METHOD OF PREPARING LANTHANIDE-DOPED KMnF₃ NANOPARTICLES

Figure 2

Abstract: The present invention discloses a method for preparing lanthanide-doped KMnF₃ nanoparticles which exhibit single-band upconversion emission, comprising the steps of: mixing a manganese oleate precursor and at least one lanthanide precursor in a solvent comprising oleic acid to obtain a manganese oleate complex; mixing a solution of potassium fluoride (KF) with the manganese oleate complex to form a mixture; and heating the mixture to form the nanoparticles. There is also provided uses of the prepared nanoparticles.

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Method of preparing lanthanide-doped $\text{KMnF}_3$ nanoparticles

Field of the invention

The present invention relates to a method of preparing lanthanide-doped $\text{KMnF}_3$ nanoparticles. The present invention also relates to uses of the prepared lanthanide-doped $\text{KMnF}_3$ nanoparticles.

Background of the invention

Upconversion (UC) nanoparticles which exhibit anti-Stokes emission are important for applications in fields as diverse as photonics, photovoltaics, biological imaging, and therapeutics. The nanoparticles may also be useful as taggant materials for product identification, authentication, and anti-counterfeiting applications. In particular, there has been an increasing focus on the synthesis of nanoparticles with tunable UC emission from ultraviolet to near-infrared through doping with lanthanide ions. However, it has been challenging to synthesise nanoparticles featuring single-band UC with high chromatic purity, as lanthanide ions generally have more than one metastable excited state. Accordingly, the lanthanide-doped nanoparticles display multipeak emission profiles.

Several attempts have been made to obtain high purity of single-band UC nanoparticles. For example, high red-to-green (R/G) emission ratio is achieved by increasing the concentration of $\text{Yb}^{3+}$ in Yb/Er co-doped NaYF$_4$ nanoparticles. However, this is not an efficient method as the emission is dependent on the concentration of $\text{Yb}^{3+}$ ions.

There is therefore a need for an improved method to prepare lanthanide-doped nanoparticles which exhibit single-band UC emission.

Summary of the invention

The present invention seeks to address at least one of the problems in the prior art, and provides a low cost and environmentally friendly method of preparing lanthanide-doped nanoparticles which exhibit single-band upconversion emission upon excitation.
According to a first aspect, there is provided a method of preparing lanthanide-doped KMnF$_3$ nanoparticles comprising the steps of:

(a) mixing a manganese oleate precursor and at least one lanthanide precursor in a solvent comprising oleic acid to obtain a manganese oleate complex;

(b) mixing a solution of potassium fluoride (KF) with the manganese oleate complex to form a mixture; and

(c) heating the mixture to form the nanoparticles,

wherein the lanthanide-doped KMnF$_3$ nanoparticles exhibit single-band upconversion emission.

The KMnF$_3$ nanoparticles may be doped with any suitable lanthanide. For example, the KMnF$_3$ nanoparticles may be doped with Yb$^{3+}$ and at least one of Er$^{3+}$, Tm$^{3+}$ and Ho$^{3+}$. According to a particular embodiment, the at least one lanthanide precursor may be selected from the group consisting of: ytterbium trichloride (YbCl$_3$), erbium trichloride (ErCl$_3$), thulium trichloride (TmCl$_3$) and holmium trichloride (HoCl$_3$).

According to a particular aspect, the lanthanide-doped KMnF$_3$ nanoparticles may be selected from the group consisting of: KMnF$_3$:Yb/Er, KMnF$_3$:Yb/Tm and KMnF$_3$:Yb/Ho. In particular, the lanthanide-doped KMnF$_3$ nanoparticles may be KMnF$_3$:Yb/Er.

Any suitable manganese oleate precursor may be used for the purposes of the present invention. In particular, the manganese oleate precursor may be prepared by mixing manganese chloride and potassium oleate.

The solvent in which the precursors are mixed may further comprise other suitable solvents. For example, the solvent may further comprise oleyamine and/or 1-octadecene.

The mixing steps may be carried out under suitable conditions. According to a particular aspect, the mixing of (b) may be carried out at room temperature.

The heating may be carried out under suitable conditions. According to a particular aspect, the heating may be carried out at a temperature of approximately 200°C.
approximately 300°C. According to another particular aspect, the heating may be carried out under inert conditions.

The lanthanide-doped KMnF₃ nanoparticles may have any suitable structure. For example, the lanthanide-doped KMnF₃ nanoparticles may have a cubic structure.

The lanthanide-doped KMnF₃ nanoparticles may be of any suitable size. According to a particular aspect, the lanthanide-doped KMnF₃ nanoparticles each comprise at least one dimension of size ≤ 100 nm. In particular, the nanoparticles each comprise at least one dimension of size 1-100 nm, 5-90 nm, 10-80 nm, 15-70 nm, 20-60 nm, 25-50 nm, 30-40 nm. Even more in particular, the nanoparticles each comprise at least one dimension of <50 nm.

The lanthanide-doped KMnF₃ nanoparticles may be NIR-to-visible upconversion nanoparticles. According to a particular aspect, the lanthanide-doped KMnF₃ nanoparticles may exhibit single-band upconversion emission when excited under NIR. In particular, the nanoparticles may exhibit single-band upconversion emission when excited under 980 nm NIR.

According to a second aspect, the present invention provides lanthanide-doped KMnF₃ nanoparticles prepared according to the method described above. The lanthanide-doped KMnF₃ nanoparticles may be as described above.

According to a third aspect of the present invention, there is provided a method of identifying or authenticating a product, the method comprising the step of including the lanthanide-doped KMnF₃ nanoparticle described above as a marker in the product.

The present invention also provides a marker comprising the lanthanide-doped KMnF₃ nanoparticles prepared according to the method described above. The marker may be used in suitable applications. In particular, the marker may be a biomarker or a security marker.

According to another aspect, the present invention provides a bio-imaging and/or bio-detection apparatus comprising: at least one lanthanide-doped KMnF₃ nanoparticle prepared according to the method described above; and at least one source of excitation. The source of excitation may be any suitable source. For example, the
source may be NIR. According to a particular aspect, the source of excitation may be at 980 nm.

Brief Description of the Drawings

In order that the invention may be fully understood and readily put into practical effect there shall now be described by way of non-limitative example only exemplary embodiments, the description being with reference to the accompanying illustrative drawings. In the drawings:

Figure 1 shows an SEM image of the as-synthesized KMnF₃:Yb/Er (18:2 mol%) nanocrystals;

Figure 2 shows (a) a low-resolution TEM image of the as-synthesized KMnF₃:Yb/Er (18:2 mol%) nanocrystals; (b) high-magnification TEM image of a single nanocrystal; (c) the corresponding Fourier Transform diffraction patterns of the high-magnification TEM image shown in (b); (d) and (e) show schematic representations of lanthanide-doped KMnF₃ cubic structure in the form of K⁺ and Mn²⁺ cation vacancies, respectively;

Figure 3 shows the X-ray powder diffraction patterns of the as-synthesized KMnF₃:Yb/Er (18:2 mol%), KMnF₃:Yb/Er (9:2 mol%), and KMnF₃:Er (5 mol%) nanocrystals. (a) to (c) corresponding XRD patterns of the nanocrystals obtained after heating at 290°C for 1.5 hours in 1-octadecene, (d) to (l) are corresponding XRD patterns of the nanocrystals heated at 200°C for 24 hours in autoclave and (g) is the literature XRD for cubic KMnF₃ crystals (Joint Committee on Powder Diffraction Standards file number 82-1334);

Figure 4 shows the room-temperature UC emission spectra of solutions containing: a) KMnF₃:Yb/Er (18:2 mol%), b) KMnF₃:Yb/Ho (18:2 mol%), and c) KMnF₃:Yb/Tm (18:2 mol%) nanocrystals in cyclohexane (insets: proposed energy transfer mechanisms and corresponding luminescent photos of the colloidal solutions). All spectra were recorded under excitation of a 980 nm CW diode laser at a power density of 10 W/cm²;

Figure 5 shows the upconversion emission spectra of KMnF₃:Yb/Er (18:2 mol%) nanocrystals recorded at (a) 10K and (b) 325K;

Figure 6 shows a) Pump-power-dependent UC emission spectra of solutions containing KMnF₃:Yb/Er (18:2 mol%) and NaYF₄:Yb/Er (18:2 mol%) nanocrystals. All spectra were recorded at room temperature under excitation of a 980 nm CW diode laser at a power density of 10 W/cm² and b) Emission intensity comparison of the red emission from the KMnF₃ and NaYF₄ nanocrystals as a function of pump power;

Figure 7 shows room temperature (25°C) photoluminescence spectra of variant Yb²⁺/Er³⁺ doped KMnF₃ nanocrystals synthesized via two different methods. The nanocrystals used in (a) were obtained after heating for 1 h at 290°C in 1-octadecene while the nanocrystals used in (b) were prepared at 200°C for 24 h in an autoclave; and
Figure 8 shows the luminescence images of pork muscle tissues injected with different UC nanocrystals - a) KMnF$_3$:Yb/Er (18:2 mol%), b) NaYF$_4$:Yb/Er (18:2 mol%), c) NaYF$_4$:Yb/Er (29:1 mol%). (d) to (f) show the corresponding emission luminescence spectra of (a) to (c), respectively. All images and spectra were taken under a 980 nm laser excitation with a power density of approximately 0.2 W/cm$^2$. Note that the intensities of the two systems at 0 nm are almost the same.

Detailed description of the invention

The present invention provides a method of preparing lanthanide-doped nanoparticles, particularly lanthanide-doped KMnF$_3$ nanoparticles, which exhibit single-band upconversion emission when excited. These nanoparticles are in stark contrast to conventional materials which feature multi-peak emission profiles. In particular, the nanoparticles prepared according to the method of the present invention are highly stable even with different pump powers. The nanoparticles prepared according to the method may be useful in many applications such as product authentication, anti-counterfeiting, as well as in optical applications such as for use as bio-labels in deep tissue imaging. Further, the nanoparticles prepared according to the method exhibit the single-band emission profile independent of the concentration of the dopant in the nanoparticle, pump power and temperature.

The method of the present invention is a simple and low cost method. Further, the method of the present invention does not have an adverse environmental impact, which is an important factor in view of the concerns at which industrial methods can impact the environment. The method of the present invention may also be easily scaled up to an industrial scale.

For the purpose of the present invention the term "nanoparticle" and "nanocrystal" may be used interchangeably.

According to a first aspect, there is provided a method of preparing lanthanide-doped KMnF$_3$ nanoparticles comprising the steps of:

(a) mixing a manganese oleate precursor and at least one lanthanide precursor in a solvent comprising oleic acid to obtain a manganese oleate complex;

(b) mixing a solution of potassium fluoride (KF) with the manganese oleate complex to form a mixture; and
(c) heating the mixture to form the nanoparticles,

wherein the lanthanide-doped KMnF$_3$ nanoparticles exhibit single-band upconversion emission.

The KMnF$_3$ nanoparticles may be doped with any suitable lanthanide. The KMnF$_3$ nanoparticles may be doped with Yb, Er, Tm and Ho, or a combination thereof. According to a particular aspect, the KMnF$_3$ nanoparticles may be doped with Yb$^{3+}$ and at least one of Er$^{3+}$, Tm$^{3+}$ and Ho$^{3+}$.

The lanthanide precursor may be any suitable precursor which is able to react with the manganese oleate precursor. The lanthanide precursor may be selected based on the manganese oleate precursor. For example, the lanthanide precursor may be the chloride form of the lanthanides. According to a particular embodiment, the at least one lanthanide precursor may be selected from the group consisting of: ytterbium trichloride (YbCl$_3$), erbium trichloride (ErCl$_3$), thulium trichloride (TmCl$_3$) and holmium trichloride (HoCl$_3$).

The manganese oleate precursor may be in any suitable form for the purposes of the present invention. The manganese oleate precursor may be a commercially available precursor or may be prepared prior to the mixing with the lanthanide precursor. According to a particular embodiment, the method comprises preparing the manganese oleate precursor prior to the mixing of (a). The preparing the manganese oleate precursor may comprise mixing manganese chloride and potassium oleate. The manganese chloride and the potassium oleate may be mixed in a suitable solvent. For example, the solvent may be a solvent mixture comprising ethanol, distilled water and hexane. The mixing of the manganese chloride and the potassium oleate may be carried out under suitable conditions.

The solvent used in the mixing of (a) may comprise at least oleic acid. The solvent used in the mixing of (a) may be a solvent mixture comprising oleic acid and other suitable solvents. For example, the other suitable solvents may include oleyamine and/or 1-octadecene.

The mixing of (a) and (b) may be carried out under suitable conditions. For example, the mixing of (a) may be carried out at room temperature. According to a particular
embodiment, the mixing of (a) may be carried out under vigorous stirring. The stirring may be by any suitable means.

The method may further comprise heating the manganese oleate complex formed after the mixing of (a). The manganese oleate complex may be heated at any suitable temperature. For example, the manganese oleate complex may be heated at a temperature of about 100-200°C. In particular, the manganese oleate complex may be heated at a temperature of about 120-170°C, 140-160°C, 145-155°C. Even more in particular, the manganese oleate complex may be heated at a temperature of about 150°C.

The manganese oleate complex may be heated for a suitable period of time. For example, the manganese oleate complex may be heated until the manganese oleate complex changes colour. In particular, the manganese oleate complex may be heated for a period of about 30-90 minutes, 40-80 minutes, 45-65 minutes, 50-60 minutes. Even more in particular, the manganese oleate complex may be heated for about 60 minutes.

According to a particular aspect, once the manganese oleate complex changes colour, the manganese oleate complex may be cooled. For example, the manganese oleate complex may be cooled to room temperature prior to the mixing of (b).

The mixing of (b) comprises mixing a solution of potassium fluoride (KF) with the manganese oleate complex to form a mixture. The mixing of step (b) may initiate crystal growth. The potassium fluoride may be dissolved in a suitable solvent. For example, the potassium fluoride may be dissolved in methanol to form a methanolic solution of KF.

The mixing of (b) may be carried out at room temperature. The mixing of (b) may comprise constant stirring. The stirring may be by any suitable means.

The stirring may be for a suitable period of time. For example, the mixture may be stirred for a period of about 10-60 minutes, 15-45 minutes, 20-40 minutes, 25-35 minutes. Even more in particular, the mixture may be heated for about 30 minutes.

The mixing of (b) may comprise stirring the mixture at a suitable temperature above room temperature. For example, the stirring may be carried out at a temperature of
about 40-80°C, 45-75°C, 50-70°C, 55-65°C. In particular, the stirring may be carried out at a temperature of about 65°C.

The heating of (c) may be carried out under suitable conditions. According to a particular aspect, the heating may be carried out at a temperature of approximately 200 - approximately 300°C thereby producing a reaction mixture comprising the nanocrystals/nanoparticles. In particular, the heating may be carried out at a temperature of about 220-290°C, 230-280°C, 240-270°C, 250-260°C. Even more in particular, the heating may be carried out at about 290°C.

According to another particular aspect, the heating may be carried out under inert conditions. For example, the heating may be carried out in a nitrogen or argon atmosphere. In particular, the heating may be carried out in a nitrogen atmosphere.

The heating may be carried out for any suitable period of time. For example, the heating may be carried out for a period of about 30-120 minutes, 45-100 minutes, 60-90 minutes, 70-80 minutes, 60-65 minutes. In particular, the heating may be carried out for about 90 minutes. The heating may facilitate the growth of the nanocrystals.

The method of the present invention may further comprise cooling the nanoparticles to room temperature after the heating. The prepared lanthanide-doped KMnF$_3$ nanoparticles may then be separated and recovered from the reaction mixture by any suitable method. For example, the nanoparticles may be separated by centrifugation.

The method of the present invention presents several advantages. First, it produces nanoparticles exhibiting single-band upconversion emission which increases the usefulness of the nanoparticles. Further, the method is simple and uses technical-grade solvents and precursors, and does not involve sophisticated equipment. This makes the method very cost-effective as well. In the method of the present invention, the oleic acid forms an oleate metal complex with the lanthanide dopant ions and the manganese ions. Subsequently, the metal oleate complex undergoes a reaction with the fluoride ions at a particular reaction speed controlled by the oleic acid to incorporate the lanthanide ions into the managanese host lattice. In this way, the lanthanide dopants are homogeneously incorporated in the host KMnF$_3$ lattice, resulting in the efficient transfer of energy between the dopant ion and host Mn$^{2+}$ ion to produce the single-band upconversion emission. In particular, the oleic acid used in
the method helps to control the nanoparticle formation speed, thereby enabling the formation of monodisperse nanoparticles.

The present invention also relates to lanthanide-doped KMnF₃ nanoparticles prepared by the above-described method. The nanoparticles have unexpected properties of exhibiting single-band upconversion emission. In particular, the nanoparticles exhibit a single-band upconversion emission profile when excited with a suitable energy source.

According to a particular aspect, the prepared lanthanide-doped KMnF₃ nanoparticles may be selected from the group consisting of: KMnF₃:Yb/Er, KMnF₃:Yb/Tm and KMnF₃:Yb/Ho. In particular, the lanthanide-doped KMnF₃ nanoparticles may be KMnF₃:Yb/Er.

For the purposes of the present invention, a nanoparticle may be defined as being one comprising constituents which has at least one dimension in the nanoscale. The nanoparticle prepared from the method according to any aspect of the present invention may be of a suitable size. For example, the nanoparticle may comprise at least one dimension having size ≤ 1000 nm, ≤ 100 nm, or ≤ 50 nm. More in particular, the nanoparticles each comprise at least one dimension of size 1-100 nm, 5-90 nm, 10-80 nm, 15-70 nm, 20-60 nm, 25-50 nm, 30-40 nm. Even more in particular the nanoparticle may comprise at least one dimension of size ≤ 10 nm or ≤ 5 nm.

The nanoparticles may have any suitable structure. For example, the lanthanide-doped KMnF₃ nanoparticles may have a cubic structure.

The lanthanide-doped KMnF₃ nanoparticles are luminescent nanoparticles. In particular, the lanthanide-doped KMnF₃ nanoparticles are upconversion nanoparticles. According to a particular aspect, the lanthanide-doped KMnF₃ nanoparticles may be NIR-to-visible upconversion nanoparticles wherein the nanoparticles may be capable of converting near-infrared into visible light. In particular, the lanthanide-doped KMnF₃ nanoparticles may exhibit single-band upconversion emission when excited under a suitable light source.

Light sources for excitation wavelengths can be any source known in the art that can provide the desired light. In particular, the light source may be any light source
capable of providing NIR light. Even more in particular, the light source may be a light source capable of providing 980 nm light. For example, the light source may be a 980 nm laser source. Light sources can generally disperse light, or the light can be channelled through optics and/or monochromometers for selected and directed excitation wavelengths.

According to a particular aspect, the light source may be a near-infrared (NIR) source. The nanoparticles may exhibit single-band upconversion emission when excited under 980 nm NIR. Even more in particular, the nanoparticles may emit visible light under 980 nm laser diode excitation via the upconversion process under relatively low excitation power densities. As a result of efficient energy transfer between the dopant lanthanide ion and host Mn²⁺ ion, pure single-band upconversion emissions may be generated in the red and near-infrared spectral regions.

The lanthanide-doped KMnF₃ nanoparticles prepared from the method of the present invention may be suitable for various applications in view of its capability of exhibiting single-band upconversion emission. For example, the lanthanide-doped KMnF₃ nanoparticles may be used as markers for the identification or authentication of products. The lanthanide-doped KMnF₃ nanoparticles may also be used as taggants.

Accordingly, the present invention provides a marker comprising the lanthanide-doped KMnF₃ nanoparticles prepared according to the method described above. The marker may be a biomarker or a security marker. For example, the security marker may be used in authenticating a product. A biomarker may be for various uses, such as deep-tissue labelling and/or imaging.

The lanthanide-doped KMnF₃ nanoparticles may be required to be surface-modified before being used as markers. Accordingly, the present invention provides a method of modifying a surface of the lanthanide-doped KMnF₃ nanoparticles. The surface of the lanthanide-doped KMnF₃ nanoparticles may be modified by any suitable material. For example, the lanthanide-doped KMnF₃ nanoparticles may be modified by adding at least one surfactant, lipid, polymer, inorganic material, or a mixture thereof, to the surface of the lanthanide-doped KMnF₃ nanoparticle. In particular, the surface of the lanthanide-doped KMnF₃ nanoparticle may be modified by a polymer before being used as a biomarker.
The surface of the lanthanide-doped KMnF$_3$ nanoparticle may be modified to confer certain properties onto the nanoparticle. For example, the surface of the nanoparticle may be modified to make the nanoparticle more hydrophilic, hydrophobic or amphiphilic. In particular, the nanoparticle may be made hydrophilic in order to better attach the nanoparticle to biomolecules such as proteins and DNA. The nanostructured material may be made more hydrophilic by surfactant(s) and/or lipid(s).

The present invention also provides a method of identifying or authenticating a product, the method comprising a step of including the lanthanide-doped KMnF$_3$ nanoparticle described above as a marker in the product. The step of including the lanthanide-doped KMnF$_3$ nanoparticles may be by application onto or incorporation of the nanoparticles into the product. For example, the lanthanide-doped KMnF$_3$ nanoparticles may be deposited or coated on a product by methods known in the art such as inkjet printing and the like.

Examples of products that may comprise the lanthanide-doped KMnF$_3$ nanoparticles include, but are not limited to, bank notes, cheques, passports, security inks, security papers, fuels, packaging such as for pharmaceuticals and controlled products, and branded products. In particular, the product may be an ink, a fuel, paper, cardboard, or textile.

The method of identifying or authenticating may further comprise the step of exciting the nanoparticle in the product with an appropriate excitation wavelength, and detecting the unique emission wavelength emitted from the product.

The present invention also provides a bio-imaging and/or bio-detection apparatus comprising: at least one lanthanide-doped KMnF$_3$ nanoparticle prepared according to the method described above; and at least one source of excitation. The source of excitation may be any suitable source. For example, the source may be as described above. In particular, the source may be NIR. According to a particular aspect, the source of excitation may be at 980 nm.

The lanthanide-doped KMnF$_3$ nanoparticles may be surface modified. In particular, the lanthanide-doped KMnF$_3$ nanoparticles may be surface modified as described above.
Having now generally described the invention, the same will be more readily understood through reference to the following examples which are provided by way of illustration, and are not intended to be limiting.

**EXAMPLES**

5 Reagents manganese chloride (MnCl₂·4H₂O) (98%), potassium oleate, YbCl₃·6H₂O (99.99%), ErCl₃·6H₂O (99.99%), TmCl₃·6H₂O (99.99%), HoCl₃·6H₂O (99.99%), NaOH (98+%), KF (99+%), 1-octadecene (90%), oleic acid (90%), and oleylamine (70%) were purchased from Sigma-Aldrich. All the chemicals were used as starting materials without further purification.

10 *Preparation of manganese oleate precursor*

The manganese-oleate complex was prepared by reacting manganese chloride and potassium oleate. 40 mmol of manganese chloride and 120 mmol of potassium oleate were dissolved in a solvent mixture composed of 80 mL of ethanol, 60 mL of distilled water and 140 mL of hexane. The resulting solution was stirred at room temperature for four hours. Upon completion of the reaction the upper organic layer containing the manganese oleate complex was separated and washed three times with 30 mL of distilled water. After washing, hexane was removed, yielding manganese oleate complex in a waxy solid form.

*Preparation of Yb/Er-doped KMnF₃ nanoparticles*

20 Synthesis of the lanthanide-doped KMnF₃ nanocrystals at 290°C included adding the prepared manganese oleate precursor (197.7 mg) to YbCl₃ (0.072 mmol) and ErCl₃ (0.008 mmol) to a flask containing a mixture of oleylamine (1 mL), oleic acid (1 mL), and 1-octadecene (8 mL) under vigorous stirring at room temperature. The resulting mixture was then heated at 150°C for 1 hour, at which time the solution turned from colorless to yellowish. After the solution was cooled to room temperature, a methanolic solution (2 mL) of KF (1.2 mmol) was injected into the flask. The mixture was stirred at 65°C for 30 minutes and then purged by nitrogen at 105°C for 10 minutes. Subsequently, the temperature was raised to 290°C and kept for 90 minutes under nitrogen atmosphere. Finally, the reaction was cooled to room temperature. The as-prepared nanocrystals were collected by centrifugation, washed with ethanol and methanol several times, and finally re-dispersed in cyclohexane.
Preparation of Yb/Tm-doped KMnF<sub>3</sub> nanoparticles

The method described in preparing Yb/Er-doped KMnF<sub>3</sub> nanoparticles was followed except ErCl<sub>3</sub> was replaced with TmCl<sub>3</sub>.

Preparation of Yb/Ho-doped KMnF<sub>3</sub> nanoparticles

The method described in preparing Yb/Er-doped KMnF<sub>3</sub> nanoparticles was followed except ErCl<sub>3</sub> was replaced with HoCl<sub>3</sub>.

Preparation of lanthanide-doped NaYF<sub>4</sub> nanoparticles

In a typical experiment, 2 mL of RECl<sub>3</sub> (0.2 M, RE = Y, Yb, Er and Tm) each in methanol was added to a 50-mL flask containing 3 mL of oleic acid and 7 mL of 1-octadecene. The resultant solution was heated to 150°C for 30 minutes and then cooled down to room temperature. Thereafter, 5 mL of methanol solution of NH<sub>4</sub>F (1.6 mmol) and NaOH (1 mmol) was added and the solution was stirred for 30 minutes. Upon removal of methanol, the solution was heated to 300°C under argon for 1.5 hours and then cooled down to room temperature. The resulting nanoparticles were precipitated by the addition of ethanol, collected by centrifugation, washed with methanol and ethanol several times, and finally re-dispersed in cyclohexane.

Characteristics of the lanthanide-doped nanoparticles

Figure 1 shows a scanning electron microscopy (SEM) image of the as-synthesized KMnF<sub>3</sub>-Yb/Er (18:2 mol%) nanocrystals with cubic morphology. Figure 2a shows the corresponding transmission electron microscopy (TEM) image of the as-synthesized KMnF<sub>3</sub>-Yb/Er (18:2 mol%) nanocrystals. The high-magnification TEM image of a single KMnF<sub>3</sub>-Yb/Er nanocube shown in Figure 2b reveals lattice fringes of the {110} with a d spacing of 0.31 nm, which is typical for cubic KMnF<sub>3</sub> (Figure 2b). Selected-area electron diffraction patterns obtained from the Fourier transform of the high-magnification TEM image confirms single-crystalline cubic phase of the nanocube (Figure 2c). It should be noted that charge balance will be disturbed when the trivalent lanthanide ions are substituted for the Mn<sup>2+</sup> ions in KMnF<sub>3</sub> nanocrystals. To maintain charge balance, either manganese or potassium vacancies are formed (Figure 2d,e). X-ray powder diffraction studies (Figure 3) show peak positions and intensities that
can be well indexed in accordance with cubic KMnF₃ crystals (JCPDS file no. 82-1334), which is consistent with TEM analysis of the samples.

Figure 4a displays the room-temperature upconversion (UC) emission spectrum of the irradiated KMnF₃ nanocrystals. A narrowband visible emission centered at 660 nm was observed, in stark contrast to Yb³⁺/Er³⁺ co-doped NaYF₄ and LaF₃ nanocrystals, which typically show a set of emission bands in the visible spectral region. The single-band UC emission can be ascribed to nonradiative energy transfer from the ²H₉/₂ and ⁴S₃/₂ levels of Er³⁺ to the ⁴I₁ level of Mn²⁺, followed by backenergy transfer to the ⁴F₉/₂ level of Er³⁺ (Figure 4b). The complete disappearance of blue and green emissions of Er³⁺ suggests an extremely efficient exchange-energy transfer process between the Er³⁺ and Mn²⁺ ions, which can be largely attributed to the close proximity and effective mixing of wave functions of the Er³⁺ and Mn²⁺ ions in the crystal host lattices. The low-temperature (10 K) UC emission spectrum of the KMnF₃·Yb/Er (18:2 mol%) nanocrystals also showed a single-band emission (Figure 5), indicating that the phonon participation in the transfer process has only a marginal effect on the emission.

To investigate the compositional effect of the irradiation, KMnF₃ nanocrystals codoped with Yb³⁺/Ho³⁻ and Yb³⁻/Tm³⁺, respectively, were synthesized. Importantly, these nanocrystals also displayed single-band emissions involving the ⁵F₅→⁵I₆ transition in Ho³⁻ and the ³H₄→³H₆ transition in Tm³⁺ (Figure 4b,c). The full width at half maximum (FWHM) has also been measured to be 20, 23, and 35 nm for KMnF₃·Yb/Er, KMnF₃·Yb/Ho, and KMnF₃·Yb/Tm nanocrystal systems, respectively.

Significantly, the single-band feature of the KMnF₃·Yb/Er nanocrystals remained the same on increasing the pump power (Figure 6a). In contrast, NaYF₄·Yb/Er nanocrystals showed multipeak emissions with relative intensity ratios closely associated with the pump power (Figure 6a). The red emission intensity of the KMnF₃·Yb/Er nanocrystals was found to be substantially higher than that of the NaYF₄·Yb/Er nanocrystals of similar particle size irrespective of the pump power (Figure 6b).

In a further set of experiments, the photoluminescence properties of the KMnF₃·Yb/Er nanocrystals as a function of dopant concentration was examined (Figure 7). As shown in Figure 7a, the KMnF₃ nanocrystals doped with different amounts of Yb³⁻/Er³⁻ (0-18:2-5 mol%) all displayed a single-band emission centered at 660 nm, thus confirming the dominant effect of energy transfer process between the Er³⁻ and Mn²⁻.
ions. It is noted that the KMnF$_3$:Yb/Er (18:2 mol%) nanocrystals hydrothermally prepared by Zeng et al, 2007, Cryst. Growth Des., 7:2774, show a weak green emission at 540 nm in addition to the dominant 660 nm red emission. The additional emission band was attributed to an insufficient energy transfer process between the Er$^{3+}$ and Mn$^{2+}$ ions, caused by segregation of dopant ions from the host lattices. The segregation of dopant ions is typically observed when divalent host ions are substituted for trivalent lanthanide ions at high concentration. To validate this, a series of KMnF$_3$ samples doped with different concentrations of Yb$^{3+}$/Er$^{3+}$ were prepared according to the reported hydrothermal method. The nanocrystals with relatively low concentrations of Yb$^{3+}$/Er$^{3+}$ (9:2 and 0:5 mol%) showed single-band emissions, whereas nanocrystals doped with 18:2 mol% Yb$^{3+}$/Er$^{3+}$ exhibited similar emission patterns to those previously reported (Figure 7). Taken together, these comparative studies suggest that the oil-based synthetic procedure of preparing the lanthanide-KMnF$_3$ nanocrystals with controlled stirring enables more homogeneous doping of large lanthanide content into the KMnF$_3$ host lattices than the hydrothermal method.

**Application of the lanthanide-doped KMnF$_3$ nanoparticles**

An application of single-band red-emission KMnF$_3$:Yb/Er nanocrystals is the development of suitable luminescent biomarkers for deep tissue labeling and imaging. The emission wavelength of KMnF$_3$:Yb/Er nanocrystals falls within the "optical window" in biological tissue, where the emitted light has its maximum depth of penetration. As a proof-of-concept experiment, polymer-modified KMnF$_3$:Yb/Er nanocrystals were injected into pork muscle tissue at varied depths (0-10 mm) and imaged them by a modified Maestro in vivo imaging system.

Imaging of biological samples - Polymer-functionalized water-soluble KMnF$_3$:Yb/Er were prepared by functionalizing the KMnF$_3$:Yb/Er nanoparticles with octylamine-poly(acrylic acid)-polyethylene glycol (OA-PAA-PEG) copolymer. In particular, 200 μL chloroform solution comprising the KMnF$_3$:Yb/Er nanoparticles and 5 mg of the copolymer were mixed in 5 mL of chloroform and stirred for 15 minutes to obtain a clear solution. The chloroform was then removed by purging with argon at room temperature, resulting in the formation of the polymer-functionalized dry nanoparticles.

The polymer-functionalized water-soluble KMnF$_3$:Yb/Er (10 mg/mL) and NaYF$_4$:Yb/Er nanocrystals (10 mg/mL) were dissolved in 1% warm agarose solutions and
transferred into a 96-well plate (100 µL for each well). After cooling to the room temperature, the solidified agarose gel plates containing the nanoparticles were taken and placed into pork muscle tissues at different depths (0 mm, 3 mm, 5 mm, and 10 mm). Upconversion luminescence images of pork tissues with nanocrystal gel plates embedded were taken by a modified Maestro in vivo imaging system using a 980 nm optical fiber-coupled laser as the excitation source. The laser power density was 0.2 W/cm² during imaging. An 850 nm short-pass emission filter was applied to prevent the interference of excitation light to the CCD camera. Spectral imaging from 500 nm to 720 nm (10 nm steps) was carried out with an exposure time of 500 ms for each image frame.

As shown in Figure 8a, the nanocrystals can be visualized even at a depth of 10 mm under an excitation power density of approximately 0.2 W/cm². Under identical experimental settings, however, NaYF₄ nanocrystals co-doped with Yb³⁺/Er³⁺ at different ratios can only be detected at about 5 mm beneath the tissue surface (Figure 8b,c). Notably, the emission color of the KMnF₃:Yb/Er nanocrystals did not change as a function of sample imaging depth, as confirmed by the recorded corresponding emission spectra (Figure 8d). In stark contrast, the NaYF₄ nanocrystals injected at different depths showed significant changes in emission color, which can be attributed to rapid attenuation of the green emission relative to red emission in tissue (Figure 8e,f).

Whilst the foregoing description has described exemplary embodiments, it will be understood by those skilled in the technology concerned that many variations in details of design, construction and/or operation may be made without departing from the present invention.
Claims

1. A method of preparing lanthanide-doped KMnF$_3$ nanoparticles comprising the steps of:
   (a) mixing a manganese oleate precursor and at least one lanthanide precursor in a solvent comprising oleic acid to obtain a manganese oleate complex;
   (b) mixing a solution of potassium fluoride (KF) with the manganese oleate complex to form a mixture; and
   (c) heating the mixture to form the nanoparticles, wherein the lanthanide-doped KMnF$_3$ nanoparticles exhibit single-band upconversion emission.

2. The method according to claim 1, wherein the at least one lanthanide precursor may be selected from the group consisting of: ytterbium trichloride (YbCl$_3$), erbium trichloride (ErCl$_3$), thulium trichloride (TmCl$_3$) and holmium trichloride (HoCl$_3$).

3. The method according to claim 1, wherein the solvent may further comprise oleyamine and/or 1-octadecene.

4. The method according to claim 1, wherein the manganese oleate precursor is prepared by mixing manganese chloride and potassium oleate.

5. The method according to claim 1, wherein the mixing of (b) is carried out at room temperature.

6. The method according to claim 1, wherein the heating is carried out at a temperature of approximately 200°C - approximately 300°C.

7. The method according to claim 1, wherein the heating is carried out under inert conditions.

8. The method according to claim 1, wherein the lanthanide-doped KMnF$_3$ nanoparticles are KMnF$_3$:Yb/Er, KMnF$_3$:Yb/Tm or KMnF$_3$:Yb/Ho.
9. The method according to claim 1, wherein the lanthanide-doped \( \text{KMnF}_3 \) nanoparticles have a cubic structure.

10. The method according to claim 1, wherein the lanthanide-doped \( \text{KMnF}_3 \) nanoparticles each comprise at least one dimension of size \( \leq 100 \) nm.

11. The method according to claim 1, wherein the lanthanide-doped \( \text{KMnF}_3 \) nanoparticles are NIR-to-visible upconversion nanoparticles.

12. The method according to claim 1, wherein the lanthanide-doped \( \text{KMnF}_3 \) nanoparticles exhibit single-band upconversion emission when excited under NIR.

13. The method according to claim 12, wherein the single-band upconversion emission is exhibited under 980 nm NIR excitation.

14. A lanthanide-doped \( \text{KMnF}_3 \) nanoparticle prepared according to the method of claim 1.

15. A method of identifying or authenticating a product, the method comprising the step of including the lanthanide-doped \( \text{KMnF}_3 \) nanoparticle according to claim 14 as a marker in the product.

16. A marker comprising the lanthanide-doped \( \text{KMnF}_3 \) nanoparticle according to claim 14.

17. The marker according to claim 16, wherein the marker is a biomarker or a security marker.

18. A bio-imaging and/or bio-detection apparatus comprising: at least one lanthanide-doped \( \text{KMnF}_3 \) nanoparticle according to claim 14; and at least one source of excitation.

19. The apparatus according to claim 18, wherein the source of excitation is NIR.
20. The apparatus according to claim 19, wherein the source of excitation is at 980 nm.
Figure 3

(a) Yb/Er (18/2 mol%)  
(b) Yb/Er (9/2 mol%)  
(c) Yb/Er (0/5 mol%)  
(d) Yb/Er (18/2 mol%)  
(e) Yb/Er (9/2 mol%)  
(f) Yb/Er (0/5 mol%)  
(g) JCPDS: 82-1334
Figure 5

(a) 10K

(b) 325K
Figure 6

a) KMnF$_3$:Yb/Er and NaYF$_4$:Yb/Er

b) KMnF$_3$:Yb/Er and NaYF$_4$:Yb/Er
Figure 7

(a) 290°C, 1.5h
Yb/Er: 18/2 mol%

(b) 200°C, 24h
Yb/Er: 18/2 mol%

Intensity (a.u.)

Wavelength (nm)
Figure 8

(a) KMnF$_3$:Yb/Er (18/2 %)
(b) NaYF$_4$:Yb/Er (18/2 %)
(c) NaYF$_4$:Yb/Er (29/1 %)

Depth / mm

Wavelength / nm

Legend:
- 0 mm
- 3 mm
- 5 mm
- 10 mm
INTERNATIONAL SEARCH REPORT

A. CLASSIFICATION OF SUBJECT MATTER

B82B 3/00 (2006.01)  B82Y 5/00 (2011.01)  B82Y 40/00 (2011.01)  COW 3/02 (2006.01)  C01G 45/06 (2006.01)

According to International Patent Classification (IPC) or both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EPODOC, WPI and INSPEC
Keywords: Nanoparticles, nanocrystals, nanoclusters; fluoride; lanthanide, rare earth and similar terms

Google Scholar
Keywords: Xiaogang Liu, Fuyou Li (author searches), manganese oleate, upconversion nanoparticles, KMnF3

C. DOCUMENTS CONSIDERED TO BE RELEVANT

<table>
<thead>
<tr>
<th>Category*</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
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Documents are listed in the continuation of Box C

X Further documents are listed in the continuation of Box C

See Patent family annex

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<td>&quot;A&quot;</td>
<td>document defining the general state of the art which is not considered to be of particular relevance</td>
</tr>
<tr>
<td>&quot;E&quot;</td>
<td>earlier application or patent but published on or after the international filing date</td>
</tr>
<tr>
<td>&quot;L&quot;</td>
<td>document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)</td>
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<td>&quot;0&quot;</td>
<td>document referring to an oral disclosure, use, exhibition or other means</td>
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<td>document published prior to the international filing date but later than the priority date claimed</td>
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<td>later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention</td>
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Date of the actual completion of the international search: 23 October 2012

Date of mailing of the international search report: 23 October 2012

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Form PCT/ISA/210 (fifth sheet) (July 2009)
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<tr>
<td>A</td>
<td>WANG, F. et al., &quot;Upconversion nanoparticles in biological labeling, imaging and therapy&quot;, Analyst, 2010, vol. 135, p1839-1854. Abstract, Figure 13 and Figure 18.</td>
<td>15 - 20</td>
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<td>This international search report has not been established in respect of certain claims under Article 17(2)(a) for the following reasons:</td>
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<td>1. ☐ Claims Nos.: because they relate to subject matter not required to be searched by this Authority, namely:</td>
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<tr>
<td>2. ☐ Claims Nos.: because they relate to parts of the international application that do not comply with the prescribed requirements to such an extent that no meaningful international search can be carried out, specifically:</td>
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<tr>
<td>3. ☑️ Claims Nos: because they are dependent claims and are not drafted in accordance with the second and third sentences of Rule 6.4(a)</td>
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<td>This International Searching Authority found multiple inventions in this international application, as follows:</td>
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<tr>
<td>See Supplemental Box for Details</td>
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<tr>
<td>j. ☐ As all required additional search fees were timely paid by the applicant, this international search report covers all searchable claims.</td>
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<tr>
<td>2. ☒️ As all searchable claims could be searched without effort justifying additional fees, this Authority did not invite payment of additional fees.</td>
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<tr>
<td>3. ☐ As only some of the required additional search fees were timely paid by the applicant, this international search report covers only those claims for which fees were paid, specifically claims Nos.:</td>
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<tr>
<td>4. ☐ No required additional search fees were timely paid by the applicant. Consequently, this international search report is restricted to the invention first mentioned in the claims; it is covered by claims Nos.:</td>
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</table>

**Remark on Protest**

- ☐ The additional search fees were accompanied by the applicant’s protest and, where applicable, the payment of a protest fee.
- ☑️ The additional search fees were accompanied by the applicant’s protest but the applicable protest fee was not paid within the time limit specified in the invitation.
- ☐ No protest accompanied the payment of additional search fees.
Continuation of: Box H1

This International Application does not comply with the requirements of unity of invention because it does not relate to one invention or to a group of inventions so linked as to form a single general inventive concept.

This Authority has found that there are different inventions based on the following features that separate the claims into distinct groups:

- Claims 1 to 13 are directed to a method of preparing lanthanide-doped KMnF3 nanoparticles. The features of mixing a manganese oleate complex with at least one lanthanide precursor in a solvent containing oleic acid, then adding potassium fluoride and finally heating the mixture is specific to this group of claims.

- Claim 14 is directed to the lanthanide-doped KMnF3 nanoparticle. The feature of the nanoparticle is specific to this claim. (It should be noted that the construction of this claim is according to PCT guidelines A5.26[I] where a product of a process and is construed as a claim to the product per se. A product is not rendered novel merely by the fact that it is produced by means of a new process.)

- Claims 15 is directed to a method of identifying and authenticating a product. The feature of using a lanthanide-doped KMnF3 nanoparticle as the marker in the product is specific to this group of claims.

- Claims 16 and 17 are directed to a marker. The feature of a lanthanide-doped KMnF3 nanoparticle is specific to this claim.

- Claims 18-20 are directed to a bio-imaging and/or biodetection apparatus. The feature of a lanthanide-doped KMnF3 nanoparticle and an excitation source is specific to this group of claims.

PCT Rule 13.2, first sentence, states that unity of invention is only fulfilled when there is a technical relationship among the claimed inventions involving one or more of the same or corresponding special technical features. PCT Rule 13.2, second sentence, defines a special technical feature as a feature which makes a contribution over the prior art.

When there is no special technical feature common to all the claimed inventions there is no unity of invention.

In the above groups of claims, the identified features may have the potential to make a contribution over the prior art but are not common to all the claimed inventions and therefore cannot provide the required technical relationship. The only feature common to all of the claimed inventions and which provides a technical relationship among them is the lanthanide-doped KMnF3 nanoparticle.

However this feature does not make a contribution over the prior art because it is disclosed in: ZENG J. H. et al., "Monodispersed nanocrystalline fluoroperovskite up-conversion phosphors", Crystal Growth & Design, 2007, vol. 7 p2774-2777.
Therefore in the light of this document this common feature cannot be a special technical feature. Therefore there is no special technical feature common to all the claimed inventions and the requirements for unity of invention are consequently not satisfied *a posteriori.*