output couplers; L_P, 6.28-cm focusing lens.

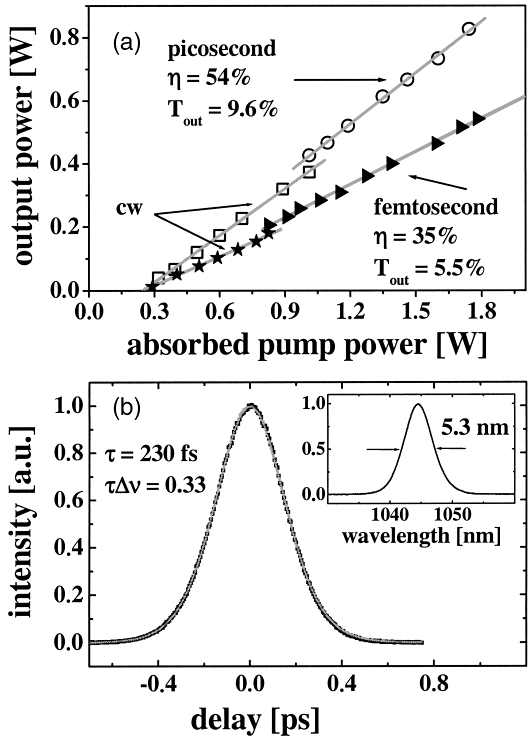

Fig. 3. Performance of the $Yb:Sc_2O_3$ mode-locked laser with a Ti:Sa pump source. (a) Output power versus absorbed pump power in the picosecond and femtosecond regimes and below their mode-locking thresholds (cw); η, slope efficiency. (b) Autocorrelation trace and spectrum (inset) in the femtosecond regime.

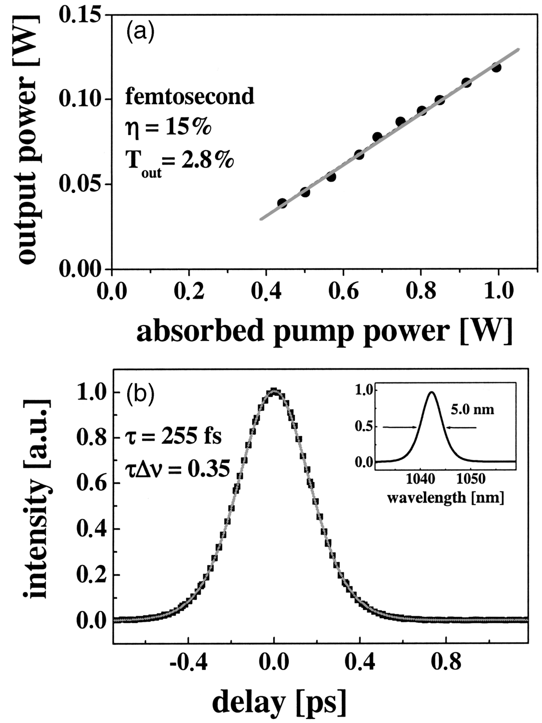

Fig. 4. Performance of the $Yb:Sc_2O_3$ mode-locked laser with the TDL as the pump source in the femtosecond regime. (a) Output power versus absorbed pump power. (b) Autocorrelation trace and spectrum (inset).

L_P, the diode pump power launched into the cavity was reduced by the aperturing effect of mirror M_2. The lower efficiency [Fig. 4(a)] compared with that in the Ti:Sa-pumped experiments is a consequence of an imperfect match of pump and resonator modes and the lower beam quality of the diode emission. At a pulse repetition rate of 86 MHz a pulse duration of 255 fs was achieved at maximum output power, as shown in Fig. 4(b). The corresponding spectrum (centered at 1042.5 nm) had a FWHM of 5.0 nm [Fig. 4(b), inset] which yields a time–bandwidth product ($\tau\Delta\nu$) of 0.35.

The observed transversal mode structure of the $Yb:Sc_2O_3$ laser remained basically TEM_{00} in both the Ti:Sa- and the diode-pumped configurations. For all arrangements investigated, the mode-locked operation showed no tendencies toward passive Q switching[1] and was stable for hours in the diode-pumped configuration. The pulse durations obtained are substantially shorter than the 340-fs limit reported with Yb:YAG,[1] a fact that can be attributed to the larger gain bandwidth of $Yb:Sc_2O_3$ (Table 1).

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