



HAL
open science

Highly efficient lasing and thermal properties of Tm:Y₂O₃ and Tm:(Y,Sc)₂O₃ ceramics

Kirill Ereemeev, Pavel Loiko, Roman Maksimov, Vladislav Shitov, Vladimir Osipov, Dmitry Vakalov, Viacheslav Lapin, Patrice Camy, Weidong Chen, Uwe Griebner, et al.

► **To cite this version:**

Kirill Ereemeev, Pavel Loiko, Roman Maksimov, Vladislav Shitov, Vladimir Osipov, et al.. Highly efficient lasing and thermal properties of Tm:Y₂O₃ and Tm:(Y,Sc)₂O₃ ceramics. *Optics Letters*, 2023, 48 (15), pp.3901-3904. 10.1364/OL.495516. hal-04209387

HAL Id: hal-04209387

<https://hal.science/hal-04209387>

Submitted on 1 Nov 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Highly efficient lasing and thermal properties of Tm:Y₂O₃ and Tm:(Y,Sc)₂O₃ ceramics

KIRILL EREMEEV,¹ PAVEL LOIKO,¹ ROMAN MAKSIMOV,^{2,3} VLADISLAV SHITOV,² VLADIMIR OSIPOV,² DMITRY VAKALOV,⁴ VIACHESLAV LAPIN,⁴ PATRICE CAMY,¹ WEIDONG CHEN,⁵ UWE GRIEBNER,⁵ VALENTIN PETROV,⁵ AND ALAIN BRAUD^{1,*}

¹Centre de Recherche sur les Ions, les Matériaux et la Photonique (CIMAP), UMR 6252 CEA-CNRS-ENSICAEN, Université de Caen, 6 Boulevard Maréchal Juin, 14050 Caen Cedex 4, France

²Institute of Electrophysics, Ural Branch of the Russian Academy of Sciences, 106 Amundsen St., 620016 Ekaterinburg, Russia

³Ural Federal University named after the first President of Russia B. N. Yeltsin, 19 Mira St., 620002 Ekaterinburg, Russia

⁴North-Caucasus Federal University, 2 Kulakova Ave., 355017 Stavropol, Russia

⁵Max Born Institute for Nonlinear Optics and Short Pulse Spectroscopy, Max-Born-Str. 2a, D-12489 Berlin, Germany

*Corresponding author: alain.braud@ensicaen.fr

Received XX Month XXXX; revised XX Month, XXXX; accepted XX Month XXXX; posted XX Month XXXX (Doc. ID XXXXX); published XX Month XXXX

We report on thermal, spectroscopic and laser properties of transparent 5 at.% Tm³⁺-doped yttria and “mixed” yttria-scandia ceramics fabricated by vacuum sintering at 1750 °C using nanoparticles produced by laser ablation. The solid-solution (Tm_{0.05}Y_{0.698}Sc_{0.252})₂O₃ ceramic features a broadband emission extending up to 2.3 μm (gain bandwidth: 167 nm) and high thermal conductivity of 4.48 Wm⁻¹K⁻¹. A Tm:Y₂O₃ ceramic laser generated 812 mW at 2.05 μm with a slope efficiency η of 70.2%. For the Tm:(Y,Sc)₂O₃ ceramic, the output power was 523 mW at 2.09 μm with η = 44.7%. These results represent record-high slope efficiencies for any parent or “mixed” Tm³⁺-doped sesquioxide ceramics. © 2023 Optical Society of America

<http://dx.doi.org/10.1364/OL.99.099999>

Thulium ions (Tm³⁺, electronic configuration: [Xe]4f¹²) are known for their broadband emission in the eye-safe spectral range around 2 μm due to the ³F₄ → ³H₆ electronic transition [1]. Tm³⁺ ions offer intense absorption at 0.8 μm (the spectral range covered by AlGaAs diode lasers) and a cross-relaxation (CR) process, ³H₄ + ³H₆ → ³F₄ + ³F₄, leading to a pump quantum efficiency up to 2 (a one-to-two pump process) [2]. Due to the large Stark splitting of the ground-state (³H₆, 788 cm⁻¹ for Tm:Y₂O₃ [3]), Tm³⁺-doped crystals are extremely suitable for broadly tunable and mode-locked lasers [4,5].

Among the host matrices for Tm³⁺ doping, cubic (sp. gr. Ia $\bar{3}$, C-type) rare-earth sesquioxides A₂O₃ (A = Y, Lu, Sc) appear attractive because of a combination of good thermal conductivity of the host matrix (κ = 12.7 Wm⁻¹K⁻¹ for Y₂O₃) and advantageous spectroscopic properties of the dopant ions, i.e., broad emission spectra extending well above 2 μm owing to strong crystal-fields, long upper laser level luminescence lifetimes and efficient CR [1]. Highly-efficient and power-scalable Tm:A₂O₃ lasers at ~2 μm are known [1,6,7]. Loiko *et al.* reported on a diode-pumped Tm:Lu₂O₃ crystal-rod laser generating 47.5 W at 2.1 μm with a slope efficiency of 59% [1].

However, the growth of Tm:A₂O₃ single-crystals is complicated by their high melting points (2425 °C for Y₂O₃) which are withstood only by Rh crucibles [8].

Transparent ceramics are polycrystalline materials composed of closely packed single-crystalline grains with a random orientation featuring a weak light scattering under a low density of pores and a lack of secondary phases. The ceramic technology is well applicable to cubic sesquioxides [7,9,10] offering lower synthesis temperature (~1750 °C), well-preserved spectroscopic behavior of the dopant ions, good thermo-mechanical properties (under proper synthesis conditions) and well-controlled doping. Tm:A₂O₃ laser ceramics are known [7,11-13]. Wang *et al.* reported on a diode-pumped 2 at.% Tm:Y₂O₃ ceramic laser delivering 7.25 W at 2.05 μm with a slope efficiency of 40% exceeding the Stokes limit [13].

Apart from the parent sesquioxides, their binary solid-solutions Tm:(A_{1-x}B_x)₂O₃ attract attention for generation of ultrashort pulses from mode-locked lasers [5,14]. This is due to an inhomogeneous spectral broadening in such compounds. Zhao *et al.* reported on a mode-locked Tm:LuYO₃ ceramic laser delivering pulses as short as 57 fs at 2045 nm, i.e., 8 optical cycles [5]. The ceramic technology is suited for the precise control of the A/B balances in such materials.

In the present work, we report on the thermal and spectroscopic properties and highly-efficient ~2 μm laser operation of Tm:Y₂O₃ and Tm:(Y,Sc)₂O₃ transparent sesquioxide ceramics fabricated by an original method employing laser-ablated nanoparticles.

Transparent Tm:(Y_{1-x}Sc_x)₂O₃ ceramics were fabricated by solid-state consolidation of nanoparticles synthesized by laser ablation of a solid target material [15]. To prepare the targets, commercial high-purity A₂O₃ (A = Y, Sc, Tm) powders were dry-mixed for 24 h in the proportion Tm_{0.05}(Y_{1-x}Sc_x)_{1.95}O₃ (x = 0, 0.125, 0.25). A small amount of ZrO₂ (1.7 mol%) acting as a grain growth inhibitor was used [16]. The mixtures were compacted and sintered at 1100 °C for 5 h in air. The vapor phase above the target surface formed under irradiation by a pulsed CO₂ laser was cooled by an air flow to condense and crystallize as nanoparticles. Their composition was (Tm_{0.05}Y_{0.95})₂O₃, (Tm_{0.05}Y_{0.829}Sc_{0.121})₂O₃ and (Tm_{0.05}Y_{0.698}Sc_{0.252})₂O₃ according to the ICP-MS analysis. They were calcined at 1050 °C and

uniaxially pressed in a stainless-steel die at 200 MPa to form green bodies, which were sintered at 1750 °C for 5 h under a residual gas pressure of 10^{-3} Pa. The sintered ceramics were annealed at 1400 °C for 2 h in air. The ceramic disks ($\Phi 12$ mm, ~ 1.8 -1.9 mm-thick) were polished to laser-grade quality on both sides. A photograph of annealed polished ceramic disks is shown in Fig. 1(a). They were transparent with a slight yellow coloration due to Tm^{3+} doping.

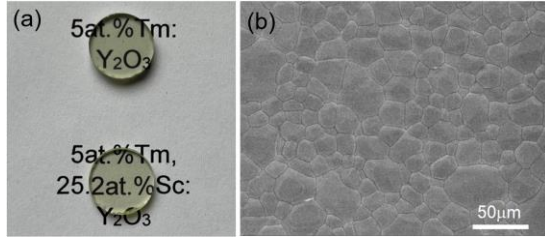


Fig. 1. 5 at.% $\text{Tm}:(\text{Y}_{1-x}\text{Sc}_x)_2\text{O}_3$ ceramics: (a) a photograph of laser-grade polished ceramic disks; (b) a typical SEM image of an etched surface of the $(\text{Tm}_{0.05}\text{Y}_{0.829}\text{Sc}_{0.121})_2\text{O}_3$ ceramic.

The ceramics were of single-phase nature (sp. gr. $Ia\bar{3}$, bixbyite structure). A typical SEM image of a thermally etched surface of the $(\text{Tm}_{0.05}\text{Y}_{0.829}\text{Sc}_{0.121})_2\text{O}_3$ ceramic is shown in Fig. 1(b). The samples consisted of polyhedral-shaped micro-crystallites separated by well-defined and clean boundaries. Partial substitution of Y^{3+} by Sc^{3+} accelerated the diffusion processes and caused a notable increase in the grain size ($D_{\text{grain}} = 6.8, 21.2$ and $28.2 \mu\text{m}$ for 0, 12.1 and 25.2 at.% Sc^{3+}). The content of μm -sized pores progressively increased, $X_{\text{pore}} = 0.6, 25.9$ and 46.1 ppm, respectively. It is likely that the accelerated grain growth led to entrapment of a considerable fraction of pores. The transmission of the ceramic disks at $\sim 1 \mu\text{m}$ was $T = 81.5\%, 81.0\%$ and 80.5% , respectively, close to the theoretical limit.

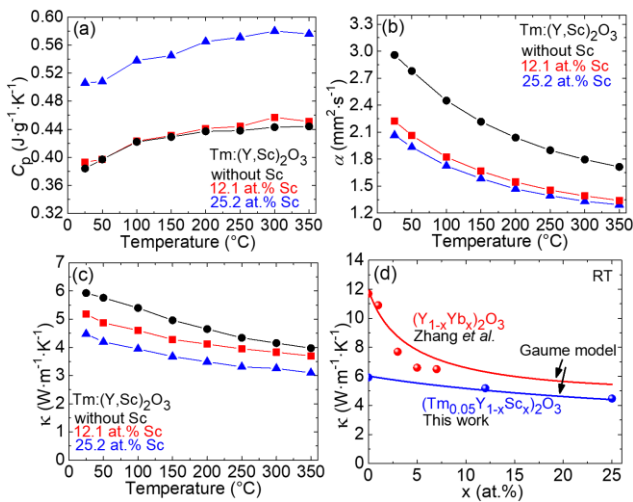


Fig. 2. 5 at.% $\text{Tm}:(\text{Y}_{1-x}\text{Sc}_x)_2\text{O}_3$ ceramics: temperature dependence of (a) specific heat C_p , (b) thermal diffusivity α and (c) thermal conductivity κ ; (d) RT thermal conductivity for $(\text{Tm}_{0.05}\text{Y}_{1-x}\text{Sc}_x)_2\text{O}_3$ and $(\text{Y}_{1-x}\text{Yb}_x)_2\text{O}_3$ [17] ceramics, points – experiment, curves – simulation (Gaume model).

The thermophysical characteristics of ceramics were studied by the laser flash method using a NETZSCH LFA 467 HyperFlash at 25

– 350 °C under Ar atmosphere. The samples were covered with a graphite layer. The thermal conductivity was calculated as $\kappa = \alpha C_p \rho$, where α is the thermal diffusivity, C_p is the specific heat and ρ is the density evaluated from the XRD analysis, see Fig. 2(a-c). At room temperature (RT), κ gradually decreases from 5.93 to $4.48 \text{ W m}^{-1}\text{K}^{-1}$ when raising the Sc^{3+} content from 0 to 25.2 at.%. The concentration dependence of κ for $(\text{Tm}_{0.05}\text{Y}_{1-x}\text{Sc}_x)_2\text{O}_3$ and $(\text{Y}_{1-x}\text{Yb}_x)_2\text{O}_3$ [17] ceramics is well explained using the Gaume model [18], Fig. 2(d).

The formation of a substitutional solid-solution for Sc-containing ceramics was confirmed by Raman spectroscopy, Fig. 3. The most intense Raman band assigned to $F_g + A_g$ modes of the cubic bixbyite structure broadens and experiences a progressive shift towards higher frequencies with increasing the Sc^{3+} content. For 25.2 at.% Sc^{3+} , it is centered at 390 cm^{-1} (bandwidth: 31 cm^{-1}) and the highest phonon energy is 614 cm^{-1} .

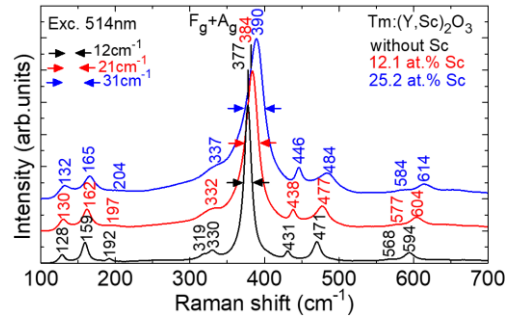


Fig. 3. Raman spectra of 5 at.% $\text{Tm}:(\text{Y}_{1-x}\text{Sc}_x)_2\text{O}_3$ ceramics, $\lambda_{\text{exc}} = 514 \text{ nm}$, numbers – Raman frequencies in cm^{-1} .

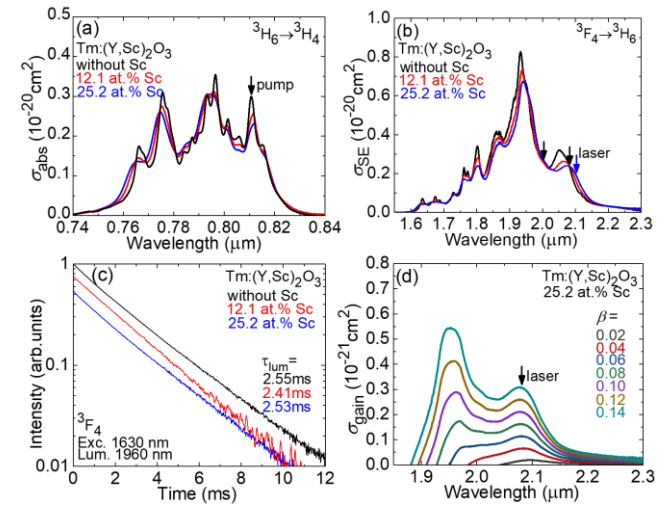


Fig. 4. Spectroscopy of Tm^{3+} ions in $(\text{Y}_{1-x}\text{Sc}_x)_2\text{O}_3$ ceramics ($x = 0 - 0.252$): (a) absorption cross-sections, σ_{abs} , for the ${}^3\text{H}_6 \rightarrow {}^3\text{H}_4$ transition; (b) SE cross-sections, σ_{SE} , for the ${}^3\text{F}_4 \rightarrow {}^3\text{H}_6$ transition; (c) luminescence decay curves from the ${}^3\text{F}_4$ manifold, $\lambda_{\text{exc}} = 1630 \text{ nm}$, $\lambda_{\text{lum}} = 1960 \text{ nm}$, powdered samples, τ_{lum} – luminescence lifetime; (d) gain cross-sections, $\sigma_{\text{gain}} = \beta \sigma_{\text{SE}} - (1 - \beta) \sigma_{\text{abs}}$, $\beta = N_2({}^3\text{F}_4) / N_{\text{Tm}}$ – inversion ratio. Arrows indicate the pump and laser wavelengths.

Figure 4(a) shows the absorption cross-sections, σ_{abs} , for the ${}^3\text{H}_6 \rightarrow {}^3\text{H}_4$ Tm^{3+} transition. The Tm^{3+} ion density N_{Tm} was 1.35, 1.38 and

1.42 [10²¹ at/cm³] for 0, 12.1 and 25.2 at.% Sc³⁺, respectively. By adding Sc³⁺, the absorption spectra become less structured. For the (Tm_{0.05}Y_{0.698}Sc_{0.252})₂O₃ ceramic, the maximum σ_{abs} is 0.31×10⁻²⁰ cm² at 795.3 nm corresponding to an absorption bandwidth (FWHM) of 25 nm. The stimulated-emission (SE) cross-section spectra for the ³F₄ → ³H₆ transition are plotted in Fig. 4(b). By replacing Y³⁺ cations ($R_Y = 0.9 \text{ \AA}$ for VI-fold O²⁻ coordination) with much smaller Sc³⁺ ones ($R_{\text{Sc}} = 0.745 \text{ \AA}$), the emission spectra of Tm³⁺ ions broadened and shifted towards longer wavelengths due to increased crystal-field strength in scandia as compared to yttria. In the spectral range where laser operation is expected for the (Tm_{0.05}Y_{0.698}Sc_{0.252})₂O₃ ceramic, $\sigma_{\text{SE}} = 0.24 \times 10^{-20} \text{ cm}^2$ at 2075.6 nm. The reabsorption-free upper laser level (³F₄) lifetime of Tm³⁺ ions was weakly dependent on the Sc³⁺ content, $\tau_{\text{lum}} = 2.41 - 2.55 \text{ ms}$, Fig. 4(c). The gain cross-sections, $\sigma_{\text{gain}} = \beta\sigma_{\text{SE}} - (1 - \beta)\sigma_{\text{abs}}$, for the ³F₄ ↔ ³H₆ transition were calculated. For (Tm_{0.05}Y_{0.698}Sc_{0.252})₂O₃, for small inversion ratios $\beta < 0.06$, a local peak at ~2.09 μm dominates in the spectra and for higher β , another peak at ~1.95 μm appears. For small $\beta = 0.06$, the gain bandwidth (FWHM) reaches 167 nm indicating a great potential for ultrashort (sub-100 fs) pulse generation.

The inhomogeneous spectral broadening of Tm³⁺ absorption / emission bands in “mixed” (solid-solution) ceramics was confirmed by low temperature (12 K) spectroscopy of the ³F₄ ↔ ³H₆ transition, Fig. 5. An additional spectral broadening as compared to Tm:Y₂O₃ single-crystals was induced by ZrO₂.

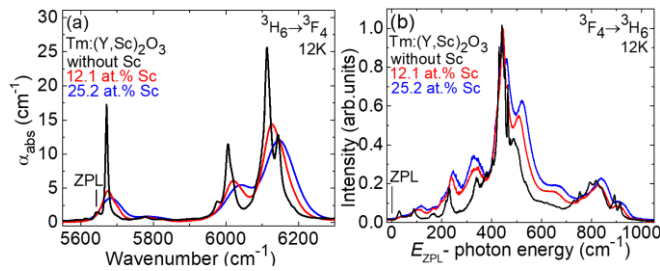


Fig. 5. Low-temperature (LT, 12 K) spectroscopy of Tm³⁺ ions in the Y₂O₃ and (Y,Sc)₂O₃ ceramics: (a) the ³H₆ → ³F₄ transition in absorption; (b) the ³F₄ → ³H₆ transition in emission. ZPL – zero-phonon line.

For laser experiments, we employed the (Tm_{0.05}Y_{0.698}Sc_{0.252})₂O₃ and (Tm_{0.05}Y_{0.95})₂O₃ ceramics. The laser elements were cut from the central part of the ceramic disks, they were double-side polished to laser-grade quality with good parallelism and left uncoated. They were fixed on a passively cooled Cu-holder using a silver paint. A hemispherical cavity was formed by a flat pump mirror (PM) coated for high transmission (HT, $T = 78.7\%$) at 0.81 μm and high reflection (HR, $R > 99.9\%$) at 1.86 – 2.33 μm and a concave (radius of curvature: -100 mm) output coupler (OC) with a transmission T_{OC} in the range of 0.2% - 3.5% at the laser wavelength. The total cavity length was 102 mm. The laser element was placed near the PM with an airgap of <1 mm. The pump source was a Ti:Sapphire laser (3900S, Spectra Physics) delivering up to 4.0 W at 811 nm with a nearly diffraction limited beam ($M^2 \sim 1$). The pump radiation was focused into the ceramic through the PM using an AR-coated aspherical lens ($f = 75 \text{ mm}$). The pump spot diameter in the focus was 50±10 μm . The pumping was in double-pass due to a back-reflection from the OCs at the pump wavelength ($R \sim 80\%$). For the (Tm_{0.05}Y_{0.95})₂O₃ ceramic and the optimum $T_{\text{OC}} = 3.5\%$, the total pump absorption under lasing conditions was 51.0% representing

certain ground-state (³H₆) bleaching. The radius of the laser mode in the ceramic was calculated using the ABCD method accounting for the thermal lens in Tm:Y₂O₃, $w_L = 57 \pm 5 \mu\text{m}$, indicating a good mode-matching. The spectra of laser emission were measured using an optical spectrum analyzer (Yokogawa, AQ6376).

The (Tm_{0.05}Y_{0.95})₂O₃ ceramic delivered a maximum output power of 812 mW with a high slope efficiency η of 70.2% (vs. the absorbed pump power) for $T_{\text{OC}} = 3.5\%$, Fig. 6(a). With increasing the output coupling, the laser threshold gradually increased from 90 mW ($T_{\text{OC}} = 0.2\%$) to 393 mW ($T_{\text{OC}} = 3.5\%$). The emission wavelength experienced a slight blue-shift with increasing the output coupling, from 2061–2085 nm ($T_{\text{OC}} = 0.2\%$) to 2048–2063 nm ($T_{\text{OC}} = 3.5\%$) owing to the quasi-three-level nature of the ³F₄ → ³H₆ transition with reabsorption, Fig. 6(c). The obtained laser slope efficiency exceeds the Stokes limit, $\eta_{\text{StL}} = \lambda_P / \lambda_L = 39.6\%$, owing to an efficient CR among adjacent Tm³⁺ ions. After Loiko *et al.* [1], for 5 at.% Tm³⁺ doping in Y₂O₃, the quantum efficiency of excitation into the ³F₄ manifold is $\eta_q = 1.97 \pm 0.03$ (almost ideal one-to-two process). The upper limit for the slope efficiency is then [2] $\eta < \eta_{\text{StL}} \eta_q \eta_{\text{mode}} \eta_{\text{OC}} = 69 \pm 3\%$, where $\eta_{\text{OC}} = \ln[1 - T_{\text{OC}}] / \ln[(1 - T_{\text{OC}})(1 - L)] = 87 \pm 3\%$ is the output-coupling efficiency (L is the round-trip passive loss, see below) and $\eta_{\text{mode}} \approx 1$ is the mode-matching one.

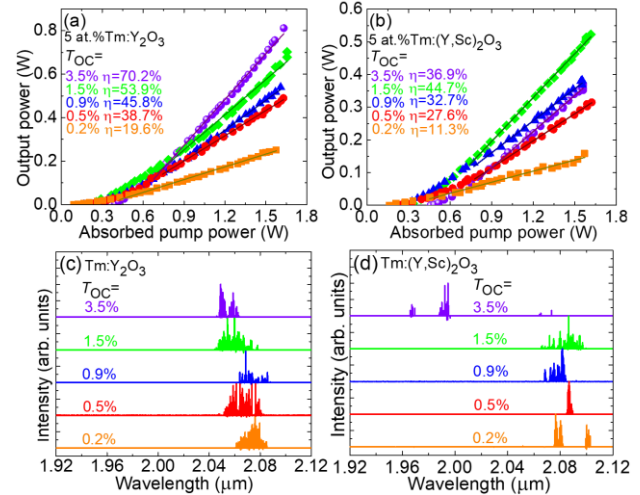


Fig. 6. ~2 μm laser performance of (a,c) (Tm_{0.05}Y_{0.95})₂O₃ and (b,d) (Tm_{0.05}Y_{0.698}Sc_{0.252})₂O₃ ceramics: (a,b) input-output dependences, η – slope efficiency; (c,d) typical spectra of laser emission.

For the yttria-scandia (Tm_{0.05}Y_{0.698}Sc_{0.252})₂O₃ ceramic, the laser generated 523 mW at 2065 – 2097 nm with a lower η of 44.7% and a laser threshold of 275 mW (for $T_{\text{OC}} = 1.5\%$), Fig. 6(c). The laser threshold was in the range 165 – 484 mW for output coupler transmissions between 0.3% and 3.5%. The lower slope efficiency for the Sc-containing ceramic is related to higher passive losses caused by the residual porosity. The laser emission spectra for the “mixed” ceramic are shown in Fig. 6(d). For $T_{\text{OC}} \leq 1.5\%$, the laser operated at 2.08 μm and for higher output coupling, additional lines at 1.96 and 1.99 μm appeared. This behavior agrees with the gain spectra for increased inversion ratios, cf. Fig. 4(d). A clear red-shift of the laser wavelength due to the Sc³⁺ effect on the emission spectra was observed.

The round-trip passive losses in the ceramics were evaluated using the Findlay-Clay analysis [19] by plotting the laser threshold

P_{th} versus $\ln(1/R_{oc})$ where $R_{oc} = 1 - T_{oc}$ is the output coupler reflectivity, Fig. 7. This analysis yielded $L = 0.5 \pm 0.2\%$ and $1.5 \pm 0.3\%$ for the yttria and yttria-scandia ceramics, respectively. The increase in the passive losses for the Sc-containing ceramic agrees with the higher content of pores for this material.

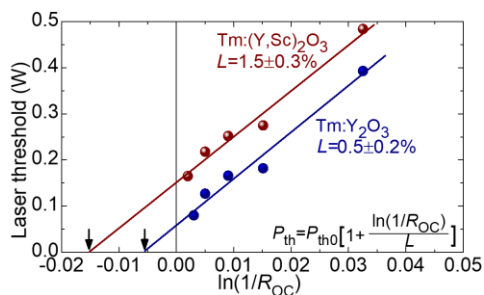


Fig. 7. The Findlay-Clay analysis for estimating the round-trip passive loss L for $(Tm_{0.05}Y_{0.95})_2O_3$ and $(Tm_{0.05}Y_{0.698}Sc_{0.252})_2O_3$ ceramics.

Suzuki *et al.* studied $(Tm_{0.031}Y_{0.474}Sc_{0.495})_2O_3$ single-crystals grown by the Czochralski method at a reduced temperature of 2100 °C. Under diode-pumping at 780 nm, an output power of 422 mW was generated at 2.11 μm with $\eta = 45\%$ [20]. Jing *et al.* reported on a diode-pumped $(Tm_{0.048}Lu_{0.635}Sc_{0.317})_2O_3$ ceramic laser delivering 1.01 W at 2.10 μm with lower $\eta = 24\%$ [12]. Pirri *et al.* reported on a quasi-CW diode-pumped $(Tm_{0.05}Sc_{0.252}Y_{0.698})_2O_3$ ceramic laser generating 1.24 W at 2.08 μm with lower $\eta = 9.5\%$ [21]. Our results for the $Tm:(Y,Sc)_2O_3$ ceramic in terms of laser slope efficiency are superior to all previously studied Tm^{3+} -doped “mixed” sesquioxide ceramics and close to the best results for single-crystals.

The best result for the parent $Tm:Y_2O_3$ ceramic was achieved by Wang *et al.*: a diode-pumped $(Tm_{0.02}Y_{0.98})_2O_3$ laser generated 7.25 W at 2.05 μm with $\eta = 40\%$ [13]. The slope efficiency achieved in this work with the $Tm:Y_2O_3$ ceramic is close to the best results reported for single-crystalline Tm^{3+} -doped sesquioxides [1,22].

To conclude, we report on highly-efficient $\sim 2 \mu m$ laser operation of $Tm:Y_2O_3$ and $Tm:(Y,Sc)_2O_3$ transparent sesquioxide ceramics. For the both parent and solid-solution ceramics, the achieved laser slope efficiencies (70.2% and 44.7%) represent record-high values for any Tm^{3+} -doped sesquioxide ceramics being comparable with the best results for the corresponding single-crystals. It is due to an efficient cross-relaxation under high Tm^{3+} doping level (5 at.%) and relatively low passive losses even for “mixed” compounds owing to an optimized synthesis procedure involving $Tm:(Y_{1-x}Sc_x)_2O_3$ laser-ablated nanoparticles with a mixture of cations at the atomic level and ZrO_2 as a grain growth inhibitor. The high thermal conductivity of ceramics paves the way towards power scaling under pumping by AlGaAs laser diodes at 0.8 μm or Raman-shifted Erbium fiber lasers at 1.68 μm (in-band pumping). The laser efficiency for “mixed” ceramics could be improved by reducing their residual porosity through optimization of the processing conditions and purification of the Sc_2O_3 raw powder. The solid-solution $Tm:(Y,Sc)_2O_3$ ceramics feature inhomogeneously broadened emission spectra extending up to 2.3 μm making them promising for sub-100 fs pulse generation from SESAM or Kerr-lens mode-locked lasers.

Funding. Agence Nationale de la Recherche (ANR-19-CE08-0028); Région Normandie (Chaire d’excellence “RELANCE”); Fonds Européen de Développement Régional (FEDER); Contrat de Plan

État-Région (CPER) de Normandie; RFBR (21-53-15014); Ministry of Science and Higher Education of the Russian Federation (RF-2296.61321X0029, agreement 075-15-2021-687; Ural Federal University Program of Development Priority-2030).

Acknowledgements. The thermal properties were studied at the Center for Collective Use of the North-Caucasus Federal University.

Disclosures. The authors declare no conflicts of interest.

Data availability. Data underlying the results presented in this paper are not publicly available at this time but may be obtained from the authors upon reasonable request.

References

- P. Loiko, P. Koopmann, X. Mateos, J. M. Serres, V. Jambunathan, A. Lucianetti, T. Mocek, M. Aguiló, F. Díaz, U. Griebner, V. Petrov, and C. Kränkel, *IEEE J. Sel. Top. Quantum Electron.* **24**, 1600713 (2018).
- K. van Dalen, S. Aravazhi, C. Grivas, S. M. García-Blanco, and M. Pollnau, *Opt. Lett.* **39**, 4380 (2014).
- R. P. Leavitt, J. B. Gruber, N. C. Chang, and C. A. Morrison, *J. Chem. Phys.* **76**, 4775 (1982).
- A. Suzuki, C. Kränkel, and M. Tokurakawa, *Opt. Express* **29**, 19465 (2021).
- Y. Zhao, L. Wang, Y. Wang, J. Zhang, P. Liu, X. Xu, Y. Liu, D. Shen, J. E. Bae, T. G. Park, F. Rotermund, X. Mateos, P. Loiko, Z. Wang, X. Xu, J. Xu, M. Mero, U. Griebner, V. Petrov, and W. Chen, *Opt. Lett.* **45**, 459 (2020).
- O. L. Antipov, A. A. Novikov, N. G. Zakharov, and A. P. Zinov’ev, *Opt. Mater. Express* **2**, 183 (2012).
- O. Antipov, A. Novikov, S. Larin, and I. Obronov, *Opt. Lett.* **41**, 2298 (2016).
- L. Fornasiero, E. Mix, V. Peters, K. Petermann, and G. Huber, *Ceram. Int.* **26**, 589 (2000).
- J. Lu, J. F. Bisson, K. Takaichi, T. Uematsu, A. Shirakawa, M. Musha, K. Ueda, H. Yagi, T. Yanagitani, and A. A. Kaminskii, *Appl. Phys. Lett.* **83**, 1101 (2003).
- J. Lu, K. Takaichi, T. Uematsu, A. Shirakawa, M. Musha, K. I. Ueda, H. Yagi, T. Yanagitani, and A. A. Kaminskii, *Jpn. J. Appl. Phys.* **41**, L1373 (2002).
- Z. Zhou, X. Guan, X. Huang, B. Xu, H. Xu, Z. Cai, X. Xu, P. Liu, D. Li, J. Zhang, and J. Xu, *Opt. Lett.* **42**, 3781 (2017).
- W. Jing, P. Loiko, J. Maria Serres, Y. Wang, E. Vilejshikova, M. Aguiló, F. Díaz, U. Griebner, H. Huang, V. Petrov, and X. Mateos, *Opt. Mater. Express* **7**, 4192 (2017).
- H. Wang, H. Huang, P. Liu, L. Jin, D. Shen, J. Zhang, and D. Tang, *Opt. Mater. Express* **7**, 296 (2017).
- Y. Wang, W. Jing, P. Loiko, Y. Zhao, H. Huang, X. Mateos, S. Suomalainen, A. Härkönen, M. Guina, U. Griebner, and V. Petrov, *Opt. Express* **26**, 10299 (2018).
- V. V. Osipov, V. V. Platonov, V. V. Lisenkov, A. V. Podkin, and E. E. Zakharova, *Phys. Status Solidi C* **10**, 926 (2013).
- P. Loiko, L. Basyrova, R. Maksimov, V. Shitov, M. Baranov, F. Starecki, X. Mateos, and P. Camy, *J. Lumin.* **240**, 118460 (2021).
- L. Zhang, W. Pan, and J. Feng, *J. Eur. Ceram. Soc.* **35**, 2547 (2015).
- R. Gaumé, B. Viana, D. Vivien, J. P. Roger, and D. Fournier, *Appl. Phys. Lett.* **83**, 1355 (2003).
- J. A. Caird, S. A. Payne, P. Staber, A. Ramponi, L. Chase, and W. F. Krupke, *IEEE J. Quantum Electron.* **24**, 1077 (1988).
- A. Suzuki, S. Kalusniak, H. Tanaka, M. Brützmam, S. Ganschow, M. Tokurakawa, and C. Kränkel, *Opt. Express* **30**, 42762 (2022).
- A. Pirri, R.N. Maksimov, V.A. Shitov, V.V. Osipov, E. Sani, B. Patrizi, M. Vannini, and G. Toci, *J. Alloys Compd.* **889**, 161585 (2021).
- P. Koopmann, R. Peters, K. Petermann, and G. Huber, *Appl. Phys. B* **102**, 19 (2011).

Full references

1. P. Loiko, P. Koopmann, X. Mateos, J. M. Serres, V. Jambunathan, A. Lucianetti, T. Mocek, M. Aguiló, F. Díaz, U. Griebner, V. Petrov, and C. Kränkel, "Highly-efficient, compact Tm³⁺:RE₂O₃ (RE = Y, Lu, Sc) sesquioxide lasers based on thermal guiding," *IEEE J. Sel. Top. Quantum Electron.* **24**(5), 1600713-1-13 (2018).
2. K. van Dalfsen, S. Aravazhi, C. Grivas, S. M. García-Blanco, and M. Pollnau, "Thulium channel waveguide laser with 1.6 W of output power and ~80% slope efficiency," *Opt. Lett.* **39**(15), 4380-4383 (2014).
3. R. P. Leavitt, J. B. Gruber, N. C. Chang, and C. A. Morrison, "Optical spectra, energy levels, and crystal-field analysis of tripositive rare-earth ions in Y₂O₃. II. Non-Kramers ions in C₂ sites," *J. Chem. Phys.* **76**(10), 4775-4788 (1982).
4. A. Suzuki, C. Kränkel, and M. Tokurakawa, "Sub-6 optical-cycle Kerr-lens mode-locked Tm:Lu₂O₃ and Tm:Sc₂O₃ combined gain media laser at 2.1 μm," *Opt. Express* **29**(13), 19465-19471 (2021).
5. Y. Zhao, L. Wang, Y. Wang, J. Zhang, P. Liu, X. Xu, Y. Liu, D. Shen, J. E. Bae, T. G. Park, F. Rotermond, X. Mateos, P. Loiko, Z. Wang, X. Xu, J. Xu, M. Mero, U. Griebner, V. Petrov, and W. Chen, "SWCNT-SA mode-locked Tm:LuYO₃ ceramic laser delivering 8-optical-cycle pulses at 2.05 μm," *Opt. Lett.* **45**(2), 459-462 (2020).
6. O. L. Antipov, A. A. Novikov, N. G. Zakharov, and A. P. Zinov'ev, "Optical properties and efficient laser oscillation at 2066 nm of novel Tm:Lu₂O₃ ceramics," *Opt. Mater. Express* **2**(2), 183-189 (2012).
7. O. Antipov, A. Novikov, S. Larin, and I. Obronov, "Highly efficient 2 μm CW and Q-switched Tm³⁺:Lu₂O₃ ceramics lasers in-band pumped by a Raman-shifted erbium fiber laser at 1670 nm," *Opt. Lett.* **41**(10), 2298-2301 (2016).
8. L. Fornasiero, E. Mix, V. Peters, K. Petermann, and G. Huber, "Czochralski growth and laser parameters of RE³⁺-doped Y₂O₃ and Sc₂O₃," *Ceram. Int.* **26**(6), 589-592 (2000).
9. J. Lu, J. F. Bisson, K. Takaichi, T. Uematsu, A. Shirakawa, M. Musha, K. Ueda, H. Yagi, T. Yanagitani, and A. A. Kaminskii, "Yb³⁺:Sc₂O₃ ceramic laser," *Appl. Phys. Lett.* **83**(6), 1101-1103 (2003).
10. J. Lu, K. Takaichi, T. Uematsu, A. Shirakawa, M. Musha, K. I. Ueda, H. Yagi, T. Yanagitani, and A. A. Kaminskii, "Yb³⁺:Y₂O₃ ceramics – a novel solid-state laser material," *Jpn. J. Appl. Phys.* **41**(12A), L1373-L1375 (2002).
11. Z. Zhou, X. Guan, X. Huang, B. Xu, H. Xu, Z. Cai, X. Xu, P. Liu, D. Li, J. Zhang, and J. Xu, "Tm³⁺-doped LuYO₃ mixed sesquioxide ceramic laser: effective 2.05 μm source operating in continuous-wave and passive Q-switching regimes," *Opt. Lett.* **42**(19), 3781-3784 (2017).
12. W. Jing, P. Loiko, J. Maria Serres, Y. Wang, E. Vilejshikova, M. Aguiló, F. Díaz, U. Griebner, H. Huang, V. Petrov, and X. Mateos, "Synthesis, spectroscopy, and efficient laser operation of "mixed" sesquioxide Tm:(Lu,Sc)₂O₃ transparent ceramics," *Opt. Mater. Express* **7**(11), 4192-4202 (2017).
13. H. Wang, H. Huang, P. Liu, L. Jin, D. Shen, J. Zhang, and D. Tang, "Diode-pumped continuous-wave and Q-switched Tm:Y₂O₃ ceramic laser around 2050 nm," *Opt. Mater. Express* **7**(2), 296-303 (2017).
14. Y. Wang, W. Jing, P. Loiko, Y. Zhao, H. Huang, X. Mateos, S. Suomalainen, A. Härkönen, M. Guina, U. Griebner, and V. Petrov, "Sub-10 optical-cycle passively mode-locked Tm:(Lu_{2/3}Sc_{1/3})₂O₃ ceramic laser at 2 μm," *Opt. Express* **26**(8), 10299-10304 (2018).
15. V. V. Osipov, V. V. Platonov, V. V. Lisenkov, A. V. Podkin, and E. E. Zakharova, "Production of nanopowders of oxides by means of fiber and pulse-periodical CO₂ lasers," *Phys. Status Solidi C* **10**(6), 926-932 (2013).
16. P. Loiko, L. Basyrova, R. Maksimov, V. Shitov, M. Baranov, F. Starecki, X. Mateos, and P. Camy, "Comparative study of Ho:Y₂O₃ and Ho:Y₃Al₅O₁₂ transparent ceramics produced from laser-ablated nanoparticles," *J. Lumin.* **240**, 118460-1-22 (2021).
17. L. Zhang, W. Pan, and J. Feng, "Dependence of spectroscopic and thermal properties on concentration and temperature for Yb:Y₂O₃ transparent ceramics," *J. Eur. Ceram. Soc.* **35**(9), 2547-2554 (2015).
18. R. Gaumé, B. Viana, D. Vivien, J. P. Roger, and D. Fournier, "A simple model for the prediction of thermal conductivity in pure and doped insulating crystals," *Appl. Phys. Lett.* **83**(7), 1355-1357 (2003).
19. J. A. Caird, S. A. Payne, P. Staber, A. Ramponi, L. Chase, and W. F. Krupke, "Quantum electronic-properties of the Na₃Ga₂Li₃F₁₂:Cr³⁺ laser," *IEEE J. Quantum Electron.* **24**(6), 1077-1099 (1988).
20. A. Suzuki, S. Kalusniak, H. Tanaka, M. Brützmam, S. Ganschow, M. Tokurakawa, and C. Kränkel, "Spectroscopy and 2.1 μm laser operation of Czochralski-grown Tm³⁺:YScO₃ crystals," *Opt. Express* **30**(23), 42762-42771 (2022).
21. A. Pirri, R.N. Maksimov, V.A. Shitov, V.V. Osipov, E. Sani, B. Patrizi, M. Vannini, and G. Toci, "Continuously tuned (Tm_{0.05}Sc_{0.252}Y_{0.698})₂O₃ ceramic laser with emission peak at 2076 nm," *J. Alloys Compd.* **889**, 161585 (2021).
22. P. Koopmann, R. Peters, K. Petermann, and G. Huber, "Crystal growth, spectroscopy, and highly efficient laser operation of thulium-doped Lu₂O₃ around 2 μm," *Appl. Phys. B* **102**(1), 19-24 (2011).