Watt-level femtosecond Tm:$(Lu,Sc)_2O_3$ ceramic laser

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The cubic sesquioxides (RE_2O_3, where RE = Lu, Y, Sc, or their mixture) combine superior thermo-mechanical properties, relatively low phonon energies, and broad and smooth gain spectra, making them attractive for high-average-power ultrafast lasers in the 2-μm spectral range. To date, nearly all sub-100-fs mode-locked bulk Tm-lasers with average powers exceeding 100 mW have relied on crystalline or ceramic type sesquioxides hosts [1]. With in-band pumping ($^3H_6 \rightarrow {}^3F_4$ transition in Tm^{3+}) which combines the high brightness of the single-mode fiber and a low quantum defect, an average power up to 1 W has been obtained from a Kerr-lens mode-locked Tm:Sc_2O_3 crystalline laser [2]. Nevertheless, growth of high-quality crystalline sesquioxides is still a challenge due to their high melting temperature (> 2400 °C [3]). In comparison, polycrystalline sesquioxide ceramics can be easily fabricated in the form of large size or "mixed" structures which exhibit inhomogeneous gain spectral broadening caused by compositional disorder. Here, we study the performance of a SESAM mode-locked Tm:$(Lu,Sc)_2O_3$ ceramic laser in-band pumped by a Raman fiber laser at 1627 nm. More than 1-W average power is achieved with a pulse duration of 280 fs at 2060 nm.

An astigmatically compensated *X*-shaped cavity with two flat chirped mirrors in the longer arm terminated by a flat-wedged output coupler (OC) was employed. Each chirped mirror provides a group delay dispersion (GDD) of ~ –125 fs^2 per bounce at 2.08 μm. The uncoated ceramic sample with dimensions of 3 × 3 × 3 mm^3 was placed at Brewster's angle between two concave (RoC = -100 mm) dichroic mirrors. The simulated laser beam radius on the ceramic was 32 μm × 57 μm in the sagittal and tangential planes, respectively. A SESAM was employed for starting and stabilizing the mode-locking, and the calculated beam radius on it was ~ 50 μm.

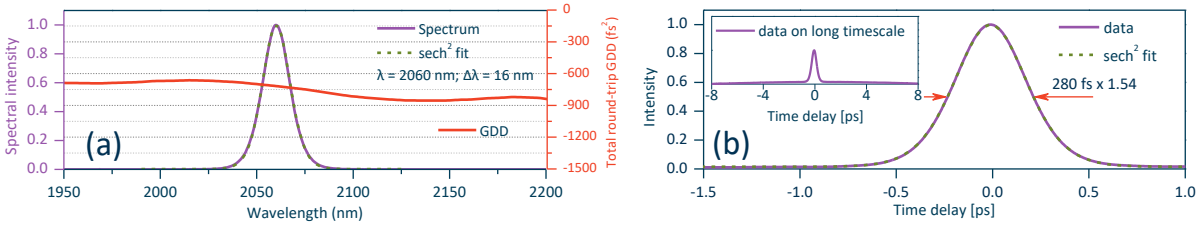

Fig. 1 Optical spectrum (a) and autocorrelation trace (b) of the SESAM mode-locked Tm:$(Lu,Sc)_2O_3$ ceramic laser with T_{OC} = 3%. Solid red curve in (a): total round-trip GDD. *Inset* in (b): long-timescale (± 8 ps) autocorrelation trace.

With a 3% OC, the highest average output power of 1.02 W at 86.5 MHz repetition rate was achieved from the self-starting femtosecond mode-locked Tm:$(Lu,Sc)_2O_3$ ceramic laser, yielding a single pulse energy of 11.8 nJ. The corresponding laser efficiency with respect to the absorbed pump power amounted to 36.4%. The measured optical spectrum, with a central wavelength of 2060 nm, is shown in Fig. 1(a). Fitting the spectral profile with a $sech^2$-function gives a FWHM (full width at half maximum) of 16 nm. Figure 1(b) shows the measured noncollinear autocorrelation trace at the highest average power. By assuming a $sech^2$ pulse intensity profile, the pulse duration amounted to 280 fs, thus leading to a time-bandwidth product (TBP) of 0.317, which is an indication of transform-limited pulses. The long-timescale autocorrelation trace shown by the inset in Fig. 4(b) is an evidence of single pulse operation of the mode-locked ceramic laser without any temporal satellites.

The demonstrated Tm:$(Lu,Sc)_2O_3$ ceramic laser performance is comparable to the crystalline laser in [2] and represents the highest power level ever reported from Tm- or Tm,Ho femtosecond mode-locked bulk lasers.

References

[1] V. Petrov, Y. Wang, W. Chen, Z. Pan, Y. Zhao, L. Wang, M. Mero, S. Y. Choi, F. Rotermund, W. B. Cho, W. Jing, H. Huang, H. Yuan, H. Cai, L. Zhang, Z. Lin, P. Loiko, X. Mateos, X. Xu, J. Xu, H. Yu, H. Zhang, S. Suomalainen, M. Guina, A. Härkönen, and U. Griebner, "Sub-100-fs bulk solid-state lasers near 2-micron," Proc. SPIE. **11209**, 112094G (2019).

[2] M. Tokurakawa, E. Fujita, and C. Kränkel, "Kerr-lens mode locked Tm^{3+}:Sc_2O_3 single-crystal laser in-band pumped by an Er:Yb fiber MOPA at 1611 nm," Opt. Lett. **42**(16), 3185-3188 (2016).

[3] C. Kränkel, "Rare-earth-doped sesquioxides for diode-pumped high-power lasers in the 1-, 2-, and 3-μm spectral range," IEEE J. Sel. Top. Quantum Electron. **21**(1), 1602013 (2015).