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Erbium-doped yttria-stabilised zirconia thin films grown by PLD for photonic applications.

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ABSTRACT

On-chip optical amplifiers operating at telecom wavelengths are crucial elements for signal recovering and routing in photonic integrated circuits. In this work, we present the optical and structural properties of Er-doped Yttria-Stabilized Zirconia (YSZ) thin films for the implementation of on-chip optical amplifiers in hybrid multifunctional photonic platforms. Photoluminescence excitation measurements have revealed strong luminescence at 1530 nm under 960 nm wavelength pumping, with lifetime values around 2 ms and a strong Er³⁺- Er³⁺ interaction for Er³⁺ doping concentrations beyond 1.5 atomic percentage (at.%). This work contributes to establish the solid foundations for a new class of Er-doped on-chip amplifiers using the robust and stable YSZ host matrix.

1. Introduction

Silicon photonics is considered as a game-changing technology able to circumvent the microelectronics interconnection bottleneck. Furthermore, the need to efficiently manage nowadays' massive data traffic volumes has accelerated the search for multi-functional photonic integrated circuits able to adapt and reconfigure their optical properties in real-time conditions. In this regard, one of the most rewarding components is the integrated optical amplifier. This device could play a key role in the recovery of weak on-chip optical signals and routing. For that, advances on new materials engineering for hybrid integration on silicon platforms are the key to conquer limitations by adding other functionalities such more efficient electro-optic effects, enhanced nonlinearities or integrated on-chip laser to heterostructures [1-3]. For this purpose, functional oxides summon attention by its outstanding properties such as superconductivity, magnetism, ferroelectricity, catalytic activity, resistive switching, electro-optic effects, piezoelectricity, or optical nonlinearities [4-9]. One of the main challenges in hybrid integration platforms is lattice mismatch hindering epitaxial growth on silicon and introducing defects. Yttria-stabilized zirconia (YSZ) is a well-known ceramic buffer layer for functional oxides such as PZT, CoFe₂O₄ LiNbO₃, SrRuO₃ [10-13] with a lattice constant compatible with the one of silicon. YSZ thermal and chemical properties, hardness and mechanical durability makes this oxide a good candidate for photonic applications [14-16]. Moreover, it belongs to the mid-index contrast material family with promising optical properties [17]: low propagation loss [18], absence of two photon absorption

(TPA), a large transparency window from the ultraviolet to the mid-infrared [19] and good Kerr effect [20] to name a few. Lasing on silicon remains one of the last missing elementary components of compact silicon-based photonics. In this regard, III-V materials, RE doping, quantum effects (Si quantum dots) or forcing direct bandgap recombination of excitons or hyper doping schemes levels in Ge [21-25] are some of the strategies used to obtain optical gain. Rare-earth-doped functional oxides are active materials used for optical amplification due to their light enhancement properties with wavelengths within the optical communications range [26]. To avoid non-radiative radiation, low phononic materials are required to host rare-earth ions [27]. Optical amplification has been demonstrated in RE doped functional oxides as LiNbO_3 , Al_2O_3 or Y_2O_3 [28-31]. Moreover, doping introduces undesirable defects within the bulk crystalline matrix promoting optical losses within the material [32]. Another challenge whilst doping is to avoid ion-ion interaction that hinders luminescence and thus prevents from optical amplification. Er^{3+} ion transitions within the near-infrared (near-IR) wavelengths make this RE ion the perfect candidate for the development of efficient light emitting functional oxides at telecommunication wavelengths.

Recent studies demonstrated YSZ waveguides grown with propagation losses as low as 2 dB/cm at a wavelength of 1380 nm [33] proving this oxide to be a good candidate for optical propagation. Therefore, in this paper, we study the crystallinity of variable concentration Er:YSZ thin films deposited by PLD on a c-cut sapphire substrate. Moreover, optimal Er^{3+} ion excitation at 960 nm wavelength is observed for emission in the near-IR. Luminescence efficiency and lifetime studies for different Er^{3+} concentrations have also been performed to find the optimal doping for a YSZ host.

2. Experimental details

Pulsed laser deposition (PLD) is a technique known to achieve high crystallinity in thin film oxides. In this regard, deposition of erbium-doped oxide thin layers grown by means of PLD was carried out in a high-vacuum stainless-steel chamber. KrF excimer laser pumping at 248 nm wavelength, a fluence of 3 J/cm², and at 5 Hz repetition rate ablates a sintered erbium-doped YSZ target with an incident angle of 45°. Rotating sintered ceramic targets of variable percentage in erbium-doped 8 mol% yttria-stabilized zirconia were placed at 50 mm from the substrate on a heated holder. Sapphire substrate was heated from room temperature to 800 °C at a rate of 10 °C/min at an initial pressure of 10⁻⁶ Torr. The chamber receives a constant flux of oxygen at a pressure of 30 mTorr during deposition. Thereafter, the sample is cooled under 300 Torr oxygen at a rate of 10 °C/min. Variable angle spectroscopic ellipsometry (J.A. Woollam) analysed by a Kramers–Kronig consistent model was performed to extract the layer thickness and the refractive index of 2.15. Thin film structural analysis was performed by x-ray diffraction (XRD) using PANalytical X'Pert Pro diffractometer in parallel beam configuration with monochromated Cu K α 1 radiation (wavelength of 1.540 598 Å).

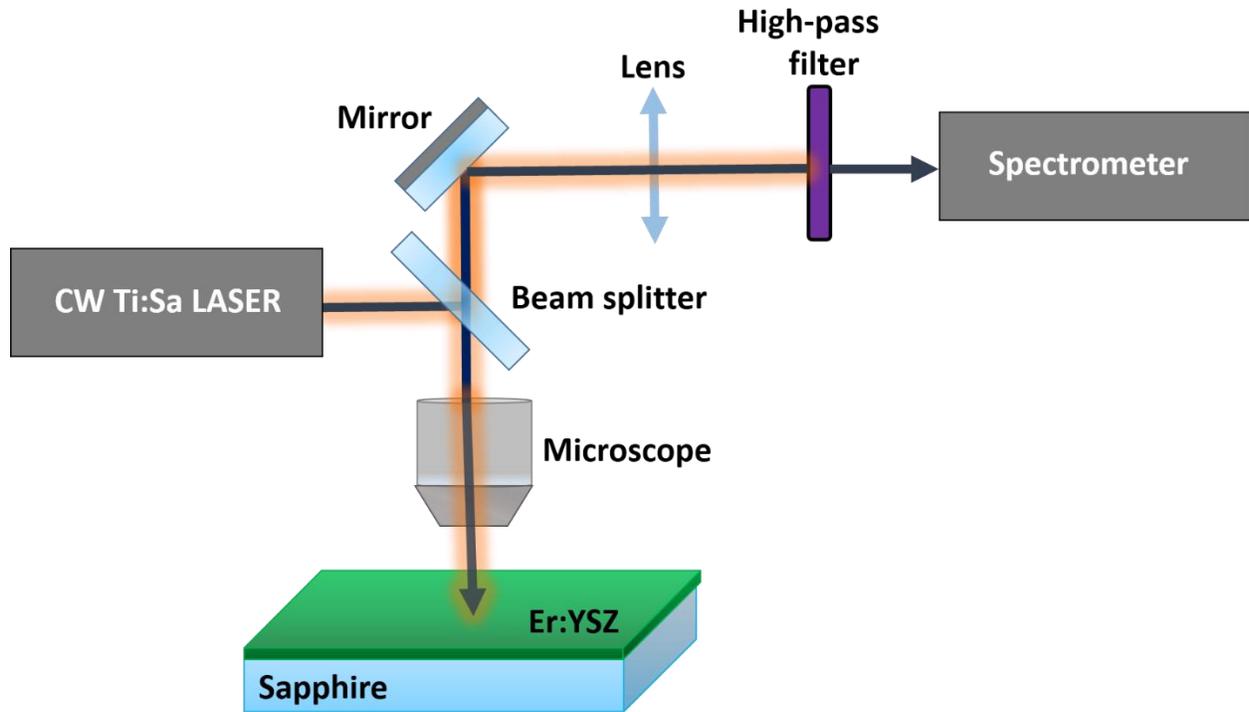


Fig. 1. (a) Scheme of ut-of-plane photoluminescence setup

Optical characterization of Er:YSZ thin films explores the luminescence of the Er^{3+} first excited state in the near IR as a function of the Er concentration within the YSZ matrix. Such inspection is interesting to identify the best trade-off between quenching effects caused by Er^{3+} - Er^{3+} interaction and the solubility of RE dopants in the crystalline YSZ matrix.

2.1. Structural Characterization

Erbium-doped YSZ (Er:YSZ) thin films were grown on a (0001) oriented sapphire substrate following two steps: i) annealing of the substrate and ii) deposition of Er:YSZ layer by PLD.

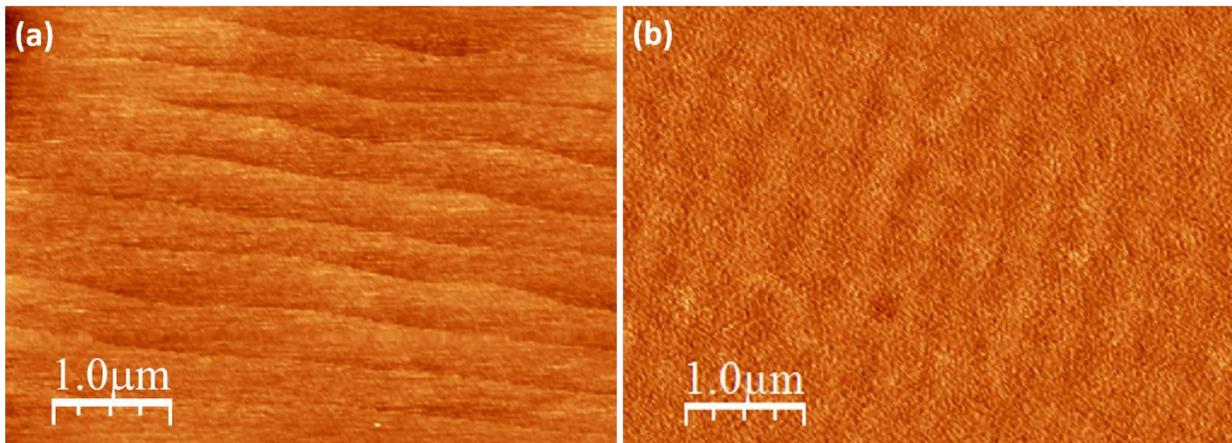


Fig. 2. AFM images of (a) sapphire substrate annealed surface and (b) thin film surface after PLD deposition.

First, we cleaned the sapphire substrate with a dissolution of acetone and ethanol at room temperature. Then, we annealed the sample at 1200 °C during 12h under and pure oxygen atmosphere. In Fig. 2 (a), we observe by atomic force microscopy (AFM) an expected well-defined terrace-step structures characteristic of sapphire substrate annealed on an oxygen atmosphere [33]. AFM analysis of its surface proves an average height of 4 Å.

On a second step, we performed PLD to deposit 300 nm thick Er: YSZ thin films of variable erbium percentage under the same chamber conditions. After deposition, AFM (Fig. 2 (b)) was performed for all Er:YSZ sample surfaces, presenting all of them an average height of 20 Å. Such accentuation of the surface relief lies within the expected rugosity values.

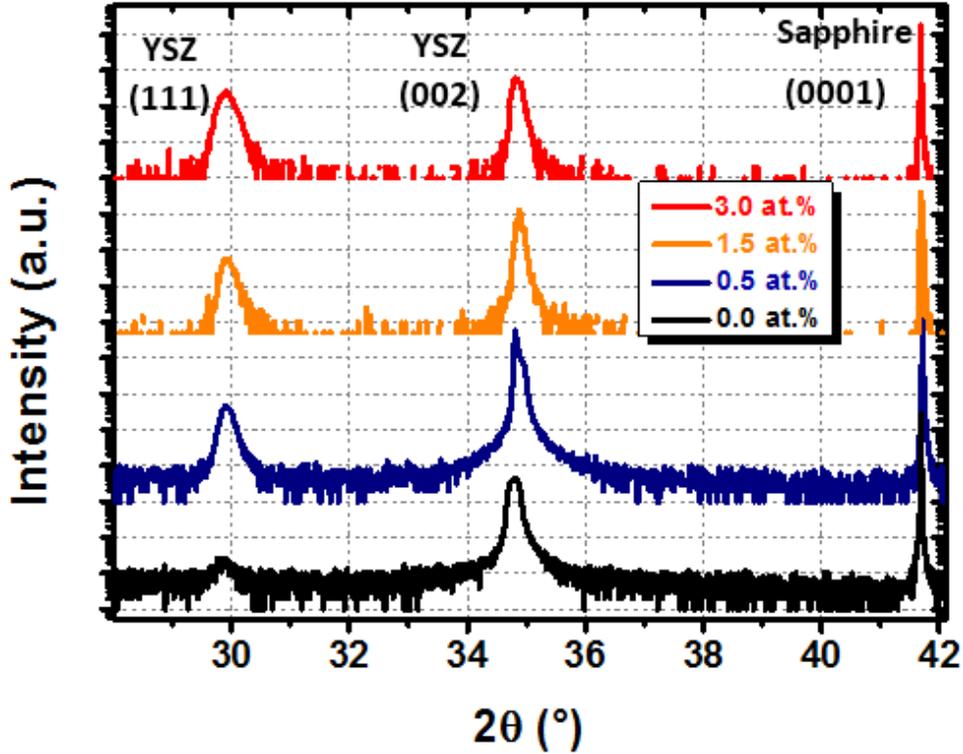


Fig. 3. (a) X-ray diffraction arranged from bottom to top in ascendant percentage of erbium doping YSZ (0, 0.5, 1.5 and 3%).

To structurally characterize Er:YSZ thin films and study its crystallinity we performed X-ray diffraction (XRD). In Fig. 3 we observe a diffraction peak common to all samples that corresponds to the (0001) sapphire orientation at 42°[34]. A different peak attributed to the YSZ thin film (Figure 2) has been observed in the (002) direction, consistent with the study reported by Marcaud et al. [33] for YSZ thin films grown on oxygen-annealed sapphire substrates. Nevertheless, for Er:YSZ thin films, two growth orientations corresponding to the (111) and (002) directions at 29.8° and 34.9° respectively, are observed. It can be observed in Fig. 3 an increase in intensity of the diffracted peak corresponding to the (111) orientation with the increase of Er^{3+} concentration within the YSZ matrix.

2.2. Optical Characterization

2.2.1. Photoluminescence emission

Photoluminescence excitation (PLE), photoluminescence (PL) and optical power efficiency study were performed on a free-space optical bench using an out-of-plane scheme similar to the one shown in Fig. 1. Continuous wave Ti:Sapphire laser at variable wavelengths excites Er^{3+} ions perpendicular to the sample surface using a microscope with x50 magnification objective and numerical aperture of 0.55. Emission and probe signals are perpendicularly

collected by the same objective after Er^{3+} de-excitation and focused by a convergent lens of 50 cm focal plane from the detector. Laser wavelength is filtered with a high-pass filter (1100 nm) and only Er^{3+} emission in near-IR is detected on a iHR320 spectrometer with a nitrogen-cooled-detector.

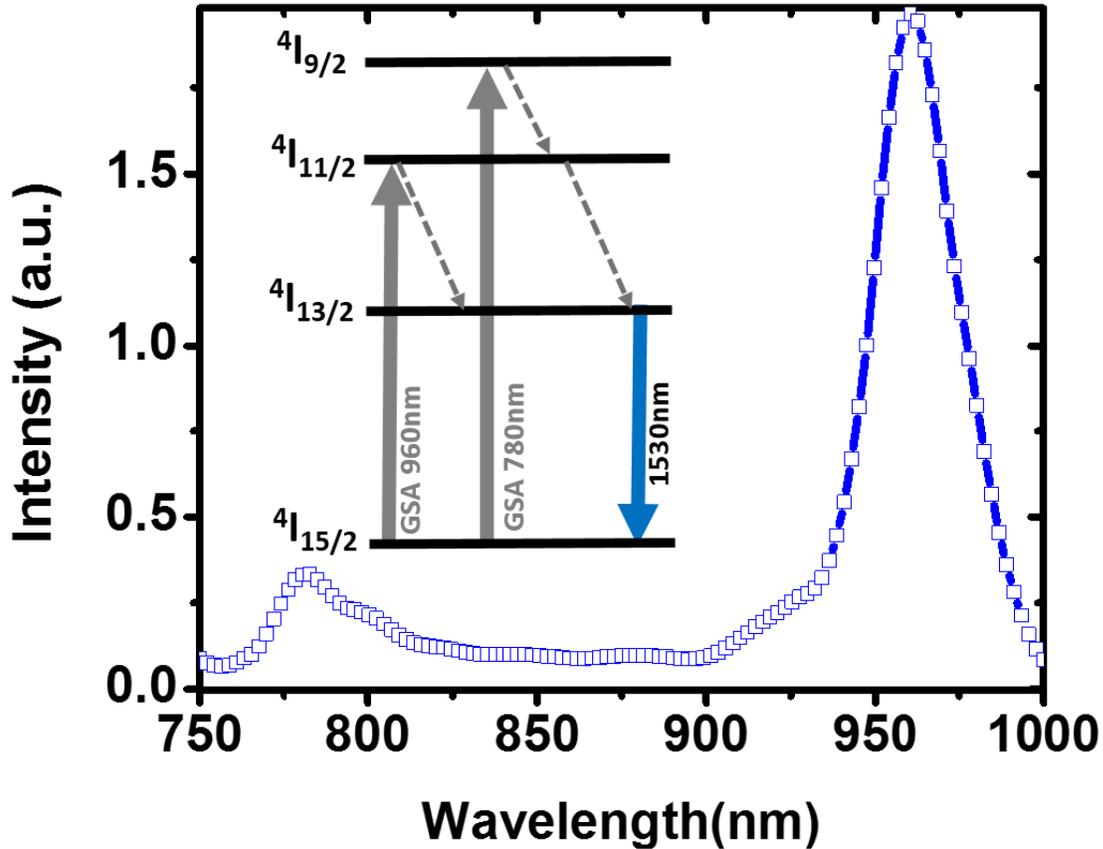


Fig. 4. PLE study of Er:YSZ thin film. Inset: scheme of ground state absorptions of Er^{3+} -doped YSZ (grey arrows) and its emission in the near-IR (blue arrow).

Photoluminescence excitation (PLE) was performed to reveal optimal Er^{3+} ions excitation wavelengths for Er:YSZ thin film emission at 1530 nm corresponding to the ${}^4\text{I}_{13/2} \rightarrow {}^4\text{I}_{15/2}$ transition. Emission at 1530 nm is reached for excitation transitions ${}^4\text{I}_{15/2} \rightarrow {}^4\text{I}_{9/2}$ and ${}^4\text{I}_{15/2} \rightarrow {}^4\text{I}_{11/2}$ corresponding at around 800 and 980 nm wavelength due to its high absorption cross-section, decaying to the ${}^4\text{I}_{13/2} \rightarrow {}^4\text{I}_{15/2}$ transition [35,36]. Despite excitation transitions are characteristic of Er^{3+} ions, its correspondent energy level is host dependent [37]. Following the scheme of Fig 4, in-plane PLE by Ti:Sapphire laser at 5 mW power and variable wavelength was carried out on Er:YSZ thin films. Intensity measurements for 1530 nm emission peak were recorded for excitation wavelengths between 750 and 1000 nm. Therefore, in order to keep incident photon energy constant, pumping power of 5mW has been adjusted for each wavelength. In Fig. 4, we observe two PLE maximum in intensity for all the Er: YSZ thin films: at 780 nm and 960 nm can be found a local and an absolute maximum corresponding to the ${}^4\text{I}_{15/2} \rightarrow {}^4\text{I}_{11/2}$ and ${}^4\text{I}_{15/2} \rightarrow {}^4\text{I}_{9/2}$ excitation transitions, respectively (Fig. 4 inset). Therefore, excitation of Er:YSZ thin films at 960 nm will give the most efficient emission at 1530 nm.

2.2.2. Photoluminescence

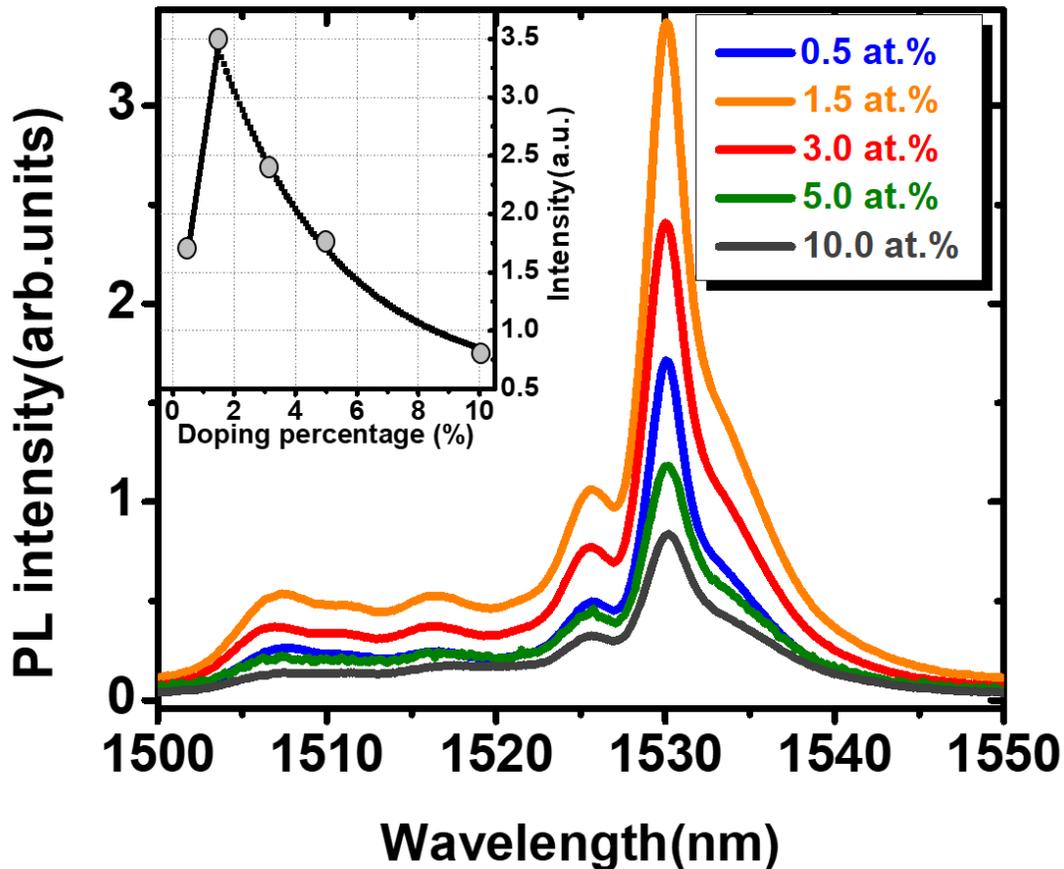


Fig. 5. Er^{3+} emission profile by PL for variable percentage of Er^{3+} ions. Inset, evolution of Er^{3+} maximum emission peak at 1530nm with doping percentage.

Optimal excitation wavelength by PLE to excite Er^{3+} ions within a YSZ host was proved to be 960 nm. Maximum of Er^{3+} emission is reached when increasing the number of Er^{3+} ions within the matrix whilst avoiding quenching effects by Er^{3+} - Er^{3+} ion interaction. Therefore, we excited Er^{3+} doped YSZ thin layer at a 960 nm wavelength and 10 mW power for all samples to perform out-of-plane photoluminescence (PL) on an optical setup (Fig. 1). In Fig. 5, we observe the characteristic Er^{3+} emission profile for an increasing Er^{3+} concentration. Fig. 5 inset shows the evolution of maximum emission peak at 1530 nm with increasing doping concentration. Optimal trade-off between quenching effect and maximum RE doping concentration on YSZ thin film corresponds to a doping of 1.5 at%. Therefore, hindering luminescence intensity with increasing doping can be observed in figure 4 inset, hence, 1.5 at% is the most effective doping concentration of Er^{3+} ions within the YSZ matrix in terms of near-IR luminescence.

2.2.3. Power efficiency

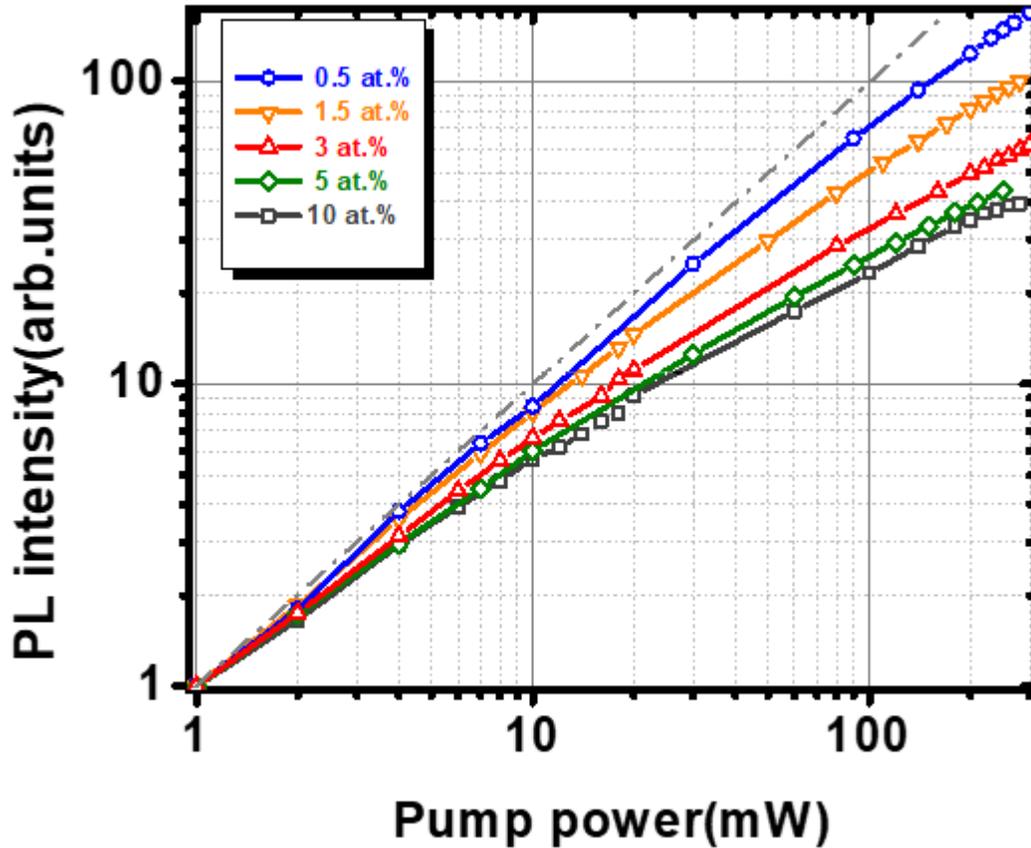


Fig. 6. (a) Log-log graphic of power study of Er:YSZ at Er^{3+} doping at different percentages.

Additionally, luminescence intensity can be enhanced by excitation of a higher number of Er^{3+} ions by increasing the laser pumping power. A decrease of the slope in the power efficiency is observed in fig. 6 under high pumping conditions, denoting the beginning of the saturation regime commonly observed when all optically active Er ions are excited in the matrix. For comparison, a grey dashed line with slope 1, reports the rate of Er^{3+} ions excited and radiatively emitted remaining constant, leading to no Er^{3+} - Er^{3+} interaction. In Fig.6 it is shown in log-log scale the correspondence between increasing pumping power with the detected PL intensity for different doping percentages. At high pumping powers (around 140 mW) saturation of PL intensity due to nonradiative decay of Er^{3+} ions by temperature quenching effects can be observed. Therefore, the most efficient concentration of Er^{3+} doping corresponds to 0.5 at% with a slope around 0.96, followed by increasing doping percentages of 1.5, 3, 5 and 10 at.%. Moreover, saturation is shown for doping percentages higher than 3 at.% at around 140 mW. This study reveals 0.5 at% doping to show low Er^{3+} - Er^{3+} interaction which progressively increases with doping concentration.

2.2.4. Lifetime

Long lifetime of Er^{3+} excited state (${}^4\text{I}_{13/2}$) is desired in order to reach population inversion for optical amplification purposes [38]. We have measured the decay curves of luminescence of three samples with different Er^{3+} concentration. Therefore, we performed direct excitation of the ${}^4\text{I}_{11/2}$ state by PL at room temperature. In Fig. 7, we can observe that lifetime of the state ${}^4\text{I}_{13/2}$ increase with increasing of erbium doping concentration. Lifetimes of 2.0, 1.6 and 1.2 ms

were measured for Er:YSZ thin films with Er^{3+} concentrations of 3, 1.5 and 0.5 at.%, respectively. Accordingly, studies of Laversenne et al. proved a direct relation between increase of Er^{3+} concentration and increase of lifetime of ${}^4\text{I}_{13/2}$, consistent with our results [39].

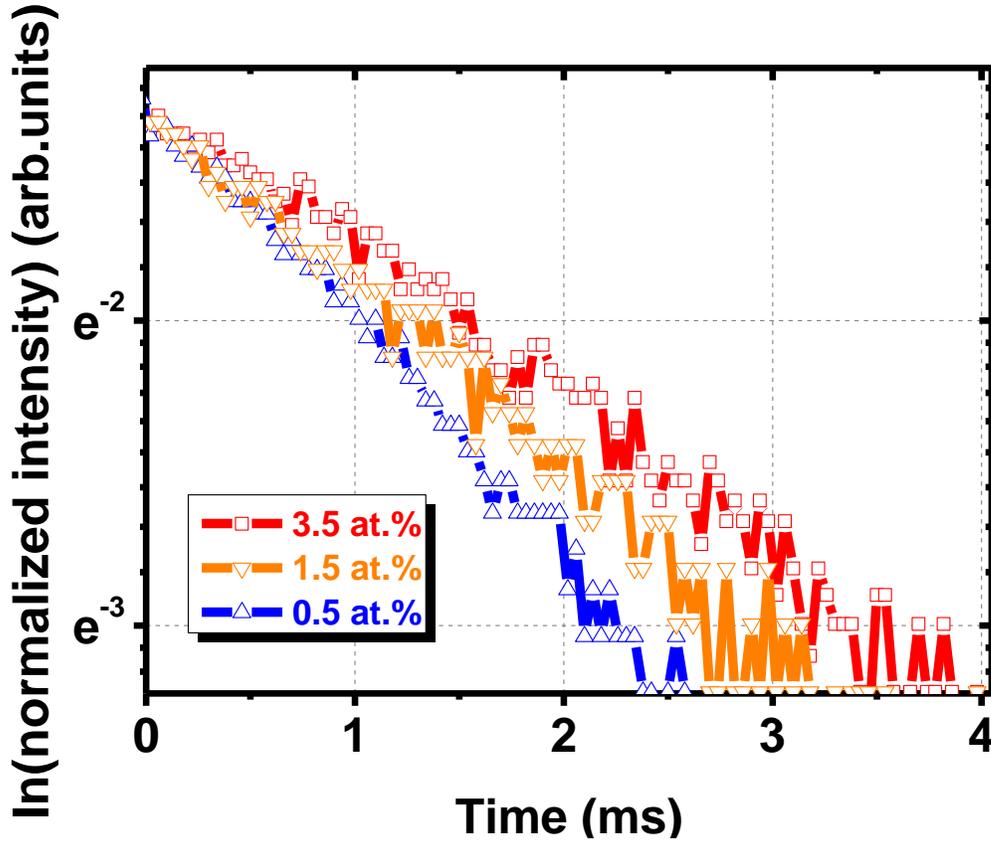


Fig. 7. Lifetime of out-of-plane Er:YSZ thin films for three different Er^{3+} concentrations.

3. Conclusions

In this study, we have grown 300nm thick Er:YSZ thin films with a refractive index of 2.15 on a sapphire substrate by PLD at different Er^{3+} concentrations. Structural characterization by AFM of the film surface, states a roughness as low as 2 nm for all the samples. Furthermore, XRD proves two YSZ crystalline orientations. Whilst (002) reflection peak is observed for all the samples, an increase of (111) orientation is related to an increase of Er^{3+} concentration. In this regard, studies in the literature relate doping increase with bulk defects and multiple crystal orientations.

PLE study for 1530 nm emission proves 780 nm and 960 nm to be the two excitation wavelengths corresponding to the Er^{3+} ions ${}^4\text{I}_{15/2} \rightarrow {}^4\text{I}_{9/2}$ and ${}^4\text{I}_{15/2} \rightarrow {}^4\text{I}_{11/2}$ transitions within YSZ crystal, respectively. Transition ${}^4\text{I}_{11/2}$ presents higher cross-section absorption, therefore, we fixed this excitation wavelength for PL, power efficiency, and lifetime studies. Results of PL proves emission for the ${}^4\text{I}_{13/2} \rightarrow {}^4\text{I}_{15/2}$ transition at 1530 nm for all Er^{3+} doping concentrations. While in PL measurements we can observe intensity emission within a bulk volume excited by the laser, power efficiency studies show a linear ratio between the pumping power and the emitted PL, which decreases for high pumping values. Such decrease of the power efficiency has been attributed to Er^{3+} - Er^{3+} interaction due to highly RE doping concentrations.

Therefore, despite observing higher PL emission at 1530 nm for 1.5 at. %, it has been found for 0.5 at. % Er³⁺ concentration to have higher power efficiency. Hence, while concentration of 0.5 at. % proves higher excitation-emission ratio, samples with a concentration of 1.5 at. % have higher number of active Er³⁺ ions showing higher PL intensities. For concentrations higher than 1.5 at%, Er³⁺- Er³⁺ interaction strongly hinders Er³⁺ emission by PL. Lifetime for three different Er³⁺ concentrations have been measured. As expected, higher Er³⁺ doped samples present higher lifetimes.

In this work, we have demonstrated efficient concentration of 1.5 at. % Er³⁺ ions on YSZ thin films presents high lifetime and PL intensities. Increasing quenching effects are shown with increase of Er³⁺ ion concentration, hindering luminescence for concentrations higher than 1.5 at.%.

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