



Cross-relaxation and ion clustering in Tm³⁺:CaF₂ crystals

Pavel Loiko, A. Braud, Lauren Guillemot, Jean-Louis Doualan, Abdelmjid Benayad, Patrice Camy

► To cite this version:

Pavel Loiko, A. Braud, Lauren Guillemot, Jean-Louis Doualan, Abdelmjid Benayad, et al.. Cross-relaxation and ion clustering in Tm³⁺:CaF₂ crystals. SPIE Photonics Europe, Apr 2020, Online Only, France. pp.23, <10.1117/12.2555057>. <hal-03140566>

HAL Id: hal-03140566

<https://hal.science/hal-03140566v1>

Submitted on 7 Oct 2021

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.



HAL Authorization

Cross-relaxation and ion clustering in $\text{Tm}^{3+}:\text{CaF}_2$ crystals

Pavel Loiko^{a,*}, Alain Braud^a, Lauren Guillemot^a, Jean-Louis Doualan^a, Abdelmjid Benayad^a,
and Patrice Camy^a

^aCentre de recherche sur les Ions, les Matériaux et la Photonique (CIMAP), UMR 6252 CEA-CNRS-ENSICAEN, Université de Caen, 6 Boulevard du Maréchal Juin, 14050 Caen, France

ABSTRACT

We systematically study cross-relaxation (CR) and ion clustering in $\text{Tm}^{3+}:\text{CaF}_2$ crystals using a spectroscopic approach. For this, the luminescence from the $^3\text{H}_4$ and $^3\text{F}_4$ states was monitored for a broad range of Tm^{3+} doping concentrations, from 0.01 at.% to 7 at.%. The decay curves were fitted using a model of two ions classes, namely isolated ions showing no energy-transfer processes and ions with neighbors exhibiting both CR and energy-transfer upconversion (ETU), and accounting for energy-migration. The fraction of ions with neighbors and the microscopic concentration-independent CR and ETU parameters are deduced. The critical Tm^{3+} doping level for which at least half of the active ions are clustered is only 0.7 at.%. The obtained results are relevant for achieving efficient laser operation of $\text{Tm}^{3+}:\text{CaF}_2$ crystals at the $^3\text{F}_4 \rightarrow ^3\text{H}_6$ (at $\sim 1.9 \mu\text{m}$) and the $^3\text{H}_4 \rightarrow ^3\text{H}_5$ (at $\sim 2.3 \mu\text{m}$) transitions.

Keywords: calcium fluoride, thulium ions, cross-relaxation, ion clustering, luminescence.

1. INTRODUCTION

Cubic (fluorite-type) calcium fluoride (CaF_2) crystals are well-known for fabrication of optical elements because of their good thermo-mechanical properties (thermal conductivity: $\kappa \sim 9.7 \text{ W}/(\text{mK})$ for an undoped crystal), broad transparency range (0.13–10 μm) and low refractive index ($n = 1.424$ at $\sim 2 \mu\text{m}$). CaF_2 crystals are also suitable for doping with trivalent rare-earth ions (RE^{3+}) for laser applications [1-3]. They feature a strong RE^{3+} ion clustering even at low doping concentrations about 0.1–1 at.% [4,5] resulting in broad and smooth spectral bands both in absorption and emission (the so-called glassy-like spectroscopic behavior). It is of interest for broadly tunable [6] and mode-locked [7,8] lasers. The good thermal properties of the host matrix allow for power scaling.

Thulium (Tm^{3+}) doped CaF_2 crystals exhibit a broadband emission at $\sim 1.9 \mu\text{m}$ due to the $^3\text{F}_4 \rightarrow ^3\text{H}_6$ electronic transition. Efficient $\text{Tm}^{3+}:\text{CaF}_2$ lasers were reported [2,9]. Camy *et al.* reported on a laser-pumped $\text{Tm}:\text{CaF}_2$ laser delivering $\sim 135 \text{ mW}$ at 1887 nm with a slope efficiency of 41% and a laser threshold of only 68 mW [2]. Liu *et al.* reported on power scaling of a $\text{Tm}:\text{CaF}_2$ laser under diode-pumping yielding 2.71 W with a higher slope efficiency of 70.1% [9]. The same group of authors demonstrated continuous wavelength tunability for this laser between 1.85 and 2.04 μm (189 nm broad) and mode-locked operation employing a SESAM. In the latter case, 15 ps-long pulses were obtained at a central wavelength of 1886.8 nm with a repetition rate of 96.35 MHz [9]. Thin films of $\text{Tm}:\text{CaF}_2$ were grown [10].

It was proven that the ion clustering determines the emission properties of Tm^{3+} ions in CaF_2 [5]. For low doping levels (0.01-0.1 at.%), the Tm^{3+} ions are mostly isolated and they accommodate in sites with different symmetry depending on the charge compensation mechanism involving interstitial F^- anions. For higher doping levels, ion clusters are formed. To prevent the clustering of active ions, the CaF_2 crystals were codoped by Tm^{3+} ions and optically passive “buffer” ions Ln^{3+} such as Gd^{3+} , Lu^{3+} , La^{3+} or Y^{3+} [11,12]. Laser operation with such codoped crystals was also demonstrated. Zhang *et al.* reported on a $\text{Tm},\text{La}:\text{CaF}_2$ laser delivering 4.27 W at 1921 nm with a slope efficiency of 67.8% [12].

A key spectroscopic process which determines the laser efficiency of $\sim 1.9 \mu\text{m}$ Tm lasers is the cross-relaxation (CR) for adjacent Tm^{3+} ions, $^3\text{H}_4(\text{Tm}_1) + ^3\text{H}_6(\text{Tm}_2) \rightarrow ^3\text{F}_4(\text{Tm}_1) + ^3\text{F}_4(\text{Tm}_2)$, potentially leading to a pump quantum efficiency of 2 [13]. This means that after an excitation at $\sim 0.8 \mu\text{m}$ (to the $^3\text{H}_4$ pump level), there can be up to 2 excited ions in the upper laser level ($^3\text{F}_4$). CR in Tm^{3+} -doped laser materials increases the laser slope efficiency and reduces the heat dissipation. Up to now, no detailed study of CR for $\text{Tm}:\text{CaF}_2$ crystals was performed.

*e-mail: pavel.loiko@ensicaen.fr

The aim of the present work is to study the cross-relaxation (and other energy-transfer processes, such as energy-transfer upconversion (ETU)) in Tm:CaF₂ crystals accounting for the ion clustering. For this, we involve the spectroscopic model of distinct ion classes which was recently developed [14].

2. EXPERIMENTAL RESULTS

For the spectroscopic studies, we grew a series of Tm³⁺:CaF₂ crystals with the doping level ranging from 0.01 at.% to 7 at.%. The Tm:CaF₂ crystals were grown using a conventional Bridgman technique with a homemade furnace. A mixture of high purity (4N) CaF₂ and TmF₃ powders was introduced in a graphite crucible. A good vacuum (<10⁻⁵ mbar) was realized before introducing Ar and CF₄ gases to avoid oxygen pollution. The furnace temperature was set to about 50 K higher than the melting point of CaF₂. After soaking, the charge was thoroughly melted and the crystal growth was carried out with a rate of 2-4 mm/h. When the growth was finished, the crystal was cooled down to room temperature (RT, 293 K) within 48 hours.

2.1 Absorption and luminescence

The RT absorption spectra of Tm³⁺:CaF₂ crystals containing predominantly isolated ions (0.05 at.% Tm) and ion clusters (1.5 at.% and 4.5 at.% Tm) are shown in Fig. 1. It is known that in Tm³⁺-doped CaF₂ crystals with very low doping levels, the active ions are distributed over three types of sites with the symmetry C_{3v} (trigonal), C_{4v} (tetragonal) or O_h (cubic). The particular symmetry depends on the charge compensation mechanism (as trivalent Tm³⁺ ions are replacing the divalent Ca²⁺ ones). The latter is provided by an interstitial fluorine anion (F_i⁻). Here, we do not consider the possible charge compensation by oxygen (O²⁻) or univalent alkali metal cations (Na⁺, K⁺) leading to other types of sites. As a result, the absorption spectra of the 0.05 at.% Tm³⁺:CaF₂ crystal represent a superposition of sharp absorption lines of Tm³⁺ ions in all three sites. For high doping levels, the Tm³⁺ ions are mostly arranged in clusters leading to smooth and broad spectral bands. There is no significant change in the absorption spectra of 1.5 at.% Tm and 4.5 at.% Tm-doped crystals, except of the ³H₆ → ³H₅ transition. The small changes may reflect the transition from simple clusters (dimers, trimers) to large agglomerates of active ions.

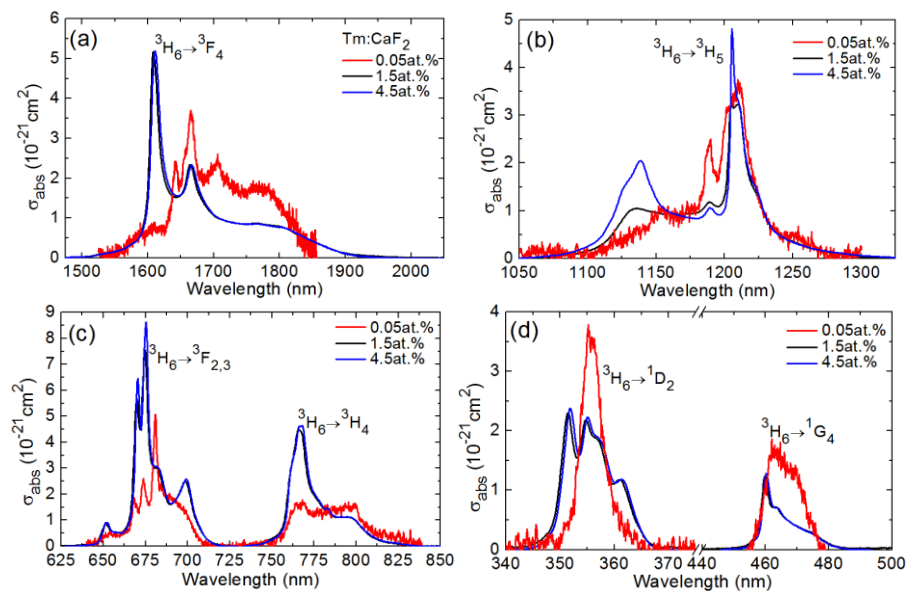


Figure 1. RT absorption cross-section, σ_{abs} , spectra of Tm³⁺:CaF₂ crystals with different Tm doping concentrations (0.05 at.%, 1.5 at.% and 4.5 at.%): transitions from the ground-state (³H₆) to the excited-states: (a) ³F₄, (b) ³H₅, (c) ³H₄ and ³F_{2,3}, and (d) ¹G₄ and ¹D₂.

For the ³H₆ → ³H₄ pump transition, the maximum absorption cross-section σ_{abs} is $0.46 \times 10^{-20} \text{ cm}^2$ at 766.2 nm and the full width at half maximum (FWHM) of the absorption band is 13.2 nm (for the 4.5 at.% Tm doping). For the 0.05 at.% Tm doping, the peak σ_{abs} value is much lower, $0.17 \times 10^{-20} \text{ cm}^2$ at ~768 nm.

The evolution of RT luminescence spectra for the $^3\text{H}_4 \rightarrow ^3\text{H}_6$ (at $\sim 0.8 \mu\text{m}$) and $^3\text{F}_4 \rightarrow ^3\text{H}_6$ (at $\sim 1.9 \mu\text{m}$) transitions in emission was studied for a broad range of Tm doping concentrations (0.01–7 at.%). This comparative study revealed a critical Tm concentration (0.5–0.7 at.%) for which a significant change in the shape of the emission bands is observed: the spectra become smooth and broad and they resemble to a great extent those for Tm^{3+} -doped fluoride glasses. This is an indication of a change in the predominant ion coordination (a transition from isolated ions to clusters). Figure 2 shows such a comparison for the emission from the pump level ($^3\text{H}_4$) at $\sim 0.8 \mu\text{m}$.

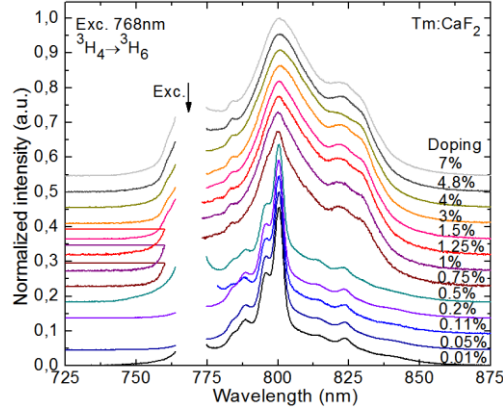


Figure 2. Normalized RT luminescence spectra of $\text{Tm}^{3+}:\text{CaF}_2$ crystals with different doping concentrations (the $^3\text{H}_4 \rightarrow ^3\text{H}_6$ transition), $\lambda_{\text{exc}} = 769 \text{ nm}$ (non-selective excitation).

2.2 Luminescence decay

We monitored the decay of Tm^{3+} luminescence from the $^3\text{H}_4$ and $^3\text{F}_4$ multiplets for a broad range of Tm doping levels (0.01–7 at.%) in CaF_2 . Figure 3 shows the measured luminescence decay curves for the $^3\text{H}_4 \rightarrow ^3\text{H}_6$ transition in emission (at $\sim 0.8 \mu\text{m}$). For very low doping level (0.01 at.% Tm), the luminescence decay curve is close to a single-exponential one with a characteristic lifetime τ_{lum} of 3.55 ms. Despite the existence of several species contributing to this emission (namely, isolated Tm^{3+} ions in various sites), the intrinsic lifetimes of the $^3\text{H}_4$ state for the C_{3v} and C_{4v} coordinated Tm^{3+} ions in CaF_2 are rather close: 3.03 ms and 3.59 ms, respectively (as determined in site-selective excitation experiments). With increasing Tm doping, the decay from the $^3\text{H}_4$ state becomes faster and the luminescence decay curves notably deviate from the single-exponential law.

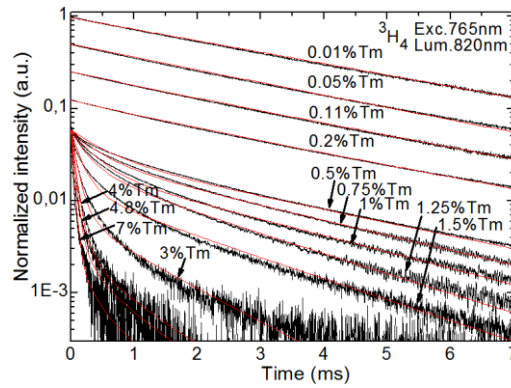


Figure 3. Luminescence decay curves from the $^3\text{H}_4$ Tm^{3+} state in $\text{Tm}^{3+}:\text{CaF}_2$: *black* – experimental data, *red* – their fitting with the rate-equation model of distinct ion classes, $\lambda_{\text{exc}} = 765 \text{ nm}$, $\lambda_{\text{lum}} = 820 \text{ nm}$. Measured under ns pulse excitation.

To explain this behavior, we used the model of spectroscopically distinct ion classes [14]. A simplified scheme of Tm^{3+} energy-levels was considered, Fig. 4. The populations of the Tm^{3+} ground-state ($^3\text{H}_6$) and two relevant excited-states ($^3\text{F}_4$ and $^3\text{H}_4$) were monitored; the population of the intermediate $^3\text{H}_5$ excited-state was assumed to be almost zero as this state is depopulated by very efficient multi-phonon non-radiative (NR) relaxation. The states above $^3\text{H}_4$ were not taken into account. The following spectroscopic processes were considered: (i) radiative (R) decay from the $^3\text{F}_4$ and $^3\text{H}_4$ states, (ii) cross-relaxation (CR) $^3\text{H}_4(\text{Tm}_1) + ^3\text{H}_6(\text{Tm}_2) \rightarrow ^3\text{F}_4(\text{Tm}_1) + ^3\text{F}_4(\text{Tm}_2)$, (iii) energy-transfer upconversion, $^3\text{F}_4(\text{Tm}_1) +$

$^3F_4(Tm_2) \rightarrow ^3H_6(Tm_1) + ^3H_4(Tm_2)$ (ETU₁) and $^3F_4(Tm_1) + ^3F_4(Tm_2) \rightarrow ^3H_6(Tm_1) + ^3H_5(Tm_2)$ (ETU₂), and (iv) energy-migration (EM) to impurities leading to de-excitations from the 3F_4 and 3H_4 multiplets. We assumed the existence of two distinct ion classes: (a) isolated ions showing no energy-transfer processes (CR and ETU) and (b) ions with neighbors exhibiting both CR and ETU. The fraction of ions with neighbors f , the macroscopic rates of CR (W_{CR}) and ETU (W_{ETU1} and W_{ETU2}) and the 3H_4 level lifetime τ_3 accounting for EM were used as free parameters of the fitting (for luminescence decay curves shown in Fig. 3). The model gives a satisfactory agreement with the experiment.

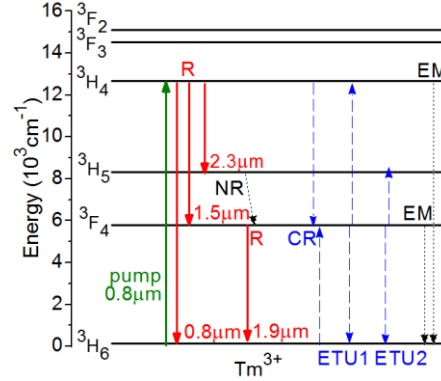


Figure 4. The scheme of energy-levels of Tm^{3+} ions (for a free-ion) showing relevant spectroscopic processes associated with the conventional pumping scheme (to the 3H_4 state): R – radiative relaxation, NR – multiphonon non-radiative relaxation, CR – cross-relaxation, ETU – energy-transfer upconversion, EM – energy-migration.

3. DISCUSSION

The results on the fraction of Tm^{3+} ions with neighbors f are shown in Fig. 5. With increasing the Tm doping level, the fraction of isolated ions ($1 - f$) gradually decreases. The critical Tm doping level for which at least half of the active ions are clustered is only 0.7 ± 0.1 at.%. This agrees well with our conclusion drawn from the measured luminescence spectra at $\sim 0.8 \mu m$. The dependence of f on the doping concentration was fitted using a statistical approach [14,15]:

$$P_{m,n} = \frac{n!}{m!(n-m)!} p^m (1-p)^{n-m}. \quad (1)$$

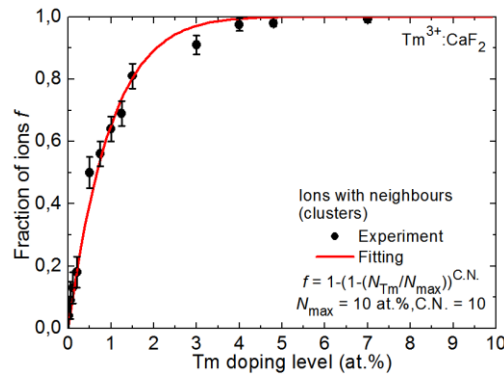


Figure 5. Ion clustering in $Tm^{3+}:CaF_2$: fraction of ions with neighbors f , *symbols* – data extracted from the modeling of the experimental luminescence decay curves using the rate-equation model of distinct ion classes, *curve* – their fit using a statistical approach.

Here, $P_{m,n}$ is the probability for occurrence of neighbor Tm^{3+} ions in the first coordination sphere of the considered Tm^{3+} ion, n is the coordination number (C.N.) by nearest-neighbor rare-earth sites, m is the actual number of Tm^{3+} ions in the first coordination sphere ($m = 0$ corresponds to a single ion and $m \geq 1$ - to an ion pair or cluster), and $p = N_{Tm}/N_{max}$ represents the relative doping concentration (N_{max} is the maximum possible concentration). The expression for the fraction of ions with neighbors ($m \geq 1$, not specifying the exact m number) is:

$$f = 1 - [1 - (N_{\text{Tm}} / N_{\text{max}})]^{\text{C.N.}} \quad (2)$$

For calculation, we assume $N_{\text{max}} = 10$ at.% and C.N. = 10 which gives a good agreement with the data obtained from the measured luminescence curves.

The model also yields the macroscopic rates W_{CR} , W_{ETU1} and W_{ETU2} [in s^{-1}], as shown in Fig. 6. The CR in $\text{Tm}^{3+}:\text{CaF}_2$ is much stronger than the ETU. W_{CR} and $W_{\text{ETU1(2)}}$ show a quadratic dependence on the Tm doping concentration (N_{Tm}):

$$W_{\text{CR}} = C_{\text{CR}} N_{\text{Tm}}^2, \quad (3a)$$

$$W_{\text{ETU1(2)}} = C_{\text{ETU1(2)}} N_{\text{Tm}}^2, \quad (3b)$$

where C_{CR} and $C_{\text{ETU1(2)}}$ are the concentration-independent microscopic energy-transfer parameters. CR in $\text{Tm}^{3+}:\text{CaF}_2$ is about one order of magnitude stronger than that in other well-known fluoride crystal, $\text{Tm}^{3+}:\text{LiYF}_4$ [16].

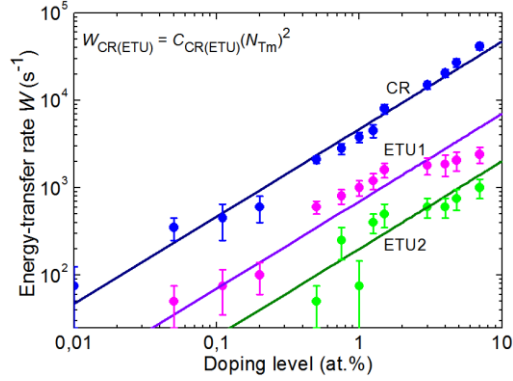


Figure 6. Energy-transfer processes in $\text{Tm}^{3+}:\text{CaF}_2$: macroscopic rates of cross-relaxation (CR) W_{CR} and energy-transfer upconversion (ETU) $W_{\text{ETU1(2)}}$, symbols – data extracted from the modeling of the experimental luminescence decay curves using the rate-equation model of distinct ion classes, lines – their quadratic fits.

4. CONCLUSIONS

To conclude, we have quantified ion clustering (in terms of fraction of ions with neighbors) and CR and ETU energy-transfer processes (in terms of macroscopic rates and microscopic concentration-independent parameters) in Tm^{3+} -doped CaF_2 crystals, for the first time, to the best of our knowledge. This information is of key importance for the design of $\text{Tm}:\text{CaF}_2$ lasers operating on the $^3\text{F}_4 \rightarrow ^3\text{H}_6$ ($\sim 1.9 \mu\text{m}$) and $^3\text{H}_4 \rightarrow ^3\text{H}_5$ ($\sim 2.3 \mu\text{m}$ [17]) transitions. Indeed, for the $\sim 1.9 \mu\text{m}$ lasers, quantification of CR is important to determine the possibility to reach high pump quantum efficiency of 2 for the upper laser level ($^3\text{F}_4$) [13]. For the $\sim 2.3 \mu\text{m}$ lasers which have not been demonstrated yet in $\text{Tm}:\text{CaF}_2$, in contrast, CR is a detrimental effect as it quenches the lifetime of the upper laser level ($^3\text{H}_4$). However, ETU1 in such lasers can play a key role in refilling the $^3\text{H}_4$ state leading to increased laser slope efficiency [16,18]. The proposed spectroscopic model can be extended to describe the ion clustering in $\text{Tm}^{3+}, \text{Ln}^{3+}:\text{CaF}_2$ crystals codoped with “buffer” ions.

5. ACKNOWLEDGEMENTS

This work was supported by the Agence Nationale de la Recherche (ANR), SPLENDID2 Project; European Community funds FEDER; Normandie region, NOVAMAT Project.

REFERENCES

- [1] F. Druon, S. Ricaud, D. N. Papadopoulos, A. Pellegrina, P. Camy, J. L. Doualan, R. Moncorgé, A. Courjaud, E. Mottay, and P. Georges, “On $\text{Yb}:\text{CaF}_2$ and $\text{Yb}:\text{SrF}_2$: review of spectroscopic and thermal properties and their impact on femtosecond and high power laser performance,” *Opt. Mater. Express* 1(3), 489–502 (2011).
- [2] P. Camy, J.L. Doualan, S. Renard, A. Braud, V. Menard, and R. Moncorgé, “ $\text{Tm}^{3+}:\text{CaF}_2$ for $1.9 \mu\text{m}$ laser operation,” *Opt. Commun.* 236(4-6), 395-402 (2004).

- [3] Labbe, C., Doualan, J.L., Camy, P., Moncorgé, R. and Thuau, M., "The 2.8 μm laser properties of Er^{3+} doped CaF_2 crystals," *Opt. Commun.* 209(1-3), 193-199 (2002).
- [4] V. Petit, P. Camy, J.-L. Doualan, X. Portier, and R. Moncorgé, "Spectroscopy of $\text{Yb}^{3+}:\text{CaF}_2$: from isolated centers to clusters," *Phys. Rev. B Condens. Matter Mater. Phys.* 78(8), 085131 (2008).
- [5] S. Renard, P. Camy, A. Braud, J. L. Doualan, and R. Moncorgé, " CaF_2 doped with Tm^{3+} : A cluster model," *J. Alloys Compd.* 451(1-2), 71-73 (2008).
- [6] A. Lucca, M. Jacquemet, F. Druon, F. Balembois, P. Georges, P. Camy, J. L. Doualan, and R. Moncorgé, "High-power tunable diode-pumped $\text{Yb}^{3+}:\text{CaF}_2$ laser," *Opt. Lett.* 29(16), 1879–1881 (2004).
- [7] A. Lucca, G. Debourg, M. Jacquemet, F. Druon, F. Balembois, P. Georges, P. Camy, J. L. Doualan, and R. Moncorgé, "High-power diode-pumped $\text{Yb}^{3+}:\text{CaF}_2$ femtosecond laser," *Opt. Lett.* 29(23), 2767–2769 (2004).
- [8] Friebe, F., Druon, F., Boudeile, J., Papadopoulos, D.N., Hanna, M., Georges, P., Camy, P., Doualan, J.L., Benayad, A., Moncorgé, R. and Cassagne, C., "Diode-pumped 99 fs $\text{Yb}:\text{CaF}_2$ oscillator," *Opt. Lett.* 34(9), 1474-1476 (2009).
- [9] Liu, J., Zhang, C., Zhang, Z., Wang, J., Fan, X., Liu, J. and Su, L., "1886-nm mode-locked and wavelength tunable Tm -doped CaF_2 lasers," *Opt. Lett.* 44(1), 134-137 (2019).
- [10] Brasse, G., Loiko, P., Grygiel, C., Leprince, P., Benayad, A., Lemarie, F., Doualan, J.L., Braud, A. and Camy, P., "Liquid Phase Epitaxy growth of Tm^{3+} -doped CaF_2 thin-films based on LiF solvent," *J. Alloys Compd.* 803, 442-449 (2019).
- [11] X. Liu, K. Yang, S. Zhao, T. Li, C. Luan, X. Guo, B. Zhao, L. Zheng, L. Su, J. Xu, and J. Bian, "Growth and lasing performance of a $\text{Tm}:\text{Y}:\text{CaF}_2$ crystal," *Opt. Lett.* 42(13), 2567-2570 (2017).
- [12] Zhang, Z., Guo, X., Wang, J., Zhang, C., Liu, J. and Su, L., "High-efficiency 2 μm continuous-wave laser in laser diode-pumped $\text{Tm}^{3+}, \text{La}^{3+}:\text{CaF}_2$ single crystal," *Opt. Lett.* 43(17), 4300-4303 (2018).
- [13] K. van Dalen, S. Aravazhi, C. Grivas, S. M. García-Blanco, and M. Pollnau, "Thulium channel waveguide laser with 1.6 W of output power and $\sim 80\%$ slope efficiency," *Opt. Lett.* 39(15), 4380-4383 (2014).
- [14] P. Loiko, and M. Pollnau, "Stochastic model of energy-transfer processes among rare-earth ions. Example of $\text{Al}_2\text{O}_3:\text{Tm}^{3+}$," *J. Phys. Chem. C* 120(46), 26480-26489 (2016).
- [15] Voron'ko, Y.K., Mamedov, T.G., Osiko, V.V., Timoshechkin, M.I. and Shcherbakov, I.A., "Effect of donor-donor and donor-acceptor interactions on the decay kinetics of the metastable state of Nd^{3+} in crystals," *Sov. J. Exp. Theor. Phys.* 38, 565 (1974).
- [16] Loiko P., Soulard R., Guillemot L., Brasse G., Doualan J.L., Braud A., Tyazhev A., Hideur A., Druon F., and Camy P., "Efficient $\text{Tm}:\text{LiYF}_4$ lasers at 2.3 μm : Effect of energy-transfer upconversion," *IEEE J. Quantum Electron.* 55(6), 1700212 (2019).
- [17] Pinto J. F., Esterowitz L., and Rosenblatt G. H., " $\text{Tm}^{3+}:\text{YLF}$ laser continuously tunable between 2.20 and 2.46 μm ," *Opt. Lett.* 19(12), 883-885 (1994).
- [18] Guillemot L., Loiko P., Soulard R., Braud A., Doualan J.L., Hideur A., and Camy P., "Close look on cubic $\text{Tm}:\text{KY}_3\text{F}_{10}$ crystal for highly efficient lasing on the $^3\text{H}_4 \rightarrow ^3\text{H}_5$ transition," *Opt. Express* 28(3), 3451-3463 (2020).