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Liza Basyrova, Pavel Loiko, Wei Jing, Yicheng Wang, Hui Huang, et al.. Spectroscopy and efficient laser operation around 2.8 $\mu$m of Er:(Lu,Sc)2O3 sesquioxide ceramics. Journal of Luminescence, 2021, 240, pp.118373. 10.1016/j.jlumin.2021.118373 . hal-03345626

**HAL Id: hal-03345626**
**https://hal.science/hal-03345626**

Submitted on 18 Nov 2022

# Spectroscopy and efficient ~2.8 μm laser operation of $Er:(Lu,Sc)_2O_3$ sesquioxide ceramics

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**Abstract:** A transparent "mixed" 7 at.% $Er:(Lu,Sc)_2O_3$ sesquioxide ceramic was fabricated by hot isostatic pressing of commercial sesquioxide powders at 1750 °C / 200 MPa in argon atmosphere. It exhibited a cubic bixbyite-type structure ($a$ = 10.198 Å), a mean grain size of 5.7 μm and high low-signal transmission of 79.1% in the near-IR. The spectroscopic properties of $Er^{3+}$ ions were studied. For the $^4I_{11/2} \rightarrow {}^4I_{13/2}$ transition, the stimulated-emission cross-section $\sigma_{SE}$ is $1.30\times10^{-20}$ cm$^2$ at 2719 nm, the corresponding luminescence branching ratio $B(JJ')$ is 19.9% and the radiative lifetime of the $^4I_{11/2}$ state is 4.80 ms, as determined using a Judd-Ofelt theory accounting for intermediate configuration interaction. The crystal-field splitting of $Er^{3+}$ multiplets was studied at 12 K. The ceramic exhibits a significant inhomogeneous broadening of spectral bands. An $Er:(Lu,Sc)_2O_3$ ceramic laser generated 342 mW at 2.71 and 2.85 μm with a high slope efficiency of 41.7% (exceeding the Stokes limit) and a laser threshold of 125 mW.

**Keywords:** transparent ceramics; sesquioxides; erbium ion; luminescence; laser operation.

## 1. Introduction

The research on mid-infrared (MIR) lasers emitting around ~2.8 μm is stimulated by their applications in medicine, especially in surgery [1,2]. Such radiation spectrally overlaps with the strong absorption of water vapors and liquid water; the corresponding short penetration depth in bio-tissues (few μm) enables precise incisions.

One of the most common ways to generate ~2.8 μm radiation is to use erbium ($Er^{3+}$) doped materials according to the $^4I_{11/2} \rightarrow {}^4I_{13/2}$ electronic transition [3,4]. The upper laser level lifetime for this transition is typically shorter than that of the lower laser level (a self-terminating transition). Still, continuous-wave (CW) laser action at ~2.8 μm can be achieved in certain $Er^{3+}$-doped materials due to the energy-transfer upconversion (ETU) process for adjacent ions, $^4I_{13/2} + {}^4I_{13/2} \rightarrow {}^4I_{15/2} + {}^4I_{11/2}$, depleting the lower laser manifold and refilling the upper one [5,6]. As a result, laser slope efficiencies exceeding the Stokes limit can be achieved owing to the energy recycling via ETU [7]. This dictates the need of high $Er^{3+}$ doping concentrations promoting efficient ETU. Another argument for the material selection is the low phonon energy of the host matrix providing favorable ratios of upper-state to lower-state ($^4I_{11/2}$ to $^4I_{13/2}$) lifetimes by reducing the multi-phonon non-radiative relaxation.

So far, cubic sesquioxides $A_2O_3$ (where A stands for Y, Sc, Lu or their combination) were found to be very suitable for $Er^{3+}$ doping with the aim of ~2.8 μm laser operation [8]. These crystals provide good thermal properties such as high thermal conductivity with weak concentration-dependence ($\kappa$ ~10.7 $Wm^{-1}K^{-1}$ for ~7 at.% $Er:Lu_2O_3$ [9]) and positive thermo-optic coefficients [10], low phonon energies (the most intense phonon mode of $Lu_2O_3$ is 393 $cm^{-1}$ [11]) and easy doping with $Er^{3+}$ ions in high concentrations. In addition, sesquioxides provide high crystal-field strength resulting in large total Stark splitting of the $^4I_{13/2}$ multiplet leading to broadband emission properties [12]. Using a high-brightness pump source (an optically pumped semiconductor laser), Li *et al.* achieved an output power of 1.4 W at ~2.85 μm from an $Er:Lu_2O_3$ single-crystal laser operating with a slope efficiency as high as 36%, while using a laser diode, the output was scaled up to 5.9 W at the expense of lower slope efficiency [9].

The growth of $A_2O_3$ single crystals is complicated because of their high melting temperatures (2450 °C for $Lu_2O_3$). In the most developed heat exchanger growth method (HEM), the use of rhenium (Re) crucibles frequently results in uncontrolled Re impurities and coloration of crystals [13]. On the other hand, cubic sesquioxides are very suitable for the technology of transparent polycrystalline ceramics [14-16]. Their advantages include: (i) lower synthesis temperatures (<1800 °C, depending on the method), (ii) well-preserved spectroscopic and thermal properties, (iii) easier fabrication of solid solution compositions $(A_{1-x}B_x)_2O_3$ [17,18], (iv) well-controlled doping at high levels and (v) size-scalable production. The main challenge is reaching low optical losses and good homogeneity.

So far ~2.8 μm emission from $Er^{3+}$ sesquioxide lasers based on $Lu_2O_3$ [19-21] and $Y_2O_3$ [22-24] ceramics has been studied. Very recently, Yao *et al.* reported on a diode-pumped $Er:Lu_2O_3$ ceramic laser delivering 6.7 W at 2845 nm with a slope efficiency of 30.2%, representing record-high results in terms of output power and efficiency obtained so far [19]. $Er^{3+}$-doped $Sc_2O_3$ transparent ceramics have been also synthesized [25,26].

It is interesting to study the suitability of “mixed” sesquioxide ceramics $(A_{1-x}B_x)_2O_3$ for $Er^{3+}$ doping with the aim of obtaining ~2.8 μm laser emission. The use of solid-solution host matrix will promote inhomogeneous broadening of the spectral bands which is of interest for mode-locked lasers. Among the $(A_{1-x}B_x)_2O_3$ compositions, the system $Lu_2O_3$ – $Sc_2O_3$ looks attractive because of the difference in ionic radii of the host-forming cations, $Lu^{3+}$ and $Sc^{3+}$, and the difference of the crystal-field strengths for these two “parent” compounds [27]. Transparent “mixed” $(Lu,Sc)_2O_3$ ceramics doped with $Tm^{3+}$ and $Ho^{3+}$ ions for laser emission at ~2 μm were studied recently [18,28]. A mode-locked $Tm:(Lu,Sc)_2O_3$ ceramic laser generated ultrashort (63 fs) pulses at 2057 nm [29] owing to the broadband gain properties of this material [18].

In the present work, we report on the synthesis, spectroscopic characterization and first ~2.8 μm laser operation of a "mixed" ceramic in the $(Lu,Sc)_2O_3$ system doped with $Er^{3+}$ ions.

## 2. Fabrication of the laser ceramics

As starting materials, we used commercial oxide powders of $Er_2O_3$ (purity: 99.99%), $Lu_2O_3$ and $Sc_2O_3$ (purity: 99.999%). First, they were thoroughly mixed following the formula $(Er_{0.07}Lu_{0.78}Sc_{0.15})_2O_3$. The mixture was ball milled for 24 h in $ZrO_2$ jars at a speed of 200 rev/min. The slurry was dried at 80 °C for 24 h and the powders were sifted using a 200-mesh screen and further calcinated at a temperature of 200 °C for 12 h. The green ceramic sample was dry pressed into a disk by applying a uniaxial pressure of 20 MPa, and cold isostatically pressed at 200 MPa to increase the density of the material. Before densification sintering, the samples were calcined at a temperature of 900 °C for 10 h in order to remove residual carbon and organic impurities. Then, the $Er:(Lu,Sc)_2O_3$ disk was subjected to vacuum sintering at a temperature of 1750 °C followed by hot isostatic pressing (HIPing) at 1750 °C and 200 MPa in argon atmosphere for 2 h. The obtained ceramic was annealed at 1400 °C for 12 h in air which removed oxygen vacancies and improved its transparency. Finally, the ceramic disk was polished from both sides.

A photograph of annealed and polished ceramic elements is shown in Fig. 1. The ceramic was transparent with rose coloration due to the $Er^{3+}$ doping.

## 3. Experimental

The phase composition of the ceramic was identified by X-ray powder diffraction (XRD) using Cu Kα radiation (1.54060 Å) at 40 kV and 30 mA and a DX–1000CSC diffractometer (Tongda Co. Ltd). The diffractogram was measured for 2θ angles in the range from 10° to 80° with a scan speed of 1.2°/min and a step size of 0.02 . The microstructure of the polished ceramic surface was studied with a scanning electron microscope (SEM) MERLIN (Carl Zeiss). The grain size distribution was determined by direct counting method (for >100 grains) in the ImageJ software (the shape factor of 1.2 was applied).

The transmission spectrum of the ceramic was measured using a spectrophotometer (Lambda 1050, Perkin Elmer); the resolution (spectral bandwidth, SBW) was 0.25 nm in the visible and 0.7 nm in the near-IR. The luminescence spectrum at 1.4-1.8 μm was measured using an optical spectrum analyzer (AQ6375B, Yokogawa) with SBW = 0.5 nm, while the measurement at 2.5–3.1 μm was performed using a 0.6 m monochromator (HRS2, Jobin-Yvon), a lock-in amplifier (SR810 DSP, Stanford Research Systems) and an InSb detector (J10D series, Judson Infrared) cooled by liquid nitrogen with SBW = 4 nm. To reduce the effect of water vapor absorption, the monochromator was purged by nitrogen. The system was calibrated using a Hg lamp (Schwabe). As an excitation source, a Ti:Sapphire laser tuned to 804 nm was used.

For low-temperature (LT, 12 K) studies, the sample was mounted on an APD DE-202 closed-cycle cryo-cooler equipped with an APD HC 2 Helium vacuum cryo-compressor and a Laceshore 330 temperature controller.

The luminescence decay curves were measured using a nanosecond optical parametric oscillator (OPO, Horizon, Continuum), a 1/4 m monochomator (Oriel 77200), an InGaAs detector and an 8 GHz digital oscilloscope (DSA70804B, Tektronix).

## 4. Characterization of the ceramics

### *4.1. Structural study*

The phase purity of the ceramic was studied by XRD, Fig. 2. In the measured XRD pattern, only one phase was identified, namely, the cubic (sp. gr. $Ia\bar{3}$ - $T^7_h$, No. 206) sesquioxide phase with the so-called C-type or bixbyite-type structure [30] (bixbyite is a manganese iron oxide mineral with chemical formula $(Mn,Fe)_2O_3$). The diffraction peaks for the ceramic are located between those for undoped $Lu_2O_3$ (ICDD card #76-0162) and $Sc_2O_3$ (ICDD card # 84-1880). Accordingly, the lattice constant of the ceramic $a$ = 10.198 Å, occupies an intermediate position between those of $Lu_2O_3$ ($a$ = 10.391 Å) and $Sc_2O_3$ ($a$ = 9.857 Å) [8]. Note that a cubic stoichiometric $Er_2O_3$ phase also exists ($a$ = 10.55 Å) [31]. In the bixbyite structure, there are two rare-earth sites with the local symmetries of $C_2$ and $C_{3i}$. Both correspond to VI-fold coordination by oxygen ($O^{2-}$). In the sesquioxide unit-cell, there is a total of 32 cationic positions: 24 (3/4) correspond to the $C_2$ sites and 8 (1/4) - to the $C_{3i}$ ones. Thus, for an ideal "parent" sesquioxide (e.g., $Lu_2O_3$) one may expect that the dopant ions approximately follow the same distribution. This rule is however expected to be violated in "mixed" materials due to the difference of ionic radii of the host-forming cations ($Lu^{3+}$ (0.861 Å) and $Sc^{3+}$ (0.745 Å) [32], in our case), and the dopant ions ($Er^{3+}$ (0.890 Å) [32], in our case). Indeed, one may expect that $Er^{3+}$ ions will tend to replace predominantly the $Lu^{3+}$ ones which are closer in ionic radii. The differences in the second coordination sphere of $Er^{3+}$ ions will induce the inhomogeneous broadening of their spectral bands.

A typical SEM image of the polished surface of the $Er:(Lu,Sc)_2O_3$ ceramic is shown in Fig. 3(a). It reveals a close-packed microstructure with clean grain boundaries, a lack of secondary phases and a low concentration of µm-sized pores. The corresponding grain size distribution is shown in the inset of Fig. 3(b). The mean grain size is 5.7 µm. An environmental SEM image of a fracture surface of ceramic is presented in Fig. 3(b). It becomes evident that the intragranular fracture mechanism dominates for the ceramic.

### *4.2. Transmission and absorption*

The transmission spectrum of the polished ceramic sample (thickness: $t$ = 1.0 mm) is shown in Fig. 4. The spectrum is dominated by absorption bands of the $Er^{3+}$ ion. The UV absorption edge is at 0.25 µm. At a wavelength of 1.2 µm (out of $Er^{3+}$ absorption), the measured transmission, $T$ = 79.1% is close to the theoretical value determined by Fresnel losses and accounting for multiple reflections, $T_0 = 2n/(n^2 + 1)$, namely 82.0% (calculated assuming a linear variation of the reflective index in the $Lu_2O_3$ – $Sc_2O_3$ solid solution [33] yielding a value of $n$ = 1.916).

The absorption coefficient was calculated as $\alpha_{abs} = -\ln(T/T_0)/t$. The absorption spectra are shown in Fig. 5. The electronic configuration of $Er^{3+}$ is [Xe]$4f^{11}$. The observed absorption bands are due to the transitions of $Er^{3+}$ ions from the ground-state ($^4I_{15/2}$) to excited-states from $^4I_{13/2}$ to $^4D_{7/2}+^2D_{5/2}$. Here, the assignment is after [34]. The absorption cross-sections were calculated as $\sigma_{abs} = \alpha_{abs}/N_{Er}$, where $N_{Er}$ is the $Er^{3+}$ ion density ($20.0\times10^{20}$ $cm^{-3}$). It should be pointed out, that the spectroscopic properties of cubic sesquioxides are mainly determined by dopant ions residing in $C_2$ sites. For the $C_{3i}$ sites, the electric dipole (ED) transitions are forbidden due to the local inversion symmetry and only magnetic dipole (MD) transitions (with $\Delta J = J - J' = 0, \pm1$, except of $0 \leftrightarrow 0'$) are allowed. There exists an approach to calculate $\sigma_{abs}$ for sesquioxides assuming (3/4) of the dopant ions are residing in the $C_2$ sites. As explained above, this approach is not correct for a "mixed" material, in addition, for certain $Er^{3+}$ transitions, the MD contribution may be significant. Thus, we consider $\sigma_{abs}$ as "effective" cross-section.

For the $^4I_{15/2} \rightarrow {}^4I_{13/2}$ transition (which corresponds to in-band pumping for 1.6 µm lasers and terminal level pumping for ~2.8 µm lasers), the maximum $\sigma_{abs}$ is $1.76\times10^{-20}$ $cm^2$ at 1535 nm and the absorption bandwidth is 3.8 nm (full width at half maximum, FWHM).

For the $^4I_{15/2} \rightarrow {}^4I_{11/2}$ one (upper laser level pumping for ~2.8 μm lasers), $\sigma_{abs}$ is $0.24\times10^{-20}$ $cm^2$ at 980.6 nm.

*4.3. Judd-Ofelt analysis*

The transition intensities of the $Er^{3+}$ ion in $(Lu,Sc)_2O_3$ ceramic were analyzed using the Judd-Ofelt (J-O) formalism. More precisely, it was applied to ED contributions to transition intensities. The MD contributions were calculated separately within the Russell–Saunders approximation on wave functions of $Er^{3+}$ assuming a free-ion and considering the refractive index of the host matrix. The set of reduced squared matrix elements $U^{(k)}$ in absorption and emission was calculated using the free-ion parameters from [35]. The dispersion curves for sesquioxides were taken from [33]. The details about the calculation procedure can be found elsewhere. Here, we only discuss the used approximations.

In the standard J-O theory, the ED line strengths of the J → J' transitions $S^{ED}(JJ')$ are given by [36,37]:

$$S^{ED}_{calc}(JJ') = \sum_{k=2,4,6} U^{(k)}\Omega_k, \tag{1a}$$

$$U^{(k)} = \langle(4f^n)SLJ\|U^k\|(4f^n)S'L'J'\rangle^2 . \tag{1b}$$

Here, $U^{(k)}$ are the reduced squared matrix elements and $\Omega_k$ are the J–O parameters (or, more generally, intensity parameters). For both, $k$ = 2, 4 and 6.

For many rare-earth ions, better agreement between the experimental and calculated line strengths is achieved by accounting for configuration interaction, e.g., with the excited configuration of the opposite parity $[Xe]4f^{n-1}5d^1 = [Xe]4f^{10}5d^1$. In the case of an intermediate configuration interaction (ICI), the ED line strengths are given by [29,30]:

$$\langle S^{ED}_{calc}\rangle(JJ') = \sum_{k=2,4,6} U^{(k)}\tilde{\Omega}_k , \tag{2}$$

where $\tilde{\Omega}_k$ are the linear functions of the energies of the two multiplets ($E_J$ and $E_{J'}$) involved in the transition:

$$\tilde{\Omega}_k = \Omega_k[1+2R_k(E_J+E_{J'}-2E^0_f)], \tag{3}$$

$\Omega_k$ are new intensity parameters, $R_k$ are the parameters representing the configuration interaction and $E_f^0$ is the mean energy of the $[Xe]4f^n = [Xe]4f^{11}$ configuration. In the ICI model, there are 6 free parameters, namely $\Omega_k$ and $R_k$ ($k$ = 2, 4, 6). Assuming higher-lying excited-configurations ($R_k \rightarrow 0$), leads to $\tilde{\Omega}_k = \Omega_k$ (the standard J-O theory).

In the standard J-O theory, only the excited configurations of the opposite parity are considered and it is assumed that both the $[Xe]4f^n$ configuration and the excited ones are completely degenerated. Because of this assumption, the set of $\Omega_k$ parameters is the same for all transitions. In reality, the energy gap to the excited configuration depends on the multiplet energy. Thus, the influence of excited configurations on different multiplets will not be the same, and the intensity parameters for different transitions should depend on the multiplet energies. The terms with the parameters $R_k$ in Eq. (3) are accounting for this effect. Large values of the $R_k$ parameters and their different signs indicate a significant influence of excited configurations with a charge transfer (covalency effects).

For the analysis, initially, 9 $Er^{3+}$ transitions were considered (originating from the $^4I_{15/2}$ ground-state to the excited-states from $^4I_{13/2}$ to $^4G_{11/2}$). The experimental and calculated absorption oscillator strengths ($f_{exp}$ and $f^{\Sigma}_{calc}$, respectively, Σ stands for the total (ED + MD) value) are listed in Table 1. The direct use of the J-O theory led to a relatively small root mean square (rms) deviation between the $f_{exp}$ and $f^{\Sigma}_{calc}$ values (0.175). However, further calculation of the radiative lifetime of the first $Er^{3+}$ excited state, $^4I_{13/2}$, led to an obviously underestimated value ($\tau_{rad}$ = 4.75 ms). The use of the ICI model (the results are not shown in Table 1) slightly improved the rms deviation (0.133) but did not solve the problem of the $^4I_{13/2}$ radiative lifetime ($\tau_{rad}$ = 4.45 ms). This problem was recently discussed by Merkle *et al.* for Er:$Lu_2O_3$ [31]. The authors concluded that it arises from a significant contribution of $Er^{3+}$ ions located in $C_{3i}$ sites to MD allowed transition $^4I_{15/2} \rightarrow {}^4I_{13/2}$.

To overcome this problem, we excluded the $^4I_{15/2} \rightarrow {}^4I_{13/2}$ transition in absorption from the fit (a total of 8 transitions was thus analyzed). In this case, a reasonable $\tau_{rad}(^4I_{13/2})$ value was obtained for both the J-O and ICI theories. The latter model was selected for further calculations for two reasons: first, it provided smaller rms deviation (0.038) and second, much better agreement between $f_{exp}$ and $f^{\Sigma}_{calc}$ for another transition of interest, $^4I_{15/2} \rightarrow {}^4I_{11/2}$, as compared to the standard J-O one.

The obtained intensity parameters are listed in Table 2. For the ICI theory (when excluding the $^4I_{15/2} \rightarrow {}^4I_{13/2}$ transition from the fit), they are $\Omega_2$ = 7.267, $\Omega_4$ = 1.784 and $\Omega_6$ = 0.664 [$10^{-20}$ cm$^2$] and $R_2$ = -0.012, $R_4$ = -0.084 and $R_6$ = 0.168 [$10^{-4}$ cm].

Based on these intensity parameters, the probabilities of spontaneous radiative transitions $A^{\Sigma}_{calc}$(JJ'), the luminescence branching ratios $B$(JJ') and the radiative lifetimes of the excited-states $\tau_{rad}$ were calculated for the excited-states from $^4I_{13/2}$ up to $^4S_{3/2}$ + $^2H_{11/2}$ (considering the latter two states as thermally coupled ones), Table 3. For the first excited state ($^4I_{13/2}$), $\tau_{rad}$ = 6.28 ms and for the $^4I_{11/2}$ one, $\tau_{rad}$ = 4.80 ms. The luminescence branching ratio for the $^4I_{11/2} \rightarrow {}^4I_{13/2}$ transition which gives rise to laser emission at ~2.8 µm, $B$(JJ') = 19.9%.

### *4.4. Emission (spectra and lifetime)*

Two transitions in emission, $^4I_{13/2} \rightarrow {}^4I_{15/2}$ (at ~1.6 µm) and $^4I_{11/2} \rightarrow {}^4I_{13/2}$ (at ~2.8 µm) were analyzed. For both, the stimulated-emission (SE) cross-sections, $\sigma_{SE}$, were calculated using the Füchtbauer–Ladenburg (F-L) formula [32]:

$$\sigma_{\mathrm{SE}}(\lambda) = \frac{\lambda^5}{8\pi <n>^2 \tau_{\mathrm{rad}} c} \frac{B(JJ')W'(\lambda)}{\int \lambda W'(\lambda)\mathrm{d}\lambda}, \tag{4}$$

where, $\lambda$ is the light wavelength, $<n>$ is the refractive index of the ceramic corresponding to the mean luminescence wavelength $<\lambda_{lum}>$, $\tau_{rad}$ corresponds to the emitting state ($^4I_{13/2}$ or $^4I_{11/2}$) and $B$(JJ') – to the considered transition, $c$ is the speed of light and $W'(\lambda)$ is the luminescence spectrum accounting for the apparatus function of the set-up. For the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition for which reabsorption is expected to be particularly strong in highly doped ceramic, a complementary approach was also used, i.e., the reciprocity method (RM) [33]:

$$\sigma_{\mathrm{SE}}(\lambda) = \sigma_{\mathrm{abs}}(\lambda) \frac{Z_1}{Z_2} \exp\left(-\frac{(hc/\lambda) - E_{\mathrm{ZPL}}}{kT}\right), \tag{5a}$$

$$Z_m = \sum_k g_k^m \exp(-E_k^m / kT). \tag{5b}$$

Here, $h$ is the Planck constant, $k$ is the Boltzmann constant, $T$ is the temperature (RT), $E_{ZPL}$ is the energy corresponding to the so-called zero-phonon-line (ZPL) transition occurring between the lowest Stark sub-levels of the involved multiplets, $Z_m$ are the so-called partition functions of the lower ($m$ = 1) and upper ($m$ = 2) manifolds, and $g^m_k$ = 1 is the degeneracy of the Stark sub-level with a number $k$ and energy $E^m_k$ measured from the lowest sub-level of each multiplet. The data on the crystal-field splitting for $Er^{3+}$ obtained in the present work were used (Section 4.5).

For the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition, the simultaneous use of the F-L equation and RM gives a good agreement at wavelength above 1.6 µm (where the reabsorption becomes weak) for the $\tau_{rad}(^4I_{13/2})$ values of 8.0±0.5 ms which reasonably agrees with the J-O analysis, Fig. 6(a). The maximum $\sigma_{SE}$ is 1.43×$10^{-20}$ cm$^2$ at 1535 nm (corresponding to ZPL at RT) and at longer wavelengths where the laser operation is expected, $\sigma_{SE}$ is lower, namely $0.14\times10^{-20}$ cm$^2$ at 1658 nm, Fig. 6(a).

For the $^4I_{11/2} \rightarrow {}^4I_{13/2}$ transition, the SE cross-sections determined using the F-L equation are $1.30\times10^{-20}$ cm$^2$ at 2718 nm (ZPL) and $0.35\times10^{-20}$ cm$^2$ at 2859 nm, Fig. 6(b). The corresponding emission bandwidths (FWHM) are 25 and 44 nm, respectively.

Using the reciprocity method, Eq. (5), we have also calculated the spectrum of excited-state absorption (ESA) corresponding to the $^4I_{13/2}\rightarrow{}^4I_{11/2}$ transition, Fig. 6(b).

The RT luminescence decay curves from the $^4I_{13/2}$ and $^4I_{11/2}$ states of Er$^{3+}$ ions in 7 at.% Er:(Lu,Sc)$_2$O$_3$ ceramics, plotted in a semi-log scale are shown in Fig. 7. Both of them are measured under resonant excitation using small quantities of finely powdered ceramic to reduce the effect of radiation trapping (reabsorption).

The decay curve from the $^4I_{13/2}$ state, Fig. 7(a), is not single-exponential while it is well fitted using the Inokuti-Hirayama (I-H) model accounting for the energy transfer processes in the absence of migration [34]:

$$I(t)=I_0\exp\left(-(t/\tau_0)-\alpha(t/\tau_0)^{3/s}\right), \tag{6}$$

where, $I(t)$ is the emission intensity after pulsed excitation, $\tau_0$ is the lifetime of an isolated donor (D) or the so-called intrinsic lifetime, the parameter $s$ stands for the mechanism of the ion interaction ($s$ = 6 and $s$ = 8 for dipole-dipole (D-D) and dipole-quadrupole (D-Q) processes, respectively) and $\alpha$ is a constant describing the probability of energy-transfer. For the curve shown in Fig. 7(a), the best-fit parameters are $\tau_0$ = 11.7±0.3 ms, $s$ = 7.0±0.1 (predominantly D-D interaction) and $\alpha$ = 2.15±0.1.

The luminescence decay curve from the $^4I_{11/2}$ state strongly deviates from a single-exponential law. The attempt to use the I-H model for its description failed. The observation of a nearly single-exponential “fast” decay component, as well as another “slow” component at longer times suggested the presence of two ion classes. As mentioned above, the Er$^{3+}$ ions in the ceramic may reside in C$_2$ and C$_{3i}$ sites. However, the $^4I_{11/2} \rightarrow {}^4I_{15/2}$ transition is of purely ED nature and it cannot reveal the signatures of the C$_{3i}$ sites. Thus, we assume that the observed difference in lifetime for the two ion classes may arise from strong energy-migration (among the active ions and to defects and uncontrolled impurities). The model of migration-assisted energy-transfer is [35]:

$$I(t)=I_0\exp\left(-(t/\tau_0)-\omega t-\alpha(t/\tau_0)^{3/s}\right), \tag{7}$$

where ω is the energy-migration rate expressed in s$^{-1}$. We assume that ions belonging to class #1 experience ETU and weak EM (ω ≈ 0) and ions belonging to class #2 – ETU and strong EM leading to effective shortening of their intrinsic lifetime, $1/\tau_0^* = (1/\tau_0) - \omega$. For the decay curve shown in Fig. 7(b), the best-fit parameters are $\tau_0$ = 4.6±0.2 ms, $s$ = 6.1±0.1 (D-D interaction), $\alpha$ = 2.86±0.1 (class #1) and $\tau_0^*$ = 0.60±0.1 ms, or, equivalently, ω = $1.45\times10^3$ s$^{-1}$ (class #2). Note that due to the strong EM, it is not possible to quantify precisely the $\alpha$ value in the latter case.

The appearance of different ion classes in polycrystalline ceramics is not surprising. The granular structure of ceramics determines variation of compositional and crystallographic properties at the level of each particular grain. One can suggest two possible mechanisms of formation of two spectroscopically distinct ion classes in “mixed” ceramics. The first is the possible segregation of dopant ions at the grain boundaries where the interaction between the ions themselves and with defect and impurity centers is greatly promoted. It was indeed observed using high-resolution transmission electron microscopy in sesquioxide ceramics [36]. However, the authors of [36] concluded that it is relatively weak for small cations located in the end of the lanthanide series (as in the case of Er$^{3+}$ replacing Lu$^{3+}$). Thus, this effect is expected to be hardly visible at the level of macroscopic spectroscopic properties. Second, as pointed out above, one may expect a predominant substitution of $Lu^{3+}$ by $Er^{3+}$ leading to depletion of these host-forming cations in other regions. Thus, locally, two types of centers differing by the second coordination sphere composed mainly by $Lu^{3+}$ or $Sc^{3+}$ can be formed. It was found that among the $A_2O_3$ family materials, particularly for $Sc_2O_3$, the luminescence lifetime of the $^4I_{11/2}$ $Er^{3+}$ state is notably shortened ($\tau_{lum}$ is about 0.34-0.55 ms [37,38] even at low doping levels) as compared to its $Lu_2O_3$ and $Y_2O_3$ counterparts for which $\tau_{lum}$ is about ~2 ms at RT and 4.5 ms at LT. This matches well our observations.

For both luminescence decay curves, the mean decay time was also calculated as:

$$\langle\tau_{\mathrm{lum}}\rangle=\frac{\int t\cdot I(t)\mathrm{d}t}{\int I(t)\mathrm{d}t}. \quad (8)$$

For the decay from the $^4I_{13/2}$ and $^4I_{11/2}$ multiplets, $<\tau_{lum}>$ amounted to 4.89 and 1.07 ms, respectively. These values agree well with the previously reported data for single-crystals of $Er:Lu_2O_3$ [9].

### *4.5. Low-temperature spectroscopy*

The expected inhomogeneous broadening of spectral bands of $Er^{3+}$ ions in the "mixed" ceramic is revealed at low temperature. The LT (12 K) absorption and luminescence spectra used to determine the crystal-field splitting of $Er^{3+}$ multiplets involved in the near- and mid-IR emissions (from $^4I_{15/2}$ to $^4I_{11/2}$) are shown in Fig. 8.

For $Er^{3+}$ ions in $C_2$ sites, each $^{2S+1}L_J$ multiplet splits into J + 1/2 non-degenerated Stark sub-levels (considering non-integer J). Following the early work by Dieke [39], we will use empirical notations for these sub-levels, namely $Z_i$ ($i$ = 1...8), $Y_j$ ($j$ = 1...7) and $A_k$ ($k$ = 1...6) for the $^4I_{15/2}$, $^4I_{13/2}$ and $^4I_{11/2}$ multiplets, respectively [40]. To simplify the assignment of electronic transitions, we used the crystal-field data for $Er^{3+}$ ions in $Sc_2O_3$ derived by Lupei *et al.* [38] (shown by vertical dashes in Fig. 8). The bands related to electronic transitions of $Er^{3+}$ ions in $C_2$ sites in the $(Lu,Sc)_2O_3$ ceramic experience a significant inhomogeneous broadening, as compared to $Er^{3+}$-doped "parent" sesquioxides [37,40].

We have determined experimentally the Stark energies for all $Er^{3+}$ multiplets from $^4I_{15/2}$ up to $^4G_{11/2}$ (except of few missing levels), Table 4. The corresponding energy-level scheme is shown in Fig. 9(a) together with the processes relevant for ~2.8 µm laser operation. A close look on the crystal-field splitting of the $^4I_{11/2}$ and $^4I_{13/2}$ multiplets is given in Fig. 9(b).

As pointed out above, the spectroscopic signatures of $Er^{3+}$ ions in $C_{3i}$ sites can be found for the MD $^4I_{15/2} \rightarrow {}^4I_{13/2}$ transition. In the present work, the intense and narrow peak at 6539 $cm^{-1}$ is unambiguously assigned to $C_{3i}$ sites in agreement with the findings of Gruber *et al.* for $Er:Y_2O_3$ [41]. Other possible peaks are hardly resolved because of the broad bands due to the $C_2$ site absorption.

## **5. Laser operation**

### *5.1. Laser set-up*

The scheme of the laser set-up is shown in Fig. 10. A rectangular active element (thickness: 1.98 mm, aperture: 3.0×3.0 $mm^2$) was fabricated from the 7 at.% $Er:(Lu,Sc)_2O_3$ ceramic. It was polished to laser-grade quality from both sides and remained uncoated. The element was mounted on a passively cooled Cu-holder using a heat-conductive silver paint. A hemispherical cavity consisted of a flat pump mirror (PM) coated for high transmission (HT) at 0.78-0.83 and 0.92-1.06 µm (the pump ranges) and for high reflection (HR) at 2.6-3.0 µm and a concave output coupler (OC) with a radius of curvature (RoC) of -75 mm and a transmission $T_{OC}$ = 1.5±0.5% at 2.6-3.0 µm. The geometrical cavity length was ~75 mm. The laser element was placed close to the PM with an air gap of less than 1 mm.

As a pump source, we used a CW Ti:Sapphire laser (model 3900S, Spectra Physics) operating in the fundamental mode ($TEM_{00}$, $M^2 \approx 1$) and delivering up to 2.7 W at 804.4 nm and 2.15 W at 980.6 nm. The pump radiation was focused into the laser element through the PM using an achromatic lens (f = 75 mm). The OC was partially reflective for the pump (i.e., the pumping was in double pass). The total pump absorption under lasing conditions $\eta_{abs,L}$ amounted to 60.2% and 47.1% for $\lambda_P$ = 804.4 and 980.6 nm, respectively.

The spectra of laser emission were detected using a Fourier transform laser spectrum analyzer (771 series, Bristol). The laser mode was captured using a pyroelectric camera (Pyrocam IIIHR, Ophir-Spiricon).

### *5.2. Laser performance*

Two pump schemes were employed, namely, pumping into the $^4I_{11/2}$ and $^4I_{9/2}$ $Er^{3+}$ multiplets, Fig. 11. For optimum $\lambda_P$ = 980.6 nm, the laser generated a maximum output power of 342 mW at ~2717 and 2853-2864 nm with a slope efficiency $\eta$ of 41.7% (with respect to the absorbed pump power) and a laser threshold $P_{th}$ of 125 mW. The optical-to-optical efficiency $\eta_{opt}$ amounted to 16.5% (versus the power incident on the ceramic). Power scaling was limited by the available pump. Almost no signs of thermal effects were observed in the input-output dependence. The $\eta$ value exceeded the Stokes efficiency under lasing conditions, $\eta_{St,L} = \lambda_P/\lambda_L \approx 34\%$, indicating an efficient ETU process (#1), Fig. 9(a), refilling the population of the upper laser manifold.

For pumping into the $^4I_{9/2}$ state ($\lambda_P$ = 804.4 nm), the laser output reached 254 mW at ~2717 and 2853 nm with lower slope efficiency of 23.7% and nearly the same threshold, 142 mW. For absorbed pump powers exceeding 1.1 W, a thermal roll-over was observed. It is related to stronger heat loading for this pump scheme (in particular, the energy loss related to multiphonon non-radiative relaxation between the $^4I_{9/2}$ and $^4I_{11/2}$ states).

Typical spectra of laser emission are shown in Fig. 11(b). Lasing in two spectral regions, at ~2.71 and 2.85 µm, was observed. For the latter we consider two possible reasons. First, the main peak in the SE cross-section spectrum for the $^4I_{11/2} \rightarrow {}^4I_{13/2}$ transition overlaps with the structured water vapor absorption in the atmosphere, Fig. 6(b), which may introduce additional loss. Second, a resonant excited-state absorption (ESA) process, $^4I_{13/2} \rightarrow {}^4I_{11/2}$, which becomes efficient at high populations of the metastable $^4I_{13/2}$ state, forces the laser to operate at wavelengths longer than the ZPL (~2.71 µm).

The laser operated in the fundamental transverse mode, see the mode profile in the inset of Fig. 11(b).

For both studied pump schemes, the laser excitation curves (i.e., the dependence of the output power on the pump wavelength at a fixed incident pump power) were measured. They are shown in Fig. 12 together with the absorption cross-section spectra for the $^4I_{15/2} \rightarrow {}^4I_{11/2}$ and $^4I_{9/2}$ $Er^{3+}$ transitions. The laser excitation curves follow the shape of the $\sigma_{abs}$ spectra indicating that pumping into the most intense absorption peak is preferable for relatively short samples. CW laser operation was achieved for $\lambda_P$ in the ranges of 957-1001 nm and 786-820 nm, limited by the weak pump absorption and coatings of the laser mirrors.

## 6. Conclusions

To conclude, we report on the fabrication of high optical quality 7 at.% $Er:(Lu,Sc)_2O_3$ single-phase (C-type structure) transparent sesquioxide ceramic, its detailed spectroscopic study and first laser operation. The ceramic is fabricated by vacuum sintering at 1750 °C followed by HIPing at 1750 °C / 200 MPa using high-purity commercial sesquioxide powders. It exhibits close-packed microstructure (mean grain size: 5.7 µm), as well as high transmission in the near-IR, close to the theoretical one. The compositional disorder of the host matrix promoted by a great difference of ionic radii of the host-forming cations ($Lu^{3+}$

and $Sc^{3+}$) leads to a significant inhomogeneous broadening of the absorption and emission bands revealed at 12 K. At RT, the “mixed” ceramic features broadband mid-IR emission properties, i.e., an emission bandwidth exceeding 40 nm around ~2.86 µm. The high $Er^{3+}$ doping level results in favorable upper-level to lower-level lifetime ratio for the $^4I_{11/2} \rightarrow {}^4I_{13/2}$ transition ($<\tau_{lum}>$ = 1.07 ms and 4.89 ms, respectively).

Continuous-wave mid-infrared laser operation of the 7 at.% Er:(Lu,Sc)$_2$O$_3$ ceramic is demonstrated under pumping into the $^4I_{11/2}$ state (at ~0.98 µm) and the $^4I_{9/2}$ one (at ~0.8 µm). In the former case, the ceramic laser generated 342 mW at 2.71 and 2.85 µm with a slope efficiency of 41.7% (a record-high value for Er sesquioxide ceramic lasers) and a low laser threshold of only 125 mW. The observed slope efficiency exceeds the Stokes limit indicating an efficient ETU process recycling the population of the upper laser manifold.

## Acknowledgements

This work was supported by Spanish Government, Ministry of Science and Innovation (project No. PID2019-108543RB-I00) and by Generalitat de Catalunya (project No. 2017SGR755). Wei Jing acknowledges financial support from the National Natural Science Foundation of China (grant No. 61805219) and the Key Laboratory of Science and Technology on High Energy Laser, CAEP.

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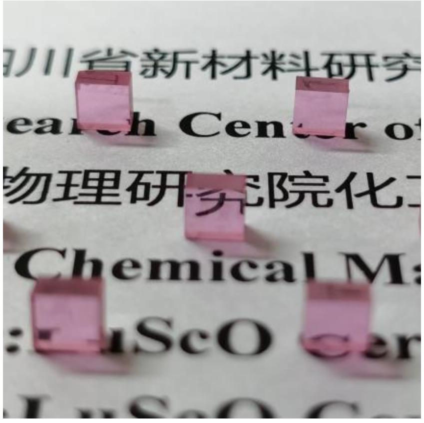

**Fig. 1.** Photograph of annealed and polished Er:$(Lu,Sc)_2O_3$ ceramic elements.

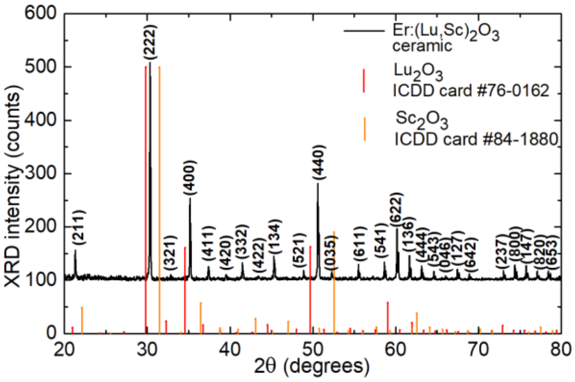

**Fig. 2.** X-ray powder diffraction pattern of Er:$(Lu,Sc)_2O_3$ ceramic, *red and orange peaks* – theoretical patterns for $Lu_2O_3$ (ICDD card #76-0162) and $Sc_2O_3$ (ICDD card #84-1880), respectively, *numbers* – Miller's indices (*hkl*).

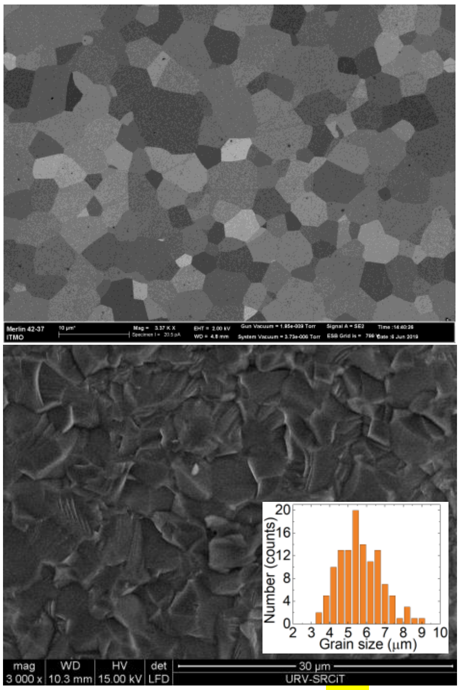

**Fig. 3.** Microstructure of Er:(Lu,Sc)$_2$O$_3$ ceramic: (a) SEM images of the polished surface; (b) environmental SEM image of the fracture surface. *Inset* in (b) – grain size distribution. Scale

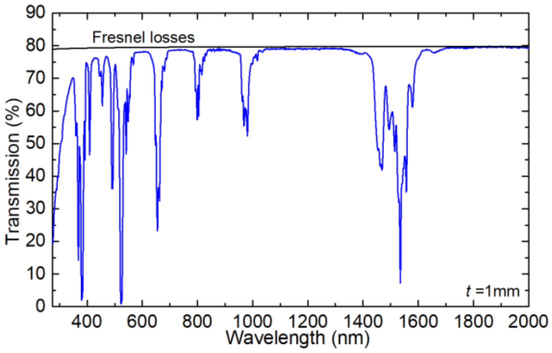

**Fig. 4.** Transmission spectrum of a laser-grade-polished Er:(Lu,Sc)$_2$O$_3$ ceramic disk (thickness, $t$ = 1.0 mm), *black curve* – theoretical transmission determined by the Fresnel losses.

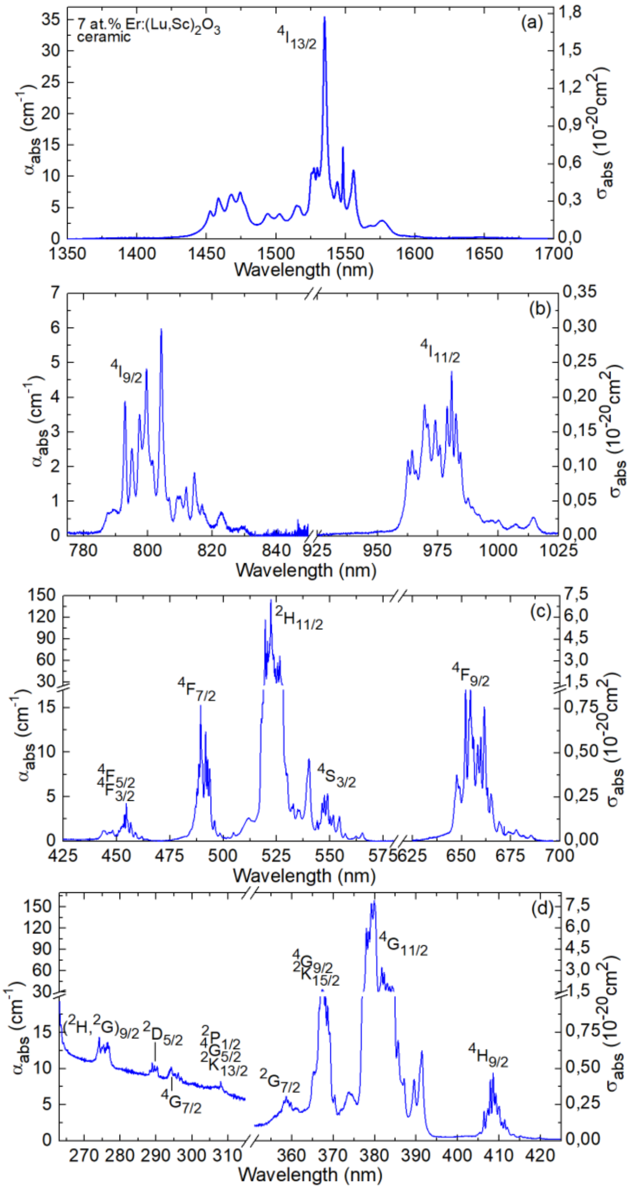

**Fig. 5.** (a-d) RT absorption spectra of 7 at.% Er:(Lu,Sc)$_2$O$_3$ ceramic ($\alpha_{abs}$ – absorption coefficient, $\sigma_{abs} = \alpha_{abs}/N_{Er}$ – absorption cross-section).

**Table 1.** Analysis of transition intensities* in absorption for $Er^{3+}$ ions in $(Lu,Sc)_2O_3$ ceramic.

| Transition $^4I_{15/2} \rightarrow {}^{2S+1}L_J$ | <*E*>, cm$^{-1}$ | *Γ*, cm$^{-1}$*nm | $f_{exp}$, $10^{-6}$ | $f^{\Sigma}_{calc}$, $10^{-6}$ | | |
|---|---|---|---|---|---|---|
| | | | | J-O | J-O** | ICI** |
| $^4I_{13/2}$ | 6558 | 819.85 | 2.020 | 1.191$^{ED}$<br>+ 0.592$^{MD}$ | *0.930*$^{ED}$<br>+ 0.592$^{MD}$ | *0.757*$^{ED}$<br>+0.592$^{MD}$ |
| $^4I_{11/2}$ | 10145 | 82.62 | 0.489 | 0.652$^{ED}$ | 0.524$^{ED}$ | 0.490$^{ED}$ |
| $^4I_{9/2}$ | 12401 | 52.13 | 0.456 | 0.393$^{ED}$ | 0.455$^{ED}$ | 0.476$^{ED}$ |
| $^4F_{9/2}$ | 15148 | 194.37 | 2.548 | 2.434$^{ED}$ | 2.509$^{ED}$ | 2.534$^{ED}$ |
| $^4S_{3/2} + {}^2H_{11/2}$ | 18686 | 665.59 | 13.660 | 13.399$^{ED}$ | 13.315$^{ED}$ | 13.655$^{ED}$ |
| $^4F_{7/2}$ | 20315 | 72.60 | 1.705 | 1.869$^{ED}$ | 1.581$^{ED}$ | 1.739$^{ED}$ |
| $^4F_{5/2} + {}^4F_{3/2}$ | 22075 | 25.87 | 0.716 | 0.770$^{ED}$ | 0.530$^{ED}$ | 0.699$^{ED}$ |
| $^2G_{9/2}$ | 24435 | 21.27 | 0.719 | 0.672$^{ED}$ | 0.529$^{ED}$ | 0.659$^{ED}$ |
| $^4G_{11/2} + {}^2K_{15/2}$ + $^4G_{9/2} + {}^2G_{7/2}$ | 26286 | 753.62 | 29.698 | 29.750$^{ED}$<br>+0.070$^{MD}$ | 29.781$^{ED}$<br>+0.070$^{MD}$ | 29.622$^{ED}$<br>+0.070$^{MD}$ |
| *r.m.s. dev.* | | | | *0.175* | *0.181* | *0.038* |

*<*E*> - “center of gravity” of the absorption band, *Γ* – integrated absorption coefficient, $f_{exp}$ and $f^{\Sigma}_{calc}$ – experimental and calculated absorption oscillator strengths, respectively, ED and MD stand for electric-dipole and magnetic dipole contributions, respectively.

**Excluding the $^4I_{15/2} \rightarrow {}^4I_{13/2}$ transition from the fit.

**Table 2.** Intensity parameters for $Er^{3+}$ ions in $(Lu,Sc)_2O_3$ ceramic.

| Parameter | Value (theory) | | |
|---|---|---|---|
| | J-O | J-O* | ICI* |
| $\Omega_2$, $10^{-20}$ cm$^2$ | 7.151 | 7.048 | 7.267 |
| $\Omega_4$, $10^{-20}$ cm$^2$ | 1.646 | 1.919 | 1.784 |
| $\Omega_6$, $10^{-20}$ cm$^2$ | 0.783 | 0.539 | 0.664 |
| $R_2$, $10^{-4}$ cm | | | -0.012 |
| $R_4$, $10^{-4}$ cm | | | -0.084 |
| $R_6$, $10^{-4}$ cm | | | 0.168 |

*Excluding the $^4I_{15/2} \rightarrow {}^4I_{13/2}$ transition from the fit.

**Table 3.** Emission probabilities* for $Er^{3+}$ ions in $(Lu,Sc)_2O_3$ ceramic calculated within the ICI approximation.

| Transition | | $\langle\lambda\rangle$, nm | $A^{\Sigma}_{calc}(JJ')$, $s^{-1}$ | $B(JJ')$ | $A_{tot}$, $s^{-1}$ | $\tau_{rad}$, ms |
|---|---|---|---|---|---|---|
| $^4I_{13/2}\rightarrow$ | $^4I_{15/2}$ | 1533 | $89.29^{ED}+69.92^{MD}$ | 1 | 159.21 | 6.28 |
| $^4I_{11/2}\rightarrow$ | $^4I_{13/2}$ | 2688 | $24.96^{ED}+16.56^{MD}$ | 0.199 | 208.50 | 4.80 |
| | $^4I_{15/2}$ | 976.1 | $166.98^{ED}$ | 0.801 | | |
| $^4I_{9/2}\rightarrow$ | $^4I_{11/2}$ | 4515 | $1.30^{ED}+2.22^{MD}$ | 0.010 | 338.38 | 2.96 |
| | $^4I_{13/2}$ | 1685 | $46.79^{ED}$ | 0.138 | | |
| | $^4I_{15/2}$ | 802.6 | $288.07^{ED}$ | 0.852 | | |
| $^4F_{9/2}\rightarrow$ | $^4I_{9/2}$ | 3650 | $8.53^{ED}+4.12^{MD}$ | 0.005 | 2522.8 | 0.40 |
| | $^4I_{11/2}$ | 2018 | $89.38^{ED}+10.17^{MD}$ | 0.039 | | |
| | $^4I_{13/2}$ | 1153 | $128.20^{ED}$ | 0.051 | | |
| | $^4I_{15/2}$ | 657.9 | $2282.4^{ED}$ | 0.905 | | |
| $^4S_{3/2}$ + $^2H_{11/2}\rightarrow$ | $^4F_{9/2}$ | 3189 | $60.20^{ED}+0.28^{MD}$ | 0.003 | 18221.5 | 0.055 |
| | $^4I_{9/2}$ | 1702 | $279.87^{ED}+1.19^{MD}$ | 0.015 | | |
| | $^4I_{11/2}$ | 1236 | $179.07^{ED}+14.53^{MD}$ | 0.011 | | |
| | $^4I_{13/2}$ | 846.7 | $762.60^{ED}+120.76^{MD}$ | 0.049 | | |
| | $^4I_{15/2}$ | 545.4 | $16803.8^{ED}$ | 0.922 | | |

$\langle\lambda\rangle$ - mean emission wavelength, $A^{\Sigma}_{calc}(JJ')$ - probability of spontaneous transition (ED and MD stand for electric and magnetic dipole contributions, respectively), $B(JJ')$ - luminescence branching ratio, $A_{tot}$ and $\tau_{rad}$ - total probability of spontaneous transitions from an excited-state and its radiative lifetime, respectively.

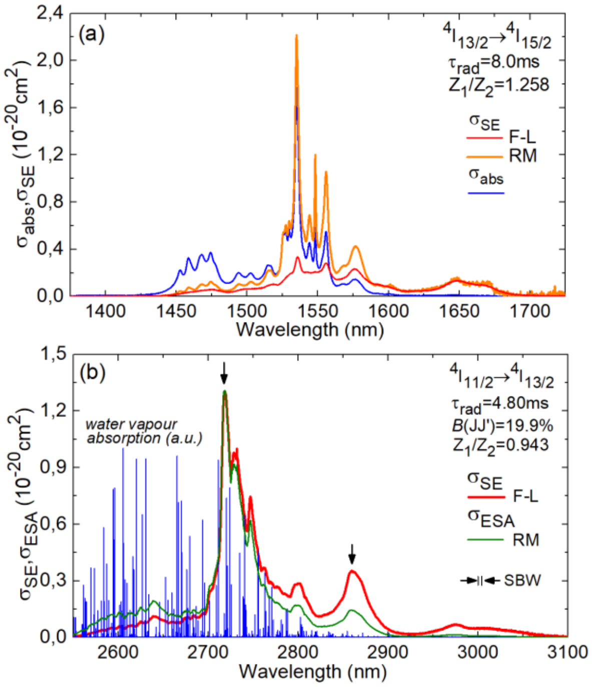

**Fig. 6.** RT stimulated-emission cross-sections, $\sigma_{SE}$, for $Er^{3+}$ ions in $(Lu,Sc)_2O_3$ ceramic: (a) the $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transition and (b) the $^4I_{11/2} \rightarrow {}^4I_{13/2}$ transition. F-L - Füchtbauer–Ladenburg equation, RM – reciprocity method. *Blue spectrum* in (b) – water vapor absorption in the atmosphere (from Hitran database). In (a), the $\sigma_{abs}$ spectrum is given for comparison. In (b), the $\sigma_{ESA}$ spectrum ($^4I_{13/2} \rightarrow {}^4I_{11/2}$) is calculated. *Arrows* indicate the observed laser lines.

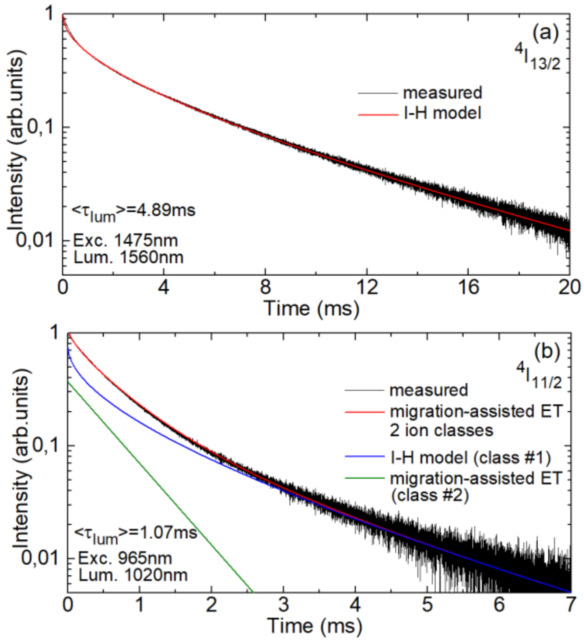

**Fig. 7.** RT luminescence decay curves for 7 at.% Er:$(Lu,Sc)_2O_3$ ceramic: (a) the $^4I_{13/2}$ state, $\lambda_{exc}$ = 1475 nm, $\lambda_{lum}$ = 1560 nm. *Black curve* – measured decay, *red curve* – its fitting using the Inokuti-Hirayama (I-H) model; (b) the $^4I_{11/2}$ state, $\lambda_{exc}$ = 965 nm, $\lambda_{lum}$ = 1020 nm. *Black curve* – measured decay, *red curve* – its fitting using the model of migration-assisted energy-transfer and two ions classes, *blue* and *green curves* – ion class #1 and #2, $<\tau_{lum}>$ - average luminescence lifetime.

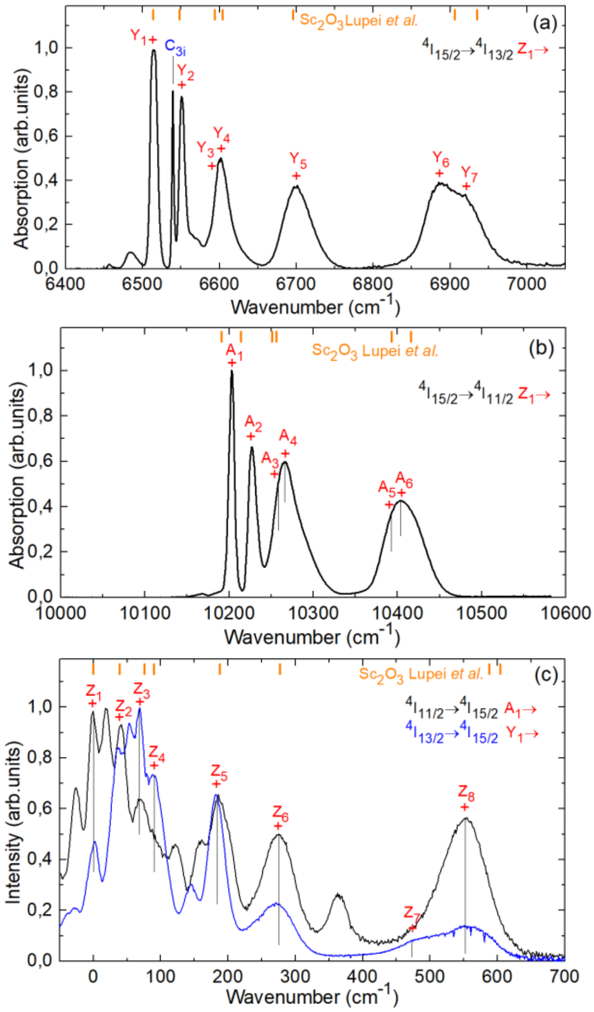

**Fig. 8.** LT (12 K) spectroscopy of $Er^{3+}$ ions in $(Lu,Sc)_2O_3$ ceramic: (a,b) absorption spectra: (a) the $^4I_{15/2} \rightarrow {}^4I_{13/2}$ transition, (b) the $^4I_{15/2} \rightarrow {}^4I_{11/2}$ transition; (c) emission spectra for the $^4I_{11/2} \rightarrow {}^4I_{15/2}$ and $^4I_{13/2} \rightarrow {}^4I_{15/2}$ transitions. $Z_i$ ($i$ = 1...8), $Y_j$ ($j$ = 1...7) and $A_k$ ($k$ = 1...6) number the Stark sub-levels of the $^4I_{15/2}$, $^4I_{13/2}$ and $^4I_{11/2}$ multiplets, respectively, for $C_2$ sites. $C_{3i}$ in (a) – lines assigned to MD transitions for $C_{3i}$ sites. Orange dashes – crystal-field splitting for $Er^{3+}$ in $C_2$ sites in $Sc_2O_3$ [37].

**Table 4.** Crystal-field splitting for $Er^{3+}$ ions in $C_2$ sites in $(Lu,Sc)_2O_3$ ceramic. The empirical notations of the multiplets are after [39].

| Manifold | Notation | Stark components ($cm^{-1}$) |
|---|---|---|
| $^4I_{15/2}$ | Z | 0, 41, 68, 90, 184, 275, 473, 552 |
| $^4I_{13/2}$ | Y | 6514, 6551, 6596, 6600, 6699, 6887, 6919 |
| $^4I_{11/2}$ | A | 10203, 10227, 10258, 10266, 10393, 10404 |
| $^4I_{9/2}$ | B | 12303, 12439, 12523, 12600, 12630 |
| $^4F_{9/2}$ | D | 15109, 15191, 15292, 15330, 15467 |
| $^4S_{3/2}$ | E | 18201, 18309 |
| $^2H_{11/2}$ | F | 19049, 19233,19307 (*3 missing*) |
| $^4F_{7/2}$ | G | 20322, 20467, 20496, 20607 |
| $^4F_{5/2}$ | H | 22050, 22179 (*1 missing*) |
| $^4F_{3/2}$ | I | 22398, 22589 |
| $^2H_{9/2}$ | K | 24337, 24554, 24614 (*2 missing*) |
| $^4G_{11/2}$ | L | 26137, 26448 (*4 missing*) |

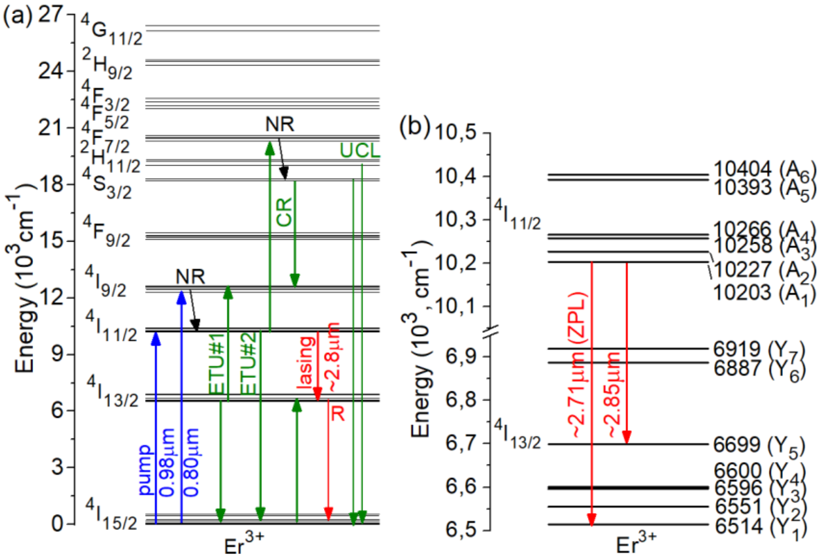

**Fig. 9.** Scheme of energy-levels of $Er^{3+}$ ions in $C_2$ sites in $(Lu,Sc)_2O_3$ ceramic: (a) general scheme: *blue and red arrows* – pump and laser transitions, respectively, ETU – energy-transfer upconversion, CR – cross-relaxation, R and NR – radiative and non-radiative transitions, respectively, UCL – upconverison luminescence; (b) splitting of the $^4I_{11/2}$ and $^4I_{13/2}$ multiplets, *arrows* – observed laser lines.

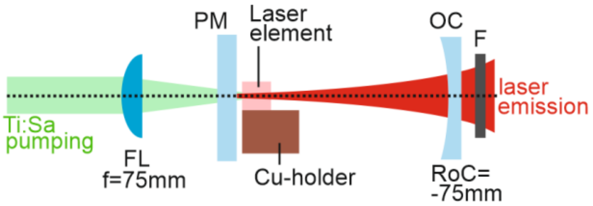

**Fig. 10.** Scheme of the Er:(Lu,Sc)$_2$O$_3$ ceramic laser: FL – focusing lens, PM – pump mirror, OC – output coupler, F – long-pass filter.

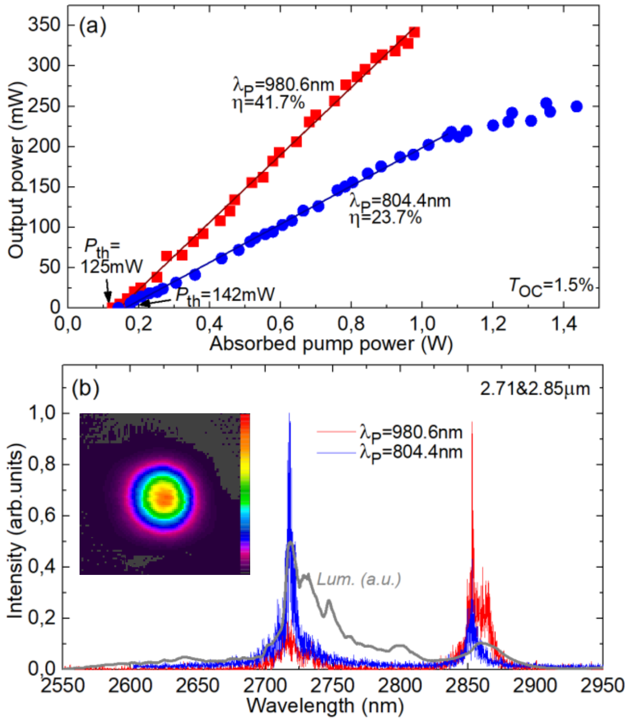

**Fig. 11.** Er:(Lu,Sc)$_2$O$_3$ ceramic laser: (a) input-output power dependences for $\lambda_P$ = 804.4 nm and 980.6 nm, $\eta$ – slope efficiency; (b) typical laser emission spectra, *inset* – spatial profile of the laser mode in the far-field. $T_{OC}$ = 1.5%. The laser emission is unpolarized. For comparison the luminescence curve is implemented (gray).

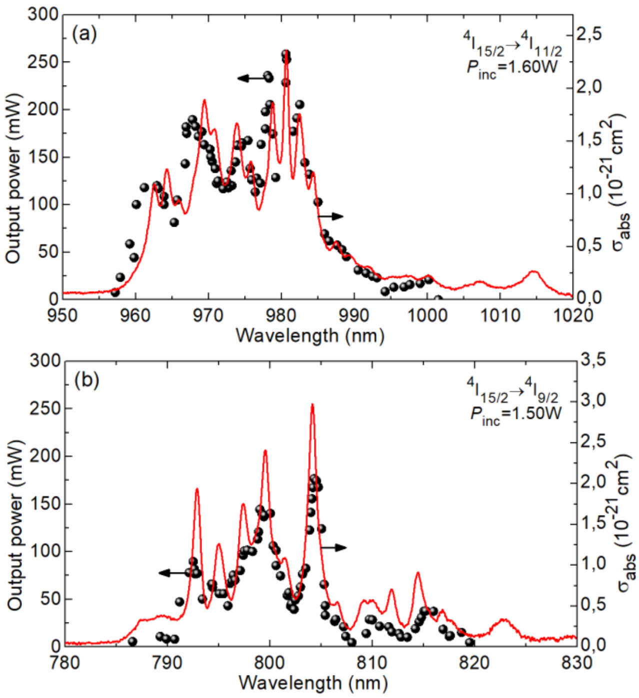

**Fig. 12.** Laser excitation curves for the Er:(Lu,Sc)$_2$O$_3$ ceramic laser (output power *vs*. the pump wavelength) measured at a fixed incident pump power $P_{inc}$: pumping into (a) the $^4I_{11/2}$ state and (b) the $^4I_{9/2}$ state. *Symbols* – laser output power, *curves* – $\sigma_{abs}$ spectra.