

Effects of sodium dodecyl sulfate surfactant on up-conversion luminescence of $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ nanocolloidal phosphor prepared by pulsed laser ablation in water

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$\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ colloidal nanocrystals were synthesized by pulsed laser ablations in de-ionized water and sodium dodecyl sulfate ($\text{NaC}_{12}\text{H}_{25}\text{SO}_4$, SDS) aqueous solution for up-conversion (UC) luminescence bio-labeling applications. The influences of the SDS molecules on the crystallinities, crystal morphologies, crystallite sizes, and UC luminescence properties of the prepared $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ colloidal nanocrystals were investigated in detail. Under a 980-nm excitation, the $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped nanocolloidal $\text{NaLa}(\text{MoO}_4)_2$ suspension exhibited a weak red emission near 670 nm and strong green UC emissions at 530 and 550 nm, corresponding to the intra 4f transitions of Er^{3+} ($^4\text{F}_{9/2}$, $^2\text{H}_{11/2}$, $^4\text{S}_{3/2}$) $\rightarrow$ Er^{3+} ($^4\text{I}_{15/2}$). When the SDS solution was used, a smaller average crystallite size, narrower size distribution, and enhanced UC luminescence were observed. These characteristics were attributed to the amphoteric SDS molecules attached to the positively charged $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ colloidal nanocrystals, effectively occupying the oxygen defect on their surfaces. The $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped nanocrystalline $\text{NaLa}(\text{MoO}_4)_2$ suspension prepared in the SDS solution exhibited a remarkably strong green emission visible to the naked eyes.

Key words: $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$, Nanocolloidal suspension, Pulsed laser ablation in liquid, Up-conversion, Bio-labeling.

Introduction

In recent years, lanthanide-ion-doped up-conversion (UC) luminescence (from near infra-red (NIR) to visible or ultraviolet (UV) light) luminescent materials have attracted significant attention owing to their desirable characteristics for various applications including phosphors, solar cells, flat-panel displays, scintillators, solid-state lasers, and fluorescence bio-medical applications [1-5]. Particularly, lanthanide-doped white UC luminescent materials have been extensively studied, owing to their potentials to replace conventional lighting sources in optical devices and to provide three-dimensional backlighting for color displays. In addition, white UC phosphors are expected to provide more simultaneous detections for bio-medical probes, compared to the conventional bio-labelling [6]. For white UC luminescence, many lanthanide ions such as Er^{3+} , Tm^{3+} , and Ho^{3+} have been used as luminescent centers for

activators owing to their abundant electronic energy levels for UC luminescence. Some of them are suitable for direct pumping by NIR radiation [7].

The metal molybdate family has a long history of optical applications, extensively studied over the past century. Particularly, for applications such as scintillating media and electro-optical devices, scheelite-type materials of the metal molybdate family have been investigated, aiming to understand the luminescent properties of molybdates [8]. Recently, $\text{NaLa}(\text{MoO}_4)_2$ has been investigated as a potential phosphor owing to its high density and more stable physical and chemical properties than those of other oxide materials [9]. In addition, $\text{NaLa}(\text{MoO}_4)_2$ has broad and intense charge transfer (CT) absorption bands in the UV region, enabling to efficiently capture the emission from a GaN-based light-emitting diode (LED) over a range of wavelengths [10]. The Mo^{6+} ions in the $\text{NaLa}(\text{MoO}_4)_2$ matrix exhibit a high polarization induced by the large electric charges and small radius, which leads to a decreased symmetry and enhanced Stark energy splitting [11]. Therefore, we expect that $\text{NaLa}(\text{MoO}_4)_2$ can be a suitable matrix for UC phosphors, providing high efficiencies in light UC applications.

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Since its development by Henglein, Cotton et al. [12,13], the pulsed laser ablation (PLA) in a liquid attracts significant attention as a new technique to prepare nanocolloidal particles. Laser ablations of various noble metals settled in solvents produce colloidal nanoparticles of these metals [14-16]. A remarkable advantage of the laser ablation method over the chemical synthesis is its simplicity. Moreover, the laser ablation in liquid can be employed to prepare nanoparticles of not only noble metals but also compound materials. Laser ablations of TiO_2 , ZnSe , GaAs and CoO in various solvents produced nanoparticles of these materials [17-20]. The above studies on noble metals and compound materials have shown that stoichiometric nanoparticles could be produced using laser ablation in liquids, i.e., the atomic compositions of the produced nanoparticles were identical to those of their source materials.

In general, the luminescence efficiency of a phosphor material decreases with the decrease in the crystallite size to the nanoscale, as the increase in the surface-to-volume ratio induces non-radiative processes related to surface defects. In previous studies, lanthanide-ion-doped nanophosphors were successfully fabricated by laser ablations in liquids [21-23]. However, the luminescence efficiency was considerably lower than the bulk target, owing to the increased number of surface defects. Therefore, it is necessary to cap such defects by an appropriate surfactant to enhance the luminescence efficiency. In this study, we propose a novel synthesis approach to directly produce highly dispersed and luminescent $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ colloidal nanocrystals by PLA in an aqueous solution for applications in luminescent bio-labeling. Moreover, the remarkable enhancement in UC luminescence intensity obtained using sodium dodecyl sulfate (SDS) as a surfactant was investigated in detail.

Experimental Method

The $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ UC phosphor was synthesized by a simple solid-state reaction method [24]. Sodium carbonate (Na_2CO_3 , purity: 99.99%, Kojundo Chemical Co. Ltd.), lanthanum oxide (La_2O_3 , purity: 99.99%, Kojundo Chemical Co. Ltd.), ammonium molybdate ($(\text{NH}_4)_6\text{Mo}_7\text{O}_{24}$, purity: 99.99%, Kojundo Chemical Co. Ltd.), erbium oxide (Er_2O_3 , purity: 99.99%, Kojundo Chemical Co. Ltd.), and ytterbium oxide (Yb_2O_3 , purity: 99.99%, Kojundo Chemical Co. Ltd.) were used as the starting materials. The Er^{3+} and Yb^{3+} doping concentrations were fixed to 7.0 and 10.0 mol%, respectively, which were determined in a previous study [24] as the optimal doping concentrations. The ceramic target was prepared by compressing the raw powder under a uniaxial pressure of 300 MPa, followed by sintering at 900 °C in air for 3 hrs. The prepared $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$

target was white. An XRD measurement showed that the target consisted of a single phase (JCPDS 24-1103).

After removal of organic contaminations by an ultrasonic cleaning in acetone, the cleaned targets were immersed in 10 mL of de-ionized water and solution of SDS ($\text{NaC}_{12}\text{H}_{25}\text{SO}_4$, 10^{-2} mol/L) as an amphoteric surfactant. Although several surfactants are widely used in the laser ablation process, SDS provides a smaller average size and narrow distribution, as well as enhanced emission intensity [25,26]. Thereafter, a pulsed laser (Nd:YAG, 355 nm, repetition rate: 30 Hz, pulse width: 8 ns, maximum output: 100 mW) was irradiated on the surface of the target. The laser beam was focused on the target to a spot with a diameter of approximately 1 mm using a lens with a focal length of 250 mm. The depth over the target immersed in ethanol was kept at ~ 25 mm during the laser ablation [27]. In order to avoid the formation of deep holes, the target was rotated at 30 rpm. The $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ colloidal suspension was prepared by laser ablation for 3 h at room temperature. Fig. 1 illustrates the PLA in the liquid medium for preparation of $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ nanocrystals.

The colloidal suspension was dropped on a copper mesh coated with an amorphous carbon film to observe the microstructure and shape of the nanocrystals by transmission electron microscopy (TEM, JEOL, JEM-2010, 200 kV, Japan). The sizes of the nanocrystals were statistically analyzed in a TEM image. A precipitate of $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ nanoparticles was obtained by a repeated centrifugation at 25,000 rpm for 30 min using an ultracentrifuge (Supra 25K, Hanil Sci. & Ind. Co., Korea). The precipitate of the $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped

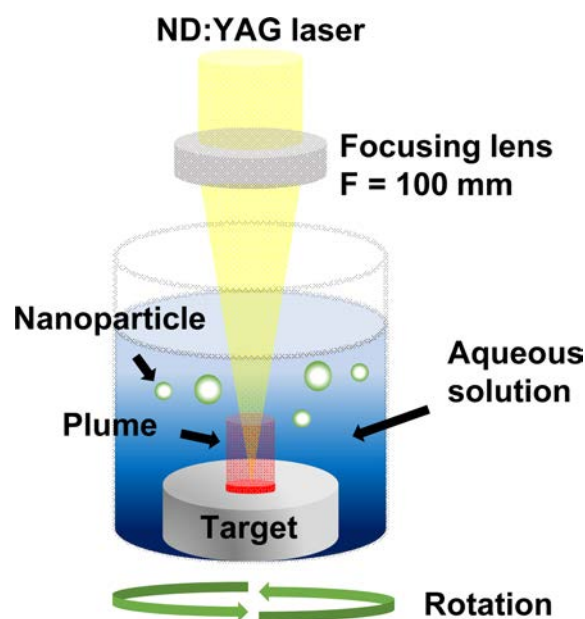


Fig. 1. Schematic of the PLA of the target in the liquid medium.

$\text{NaLa}(\text{MoO}_4)_2$ colloidal suspension was further centrifuged at 25,000 rpm by the ultracentrifuge for the XRD analysis (Rigaku RAD-C, $\text{Cu K}\alpha$ radiation). The room-temperature UC spectrum was obtained using a photoluminescence spectrophotometer (PerkinElmer, LS55 with a 100-mW laser diode, USA) in a range of 400–700 nm excited by a 980-nm laser.

Results and Discussion

Fig. 2 shows XRD patterns of the $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ nanocrystals collected from the colloidal suspensions prepared by PLAs in (a) de-ionized water and (b) SDS solution. The Bragg reflection peaks of the nanocrystals corresponded to the scheelite-type $\text{NaLa}(\text{MoO}_4)_2$ (JCPDS 24-1103); no peaks could be assigned to La_2O_3 and MoO_3 phases. The $\text{NaLa}(\text{MoO}_4)_2$ nanocrystals formed in de-ionized water contained an amorphous phase. However, in the case of the SDS solution, the broad amorphous component was diminished and the crystallinity was improved, compared to the case of the de-ionized water.

The crystal morphologies, crystal sizes, and crystallinities were further analyzed by TEM. Fig. 3 shows typical TEM micrographs of the $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ colloidal nanocrystals prepared by the PLAs in (a) de-ionized water and (b) SDS solution with corresponding electron diffraction patterns. The morphology of the nanocrystals prepared in the de-ionized water indicated that spherical aggregates coexisted with dispersed spherical nanocrystals. Corresponding selected area electron diffraction (SAED) patterns revealed diffused characteristic ring patterns, which confirmed the presence of the amorphous phase. Compared to the case of de-ionized water, smaller and more dispersed $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ nanocrystals were obtained in the SDS solution, as shown in Fig. 3(b). The SAED pattern of the $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ colloidal nanocrystals prepared in the SDS solution shown in the inset of Fig. 3(b) contain bright polycrystalline diffraction rings. The lattice spacings derived from the diffraction rings were in agreement with the scheelite-type $\text{NaLa}(\text{MoO}_4)_2$.

Fig. 4 compares the crystal size distributions of the $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ nanocrystals prepared in the (a) de-ionized water and (b) SDS solution, obtained by randomly measuring diameters of nanocrystals in the TEM images. The average size of the nanocrystals in the de-ionized water was 20.2 nm with a standard deviation of 7.3 nm. However, the $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ nanocrystals prepared in the SDS solution exhibited a smaller average size of 5.1 nm and narrower size distribution with a standard deviation of 1.5 nm. These XRD, TEM, and size distribution experimental results demonstrate that the SDS molecules have a significant effect on the crystallization and agglomeration of the $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ nanocrystals during the PLA in the aqueous medium.

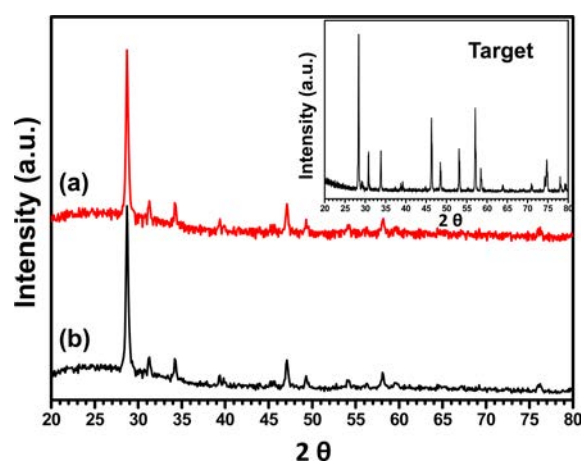


Fig. 2. XRD patterns of the $\text{Er}^{3+}/\text{Yb}^{3+}$ co-doped $\text{NaLa}(\text{MoO}_4)_2$ nanocrystals prepared by the PLAs in the (a) de-ionized water and (b) SDS solution. The inset shows the XRD pattern of an $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ bulk target fabricated by an ambient sintering.

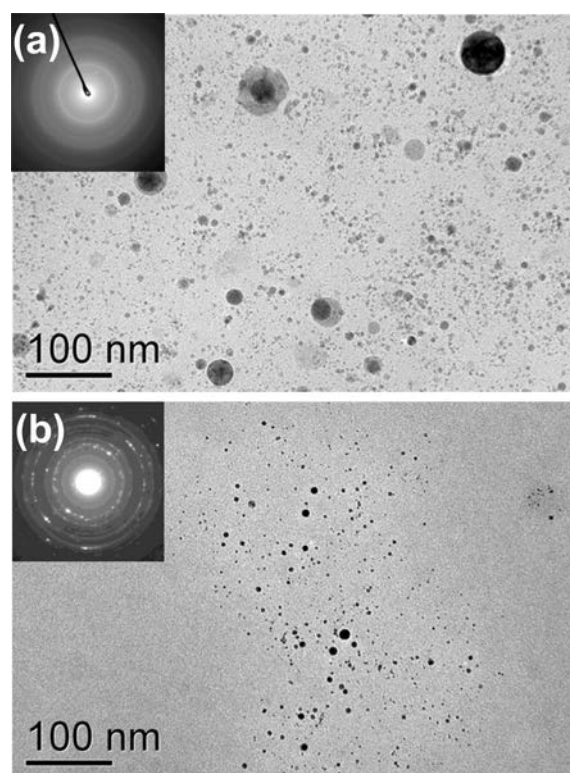


Fig. 3. Typical TEM micrographs of the $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ colloidal nanocrystals prepared by the PLAs in the (a) de-ionized water and (b) SDS solution with corresponding electron diffraction patterns.

According to previous studies on laser ablations at liquid-solid interfaces [28–30], the initial stage of the interaction between the pulsed laser beam and target surface generates a hot plasma plume over the laser spot on the ceramic target, leading to an intense evaporation from the melt surface, as that of a PLA in a

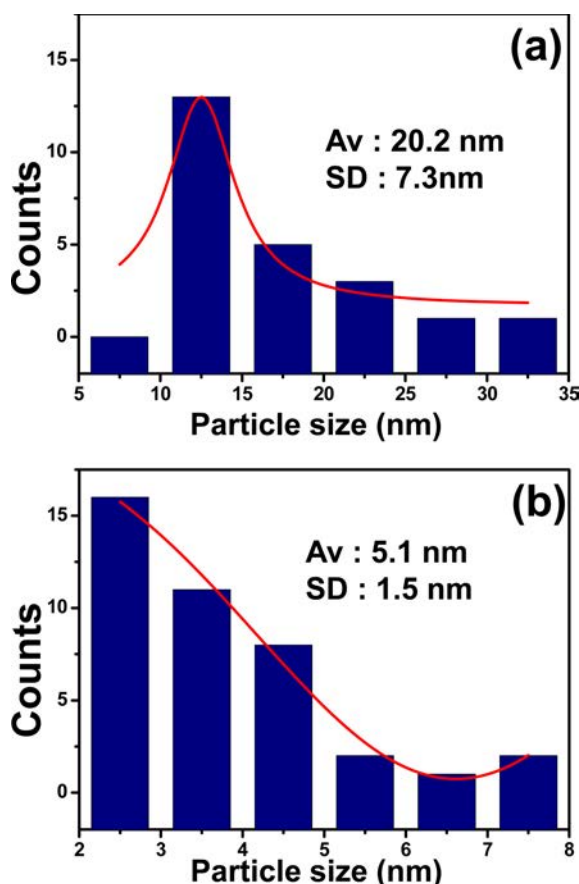


Fig. 4. Size distributions of the $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ colloidal nanocrystals prepared by the PLAs in the (a) de-ionized water and (b) SDS solution. Av and SD denote the average crystallite size and standard deviation, respectively.

gas phase or vacuum background. However, as the plasma is confined in the liquid during the laser ablation, it adiabatically expands outside at a supersonic velocity creating shock waves in front, which induces an elevated pressure and further increase in the plasma temperature. This extremely high transient pressure in the plasma plume can lead to a forceful impingement of the ablated species on the confining liquid. In our case, the active species of $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ nanoclusters could strongly react with water molecules at the interfacial region between the plasma and liquid. The initially generated plasma plume is referred to as hot-plasma zone, while the expanded plasma-liquid interfacial region is referred to as reactive quenching zone. This initial cluster served as nuclei and rapidly quenched into the liquid solution together with other radicals or ions such as $[\text{OH}]^-$ and $[\text{H}]^+$. The directly quenched cluster of $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ most likely had an amorphous phase owing to the transient reaction and rapid quenching. In addition, the quenched clusters in the solution generally had a positively charged surface, as oxygen vacancies were easily generated owing to the dissociation of oxygen

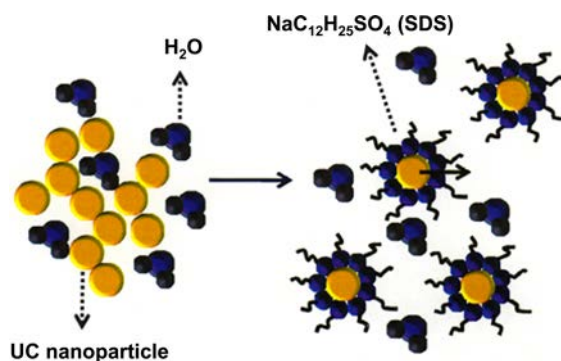


Fig. 5. Schematics describing the influences of (a) water and (b) SDS molecules on the aggregation processes of the $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ nanocrystals during the PLA in the liquid.

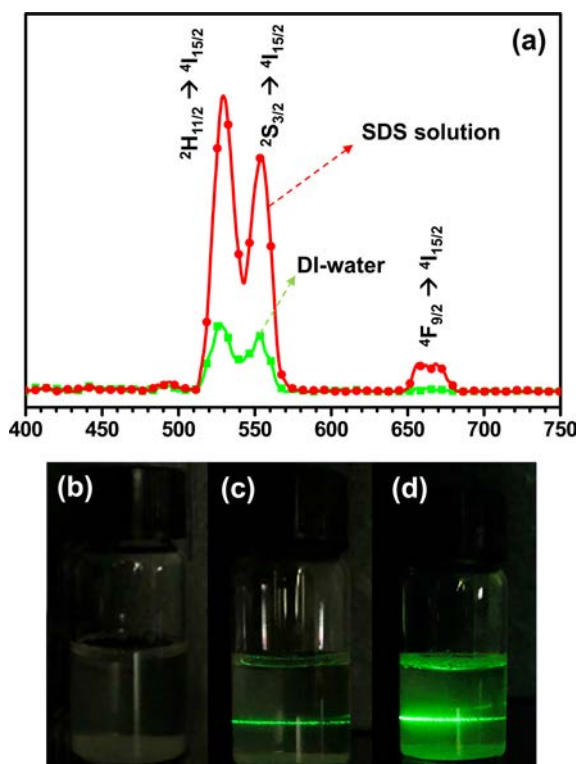


Fig. 6. (a) UC spectra of the $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ nanocolloidal suspensions prepared by the PLAs in the de-ionized water and SDS solution. Digital photographs show (b) de-ionized water, (c) $\text{Er}^{3+}/\text{Yb}^{3+}$ co-doped $\text{NaLa}(\text{MoO}_4)_2$ colloidal suspensions prepared in de-ionized water and (d) $\text{Er}^{3+}/\text{Yb}^{3+}$ co-doped $\text{NaLa}(\text{MoO}_4)_2$ colloidal suspensions prepared in SDS solution, excited by 980 nm laser diode.

induced by the instantaneously high temperature over the melting temperature during the laser ablation. A pH measurement demonstrated that the liquid solution was changed from a neutral state (6.8) to a weak acidic state (5.0) after the laser ablation.

In the following liquid zone, the surfactant had an important role in the further growth of clusters and inhibition of their aggregation. In the de-ionized

water, no stable micelle structure on the surfaces of the $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ cluster was formed. Therefore, significantly agglomerated nanocrystals containing an amorphous phase were obtained, as shown in Fig. 3(a). However, the SDS molecule, $\text{NaC}_{12}\text{H}_{25}\text{SO}_4$, had a local negative charge at the end of its hydrophilic group. Therefore, the SDS molecules surrounded the $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ nanocrystals and formed bilayer-micelles owing to the electric attractive forces between the positive surfaces of the $\text{Er}^{3+}/\text{Yb}^{3+}$ co-doped $\text{NaLa}(\text{MoO}_4)_2$ nanocrystals and negative charges of the SDS molecules, as illustrated in Fig. 5. These bilayer-micelles enabled highly dispersed stable colloidal nanocrystals with a reduced number of surface defects, higher crystallinity and smaller crystallite size.

Fig. 6(a) shows the room-temperature UC emission spectra of the $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ colloidal nanocrystals prepared by the PLAs in the de-ionized water and SDS solution, under a 980 nm excitation. The UC emissions are dominated by a strong green emission, while the red emission is significantly weaker than the green emission. The emission intensities of the nanocrystals prepared in the de-ionized water were significantly lower than those of the nanocrystals in the SDS solution. The low emission intensity may originate from the enhanced non-radiative process in the defective surface layer with the decrease in the crystal size. However, a remarkable enhancement in the emission was observed for the $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ colloidal nanocrystals prepared in the SDS solution, visible to the naked eye, excited by the 980 nm laser diode (100 mW), as shown in Fig. 6(c,d). This enhancement was not due to the difference in the number of generated nanocrystals, as the weights of the two products were approximately equal. This result

indicated that the SDS molecules could passivate surface oxygen defects. SDS is an amphoteric surfactant with a localized negative charge of oxygen in the carboxyl ion and localized positive charge of nitrogen. Therefore, it can be considered that SDS adsorbed on the surfaces of the $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ colloidal nanocrystals can effectively passivate oxygen defects, which is consistent with the explanation for the higher crystallinity, better dispersion, and narrower crystallite size distribution.

The UC emission mechanism and population processes for the green ($^4\text{I}_{11/2}$, $^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2}$) and red ($^4\text{F}_{9/2} \rightarrow ^4\text{I}_{15/2}$) UC luminescences of the in $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ structure are illustrated in Fig. 7. Under the of 980 nm excitation, Er^{3+} and Yb^{3+} ions are initially excited from their ground states to excited states through ground-state absorptions (GSA) processes (Er^{3+} : $^4\text{I}_{15/2} \rightarrow ^4\text{I}_{11/2}$, Yb^{3+} : $^2\text{F}_{7/2} \rightarrow ^2\text{F}_{5/2}$). The energy transfer (ET) process of $^2\text{F}_{5/2}(\text{Yb}^{3+}) + ^4\text{I}_{15/2}(\text{Er}^{3+}) \rightarrow ^2\text{F}_{7/2}(\text{Yb}^{3+}) + ^4\text{I}_{11/2}(\text{Er}^{3+})$ is responsible for the population at the $^4\text{I}_{11/2}$ level of Er^{3+} . For the green emissions, the energy transition from the $^4\text{I}_{11/2}$ level to the $^4\text{F}_{7/2}$ level of Er^{3+} is involved in three possible processes [31, 32]:

- (1) excited-state absorption (ESA): $^4\text{I}_{11/2} + \text{photon (980 nm)} \rightarrow ^4\text{F}_{7/2}$
- (2) ET: $^2\text{F}_{5/2}(\text{Yb}^{3+}) + ^4\text{I}_{11/2}(\text{Er}^{3+}) \rightarrow ^2\text{F}_{7/2}(\text{Yb}^{3+}) + ^4\text{F}_{7/2}(\text{Er}^{3+})$
- (3) cross relaxations (CR): $^4\text{I}_{11/2}(\text{Er}^{3+}) + ^4\text{I}_{11/2}(\text{Er}^{3+}) \rightarrow ^4\text{F}_{7/2}(\text{Er}^{3+}) + ^4\text{I}_{15/2}(\text{Er}^{3+})$

These three possible processes can populate to the $^4\text{F}_{7/2}$ level from the $^4\text{I}_{11/2}$ level of Er^{3+} , and then the $^4\text{F}_{7/2}$ level relaxes rapidly and non-radiatively to the next lower levels, $^2\text{H}_{11/2}$ and $^4\text{S}_{3/2}$ of Er^{3+} . Consequently, the above processes can produce the green emissions with the spectral lines near 530 and 550 nm. The UC emissions are dominated by the strong green emission at 530 nm ($^4\text{I}_{11/2} \rightarrow ^4\text{I}_{15/2}$) and 550 nm ($^4\text{S}_{3/2} \rightarrow ^4\text{I}_{15/2}$). For the red emission, the $^4\text{F}_{9/2}$ level is generated by a non-radiative relaxation from $^4\text{S}_{3/2}$ to $^4\text{F}_{9/2}$ and CR transition: $^4\text{F}_{7/2} + ^4\text{I}_{11/2} \rightarrow ^4\text{F}_{9/2} + ^4\text{F}_{9/2}$ [33, 34]. Finally, the $^4\text{F}_{9/2}$ level relaxes radiatively to the ground state ($^4\text{I}_{15/2}$ level), yielding the red emissions at 656 and 670 nm.

Summary

$\text{Er}^{3+}/\text{Yb}^{3+}$ co-doped $\text{NaLa}(\text{MoO}_4)_2$ colloidal nanocrystals were fabricated by the one-step simple route using PLAs in de-ionized water and SDS solution for luminescent bio-labeling applications. The obtained $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ nanocrystals had spherical shapes and highly dispersed morphology. Under the 980-nm excitation, $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ nanocolloidal suspension exhibited distinct green UC luminescences

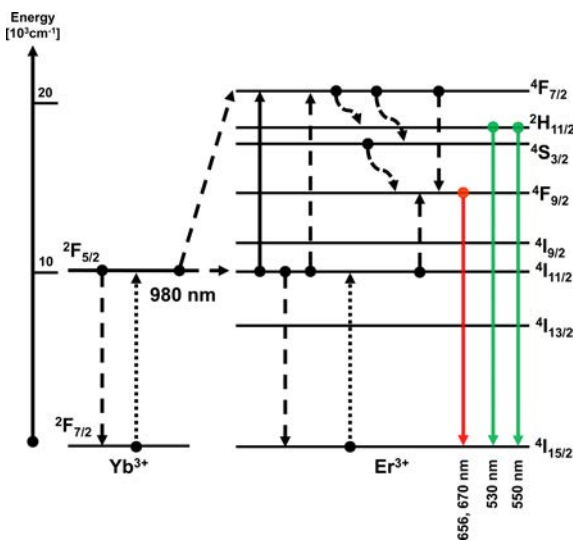


Fig. 7. Energy level diagrams of the $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ and possible UC mechanisms under the 980 nm excitation.

at 530 and 550 nm visible to the naked eye and weak red emissions at 656 and 670 nm. In the SDS solution, the crystallite size and standard deviation of the crystallite size decreased, whereas the UC emission intensity remarkably increased. This result indicated that the anionic oxygen in the SDS molecules effectively occupied the oxygen vacancy sites on the surfaces of the $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ colloidal nanocrystals by the charge matching with the positively charged colloidal nanocrystals. In this study, for the first time, we successfully demonstrated the room-temperature synthesis of the $\text{Er}^{3+}/\text{Yb}^{3+}$ -codoped $\text{NaLa}(\text{MoO}_4)_2$ nanocolloidal suspension using PLA in the liquid phase. This method is also applicable for syntheses of other metal molybdate nanoparticles and colloidal suspensions for UC luminescence bio-labeling applications.

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