Simultaneously tunable luminescence and magnetic properties in bifunctional NaYF$_4$: Yb$^{3+}$/Er$^{3+}$ microcrystals

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ABSTRACT: A series of bifunctional NaYF$_4$ microcrystals doped with Yb$^{3+}$/Er$^{3+}$ have been successfully synthesized through a facile hydrothermal method. They have been characterized by XRD, SEM, photoluminescence spectra and the magnetization. These microcrystals can emit $\sim$540 nm green light from Er$^{3+}$: $4f^1$ electronic transition $^{5}I_{15/2}$, $\sim$657 nm red light from Er$^{3+}$: $4f^1$ electronic transition $^{5}I_{15/2}$, and $\sim$407 nm violet light from Er$^{3+}$: $4f^1$ electronic transition $^{5}I_{15/2}$, under the excitation of 980 nm infrared light. It is found that the red emission is more sensitive to the doping of Yb$^{3+}$ ion than the green one, leading to the significant increase in the ratio of red emission to green emission with increasing concentration of Yb$^{3+}$ ion. In addition, the paramagnetic property was remarkably enhanced with increasing concentration of Yb$^{3+}$ ion which is ascribed to the substitution of nonmagnetic ion Y$^{3+}$ by the magnetic ion Yb$^{3+}$ with large magnetic moment.

KEYWORDS: up-conversion luminescence, bifunctional microcrystals, magnetic property, heavy doping

INTRODUCTION

Up-conversion (UC) materials are those materials that can convert near-infrared emission into visible or ultra-violet emission. They have wide spread applications in various fields such as bio-sensors, bio-imaging, environment monitoring [1, 2], information storage [3, 4], anti-counterfeiting [5–7] and solar cells [8, 9], and thus attracted a tremendous amount of attention for the past decade [10–12]. These trivalent lanthanide-doped ions have unique spectral and magnetic properties and a broad application prospects in many areas [13, 14].

As well known, the light-emitting properties of rare earth and host materials are associated with the doping concentration of rare earth ions and other factors. Among all up-conversion materials [15, 16], NaYF$_4$·Yb$^{3+}$/Er$^{3+}$ has been deemed to be the most efficient infrared-to-visible up-conversion phosphors. In the recent years, the control synthesis of morphology, crystal phase, particle size, and core/shell structure has been developed for NaYF$_4$ up-conversion micro-crystals and nanoparticles, while their up-conversion luminescent characteristics are well investigated accompanied with the detailed demonstration of energy transfer mechanisms [17, 18]. Recently, optical-magnetic bifunctional materials constructed by combining up-conversion luminescent materials with magnetic ones have attracted increasing attentions. Examples are: core-shell NaYF$_4$·Yb$^{3+}$/Tm$^{3+}$@FexOy nanocrystals for dual-modality T$_2$-enhanced magnetic resonance and NIR-to-NIR up-conversion luminescent imaging of small-animal lymphatic node [19], super-paramagnetic and up-conversion emitting of Fe$_2$O$_3$/NaYF$_4$·Yb$^{3+}$Er$^{3+}$ hetero-nanoparticles via a crosslinker anchoring strategy [20], core-shell Fe$_2$O$_3$@NaLuF$_4$: Yb$^{3+}$Er$^{3+}$/Tm$^{3+}$ nanostructure with multifunctional properties synthesized by a step-wise synthetic method [21], and MWCNTs/NaGdF$_4$: Yb$^{3+}$/Er$^{3+}$ nanocomposites synthesized by a simple liquid method with good paramagnetic, up-conversion luminescence, photothermal properties and biocompatibility [22]. However, these bifunctional materials are actually the mixture of optical materials and magnetic ones which have some intrinsic problems, such as optical
and magnetic phase-separation and non-uniform optical and magnetic properties.

More recently, Er\(^3+\)/Yb\(^3+\) doped NaGdF\(_4\) bifunctional nanocrystals with optimizing fluorescent and paramagnetic properties were successfully grown in our laboratory [23]. Furthermore, Er\(^3+\)/Yb\(^3+\) doped NaLuF\(_4\) bifunctional microcrystals co-doped with Gd\(^3+\) or Dy\(^3+\) were also successfully synthesized and enhanced up-conversion luminescence and ferromagnetic-paramagnetic transition [24].

In this work, the NaYF\(_4\):Yb\(^{3+}\)/Er\(^{3+}\) bifunctional microcrystals were successfully synthesized by a facile hydrothermal method, and their optical and magnetic properties could be simultaneously tuned by changing the doping level of Yb\(^{3+}\)/Er\(^{3+}\). Furthermore, the co-doping of magnetic ion Yb\(^{3+}\)/Er\(^{3+}\) affects the magnetic property of NaYF\(_4\) through heavy doping. Meanwhile, the heavy doping of Yb\(^{3+}\) ion would change the crystal field environment of emitter Er\(^{3+}\) so that the up-conversion emission of NaYF\(_4\):Yb\(^{3+}\)/Er\(^{3+}\) changes correspondingly. By analyzing the crystal structure, the fluorescence properties, and the dependence of magnetization on the applied magnetic field, simultaneous tuning of up-conversion luminescence and magnetic property in NaYF\(_4\) crystal was investigated.

**MATERIALS AND METHODS**

**Materials**

Rare-earth (RE) oxides including YO\(_2\) (99.9%), YbO\(_2\) (99.9%) and ErO\(_2\) (99%); trisodium citrate (99%), sodium fluoride (NaF), and nitric acid (HNO\(_3\)), were all purchased from Sinopharm Chemical Reagent Company of China. Deionized water was used throughout. Unless otherwise noted, all chemicals were used directly without further purification.

**Synthesis**

Here, NaYF\(_4\):18%Yb\(^{3+}\)/x%Er\(^{3+}\)(x = 2, 12, 22 and 32 mol%), and NaYF\(_4\):x%Yb\(^{3+}\)/2%Er\(^{3+}\)(x = 18, 38, 58 and 78 mol%) microcrystals were synthesized by the hydrothermal method using trisodium citrate as stabilizing surfactant. Firstly, 0.35 g of trisodium citrate and 10 ml of distilled water were firstly mixed together under agitation to form a homogeneous solution. Then, in a mixing state, added 1.2 ml (0.5 mmol/ml) of Y(NO\(_3\))\(_3\) solution to each drop, and continue stirring for 10 minutes. Then, in a mixing state, 20 ml (0.35 mmol/ml) of NaF aqueous solution were added dropwise. The solution was transferred to a 50 ml stainless steel autoclave and heated at 180 °C for 10 h, then the autoclave was cooled down to room temperature naturally. The samples were washed three times by the mixture of ethanol and distilled water, accompanied with centrifugal separation in order to remove other residual solvents. Finally, these samples were dried at 60 °C for 24 h in a loft drier.

**Characterization**

X-ray power diffraction (XRD) patterns were performed using a Bruker/AXS D8-ADVANCE X-ray diffractometer equipped with a copper target (\(\lambda = 1.541\) nm) for 2\(\theta\) range from 10° to 70° by a step of 0.02°. Scanning electron microscope (SEM) images were recorded on a ZEISS EVO18 scanning electron microscope. Up-conversion emission spectra of these samples were recorded with a Hitachi F-2700 fluorescence spectrophotometer, while the pump excitation source for characterization was an external 980 nm semiconductor laser. The magnetization of these NaYF\(_4\) microcrystals was recorded using a Lake-shore 7307 vibrating sample magnetometer.

**RESULTS AND DISCUSSION**

**Crystal structure**

XRD patterns of NaYF\(_4\):Yb\(^{3+}\)/Er\(^{3+}\) with different Yb\(^{3+}\) ion concentration are shown in Fig. 1. All diffraction peaks of the NaLuF\(_4\):18%Yb\(^{3+}\), 2%Er\(^{3+}\) sample match very well with the standard diffraction peaks of hexagonal phase structure NaYF\(_4\) (Joint Committee for Powder Diffraction

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**Fig. 1** XRD patterns of the NaYF\(_4\): x%Yb\(^{3+}\), 2% Er\(^{3+}\) (x = 18%, 38%, 78%).
Studies (JCPDS) card 16-0334). It can also be seen from Fig. 1 that a small quantity of diffraction peaks corresponding to cubic-phase NaYF₄ are observed when the Yb³⁺ concentration is changed from 18 mol% to 38 mol%. Furthermore, many diffraction peaks corresponding to cubic-phase NaYF₄ are observed when the Yb³⁺ ion concentration are changed from 38 mol% to 78 mol%. This means that with the increase of the Yb³⁺ ion concentration, more cubic-phase NaYF₄ crystals are mixed with the hexagonal NaYF₄ crystals, and this phenomenon is more obvious when the Yb³⁺ ions are doped heavily.

To further reveal the phase and size control, these prepared microcrystals were measured by a ZEISS EVO18 SEM. On the one hand, the Yb³⁺ concentration was held constant (18 mol%), while that of Er³⁺ ions was changed. It is observed in Fig. 2 that the NaYF₄ microcrystals with different Er³⁺ ion concentration have the shape of relatively regular hexagonal rods. With the increasing of Er³⁺ ion concentration from 2 mol% to 32 mol%, the diameter of these rods are gradually reduced, while the length of the rods are gradually increased. In addition, when the Er³⁺ concentration is 22 mol%, the NaYF₄ microcrystals have the shape of hexagonal rods and microplates. On the other hand, the Yb³⁺ concentration was held constant (2 mol%), while that of Yb³⁺ ions was changed. It is clear in Fig. 3 that these NaYF₄ crystals morphology change with different Yb³⁺ ion concentration. Furthermore, with the increasing of Yb³⁺ ion concentration from 18 mol% to 38 mol%, the NaYF₄ microcrystals have the shape of hexagonal rods and microplates mixing with some cubic-phase microplates. Especially, when the Yb³⁺ are doped heavily (58 mol% or 78 mol% Yb³⁺), the size of the NaYF₄ microcrystals is reduced and the crystals have the shape of hexagonal mixed with many cubic-phase microplates. These are consistent with the results of the above-mentioned XRD diffraction analysis. Usually, the difference in morphology may lead to the differential surface properties [25, 26]. On the other hand, the up-conversion emission is highly dependent on the surface properties [27, 28]. Then, it can inferred that the up-conversion emissions of the samples doped with 18 mol% Yb³⁺ ions are different from the other two samples. This suggestion is confirmed by the following fluorescent spectra.

**UC luminescence properties**

The up-conversion fluorescence spectra of these samples were measured with a Hitachi F-2700 spec-
trophotometer, which are shown in Fig. 4–Fig. 6. From the up-conversion emission spectra of NaYF₄: x%Yb³⁺/2%Er³⁺ (x = 18, 38 and 78) (Fig. 4), we can observe emission of violet, green and red at ∼407, ∼540 and ∼557 nm, respectively. When Yb³⁺ ion concentration is 18%, emission peak from high to low is green, red and violet, respectively. It can be seen that with the increase of Yb³⁺ ion concentration from 18% to 38%, the intensity of red emission increases while that of green emission decreases. The change of emission intensity can be explained by the change of distance between Er³⁺ and Yb³⁺. With the increase of the concentration of Yb³⁺ ion in the host lattice, the average distance between Er³⁺ and Yb³⁺ decreases, and the energy transfer from Er³⁺ to Yb³⁺ will be more effective. However, the back energy transfer suppresses the excited state of energetic ions, which decreases the intensity of violet and green emission, and increases the emission intensity of red light. Furthermore, when Yb³⁺ ion concentration changes from 38% to 78%, the light intensity decreased significantly and the concentration was quenched as the distance between Yb³⁺ decreases further. In addition, the ratio of the red peak to the green wave crest is further increased due to the enhancement of the inverse energy transfer.

Fig. 5 showed the up-conversion luminescence spectra of NaYF₄: x%Yb³⁺/2%Er³⁺ (x = 18, 38 and 78) excited with a 980 nm laser operating at four different powers. With the increase of the excited power, all emission intensity of violet, green and red are enhanced for three different Yb³⁺/Er³⁺ doping. But the changes of three kind of emission intensity are different. For emission spectra of the NaYF₄: 18%Yb³⁺/2%Er³⁺ shown in Fig. 5a, the violet and green emission intensity increase almost proportionally with the power of excitation. When the excited power increases from 150 to 550 mW, red emission intensity is also enhanced almost proportionally with the power of excitation. However, when the excited power increases from 550 to 750 mW, the increase of red emission intensity is very small. For emission spectra of the NaYF₄: 38%Yb³⁺/2%Er³⁺ shown in Fig. 5b, the three kinds of emission intensity increase significantly when the excited power increases from 150 to 340 mW. However, the increase of luminous intensity is not obvious when the excitation power continues to be increased. For emission spectra of the NaYF₄: 78%Yb³⁺/2%Er³⁺ shown in Fig. 5c, except for the violet emission, the green and red emission intensity increase proportionally with the power of excitation.

In order to investigate the relationships among the three kinds of fluorescence, we assume that the green emission intensities of the three different Yb³⁺ ion doping are the same. Then the changes
The violet emission change 

\[ I \propto P^n \]  

Where \( I \) is the fluorescent intensity, \( P \) is the pump laser power, and \( n \) is the number of the laser photons required. The excitation power dependence of the green and red emission bands for NaYF\(_4\) microcrystals was measured, and treated by Auzel's method. The green emission intensity as a function of excitation power is shown in Fig. 7a. The parameters \( n \) for the 18\%, 38\% and 78\% Yb\(^{3+}\) doping equal to 1.36, 0.87 and 0.90, respectively. The \( n \) value of 18\% Yb\(^{3+}\) doping for green emission is observed in the range of 1–2, which corresponds to the two-photon conversion process. The \( n \) value of 1.36 means that the two-photon process is involved in the generation of near infrared emission.

The \( n \) value of 38\% Yb\(^{3+}\) doping is below 1, which is seemingly impossible. In fact, due to the increase of Yb\(^{3+}\) ion, the energy delivered by Yb\(^{3+}\) to Er\(^{3+}\) increases, so that the \( 4I_{11/2} \) level is saturated with electrons. At this time, only one electron can be absorbed, and it can jump to the \( 4I_{7/2} \) level and then releases green emission.

The \( n \) value of 78\% Yb\(^{3+}\) doping is about the same as that of 38\% Yb\(^{3+}\) doping, indicating that the energy levels of \( 4I_{11/2} \) are already saturated at the 38\% Yb\(^{3+}\) doping, and that the addition of more Yb\(^{3+}\) ions does not further reduce \( n \) value.

The red emission intensity as a function of excitation power is shown in Fig. 7b. The parameters \( n \) for the 18, 38\% and 78\% Yb\(^{3+}\) doping equal to 1.56, 1.04 and 0.86, respectively. This is similar to green emission, with increase of Yb\(^{3+}\) doping ratio, \( n \) value decreases. When the value of \( n \) is in the range of 1 to 2, the process of two-photon conversion happens. When \( n \) value is less than 1, the level of \( 4I_{11/2} \) is already saturated. only need one
photon, one Er\(^{3+}\) transits from level \(^4I_{11/2}\) to level \(^4I_{7/2}\), then exchanges energy with another level in \(^4I_{11/2}\) Er\(^{3+}\), and enters into two levels of \(^4I_{9/2}\), and then emits red light.

In the Yb\(^{3+}\)/Er\(^{3+}\) co-doped materials, the up-conversion luminescence involved in multi-step excited state absorption, energy transfer of excited state Er\(^{3+}\) ions, and the continuous up-conversion energy transfer between Yb\(^{3+}\) ions and Er\(^{3+}\) ions. According to the energy matching and two or three photon processes depending on the excitation power, possible mechanism for the up-conversion emission is presented based on the simplified energy level diagrams of Yb\(^{3+}\) and Er\(^{3+}\) ions in Fig. 8. The detailed transition processes are described as follow.

As shown in Fig. 4, violet, green and red emissions are observed at \(\sim 407\) nm, \(\sim 540\) nm (and weak green emission \(\sim 520\) nm), and \(\sim 657\) nm, respectively. For the energy transfer and the relative transitions of Er\(^{3+}\) and Yb\(^{3+}\), Yb\(^{3+}\) ion is first excited by a pump photon at 980 nm, the \(^2F_{7/2}\) ground state level transits to the \(^2F_{5/2}\) excited state level (\(^2F_{7/2} \rightarrow ^2F_{5/2}\)), then Yb\(^{3+}\) ion transfers the energy to the neighboring Er\(^{3+}\) ion, so that the \(^4I_{15/2}\) ground state of Er\(^{3+}\) ion transits to the \(^4I_{11/2}\) excited state level, and at the same time Yb\(^{3+}\) ions return to the ground state (\(^2F_{5/2}(\text{Yb}^{3+}) + ^4I_{15/2}(\text{Er}^{3+}) \rightarrow ^2F_{7/2}(\text{Yb}^{3+}) + ^4I_{11/2}(\text{Er}^{3+})\)). Subsequently, Yb\(^{3+}\) ions can transfer the energy to Er\(^{3+}\) ions again through the same process, and then it is further transited from the energy \(^4I_{11/2}\) level to the \(^4F_{7/2}\) level (\(^2F_{5/2}(\text{Yb}^{3+}) + ^4I_{11/2}(\text{Er}^{3+}) \rightarrow ^2F_{7/2}(\text{Yb}^{3+}) + ^4I_{9/2}(\text{Er}^{3+})\)). The \(^4F_{7/2}\) level non-radiatively relaxes to the \(^4S_{3/2}\) low-energy excited state level, Er\(^{3+}\) followed by \(^4S_{3/2}\) level radiation photon returns to the ground state of \(^4I_{15/2}\) level, leading to stronger green light emission at the wavelength of \(\sim 540\) nm.

In addition, The \(^4F_{7/2}\) level non-radiatively relaxes to the \(^2H_{11/2}\) low-energy excited state level, leading to the weak green emission centered \(\sim 520\) nm from the transition \(^2H_{11/2} \rightarrow ^4I_{15/2}\). On the other hand, the \(^4F_{9/2}\) level can non-radiatively relax to \(^4F_{9/2}\) level, and then the \(^4F_{9/2}\) level radiates photon and returns to \(^4I_{15/2}\) ground state level, leading to red light emission at the wavelength of \(\sim 657\) nm. Furthermore, the \(^2H_{9/2}\) level can be excited to the higher \(^4G_{11/2}\) level, then decays non-radiatively to \(^2H_{9/2}\) level and transits to the ground state resulting in \(\sim 407\) nm violet emission. In addition, Er\(^{3+}\) ions at \(^4I_{11/2}\) level or \(^4F_{7/2}\) level mutually transfer energy during these transition processes.

![Energy level diagrams and the relative transitions of Er\(^{3+}\) and Yb\(^{3+}\).](image-url)
Magnetic properties

The NaYF$_4$: Yb$^{3+}$/Er$^{3+}$ microcrystals with heavy doping have specific magnetic properties. The magnetization of NaYF$_4$: x%Yb$^{3+}$/2%Er$^{3+}$ (x = 18, 38, 78) microcrystals was recorded using a Lakeshore7307. It is observed in Fig. 9a that the magnetization of NaYF$_4$: Yb$^{3+}$/Er$^{3+}$ microcrystals significantly increases with the increase of Yb$^{3+}$ ions concentration. In general, the ferromagnetism is observed by the hysteresis loop of the magnetization in many published literatures in recent years [23, 24]. Therefore, in order to observe the ferromagnetism, the local amplification of magnetization for the sample Yb$^{3+}$ doping is illustrated in Fig. 9b on the applied magnetic field from −2.5 kOe to 2.5 kOe. However, there is no clear hysteresis loop of the magnetization in Fig. 9b. In other words, the ferromagnetic properties of these microcrystals are not obvious. The magnetic properties of these microcrystals are mainly paramagnetic.

In fact, the up-conversion luminescence efficiency and paramagnetism are competitive in NaYF$_4$: Yb$^{3+}$/Er$^{3+}$ microcrystals. The increase of Yb$^{3+}$ ion will lead to the increase of the magnetization of NaYF$_4$: Yb$^{3+}$/Er$^{3+}$ microcrystals, but simultaneously leads to the decrease of their luminescent intensity. Therefore, the key is to select the optimal concentration of Yb$^{3+}$ ion for obtaining the expected up-conversion luminescence and paramagnetic property.

CONCLUSION

A series of NaYF$_4$ microcrystals doped with Yb$^{3+}$/Er$^{3+}$ have been successfully synthesized through a facile hydrothermal method. The XRD and SEM analyses reveal that these optical-magnetic bifunctional microcrystals have relatively uniform size belonging to hexagonal phase at Yb$^{3+}$ ion light doping. On the other hand, the size of the NaYF$_4$ microcrystals are reduced, with the shape of hexagonal mixed with many cubic-phase microplates at Yb$^{3+}$ ion heavy doping. Under the excitation of 980 nm infrared light, NaYF$_4$: x%Yb$^{3+}$/2%Er$^{3+}$ (x = 18, 38, 78) can emit ~657 nm red light from Er$^{3+}$→$^{4}$f$_{n}$ electronic transition $^{4}$F$_{9/2}$→$^{4}$I$_{15/2}$, ~540 nm green light from Er$^{3+}$→$^{4}$f$_{n}$ electronic transition $^{4}$S$_{3/2}$→$^{4}$I$_{15/2}$ and ~407 nm violet light from Er$^{3+}$→$^{4}$f$_{n}$ electronic transition $^{4}$H$_{9/2}$→$^{4}$I$_{15/2}$. In addition, the emission intensities of the three kinds of light are affected by the excitation power and vary with the concentration of Yb$^{3+}$ ion doping. Furthermore, the red emission is more affected by the Yb$^{3+}$ doping concentration. The ratio of red emission to green emission increases significantly by introducing Yb$^{3+}$ ion heavy doping. The measured results of magnetization reveal that the paramagnetism of the NaYF$_4$ microcrystals significantly increases with the increase of Yb$^{3+}$ ions concentration. Therefore, up-conversion luminescence and magnetic property in NaYF$_4$ can be tuned simultaneously by introducing Yb$^{3+}$ ion heavy doping.

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