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Analysing the effect of the crystal structure on upconversion luminescence in Yb$^{3+}$, Er$^{3+}$-co-doped NaYF$_4$ nanomaterial

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NaYF$_4$:Yb:Er nanoparticles (UCNP) were synthesized under mild experimental conditions to obtain a pure cubic lattice. Upon annealing at different temperatures up to $T_{\text{an}} = 700^\circ$C phase transitions to the hexagonal phase and back to the cubic phase were induced. The UCNP materials obtained for different $T_{\text{an}}$ were characterized with respect to the lattice phase using standard XRD and Raman spectroscopy as well as steady state and time resolved upconversion luminescence. The standard techniques showed that for the annealing temperature range $300^\circ$C < $T_{\text{an}} < 600^\circ$C the hexagonal phase was dominant. For $T_{\text{an}} < 300^\circ$C hardly any change in the lattice phase could be deduced, whereas for $T_{\text{an}} > 600^\circ$C a back transfer to the α-phase was observed. Complementary, the luminescence upconversion properties of the annealed UCNP materials were characterized in steady state and time resolved luminescence measurements. Distinct differences in the upconversion luminescence intensity, the spectral intensity distribution and the luminescence decay kinetics were found for the cubic and hexagonal lattice phase, respectively, corroborating the results of the standard analytical techniques used. In laser power dependent measurements of the upconversion luminescence intensity it was found that the green (G1, G2) and red (R) emission of Er$^{3+}$ showed different effects of $T_{\text{an}}$ on the number of required photons reflecting the differences in the population routes of the different energy levels involved. Furthermore, the intensity ratio of G/R is highly effected by the laser power only when the β-phase is present, whereas the G1/G2 intensity ratio is only slightly effected regardless of the crystal phase. Moreover, based on the different upconversion luminescence kinetics characteristic for the cubic and hexagonal phase time-resolved area normalized emission spectra (TRANES) proved to be a very sensitive tool to monitor the phase transition between cubic and hexagonal phase. Based on the TRANES analysis it was possible to resolve the lattice phase transition in more detail for $200^\circ$C < $T_{\text{an}} < 300^\circ$C, which was not possible with the standard techniques.

1. Introduction

Nanomaterials labeled with fluorescent dyes have been widely used in life-science applications and biological studies.1–6 Typically, these labeling compounds are organic dyes, such as Alexa Fluor, fluorescein isothiocyanate (FITC), cyanine dyes (Cy3, Cy5 or Cy7) and rhodamin derivates.7–9 Recently, semiconductor quantum dots have emerged as great potential candidates for life-science applications.10–16 These conventional down conversion luminescence probes require light in the ultraviolet or visible spectral range for excitation. Their main disadvantages are the background-related auto-fluorescence of biological samples due to the UV/Vis excitation wavelengths typically used, photobleaching of the probes, low light penetration depth in tissues like skin and possible damages to the biological matrix under investigation.1,7,17

Upconversion (UC) luminescent materials have attracted a great interest in recent years due to their outstanding photophysical properties and the resulting application potentials in various fields such as solid-state lasers, solar cells, color displays or life sciences.18–27 Upconversion materials based on lanthanide-doped fluorides received a lot of attention owing to their high UC efficiency and photostability. Highly efficient UC materials among various fluoride based UC phosphors are β-phase NaYF$_4$ doped with Yb$^{3+}$ and Er$^{3+}$ or Yb$^{3+}$ and Tm$^{3+}$ as sensitizer-activator pair, respectively.28–33 The luminescence properties of upconversion nanoparticles (UCNP) are dependent on a complex interplay between the different dopant ions on the one hand side and the host lattice on the other hand side.6,9,34 Thus, the luminescence of these particles can be tuned by the crystal structure of the host lattice, the particle size, the ratio of the different lanthanides used as dopands, and the power density of the excitation light.35 E.g., for NaYF$_4$ the host lattice geometry can be switched by annealing between the different cubic (α) and the hexagonal (β) phase subsequently also tuning the UC properties of the materials.20,36–39

In the present study, the UCNP were synthesized under mild reaction conditions ($T_{\text{synthesis}} = 160^\circ$C) in order to obtain a pure cubic (α) phase host lattice. Subsequently, in order to investigate the influence of the crystal phase on the upconversion luminescence properties different annealing temperatures ($T_{\text{an}}$) were applied to induce a phase transition in the material. The alterations in the photophysical properties of
the UCNP materials obtained for different $T_{an}$ were monitored using steady state and time-resolved luminescence techniques. Time-resolved area-normalized emission spectra (TRANCES) can often be useful method to illustrate the overall dynamic, especially to identify at least two emissive states.\textsuperscript{30-41} Based on the luminescence data the interplay of the population routes of sensitizer and activator electronic states involved in the different luminescence upconversion processes were analyzed in order to increase the understanding of the UCNP photophysics. The detailed knowledge of it on a molecular level provides the basis for UCNP material synthesis tailored for the specific needs of applications they are going to be used such as multiplexing applications like temperature sensing or in vivo imaging. The upconversion luminescence data are complemented by Raman, SEM and XRD measurements to determine the size and the crystal phase of the UCNP investigated and to underline the power of luminescence techniques in the structural characterization of such materials.

2. Experimental

2.1 Materials

All rare earth oxides RE$_2$O$_3$ (RE: Y, Yb and Er) were purchased from Chem Pur Feinchemikalien and Forschungsbedarf GmbH. Sodium fluoride (NH$_4$F, 99%) was purchased from Sigma Aldrich. Nitric acid solution (HNO$_3$, 65%), sodium chloride and ethanol (99.5%) was purchased from Carl Roth. Polyvinylpyrrolidone (PVP 40). In the experiments double distilled water was used. In the synthesis all chemical reagents were used as received.

2.2 Synthesis of NaYF$_4$:Yb$_3$+Er$_3$+ UCNP

The UCNPs were synthesized according to a previously reported procedure in which a well-known hydrothermal method with PVP 40 as a capping agent was applied.\textsuperscript{1,29,46} The rare earth nitrates (RE(NO$_3$)$_3$) were prepared from the corresponding oxides in stoichiometric amounts of Y$_2$O$_3$ (3.9 mmol), Yb$_2$O$_3$ (1.0 mmol) and Er$_2$O$_3$ (0.1 mmol) dissolved in nitric acid (200 mL, 10%) according to the literature method.\textsuperscript{47} Typically, the obtained RE(NO$_3$)$_3$ was dissolved in 200 mL ethylene glycol and was treated with a mixture of NaCl (20 mmol) and 8.9 g PVP 40 (solution A). NH$_4$F (80 mmol) was dissolved in 200 mL ethylene glycol and heated to 80°C in a second reaction vessel until a clear solution was obtained (solution B). Subsequently solution A was heated to 80°C and solution B was released into the hot solution within a few seconds. The combined solutions were heated to 160°C. After 2 h the solution was cooled down to room temperature (RT) and the product was separated via centrifugation (4000 rpm for 20 min). The particles were further purified alternately with water and absolute ethanol. Finally, the precipitate was dried at 85°C for 5 h and a white powder was obtained. Taking into account the amount of volatile organic material present in the material (approximately 11 % mass loss according to thermo gravimetric studies) a yield of 75% - 90 % was calculated. The composition of the UCNP is shown in Table 1. The chosen Er$^{3+}$ concentration was small in order to eliminate possible cross relaxation between two excited Er$^{3+}$ ions (see Scheme 1).

![Scheme 1](image1)

To calculate the yields of the synthesis for the different as-synthesized UCNP a thermo balance (LB1 and STA PT-1600 Fa. Linseis) with simultaneous difference thermal analysis (TG / DTA) was used.

2.3. Annealing procedures

The as-synthesized UCNP$\alpha$ were subjected to annealing at different temperatures $T_{an}$ in a range of 200 °C < $T_{an}$ < 700°C for 5 h using a muffle furnace (LM 212.11, VEBA Elektro) to induce a phase transitions in the NaYF$_4$ host lattice (see Table 1). The UCNP materials are denoted as UCNP$_x$ with $x$ = $AS$ for as-synthesized and $x = T_{an}$ ($T_{an}$ = 200°C - 700°C).

2.4. Structural characterization

The size and morphology of as-synthesized UCNP were obtained using a SEM S-4800 scanning electron microscope (Hitachi High-Technologies Canada, Inc., Toronto, Canada) operated with a cold field emission gun (FEG) as cathode and an accelerating voltage of 2kV. The samples were sputtered with platinum in order to reduce the tendency of electrostatic charging. X-ray powder diffraction (XRD) patterns were collected using a D5005 instrument (Siemens AG, Munich, Germany) in a range of 3-70° / 2θ with divergence aperture, scattering ray aperture and graphite monochromatized Cu $K_a$ radiation ($\lambda$ = 0.15406 nm). The scanning step was 0.02° / 2θ with a counting time of 4s per step. From the XRD spectra the nanocrystalline domain sizes were calculated using the Debeye-Scherer equation (see eq. 1):

$$D = \frac{0.89 \lambda}{\theta \cos(\theta)}$$  

(1)

D is the domain size to be determined, $\lambda$ is the wavelength of the x-ray, B is the FWHM of the diffraction peak of interest and $\theta$ is the angle of the corresponding diffraction peak.

Raman measurements were carried out using a confocal Raman microscope 300α (WIITec Wissenschaftliche Instrumente und Technologie GmbH, Ulm, Germany) equipped with an upright optical microscope. For Raman excitation, laser light at $\lambda$ = 532 nm was used, which was coupled into a single-mode optical fiber and focused through a 100x objective (Olympus MPLanFL N, NA= 0.9) to a diffraction-limited spot of about 1.3 $\mu$m$^2$. The laser power was set between 0.4 and 1 mW and the integration time was 5 s for all samples under investigation. For the detection the UHTS 300 spectograph (WIITec, Wissenschaftliche Instrumente und Technologie GmbH, Ulm, Germany) was...
equipped with a grating (600 lines/mm) and a cooled CCD camera (DU40LA-BR-DD-532, WITec, Wissenschaftliche Instrumente und Technologie GmbH, Ulm, Germany).

2.5. Luminescence characterization

2.5.1. Steady state and time resolved upconversion luminescence

Room temperature steady state and time resolved upconversion emission spectra of the solid samples were obtained using a wavelength tunable pulsed Nd:YAG/OPO laser system (pump laser: Quantaray, Spectra--Physics, Mountain View, CA, USA; OPO: GWU, GWU-Laserotechnik Vertriebsges. mbH, Erftstadt, Germany) operated at 20 Hz as excitation light source and an intensified CCD-camera (iStar DH720-18H-13, Andor Technology, Belfast, Great Britain) coupled to a spectrometer (MS257 Modell 77700A, Oriel Instruments) equipped with a 300 l/mm grating as detector. In order to record the time-resolved luminescence spectra (and subsequently extract the luminescence decay kinetics) the "box car" technique was applied. The initial gate delay \( t_0 \) was set to 500 ns, the gate width was adjusted between 10-100 \( \mu s \) and 350 spectra were measured. For the measurements of the luminescence decay kinetics the time delay between laser excitation pulse and detection window was step-wise increase by the variable gate-step size \( t_g \) (see equation 2). This way more data points at shorter times after the laser excitation pulse were acquired in order to ensure a reliable analysis of components with fast luminescence decay kinetics. The solid samples were measured at room temperature using a specifically designed sample holder for powder samples. The sample holder consists of a cylindrical brass base body with two different thread units. A quartz disc is attached with anodized aluminium cover on one thread. The sample was filled in the base body and sealed with an anodized aluminium stamp. The upconversion luminescence was excited at \( \lambda_{exc} = 976 \) nm.

\[
t(n) = t_f + t_g(n) = t_f + \sum_{i=1}^{n} (t_i - 1) \cdot t_k
\]

(2)

2.5.2 Time resolved area normalized emission spectra (TRANES)

Measurements for TRANES analysis were carried out using a wavelength tuneable pulsed Nd:YAG/OPO laser system (laser: Quanta Ray, Spectra--Physics, Mountain View, CA, USA; OPO: GWU-Laserotechnik Vertriebsges. mbH, Erftstadt, Germany) operating at 10 Hz as excitation light source (at 26 mJ / 130 mW) and recorded by an intensified CCD-camera (iStar DH 720 18V 73, Andor Technology, Belfast, Great Britain) coupled to a spectrometer (Shamrock SR-303i, Andor Technology, Belfast, Great Britain) equipped with a 600 l/mm grating. The "box car" technique was applied for this set of measurements as well (vide supra). The initial gate delay was set to \( t_0 = 500 \) ns and the gate width was adjusted between \( \delta t = 1-30 \) \( \mu s \) and 300 spectra were measured. For the measurements the time delay between laser excitation pulse and detection window was step-wise increase by a constant gate-step size \( t_k \) (see equation 5).

\[
t(n) = t_f + t_g(n) = t_f + (n-1) \cdot t_k
\]

(5)

For the TRANES based component analysis it was considered that a mixed spectra \( m(\lambda) \) consists of a combination of the alpha and beta phase spectra \( a(\lambda) \) and \( b(\lambda) \) with the relative fractions \( C \) and \( D \), respectively (see equation 6).

\[
m(\lambda) = C \cdot a(\lambda) + D \cdot b(\lambda)
\]

(6)

The fractions (C, D) of \( \alpha \)- and \( \beta \)-phase were calculated based on the least square method.

3. Results and Discussion

3.1 As-synthesized (cubic) UCNP\(_{Al}\)

3.1.1 Basic characterization

The as-synthesized sample was first examined by XRD for its phase composition. For the Na\(_{x}\)Y\(_{1-x}\)F\(_4\) host lattice two different thermodynamically stable phases, the cubic (isotropic) \( \alpha \)-phase and the hexagonal (anisotropic) \( \beta \)-phase, are known.20,48,49 The XRD diffractogram of UCNP\(_{Al}\) with the corresponding Millerschen indices48 of the lattice planes is shown in Figure 1 (left). A comparison of the XRD diffractogram with the database of the International center of diffraction data (ICCD, No. 77-2042) showed that UCNP\(_{Al}\) is composed of the cubic \( \alpha \)-phase found for Na\(_{x}\)Y\(_{1-x}\)F\(_4\). The very sharp reflexes of different lattice planes seen in the diffractograms indicate that even though the synthesis was carried out under mild conditions a defined crystal lattice was formed.

![Figure 1](image-url)
The particle size and morphology of UCNP\textsubscript{AS} was further studied using SEM. The SEM image of UCNP\textsubscript{AS} show a cubic shape (Figure 1, right).	extsuperscript{50-53} In order to determine an average particle size from SEM images approximately 500 particles were evaluated. The results of the statistical analysis of the SEM images are shown in Table 1. In addition, the particles size was calculated using the Debye-Scherrer equation. Here, the XRD data were fitted with Lorentz functions and the average particle diameter was obtained. In comparison to the SEM-based size, the average diameter is determined approximately 25% smaller. Based on the Debye-Scherrer equation only the crystallite size of the particle is considered in the calculation, which accounts for the observed difference in size found by the two methods. Because of the mild synthesis conditions, the UCNP\textsubscript{AS} may not be fully crystallized and some amorphous domains may still be present in the particles.

3.1.2. Upconversion luminescence

In Figure 2 (left) the luminescence spectrum of UCNP\textsubscript{AS} at \( \lambda_{ex} = 976 \) nm is shown. The three typical emission bands can be observed in the green spectral region centered at \( \lambda_{em} = 525 \) nm (\( ^{2}H_{11/2} \rightarrow ^{4}I_{15/2} \) transition, G1), \( \lambda_{em} = 545 \) nm (\( ^{2}S_{1/2} \rightarrow ^{4}I_{15/2} \) transition, G2) and in the red spectral region centered at \( \lambda_{em} = 660 \) nm (\( ^{2}F_{5/2} \rightarrow ^{4}I_{15/2} \) transition, R) (see also Scheme 1).\textsuperscript{5,4,57} The observed fine structures (Stark splitting) with in the major emission peaks is induced by the crystal field of the ligands positioned around the \( \text{Er}^{3+} \) ions in the host lattice.\textsuperscript{5,5,6,56,58,59}

In Figure 2 (right) the luminescence decay kinetics (\( \lambda_{ex} = 976 \) nm) of UCNP\textsubscript{AS} are shown measured at the emission bands G2 and R, respectively. For the emission bands G2 and R a distinctly different time dependence of the luminescence was observed (see Figure 2, right), whereas no difference between G1 and G2 was observed (see SI.Fig. 1). In the data analysis a bi-exponential decay law was applied.\textsuperscript{5,5,6,56} As a trend, the calculated luminescence decay times \( \tau_{1} \) and \( \tau_{2} \) were longer for the red emission band (R) compared to the green emission bands (G1, G2).

3.2 Annealed UCNPs

The NaYF\textsubscript{4} lattice shows a phase transition from cubic to hexagonal and as a consequence the upconversion properties of UCNPs are distinctly influenced due to structure-related parameters like lattice vibrations. To study the phase transfer from the cubic (\( \alpha \)) to the hexagonal (\( \beta \)) phase in more detail the UCNP\textsubscript{AS} were annealed at different temperatures \( T_{\text{an}} \).

### Table 2: Luminescence decay times \( \tau \) with the different time components and relative fractions of the as-synthesized UCNP\textsubscript{AS} for the emission bands G2 and R, respectively.

<table>
<thead>
<tr>
<th>Decay time</th>
<th>UCNP\textsubscript{AS}</th>
<th>Relative Fraction [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau_{G2,1} ) [( \mu )s]</td>
<td>23±1</td>
<td>71</td>
</tr>
<tr>
<td>( \tau_{G2,2} ) [( \mu )s]</td>
<td>65±5</td>
<td>29</td>
</tr>
<tr>
<td>( \tau_{R,1} ) [( \mu )s]</td>
<td>51±1</td>
<td>64</td>
</tr>
<tr>
<td>( \tau_{R,2} ) [( \mu )s]</td>
<td>118±6</td>
<td>36</td>
</tr>
</tbody>
</table>

Fig. 3: Suited selection of X-ray diffraction patterns of UCNP, after annealing between 200°C < \( T_{\text{an}} \) < 700°C for 5h. The black dotted lines correspond to the position of reflexes of the cubic phase whereas red dotted lines correspond to the position of reflexes of the hexagonal phase, respectively.

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Fig. 2: (left) Upconversion luminescence spectrum of the as-synthesized UCNP\textsubscript{AS}. The spectrum was recorded from a powder sample with \( \lambda_{ex} = 976 \) nm (power density of 191 mW/cm\(^2\)). (right) Normalized upconversion luminescence decay kinetics of the \( \text{Er}^{3+} \) emission bands G2 and R of UCNP\textsubscript{AS}.
At $T_{an} > 400^\circ$C the nanoparticles tend to build up micro-domains (see Si.Fig. 2), therefore the samples are further denoted as UCNP<sub>a</sub> materials.2

### 3.2.1 XRD

In Figure 3 selected XRD diffraction patterns of UCNP<sub>a</sub> after annealing in the temperature range of 200°C < $T_{an}$ < 700°C for 5h are shown. The overall intensity of the diffraction patterns was increased with increasing temperature $T_{an}$ (see Si.Fig.3), whereas the FWHM of the different peaks stayed unaltered (see Si.Fig.3). The increase in intensity is a good indication for an improved crystallinity of the UCNP<sub>a</sub> upon annealing. The crystallite size was calculated using the Debeye Scherrer equation (see Si.Table 1). It is obvious that there is a slightly increase of the crystallite size for UCNP annealed at $T_{an} < 300^\circ$C, whereas for 300°C < $T_{an}$ < 600°C an significant increase of the crystallite size was found due to the change of the crystal phase of the host lattice and the formation of micro domains. In Figure 3 for annealing temperatures below 300°C only the cubic phase is observed in the XRD spectra, while for a annealing temperature of $T_{an} = 400^\circ$C the hexagonal phase is clearly seen as the major crystal phase. The relative fraction of this phase gradually increased with increasing $T_{an}$ up to 500°C. Based on the XRD data (for 400°C < $T_{an}$ < 500°C only a minor amount of cubic phase seems to be present in the material (see Figure 4). A further increase of $T_{an} > 500^\circ$C lead however to a decrease of the hexagonal phase and at $T_{an} = 700^\circ$C again mainly the cubic phase was found in the XRD diffractograms. From Figure 3 it can be seen that the UCNP<sub>700</sub> material is slightly different in the observed XRD peak pattern indicating that the phase back transfer may not be fully completed. This has been observed before for bulk material by Hebert et al.62-64

### 3.2.2 Raman spectroscopy

In the Raman spectra of UCNP<sub>a</sub> (cubic phase) two dominant broad bands around $\nu = 275$ cm<sup>-1</sup> and 745 cm<sup>-1</sup> were observed, which were also found for UCNP<sub>a</sub> annealed up to $T_{an} < 300^\circ$C. Moreover, the comparison of the samples annealed at $T_{an} < 300^\circ$C and the sample annealed at $T_{an} = 700^\circ$C showed only small differences with respect to peak position and spectral distribution (see Figure 5, left top). These results are complementary to the corresponding XRD data (vide supra) pointing to a cubic phase for the respective materials. The Raman spectra of the hexagonal phase materials display five main peaks at $\nu = 251$ cm<sup>-1</sup>, 303 cm<sup>-1</sup>, 359 cm<sup>-1</sup>, 492 cm<sup>-1</sup> and 625 cm<sup>-1</sup>, whereas the high phonon vibrational bands $\nu > 700$ cm<sup>-1</sup>, which have been found for the cubic phase materials, are only weakly present (see Figure 5). The observed alterations in the Raman spectra are well correlated with the phase transition of the host lattice seen in the XRD diffractograms. Moreover, also the small differences between the sample annealed at $T_{an} = 700^\circ$C and samples for $T_{an} < 300^\circ$C is confirmed by the Raman spectra (see Figure 5).

### 3.2.3 Upconversion Luminescence

The upconversion luminescence of the UCNP materials investigated in detail using (quasi) steady state and time-resolved luminescence techniques. In the (quasi) steady state luminescence measurements a detection window of 500 µs

**Fig.4:** Diagram showing the amount of $\alpha$- and $\beta$-phase in correlation to the temperature of the thermal treatment, calculated on the intensity of the different XRD reflexes of $\alpha$- and $\beta$-phase.

**Fig.5:** (left) Normalized Raman spectra of as-synthesized UCNP<sub>a</sub> and annealed UCNP<sub>a</sub> (right) Representative Raman spectra of $\alpha$- and $\beta$-phase.

**Fig.6:** (a.) Alteration in the (quasi) steady state intensity of the different luminescence bands with annealing temperature $T_{an}$. The ratio $G2/R$ (b.) and $G1/G2$ (c.) based on the integrated steady state luminescence intensity of these emission bands and amount of hexagonal $\beta$-phase, both as function of temperature $T_{an}$. The amount of $\beta$-phase was calculated based on XRD measurements. (d.) Enlargement of the G1/G2 ratio over $T_{an}$.
was used collecting more than 95% of the overall luminescence intensity. In the upconversion luminescence spectra the intensity as well as the spectral intensity distribution was altered due to the annealing (see Figure 6). For \( T_{\text{an}} < 300 \degree \text{C} \) a small increase in the upconversion luminescence intensity was found, but no alteration in the spectral intensity distribution was observed (see SI-Fig.4). For annealing temperatures in the range of \( 300 \degree \text{C} < T_{\text{an}} < 600 \degree \text{C} \) a distinct increase in the overall upconversion luminescence intensity was found with a maximum at \( T_{\text{an}} = 500 \degree \text{C} \). In addition, for this set of samples the spectral intensity distribution changed as well. Within the different emission bands (G1, G2, and R) Stark level-related substructures became apparent, but also the relative contribution of the G- and R-bands was altered (see Figure 6).

While the ratio of G1/G2 was found to be nearly independent on the annealing temperature the ratio G2/R showed a distinct change for \( T_{\text{an}} > 300 \degree \text{C} \) (see Figure 6). The sample obtained at \( T_{\text{an}} = 700 \degree \text{C} \) showed a reversed effect, here the overall intensity as well as the spectral intensity distribution were changed back according to materials obtained for \( T_{\text{an}} < 300 \degree \text{C} \). In Figure 6 the overall intensity, the ratio G2/R (as well as the G1/G2 ratio), and the amount of \( \beta \) phase in the different samples are compared. The spectral changes are well correlated with the phase transition from the cubic (\( \alpha \)) phase to the hexagonal (\( \beta \)) phase corroborating the results of the XRD and Raman measurements. In addition, for high \( T_{\text{an}} \) a reduction in lattice defects due to the annealing process and a subsequent decrease of radiationless deactivation improving the energy migration between Yb\(^{3+}\) ions within the crystal may also have a positive effect on the overall upconversion luminescence intensity.

### 3.2.4 Laser power dependent luminescence measurements

The UC luminescence intensity (\( I_{\text{UC}} \)) is proportional to the \( "n" \)th of excitation power (\( I_{\text{ex}} \)) (see equation 7).

\[
I_{\text{UC}} \sim I_{\text{ex}}^n \quad (7)
\]

\( n \) is the number of absorbed NIR photons per visible photon emitted and can be obtained from the slope of \( \log(I_{\text{UC}}/I_{\text{ex}}) \) versus \( \log(I_{\text{ex}}) \) (see Figure 7). \( \log(I_{\text{ex}}) \) and the power emitted from the laser was measured at different laser power densities (4 to 17 mW/cm\(^2\)) for UCNP\(_{\text{abs}}\) and UCNP\(_{\text{Cub}}\) bands (see Figure 7).

For the G1 and G2 luminescence two NIR photons need to be transferred (\( n = 2 \), see Figure 7) from two Yb\(^{3+}\) ions (sensitizer) to one Er\(^{3+}\) ion (activator). In contrast, the value of the R band increased from \( n = 1 \) (UCNP\(_{\text{abs}}\)) to \( n = 1.7 \) (inlet 700 \degree \text{C} to 760 \degree \text{C})). A distinct difference in the values is found for the \( "n" \)-value of the UCNP\(_{\text{Cub}}\) and the \( "n" \)-value of the UCNP\(_{\text{abs}}\) bands, but already at \( T_{\text{an}} < 400 \degree \text{C} \) a slight but steady change in the \( "n" \)-values was observed (see Figure 7). Opposing effects originating from the differences in phonon coupling in cubic and hexagonal lattice as well as from the interplay between radiationless deactivation and saturation effects at higher laser power may be the reason for the observed trends in \( n \) for the G and R band(s), respectively. While for the green emission bands G1 and G2 theoretically \( n = 2 \) is expected and the observed decrease of \( n \) with increasing \( T_{\text{an}} \) points toward a saturation effect, for the R band the change in the matrix-related phonon coupling is the major factor responsible for the overall increase of \( n \). To further elucidate the different factors the power dependence of the spectral intensity distribution was analyzed in more detail. In Figure 8 the ratio of the green luminescence bands G1/G2 (left) as well as the ratio between the red emission bands G1/R (right) depends on the laser power density (4 to 17 mW/cm\(^2\)) for UCNP\(_{\text{abs}}\) and UCNP\(_{\text{Cub}}\) bands (see Figure 8).
of the overall green and red luminescence $G_{\text{full}}/ R$ (right) is shown for different laser power ($\lambda_{\text{ex}} = 976 \text{ nm}$). For the G1/G2 ratio almost no influence of the laser power is found for the UCNP$_x$ annealed at $T_{\text{an}} < 300^\circ\text{C}$. For $T_{\text{an}} > 300^\circ\text{C}$ a slight jump in the G1/G2 ratio was found but no significant influence of the laser power. The observed “jump” falls well within the range of $T_{\text{an}}$ for which the hexagonal phase is dominant.$^{72,74}$ At $T_{\text{an}} = 700^\circ\text{C}$ a decrease and a slight power dependence was observed for the G1/G2 ratio. It is known that the G1 is mainly populated via thermal excitation from the $^4S_{3/2}$ level (G2). The energy gap between the $^4S_{3/2} - \text{and} ^2H_{11/2}$ level is decreased due to the thermal treatment (associated therewith phase transfer from $\alpha$- to $\beta$-phase) and leads to a more efficient thermal population of the $^2H_{11/2}$ level, subsequently increasing the G1/G2 ratio (see Figure 8, left). In contrast, for the $G_{\text{full}}/ R$ ratio a distinct laser power dependence was found. Especially in the range of $300^\circ\text{C} < T_{\text{an}} \leq 600^\circ\text{C}$ representative for the hexagonal phase a large increase by a factor of about 7 was measured (see Figure 8, right). As for the G1/G2 ratio at $T_{\text{an}} = 700^\circ\text{C}$ the $G_{\text{full}}/ R$ ratio dropped back (even below) to the value found for $T_{\text{an}} < 300^\circ\text{C}$ and the laser power influence disappeared. The energy mismatch of the $^2F_{5/2}$ level of Yb$^{3+}$ and the $^1I_{11/2}$ level of Er$^{3+}$ is smaller in the hexagonal phase than in the cubic phase and a better phonon matched energy transfer process between Yb$^{3+}$- and Er$^{3+}$-ions is possible which accounts for the observed lattice phase influence (especially for the G1/G2 ratio). The possibility of saturation effects (e.g., BET, cross relaxation) might be increased as well due to the improved phonon matching. In case of the $G_{\text{full}}/ R$ ratio the alteration of the R is the dominant factor. In case of a high concentration of excited Yb$^{3+}$ ions (sensitzers) the activation into the $^4F_{7/2}$ state becomes faster and can successfully compete with the radiationless deactivation from the $^4I_{11/2}$ into the $^4I_{13/2}$ state, which is a necessary prior step before the activation into the $^4F_{9/2}$ state subsequently R emission occurs (see Scheme 2).

![Scheme 2: Energy scheme of the upconversion processes in the hexagonal phase with suppressed population route of the $^4F_{9/2}$ level (underlined by the orange lines).](image-url)

3.2.5 Time-resolved luminescence

The luminescence decay kinetics of the UCNP$_x$ materials showed a complex time dependence. In Figure 9 the luminescence decay kinetics ($\lambda_{\text{ex}} = 976 \text{ nm}$) of UCNP$_{300}$ are shown for the two emission bands G2 and R. It can be seen that the kinetics of the two bands show a distinctly different time dependence.

For R an initial rise in the luminescence intensity is observed (for $t < 500 \mu$s, see Figure 9). The complexity of the observed decay kinetics could be a result of the contributions from Er$^{3+}$ ions located in different chemical environments (e.g., surface vs. volume effects, amorphous domains, which are reduced due to annealing). The experimental data of G1, G2 and R were analyzed by a bi-exponential decay kinetics.

Luminescence decay times $\tau_1$ and $\tau_2$ were calculated for the different bands G1, G2 and R of the UCNP$_x$ materials. An increase in both luminescence decay times with increasing $T_{\text{an}}$ was found. Moreover, at $T_{\text{an}} > 300^\circ\text{C}$ for both luminescence decay times an accelerated increase with increasing $T_{\text{an}}$ was calculated (see Figure 10). This trend in the decay time is accompanied by the crystal phase transfer from cubic to hexagonal (vide supra). The drop observed for $\tau_1$ and $\tau_2$ at $T_{\text{an}} = 700^\circ\text{C}$ (here, the material switched back to a cubic phase) supports the correlation of the luminescence decay kinetics and the lattice phase. The results of the luminescence kinetics measurements are in very good agreement with the other spectroscopic data presented for the G1/G2 and $G_{\text{full}}/ R$ ratio.

![Fig.9: Normalized upconversion luminescence decays of the G2 and R bands of Er$^{3+}$ in UCNP$_{300}$ ($\lambda_{\text{ex}} = 976 \text{ nm}$).](image-url)

![Fig.10 : Luminescence decay times of UCNP$_x$ annealed at different $T_{\text{an}}$ for the emission bands G2 and R, (left) the short decay component, (right) the long decay component ($\lambda_{\text{ex}} = 976 \text{ nm}$).](image-url)
3.2.6 Time-resolved area normalized emission spectra (TRANES)

In order to pinpoint the influence of the lattice on the luminescence upconversion the time-resolved emission spectra were evaluated by TRANES analysis. TRANES can be used to reveal small time-dependent variations in the spectral intensity distribution of a luminescence spectrum. They were calculated from the time-resolved emission spectra recorded for the determination of the luminescence decay kinetics by normalizing the area of the emission spectrum recorded at different delay times after the laser pulse (e.g., area of spectrum is normalized to one). In Figure 11 (top) the TRANES of UCNP200 are shown. No change in the spectral intensity distribution neither for the G1 and G2 luminescence nor for the R luminescence is detected. For UCNP300 a significant change in the intensity distribution of the luminescence is found for G1 and G2 as well as for R (see Figure 12). In the TRANES isoemissive points are found. E.g., for G1 isoemissive points can be seen at λem = 516.8 nm, 521.8 nm and 523.2 nm and the luminescence peak at λem = 529 nm becomes more pronounced (see Figure S1-4). Also in the case of G2 the intensity distribution is altered with increasing delay relative to the excitation pulse. For the R luminescence two isoemissive points are identified at λem = 651 nm and 665.8 nm. Furthermore, the shoulder at λem = 668 nm is decreased whereas a completely new peak appears at λem = 661 nm. In Figure 11 the upconversion emission spectra for UCNP400 and UCNP600 are shown as well. The variations in the spectral intensity distribution of G1 and G2 as of R are small for both materials (the luminescence intensity distribution is only slightly changed for the emission band G2). For the TRANES analysis of UCNP700 it can be seen that the spectral intensity distribution remains unchanged with increasing delay time. Moreover, a comparison with the spectra of UCNP300 – UCNP600 materials shows that for the UCNP700 material a close resemblance to the UCNP200 material is found (especially for the R luminescence). The results of the TRANES analysis nicely complement the data of the other experimental techniques reflecting the phase transition from cubic to hexagonal (and back to cubic) upon annealing in the temperature range 200°C < Tan < 700°C. However, while the other analytical techniques and data evaluation approaches gave only a rough picture of the phase transfer and its start temperature Tan in the TRANES analysis of the G1, G2 and R emission bands already small fractions of hexagonal phase could be detected. The fact, that the shape of the emission bands is changed with increasing delay time after the laser pulse in favor of the hexagonal phase related luminescence, is a consequence of the significant differences in the decay times of Er3+ luminescence in the two lattice phases involved due to difference in the symmetry of the chemical environment (vide supra). Consequently the relative luminescence intensity contribution of Er3+ ions located in the cubic and hexagonal
phase changes with time after the laser pulse and the different lattice environments, if present, can be identified in the sample from the alteration in the spectral intensity distribution. The TRANES analysis is very sensitive and allows to analyze even small difference in the material composition. The small differences in the intensity distribution of G1 and G2 of the UCNP500 material compared to UCNP200 indicate a small fraction of hexagonal phase to be still present in this material. For a complete back transfer to the cubic phase higher temperatures or/and longer annealing times seem to be necessary. Based on the diffractogram and the corresponding Debye-Scherrer calculations an increase in the crystallite size as well as an asymmetric growth of the UCNP was found, which could also have an impact on the intensity distribution of G1 and G2 of the UCNP500 material. Based on the approximation that in the UCNPAs and the UCNP500 only cubic and hexagonal phase, respectively, are present, a spectral decomposition of the emission spectra recorded at a delay time of 0 μs and 500 μs was performed in order to calculate the relative amount of cubic and hexagonal phase for the different UCNP materials (see Figure 13). It can be seen, that in the temperature range of 200°C < T\textsubscript{an} < 400°C a gradual transformation of the cubic into the hexagonal phase is already present.

4. Conclusion

NaYF\textsubscript{4} nanoparticles co-doped with Er\textsuperscript{3+} and Yb\textsuperscript{3+} were synthesized under mild conditions using PVP 40 as capping agent and as stabilizer, respectively. The UCNP\textsubscript{As} were uniform in size and shape with a cubic crystal lattice. After the annealing between 200°C < T\textsubscript{an} < 700°C for 5h changes in crystal lattice phase and subsequently in the upconversion luminescence properties of the UCNP materials were induced. The lattice phase and structure of the UCNP materials obtained at different T\textsubscript{an} were analyzed using XRD, Raman spectroscopy as well as SEM. The upconversion luminescence properties of the annealed UCNP materials were studied by steady state and time resolved luminescence. Upconversion luminescence proved to be a sensitive tool to monitor the phase transition of the host lattice. While based on XRD and Raman spectroscopy no clear indication for a change in the lattice phase was found for T\textsubscript{an} < 300°C, the upconversion luminescence proved to be more sensitive capable of resolving even small contributions of cubic and hexagonal phase, respectively, in the materials. Based on the upconversion fluorescence studies of the UCNP\textsubscript{x} materials the complex interplay of the host lattice crystal phases and the population routes of the Er\textsuperscript{3+} energy levels involved in the upconversion processes was evaluated. The laser power dependence of the green (G1, G2) and red (R) luminescence was found to be dependent on the annealing temperature. In addition, green and red luminescence was found to respond differently on the host lattice phase. A major population route of the R luminescence is attenuated at higher laser power, which is more efficient for the hexagonal lattice phase, the relative contributions expressed as the ratio between G\textsubscript{full} and R is altered (see Scheme 2). Although already regular upconversion data, like spectral intensity distribution from steady state luminescence measurements or luminescence decay kinetics, show a clear lattice phase dependent behavior, TRANES analysis proved to be superior. The basis for the full exploitation of the power of TRANES is the different luminescence decay kinetics of the upconversion in cubic and hexagonal lattice phase. While the analysis of the luminescence kinetics with respect to physical meaning full luminescence decay times is difficult due to the complex time dependence and the related challenges in the data analysis, TRANES employs a combination of time and spectral information. Based on TRANES even minor amounts of cubic or hexagonal phase could be identified in the different UCNP materials. TRANES could also be a great tool for monitoring the phase composition of UCNP \textit{in situ} during synthesis.\textsuperscript{84,85}

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References
