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Single YVO$_4$:Eu nanoparticle emission spectra using direct Eu$^{3+}$ ion excitation with a sum-frequency 465-nm solid-state laser

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Abstract: We report emission spectrum measurements on single Y$_x$Eu$_{1-x}$VO$_4$ nanoparticles. The inhomogeneous widths of the emission peaks are identical for single nanoparticles and for ensembles of nanoparticles, while being broader than those of the bulk material. This indicates that individual nanoparticles are identical in terms of the distribution of different local Eu$^{3+}$ sites due to crystalline defects and confirms their usability as identical, single-particle oxidant biosensors. Moreover, we report a 465 nm solid-state laser based on sum-frequency mixing that provides a compact, efficient solution for direct Eu$^{3+}$ excitation of these nanoparticles. Both these two aspects should broaden the scope of Eu-doped nanoparticle applications.

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1. Introduction

Biological and biomedical applications generate a strong demand for nanoparticle-based luminescent labels, sensors, imaging contrast agents or for nanoparticles as platforms for targeting and therapy approaches. In all these cases, the luminescent properties are crucial. Indeed, even when optical imaging is not the main application, it is highly desirable to be able to locate the nanoparticles in cells or in tissues.

Besides semiconductor quantum dots (QDs) and luminescent nanodiamonds, rare-earth based nanoparticles concentrate the efforts of numerous groups [1]. Eu-doped nanoparticles, in particular, are quite popular because of the efficient, red emission of Eu³⁺ ions [2,3]. In addition to DNA [4] and protein assay applications [5], we have shown that Eu-doped oxide nanoparticles are excellent single-molecule labels [6]. Indeed, they present stable, narrow-band (<10 nm) emission resulting from 4f-4f transitions, display no blinking, in contrast to quantum dots, and can therefore be used for long-term, uninterrupted single-molecule tracking [7–10]. Furthermore, we have demonstrated that oxidio-reduction processes of Eu ions in an yttrium vanadate matrix can be exploited to create a quantitative, time- and space-resolved oxidant sensor [11,12]. More recently, we have also implemented multifunctional Eu-doped nanoparticles by replacing yttrium with gadolinium which provide simultaneously...
luminescence labeling, oxidant sensing and contrast enhancement in magnetic resonance imaging (MRI) [13].

The in-depth structural and optical characterization of such nanoparticles is important for all these applications. In single-molecule tracking and oxidant sensing applications, where single nanoparticles are used, it is crucial to determine whether the signal may differ depending on the particular nanoparticle observed or not, i.e. whether the optical emission properties vary from one particle to the other. In the case of sensing and MRI imaging applications, the access of the oxidant and the water molecules, respectively, into the nanoparticle structure depends on its porosity. In that respect, we demonstrated that oxidant sensing signal variations from one nanoparticle to the other are small for different single nanoparticles [11,12]. Furthermore, we have shown that the emission intensity of single nanoparticles can be used to optically determine their size [14]. This method implicitly assumes that all nanoparticles are identical in terms of optical emission properties.

The emission properties of colloidal solutions of YVO₄:Eu nanoparticles have been addressed in [2,3,15,16]. Mialon et al. investigated the emission properties of an ensemble of YVO₄:Eu nanoparticles in comparison to those of annealed nanoparticles [17] and the bulk material and demonstrated that the emission was limited by defects affecting energy transfer and non radiative relaxation as well as by dielectric effects affecting radiative lifetime and thus quantum yield [18]. This means that the structural properties at the single-particle level, such as crystallinity and porosity, are determinant for the emission and sensor properties of these particles, in particular for nanoparticles synthesized at room temperature in which lattice imperfections are more abundant [17].

In rare-earth doped nanoparticles, the highly localized, atomic-like nature of the f electronic states ensures weak interaction with the surrounding lattice and narrow emission peaks. However, the presence of a large number of dopant ions and of multiple local dopant ion environments leads to transition energy variations and subsequently to an increase of the emission spectral width reflecting the nanoparticle internal structural heterogeneity. Inhomogeneous broadening is thus predominant even at room temperature [18]. This means that, in the case of rare-earth doped nanoparticles, structural information on single particles can be obtained from their spectra. In contrast, in the case of QDs at room temperature, the lifetime of the electronic states is dominated by the electron-phonon interaction, the resulting emission width (~25 nm) is homogeneous, and structural information can only be obtained by performing spectral measurements at low temperatures.

An issue that may limit the range of in vivo applications of Eu-based nanoparticles, is their excitation possibilities. For in vitro applications, excitation of the matrix in the UV and subsequent energy transfer to Eu ions may be used even though excitation sources are scarce. For in vivo applications, however, direct excitation of Eu ions in the visible is preferable to avoid UV laser-induced phototoxicity [6–8]. In our previous work, the 465.8-nm Argon-ion laser line has been used to excite Eu³⁺ ions in resonance with the ⁷F₀,₁ – ⁵D₂ Eu³⁺ transition. For a more widespread use of these nanoparticles, however, the availability of a compact, inexpensive, and easily transportable excitation source at the appropriate wavelength is important.

We here present a solid-state, compact 465-nm laser that may conveniently replace the Argon-ion laser used up to now to excite Eu-doped nanoparticles. Using this laser, we realized, to our knowledge, the first measurement of single Eu-doped nanoparticle emission spectra. Based on these data, we may conclude that, although crystalline imperfections in the nanoparticles induce a broadening of the emission peaks, the inhomogeneity of the Eu³⁺-ion local environments is similar in all individual nanoparticles, i.e. the nanoparticles are identical in terms of structural inhomogeneity.
2. 465-nm solid-state laser

Today, GaN laser diodes cover a wide range of wavelengths in the blue but not continuously. It appears that 465 nm corresponds precisely to a hole of emission. Laser diodes at this emission wavelength are difficult to obtain [19]. Fortunately, this wavelength can be obtained by frequency conversion of near-infrared laser sources. In the past, frequency doubling has been carried out: direct frequency conversion of laser diodes has been developed in an external resonant cavity with an LBO crystal [20] or in an intracavity configuration with periodically poled lithium niobate [21] leading to output power of up to 1 W. Diode-pumped Nd:YAP (YAlO3) laser emitting at 930 nm and frequency doubled by an LBO crystal in an intracavity configuration has produced up to 1.13 W [22]. In this work, we tried another nonlinear conversion scheme to reach 465 nm, based on the sum frequency mixing of two Nd emission wavelengths (914 nm and 946 nm) in two different host matrices (YAG and YVO₄). This solution presents the advantage of being less sensitive to intrinsic fluctuations due to longitudinal mode coupling in intracavity frequency-doubled lasers [23]. Moreover, this scheme is more simple than external frequency doubling which required active control of the resonant cavity on the laser cavity [20].

Our laser source is based on the sum-frequency mixing of two lasers operating in the same cavity: a Nd:YAG laser operating at 946 nm and a Nd:YVO₄ laser operating at 914 nm (Fig. 1). The crystals are pumped by the same fiber-coupled laser diode emitting 14.4 W from a 100-µm core fiber having a numerical aperture of 0.2. The pump beam is collimated and focused down to 170 µm diameter in the laser crystals by two doublets having focal lengths of 60 mm and 100 mm, respectively. As laser emission at 914 nm needs a more important population inversion than laser emission at 946 nm, the first crystal to be pumped is Nd:YVO₄ (length: 1.5 mm; doping concentration: 0.1%). The Nd:YAG (length: 3.5 mm; doping concentration: 0.5%) crystal is placed very close to the vanadate crystal in the same copper mount. The overall absorption by the two crystals is 63%. The laser cavity consists of four mirrors having two small waists: one for the laser crystals, adapted to the pump (radius 80 µm) and one for the nonlinear crystal (radius 50 µm). The latter is a potassium niobate crystal (KNbO₃) cut for sum frequency conversion (37° with respect to the ba plane) with a length of 4 mm. Because of the small thermal acceptance of this nonlinear crystal, its temperature was...
stabilized at 25°C with an accuracy better than 0.1°C. The four mirrors of the cavity were highly reflective in the range 900-950 nm. The input mirror (M1) was transparent at 808 nm and M4 was also highly reflective at 465 nm in order to have only one output in the blue, through M3. In addition, M2, M3, and M4 were highly transparent around 1070 nm to avoid laser oscillation at the strong four-level laser line at 1064 nm for Nd:YVO₄ and 1080 nm for Nd:YAP. At 14.4 W of incident pump power, we achieved an output power of 100 mW at 465.1 nm which is high enough for all applications using YVO₄:Eu nanoparticles including single-molecule tracking and oxidant detection.

3. Experimental

The nanoparticles are synthesized by salt coprecipitation at room temperature following [3]. An aqueous solution of 0.1 M Na₃VO₄ is freshly prepared and its pH is adjusted between 12.6 and 13 with a 1 M NaOH solution. The same volume of a 0.1-M aqueous solution of (Y,Eu)(NO₃)₃ with the desired europium content (here the molar fraction was 10% or 40%) is then added dropwise using a peristaltic pump under vigorous stirring. The solution is left under stirring for 30 min and is then purified by centrifugations (11400g, 20 min) and redispersions in pure water until its conductivity is below 100 μS.cm⁻¹. Before imaging the nanoparticles, we performed size selection using centrifugation: 5 min at 2000 g (the supernatant was retained) followed by 30 min at 4000 g (the precipitate was retained and re-dispersed) to eliminate aggregates or large nanoparticles and small nanoparticles, respectively. This leads to a nanoparticle size distribution of 20-70 nm. Note that these particles contain tens of thousands of Eu³⁺ ions: given the fact that the volume of the unit cell is 0.323 nm³ and contains four vanadate and four Y³⁺/Eu³⁺ ions, a 30-nm particle Y₀.₆Eu₀.₄VO₄ contains about 70 000 Eu³⁺ ions [14]. Moreover, the Eu³⁺ ions have been shown to be homogeneously incorporated in Y³⁺ sites based on the fact that the lattice parameter of Y₁₋ₓEuₓVO₄ nanoparticles as a function of Eu concentration follows Vegard’s rule [3]. To synthesize the bulk material, the nanoparticle solution was dried in an oven and annealed at 1000 °C for 10 h [18].

![Scheme of the experimental set-up. DM: dichroic mirror, TL: Tube lens, PH: diaphragm, BS: beam-splitter.](image)

YₓEu₁₋ₓVO₄ nanoparticles (x = 0.1 or x = 0.4) were spincoated on glass coverslips and were imaged with a wide-field microscope (Zeiss AxioObserver D1) equipped with a 63x, N.A. = 1.4 plan-apochromat objective. The nanoparticles were excited with 25 mW focused down to a FWHM of 95 μm at the coverslip. The emitted light was collected through a
To image the nanoparticle ensemble with spatial resolution, the previously deposited nanocrystals are excited non-coherently by a solid-state laser (sum-frequency laser at 380.2 nm) or a coherently by an Argon laser (465.8 nm) [2] at the same intensity. The total number of detected photons per emission spot was determined for each laser. The average ratio of emitted signal excited by the solid-state and the Argon laser at a power of 50 mW focused down to approximately 20 µm was 0.76 (N = 19 nanocrystals). This is in agreement with the fact that the sum-frequency laser wavelength does not correspond precisely to the maximum of the $^7F_{0,1} - ^5D_2$ Eu$^{3+}$ direct absorption peak in the YVO$_4$ matrix (see inset of Fig. 1).

The Eu$^{3+}$ site in bulk YVO$_4$ has no inversion symmetry. In this case, the selection rule for electrical dipole transitions is $|\Delta J| = 2, 4, 6$ if the initial or final state has $J = 0$ and $|\Delta J|\leq 6$ otherwise. We here focus on the wavelength range of the most intense Eu$^{3+}$ $^5D_0 - ^7F_2$ emission (600-620 nm). Depending on the symmetry of the host lattice and of the Eu$^{3+}$ site, the Eu$^{3+}$ energy levels can be split into up to 2J + 1 sublevels, i.e. one sublevel for $^5D_0$ and five sublevels for $^7F_2$. The Eu$^{3+}$ site in YVO$_4$ single crystals has $D_{2d}$ symmetry. This crystal field...
symmetry leads to a splitting of the fivefold $^5D_0^{-7}F_2$ transitions into two: $^5D_0(A_1)^{-7}F_2(B_2)$ and $^5D_0(A_1)^{-7}F_2(E)$ [25].

The spectrum of single YVO$_4$:Eu nanoparticles displays five peaks that can be fitted with five Lorentzians with center wavelengths 608.74 nm, 613.85 nm, 614.84 nm, 616.65 nm, 618.70 nm [Fig. 3(B)]. These emission peaks can be attributed to the transitions $^5D_0(A_1)^{-7}F_2(B_2)$ and $^5D_0(A_1)^{-7}F_2(E)$ observed in bulk YVO$_4$:Eu at 615.5 nm and 619.4 nm, respectively [2,3,15,16,25]. Note that, at low temperature, transitions starting from the $^5D_2$ level and the $^5D_1$ level have also been reported for bulk YVO$_4$:Eu in this wavelength range, in particular $^5D_2(A_1)^{-7}F_6(B_{2}^{(1)})$ at 609.7 nm, $^5D_2(E)^{-7}F_6(A_{2})$ at 611.7 nm, $^5D_2(E)^{-7}F_6(E^{(1)})$ at 613.3 nm, and $^5D_1(A_2)^{-7}F_4(B_1)$ at 616.1 nm [25]. At room temperature, however, transitions departing from the $^5D_1$ and $^5D_2$ levels are at least 100 times weaker than those departing from the $^5D_0$ level [15] due to more efficient de-excitation to the lowest lying $^5D$ energy level, $^5D_0$, before radiative de-excitation takes place. The presence of five peaks instead of two may possibly be attributed to crystalline imperfections leading to a reduced symmetry of the Eu$^{3+}$ sites with respect to the bulk crystal and thus causing further degeneracy lifting.

Local deviations from the $D_{2d}$ symmetry also lead to intensity and width variations [26,27]. Indeed, the widths of the nanoparticle emission peaks are much broader that those of bulk samples [Fig. 3(C)]. This has been reported previously for nanoparticle ensembles together with the observation that annealed, monocrystalline nanoparticles [17] display much narrower widths, close to those of bulk material [18]. The larger width is due to the lower
crystalline quality of the nanoparticles and can be interpreted as follows: in a nanoparticle, crystalline imperfections create a local environment that is somewhat different for different Eu$^{3+}$ ions in the same nanoparticle leading to slightly varying Eu$^{3+}$-ion transition energies. This collection of distinct environments and the resulting transition energies lead to a broadening of the emission peaks. Note also that, when fitting the spectra with a series of Lorentzian peaks, the bulk material spectrum shows no trace of the 616.65 nm transition peak, in agreement with the presence of a higher symmetry in the bulk material [Fig. 3(C)].

Fig. 4. A) Widths of the first, third and fifth Lorentzian peaks at 608.74, 614.84, and 618.70 nm (shown from left to right) used to reproduce the emission spectra of single Y$_x$Eu$_{1-x}$VO$_4$ nanoparticles for $x = 0.1$ and 0.4. The error bars represent the standard deviation of the measurements for 15 and 14 single nanoparticles with 10% and 40% europium, respectively. B) Center wavelength of the first, third and fifth Lorentzian peaks used to reproduce the emission spectra of single Y$_x$Eu$_{1-x}$VO$_4$ nanoparticles (black) and of an ensemble of Y$_x$Eu$_{1-x}$VO$_4$ nanoparticles (red) for $x = 0.1$ and 0.4. The error bars represent the FWHM of the corresponding peaks. For single nanoparticles, the average FWHM is shown [see A)]. C) Emission peak area of the second and third Lorentzians used to reproduce the emission spectra for single Y$_x$Eu$_{1-x}$VO$_4$ nanoparticles (black) and for an ensemble of particles (red) for $x = 0.1$ and 0.4 normalized to the peak area of the fifth Lorentzian. The error bars represent the standard deviation of the measurements for 15 and 14 single nanoparticles with 10% and 40% europium, respectively.

In contrast, the spectrum of single nanoparticles is practically identical to that of a collection of particles [Fig. 3(C)]. The question that arises is whether all nanoparticles are “identical”, i.e. whether they all feature the same collection of local environments for Eu$^{3+}$ ions. To further address this question, we measured the spectra of 15 (14) single Y$_x$Eu$_{1-x}$VO$_4$ nanoparticles for $x = 0.1$ (0.4) and fitted the spectra with five Lorentzian peaks as in Fig. 3B. We then plotted the FWHM of the different peaks, indicative of the crystalline imperfections, and, in particular, its average value and standard deviation [Fig. 4(A)]. The small standard deviation indicates the similarity of local environment distributions inside different individual nanoparticles. Moreover, the center wavelengths and the corresponding widths of the three main Lorentzian peaks used to reproduce single nanoparticle spectra [Fig. 4(B)] as well as the emission peak areas [Fig. 4(C)] agree surprisingly well with those of nanoparticle ensemble spectra.

These data lead us to conclude that each single nanoparticle encompasses the same distribution of locally different Eu$^{3+}$-ion environments including Eu$^{3+}$ ions at the surface and at the core of the nanoparticles [28]. Therefore, each nanoparticle features the same deviation from a perfect crystalline environment. This similarity of the ensemble of lattice defects found in different nanoparticles is a non trivial result. Moreover, it may seem surprising given the size dispersion of the nanoparticles. Indeed, the weight of surface ions may be expected to be more important in smaller nanoparticles than in bigger ones. However, current knowledge on
the growth process of these nanoparticles provides an explanation to our observations. Nanoparticle growth is considered to proceed by aggregation of primary grains [29]. This means that the ratio of surface to core ions remains the same independently of the size of the nanoparticles. Our observation that all nanoparticles contain the same collection of local Eu\(^{3+}\)-ion environments thus implies that these primary grains are identical in terms of crystallinity.

Our results justify the assumption that the total area under the emission spectrum is directly proportional to the number of emitting Eu\(^{3+}\) ions and thus to the volume of the nanoparticle [14]. Moreover, they explain why the response of single photoreduced Eu-doped nanoparticles to \( \text{H}_2\text{O}_2 \) and other oxidants varies only slightly from one nanoparticle to another [11,12].

Furthermore, we observe no significant increase in the peak width of single nanoparticle spectra when the doping increases from 10\% to 40\% [Fig. 4(A)]. Note also that the lattice parameter dependence on doping concentration follows Vegard’s law which demonstrates that the Eu\(^{3+}\) ions are homogeneously distributed throughout the nanoparticles [3]. The absence of width change implies that the broadening of the peaks is dominated by crystalline imperfections in the nanoparticles and that the effect of doping-related strain, lattice parameter variation or defects is negligible.

Altogether, these results show that Eu-doped vanadate nanoparticles encompass a large number of emission centers homogeneously distributed in a lattice with a microstructure that is similar for all single particles. The measured emission spectrum for single particles reflects the weak but measurable fluctuations of the Eu\(^{3+}\)-ion transition energies due to the local crystalline field, averages over the various local structural environments, and is identical for all individual particles.

5. Conclusions

By measuring the emission spectrum of single nanoparticles, we have shown that individual \( \text{Y}_x\text{Eu}_{1-x}\text{VO}_4 \) nanoparticles inside a colloidal nanoparticle solution obtained by a coprecipitation, soft chemistry synthesis route are identical in terms of the distribution of local environments provided for the Eu\(^{3+}\) ions. This insight confirms the validity of single-particle level applications of these nanoparticles, in particular in terms of size determination, single-particle tracking, and oxidant sensing. Furthermore, we have developed a sum-frequency blue solid-state laser suitable for direct excitation of Eu\(^{3+}\) ions in the visible. The linewidth of the Nd-doped fundamental laser being on the order of a nanometer, it should be possible to tune the sum-frequency emission over a range of 0.5 nm. This could be enough to excite Eu\(^{3+}\) ions embedded in other matrices than \( \text{YVO}_4 \).

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