Controlled Synthesis of BaYF₅:Er³⁺, Yb³⁺ with Different Morphology for the Enhancement of Upconversion Luminescence

Jialiang Yao¹, Fenghua Zhao¹*, Chunyang Pan¹ and Jianle Zhuang²

Abstract
In this work, Er³⁺/Yb³⁺-codoped BaYF₅ with different sizes and shapes have been synthesized by a simple solvothermal method. By changing the fluoride source, pH value, solvent, surfactants, Yb³⁺ concentration, temperature, and reaction time, the optimum synthetic conditions of BaYF₅:Er³⁺, Yb³⁺ were found to improve the upconversion luminescent properties. It is found that the emission intensity of green and red light is enhanced for several times by the way of using NaBF₄ as a fluoride source with the comparison of NH₄F and NaF. Moreover, the effects of different surfactants are not the same. Adding 5% polyetherimide (PEI) as surfactant can also improve the upconversion emission. On the contrary, when sodium citrate (CIT) as another surfactant was used to add, the sizes of the nanocrystals were gradually increased and the luminous properties also declined.

Keywords: Upconversion, Er³⁺/Yb³⁺ codoped, Luminescent properties, BaYF₅

Background
In recent year, upconversion nanophosphors (UCNPs) have attracted increasing attention due to their use in many fields such as solid state laser devices, fluorescent probe imaging, bioapplication, stereoscopic three-dimensional display, infrared quantum counter, temperature sensor, and anti-fake [1–11]. UCNPs are usually composed of matrix material, activator, and sensitizer [12]. Because of its low phonon energy and excellent chemical stability, fluorides are often used as matrix materials for the preparation of UCNPs. NaYF₄ [13] nanoparticles with good upconversion emission have a hexagonal phase structure, while the cubic phase results in poor upconversion emission. Recently, some of the UC materials based on BREF₅ (B = Mg, Ba, Ca, Sr) have also been studied and these newly developed crystals were found to be suitable for UC applications [14, 15]. Er³⁺-doped BaYF₅ extremely exhibits the strong UC luminescence ability. The luminescence intensity of Er³⁺-doped BaYF₅ is eight times that of Er³⁺-doped LaF₃ [16]. When Er³⁺ is used as activator, Yb³⁺ is a representative UC luminescence sensitizer due to their efficient energy transfer [17–21]. Moreover, the charge sizes of Er³⁺ and Y³⁺ match, and their radii are similar (Er³⁺ radius is 0.1 nm, Y³⁺ radius is 0.101 nm) [22]. Therefore, BaYF₅ is deemed to be an appropriate host for Er³⁺ ions.

The main factors affecting the luminescence properties are particle size, morphology, structure, and others [23, 24]. In order to obtain UC luminescent materials with high efficiency, the controlled synthesis of the spherical particles with suitable size is beneficial to achieve high accumulation of density and scatter light. In this work, samples of Yb³⁺/Er³⁺-codoped BaYF₅ are fabricated by a solvothermal method. Under the different reaction conditions, the samples with different morphologies and properties were synthesized. NaBF₄ as fluoride source has a higher UC luminous intensity relative to NH₄F and NaF. Perhaps it can slowly release F⁻; thus, it is more conducive to make crystal growth and promote UC luminescence. Furthermore, the influence of solvent, surfactants, Yb³⁺ concentration, pH of initial solution, temperature, and reaction time was also reported. Between UC luminous

* Correspondence: seazhaofh@126.com
¹School of Light Industry and Chemical Engineering, Guangdong University of Technology, Guangzhou 510006, China
²Full list of author information is available at the end of the article

© The Author(s). 2017 Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.
efficiency and various reaction conditions, the regularity and mechanism have been investigated.

**Experimental**
All the chemicals are analytical grade, such as Ba(OH)$_2$·xH$_2$O, Y(NO$_3$)$_3$·6H$_2$O, Yb$_2$O$_3$, (CH$_3$CO$_2$)$_3$Er, NaBF$_4$, NH$_4$F, NaF, oleic acid, and HNO$_3$, and absolute ethanol was used. Deionized water was used throughout. All chemical materials were used as received without further purification.

**Preparation of Synthetic BaYF$_5$:Er$^{3+}$, Yb$^{3+}$**
Yb$_2$O$_3$ was dissolved in dilute HNO$_3$ by heating the solution in order to gain the Yb(NO$_3$)$_3$ solution. In a typical synthetic route, Ba(OH)$_2$·xH$_2$O, Y(NO$_3$)$_3$·6H$_2$O, (CH$_3$CO$_2$)$_3$Er, and NaBF$_4$ were separately dissolved in deionized water. According to the ratio of BaY$_{1-x-y}$F$_5$:xEr$_3^+$, yYb$_3^+$, the solution of Ba(OH)$_2$·xH$_2$O, Y(NO$_3$)$_3$·6H$_2$O, (CH$_3$CO$_2$)$_3$Er, Yb(NO$_3$)$_3$, and NaBF$_4$ were put into a Teflon cup. Oleic acid and ethanol were added into the mixture for corresponding to a certain proportion. The pH value of the mixed solution was adjusted to 9 by using NH$_3$·H$_2$O. After magnetic stirring for 30 min, the Teflon cup was held into stainless steel sealing autoclave and heated to 200 °C for 16 h. When the autoclave was naturally cooled to the room temperature, the product was centrifuged by ethanol and deionized water for three times respectively and dried at 60 °C for 12 h.

**Characterization**
X-ray diffraction (XRD) was obtained on BrukerD8 advance at a scanning speed of 10°/min in the 2θ range from 10 to 70 with Cu Kα radiation. Photoluminescence spectroscopy (PL) was recorded on a fluorescence spectrometer (FLS920, Edinburgh Instruments) upon continuous wave excitation of 980-nm laser diode. Scanning electron microscope (SEM) and energy dispersive spectrometer (EDS) were recorded on S-3400N-II.

**Results and Discussion**
Figure 1 presents the XRD patterns of the BaYF$_5$:20%Yb$^{3+}$, 2%Er$^{3+}$ synthesized by different conditions. The diffraction peaks of all the samples can be readily indexed to the standard tetragonal-phase BaYF$_5$ (JCPDS no.46-0039) except for Fig. 1i (a) owing to the generation of extra phase BaF$_2$ at the pH value of 4. When the pH increased from 4 to 9, the crystalline of the sample was enhanced. In the meanwhile, the BaF$_2$ phase disappeared as well. There was no extra peaks of other phase appeared, revealing that the varying experimental conditions have little influence on the crystal structure of the sample. It is noteworthy that all the diffraction peaks are shifted to lower 2θ angles as the pH increased from 4 to 9.

---

**Fig. 1** XRD patterns of the prepared 2%Er$^{3+}$, 20%Yb$^{3+}$-codoped BaYF$_5$, pH is equal to 9 except (a), whose pH equals 4. (a) 200 °C, 16 h, (b) 200 °C, 12 h, (c) 200 °C, 16 h, (d) 200 °C, 24 h, (e) 180 °C, 16 h, (f) 220 °C, 16 h. The standard XRD pattern of BaYF$_5$ (JCPDS no.46-0039) and BaF$_2$ (JCPDS no.85-1342) is also given for comparison. **ii** EDS of the product corresponding to XRD. **iii** UC emission spectra of the samples synthesized at 200 °C, (a) 12 h, (b) 16 h, (c) 24 h. **iv** UC emission spectra of the products synthesized for 16 h, (a) 180 °C, pH = 9, (b) 200 °C, pH = 9, (c) 220 °C, pH = 9, (d) 200 °C, pH = 4. **v** SEM images of the prepared BaYF$_5$ synthesized under different conditions. (A) 200 °C, 16 h. (B) 220 °C, 16 h. (C) 200 °C, 24 h.
higher 2θ side, which indicates the lattice constant becomes smaller because the radii of Er$^{3+}$ or Yb$^{3+}$ are smaller than those of Y$^{3+}$ [25, 26]. Furthermore, it is easy to find the rules that when the reaction time increases, the intensity of the diffraction peaks is simultaneously enhanced. Similar conclusions are drawn when the reaction temperature rises. It concludes that the above reaction conditions can promote the growth of BaYF$_5$ crystals. EDS spectrum analysis of a specific sample was indicated in Fig. 1i. As shown on the diagram, the presence of the elements of Ba, Y, F, Yb, and Er in the given sample was confirmed. According to the XRD and EDS results, Er$^{3+}$ and Yb$^{3+}$ were successfully doped into BaYF$_5$. Figure 1v shows the SEM images of BaYF$_5$ synthesized under different conditions. The as-prepared samples shown in Fig. 1v (A) are microspheres with a size of approximately 45 nm. However, they are not finely dispersed and aggregated to some extent. According to its XRD diagram in Fig. 1i (c), the size of the crystal can be roughly calculated by Scherrer’s equation:

$$D = \frac{K \gamma}{B \cos \theta}$$

where $K$ is Scherrer constant ($K$ equals 0.89), $\gamma$ is the X-ray wavelength ($\gamma$ equals 0.15405 nm), $B$ is the full width at half maximum of diffraction peaks of samples, and $\theta$ is the diffraction angle of the observed peak [27, 28]. The strongest intensity of diffraction peak at $2\theta = 26.689^\circ$ was used to calculate the average size of crystal. The average size of crystal is estimated to be 41.7 nm which is closed to the size (45 nm) by observation of the SEM chart. As represented in Fig. 1v (B), when the reaction temperature was increased to 220 °C, the dispersions of the particles became relatively high. However, the size of the crystal was uneven and some larger particles with size of approximately 180 nm appeared. When the reaction time was prolonged to 24 h, the nanocrystals are relatively well dispersed with uniform particle morphology. The sizes are about 30 nm which are basically consistent with the estimates (24.9 nm) from the XRD data. Figure 1iii, iv shows the UC luminescence spectra of BaYF$_5$:Er$^{3+}$/Yb$^{3+}$ synthesized via different experimental conditions under excitation at 980 nm. The main emission band of Er$^{3+}$ is 520, 540, and 654 nm as a result of $^2H_{11/2} \rightarrow ^4I_{15/2}$ (green), $^4S_{3/2} \rightarrow ^4I_{15/2}$ (green), and $^4F_{5/2} \rightarrow ^4I_{15/2}$ (red) transitions, respectively. In Fig. 1iii, iv, as the temperature increases, it is beneficial to the crystal growth of the product, while prolonging the reaction time, increasing pH has the same effect. The UC luminescence intensity can be enhanced due to the formation of higher crystalline. When the reaction time was prolonged, or pH was adjusted from 4 to 9, the nanoparticles have better crystalline owing to their higher dispersions and more uniform sizes.

Figure 2i demonstrates the XRD patterns of the BaYF$_5$: xYb, 2%Er ($x = 10$, 30%). All the diffraction peaks are perfectly matched with the standard pattern of BaYF$_5$ crystals (JCPDS no.46-0039). It shows that the doping of rare earth ions does not affect the crystal growth. As shown in Fig. 2i, when the Yb$^{3+}$ concentration increases from 10 to 20%, the UC luminescence intensity rapidly rises until the Yb$^{3+}$ concentration exceeds 20% on account of the concentration quenching. It is concluded that the 20% concentration is the optimum concentration.

Figure 3i exhibits the XRD patterns of the BaYF$_5$:Yb$^{3+}$/Er$^{3+}$ nanocrystals obtained by adding different surfactants. All the diffraction peaks are perfectly matched with the standard card tetragonal-phase BaYF$_5$ (JCPDS no.46-0039). When 5% polyetherimide (PEI) was added, the intensity of the diffraction peaks is enhanced, which indicates that PEI can promote the growth of BaYF$_5$ crystals. Moreover, after the addition of citric acid, the diffraction peaks are shifted to lower angle. This proves that when...
citrate (CIT) was added, the cell volume of the sample becomes larger gradually. The other reason may be that citric acid is covered on the crystal surface, rare earth ions are hard to dope into the host lattices. Besides, the diffraction peaks become different from the others with a little flaw as the CIT/Y = 4:1. The conceivable reason lies in the high CIT concentration leading to the BaYF$_5$ unit cell parameter change and lattice distortion. As illustrated in Fig. 3iii (A), when 5% PEI was added in ethanol, nanocrystals became massive clumps which consist of a large number of spherical particles with narrow size distribution. Figure 3iii (B) and (C) shows that when the surfactant with a concentration of CIT/Y = 1:1 was added, the overall size of crystal relatively became larger. As can be seen from the diagram, the sample tends to aggregate without obvious boundaries in some areas. As the surfactant concentration ratio rises to 4:1, the maximum size of the particles increases to 4 μm with the surface covered by some other smaller spherical particles. As the surfactant concentration increases, the CIT coverage capacity is enhanced [29], leading to the formation of crystal clusters. As shown in Fig. 3iii, both green emission and red emission are enhanced after adding 5% PEI in ethanol. The long-chain amino groups of PEI can form the complex structures with metal ions by coordination. PEI can inhibit particle growth by tightly wrapping on the surface to improve the crystalline. On the contrary, after adding citric acid, the UC luminescence emission decreased greatly owing to the enlargement of crystal size and the decline of rare earth ion content.

Figure 4i shows the XRD pattern of products obtained from different fluoride sources. There are no peaks of impurities appear, demonstrating that the change of fluoride sources does not affect the crystallization of BaYF$_5$. It is worth noting that there are fewer shifts of the diffraction peaks of samples obtained from NH$_4$F or NaF than those of samples obtained from NaBF$_4$. This indicates that NH$_4$F and NaF released F$^-$ disorderly and rapidly, resulting in the difficulty of the control synthesis of crystals [30]. As a consequence, the rare earth ions become difficult to enter into the host lattices. Figure 4ii represents the SEM images of the sample using NH$_4$F and NaF as fluoride sources. The particles are similar to those nanocrystals synthesized by adding 5% PEI. However, the shapes are more irregular relative to those obtained from NaBF$_4$. As can be seen from Fig. 4ii, the sample which used NaBF$_4$ as fluoride source shows the highest UC emission efficiency owing to the benefits of the crystal growth generating a uniform sphere shape. Particles in smaller sizes will have more Er$^{3+}$ on the submicron surface, causing more surface vibrations for conducting acceleration in red and green emission. Moreover, the distance among Er$^{3+}$ becomes smaller and cross relaxation happens ($^2H_{11/2} + ^4I_{15/2} \rightarrow ^4I_{9/2} + ^4I_{13/2}$). As a result, the green band ($^2H_{11/2}, ^4S_{3/2} \rightarrow ^4I_{15/2}$) becomes easy to quench in smaller sizes, but the red band ($^4F_{9/2} - ^4I_{15/2}$) becomes more difficult to quench [24, 31].
Figure 5 demonstrates the schematic energy levels of Yb\(^{3+}\) and Er\(^{3+}\). In the meanwhile, it depicts the UC luminescence process mechanisms explaining the generation of green and red emissions under 980-nm laser excitation. In the Yb\(^{3+}\)/Er\(^{3+}\)-codoped BaYF\(_5\) system, via absorbing the first 980-nm photon, Yb\(^{3+}\) ion in the \(^{2}F_{7/2}\) ground state transfers to the excited state \(^{2}F_{5/2}\). When it goes back to the ground state, the energy is transferred to Er\(^{3+}\) ion to populate the \(^{4}I_{11/2}\) state. The second 980-nm photon, or energy transfer from another excited Yb\(^{3+}\), can then pump Er\(^{3+}\) ion into \(^{4}F_{7/2}\) level. The lower energy states \(^{2}H_{11/2}\) and \(^{4}S_{3/2}\) can be populated by nonradiatively decaying \(^{4}F_{7/2}\) state. The transmissions of the electron from \(^{2}H_{11/2}\) and \(^{4}S_{3/2}\) to the \(^{4}I_{15/2}\) ground state emits green emissions. Alternatively, Er\(^{3+}\) ion in the \(^{4}I_{11/2}\) state may also nonradiatively relax to \(^{4}I_{13/2}\) state. \(^{4}F_{9/2}\) state of Er\(^{3+}\) can be populated by absorption of photon or energy transfer from Yb\(^{3+}\). The UC red emissions occur through the transition of \(^{4}F_{9/2}\) to \(^{4}I_{15/2}\). Some electrons in the \(^{4}F_{9/2}\) level may be excited to \(^{2}H_{9/2}\) via a phonon-assisted energy transfer process, and blue emissions can be observed. The emission bands at 520, 540, and 654 nm could be corresponding to electron transfer from the excited level \(^{2}H_{11/2}\), \(^{4}S_{3/2}\), and \(^{4}F_{9/2}\) to the ground state \(^{4}I_{15/2}\) of Er\(^{3+}\), respectively [19, 32, 33].

**Conclusion**

In summary, BaYF\(_5\):20\%Yb\(^{3+}\), 2\%Er\(^{3+}\) have been successfully synthesized via a convenient solvothermal method. It is found that the use of NaBF\(_4\) as a fluoride source or adding 5\% PEI as surfactant can effectively improve the crystalline and particle dispersion which can promote the UC emission. Compared with PEI, as CIT concentration raised, the nanoparticles gradually become larger, which is inversely proportional to luminous properties. It is obvious that nanocrystals via 220 °C of heat treatment temperature for 24 h are an optimum reaction condition of the excellent luminescence properties. These behaviors might be attributed to their great uniform sizes, well dispersing, and high crystalline.

**Acknowledgements**

This work was supported by the National Natural Science Foundation of China (51002034) and the Natural Science Foundation of Guangdong Province (2014A030313466).
Authors’ Contributions

FHZ and CYP designed the experiments; JLY carried out the synthesis and characterization of the samples, analyzed the results, and wrote the first draft of the manuscript. FHZ, CYP, and JLZ participated in the analyses of the results and discussion of this study; FHZ, CYP, JLY, and JLZ revised the manuscript and corrected the English language of the manuscript. All authors read and approved the final manuscript.

Competing Interests

The authors declare that they have no competing interests.

Publisher’s Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Author details

1School of Light Industry and Chemical Engineering, Guangdong University of Technology, Guangzhou 510006, China. 2College of Materials and Energy, South China Agricultural University, Guangzhou 510642, China.

Received: 30 October 2017 Accepted: 30 November 2017

Published online: 19 December 2017

References

1. Dong B, Liu DP, Wang XJ, Yang T, Miao SM, Li CR (2007) Optical thermometry through infrared excited green upconversion emissions in Er3+-Yb3+ codoped Al2O3. Appl Phys Lett 90:181117
2. Wang M, Mi CC, Wang WX, Liu CH, Wu YF, Xu ZR et al (2009) Immunolabeling and NIR-excited fluorescent imaging of HeLa cells by using NaYF4:Yb, Er upconversion nanoparticles. ACS Nano 3:1580–1586
3. Maciel GS, Biswas A, Kapoor R, Prasad PN (2000) Blue cooperative upconversion in Yb3+ doped multicomponent sol-gel-processed silica glass for three-dimensional display. Appl Phys Lett 76:1978–1980
4. Dong H, Sun LD, Wang YF, Ke J, Ji S, Xiao JW et al (2015) Efficient tailoring of upconversion selectivity by engineering local structure of lanthanides in Na,REF3+x nanocrystals. J Am Chem Soc 137:5659–5676
5. Xu DK, Li AM, Yao L, Lin H, Yang SH, Zhang YL (2017) Lanthanide-doped KLuF4 nanoparticles with high upconversion luminescence performance: a comparative study by Judd-Olfelt analysis and energy transfer mechanism investigation. Sci Rep 7:43189
6. Xu JT, He F, Cheng ZY, Lu RC, Dai YL, Guzlar A et al (2017) Yolk-structured upconversion nanoparticles with biodegradable silica shell for FRET sensing of drug release and imaging-guided chemotherapy. Chem Mater 29:7615–7628
7. Xu JT, Guzlar A, Liu YH, Bi HT, Gai SL, Liu B et al (2017) Integration of IR-808 sensitized upconversion nanostructure and MoS2 nanosheet for 808 nm NIR light triggered phototherapy and bioimaging. Small 13:1–13
8. Zou R, Huang J, Sh JP, Huang L, Zhang XJ, Wong KL et al (2017) Silica-sensitized photosensitizer nanophosphors for enhanced in vivo recharged near-infrared persistent luminescence. Nano Res 10:2070–2082
9. Xu JT, Kuang Y, Li RC, Yang PP, Sun MD, Bi HT, Liu Y, Bang D et al (2017) Charge convertibility and near infrared photon co-enhanced cisplatin chemotherapy based on upconversion nanoplatform. Biomaterials 130:42–55
10. Xu JF, Yang PP, Sun MD, Bi HT, Liu Y, Bang D et al (2017) Highly emissive dye-sensitized upconversion nanostructure for dual-photo-sensitizer photodynamic therapy and bioimaging. ACS Nano 11:4133–4144
11. Zou R, Gong SM, Shi JP, Jiao J, Wang KL, Zhang HW et al (2017) Magnetic-NIR persistent luminescent dual-modal 2G0C5@ MSNs@ Gd2O3 core-shell nanoprobes for in vivo imaging. Chem Mater 29:3938–3946
12. Wei W, Zhang Y, Chen R, Goggi JL, Ren N, Huang L et al (2014) Cross relaxation induced pure red upconversion in activator-and sensitizer-rich lanthanide nanoparticles. Chem Mater 26:5183–5186
13. Sun RJ, Qu YP, Yin T, Gao G, Fu HL, Wang K et al (2016) Potassium sodium tetratrate-assisted hydrothermal synthesis of BaLu2F8: Yb3+/Er3+ nanocrystals. Particuology 24:164–169
14. del-Castillo J, Yanes AC, Abe S, Smet PF. Site selective spectroscopy in BaYF4: RE3+ (RE = Eu, Sm) nano-glass-ceramics. Journal of Alloys and Compounds. 2015;635:136-141
15. Zhang WH, Ouyang SY, Zhang ZX, Zhang YP, Xia HP (2015) Luminescent properties of Eu3+-doped glass ceramics containing BaGdF5 nanocrystals under NUV-excitation for W-LEDs. Ceram Int 41:14035–14040
16. Liu F, Wang YS, Chen DQ, Yu YL, Ma E, Zhou LH et al (2007) Upconversion emission of a novel glass ceramic containing Er3+:BaYF4 nanocrystals. Mater Lett 61:5022–5025
17. Hwang BC, Jiang S, Luo T, Watson J, Sorbello G, Peyghambarian N (2000) Cooperative upconversion and energy transfer of new high Er3+ and Yb3+-Er3+-doped phosphate glasses. J Opt Soc Am B 17:833–839
18. Yang DM, Li CX, Li GG, Shang MM, Kang XJ, Lin J (2011) Colloidal synthesis and remarkable enhancement of the upconversion luminescence of BaGdF5: Yb3+/Er3+ nanoparticles by active-shell modification. J Mater Chem 21:5923–5927
19. Groyb T, Babadnadza S, Przybylska D, Węcławiak M (2015) Upconversion luminescence in BaYF4: BaGdF5, and BaLuF5 nanocrystals doped with Yb3+, Er3+, Yb3+/Er3+, or Yb3+/Tm3+ ions. J Alloys Compounds 649:606–616
20. Chen XP, Zhang QY, Yang CH, Chen DD, Zhao C (2009) Comparative investigation on structure and luminescence properties of fluoride phosphors codoped with Er3+/Yb3+. Spectrochim Acta A Mol Biomol Spectrosc 74:441–445
21. Jiang HJ, Ahn KY, Choi SC, Lee SH, Aldinger F (2008) Low pressure sintering of sialon using different sintering additives. J Ceram Soc Jpn 116:130–136
22. Zeng JH, Su J, Li ZH, Yan RX, Li YD (2005) Synthesis and upconversion luminescence of hexagonal-phase NaYF4: Yb, Er3+ phosphors of controlled size and morphology. Adv Mater 17:2119–2123
23. Sun JY, Chen Y, Tian LJ, Yu Y, Kong KG, Zhang JW et al (2007) Controlled synthesis and morphology dependent upconversion luminescence of NaYF4: Yb, Er nanocrystals Nanotechnology 18:257609
24. Sun JY, Xiao JB, Du HY (2011) Hydrothermal synthesis of BaYF4: Yb3+/Er3+ upconversion luminescence submicrospheres by a surfactant-free aqueous solution route. J Phys Chem Solids 72:207–213
25. Du HY, Zhang WH, Sun JY (2011) Structure and upconversion luminescence properties of BaYF4: Yb3+, Er3+ nanoparticles prepared by different methods. J Alloys Compd 509:3413–3418
26. Cao ZM, Zhou SS, Jiang GC, Chen YH, Duan CK, Yin M (2014) Temperature dependent luminescence of Dy3+ doped BaYF4 nanoparticles for optical thermometry. Curr Appl Phys 14:1067–1071
27. Monshi A, Foroughi MR, Monshi MR (2012) Modified Scherrer equation to estimate more accurately nano-crystallite size using XRD. World J Nano Sci Eng 2:154–160
28. Burton AW, Ong K, Rea T, Chan IV (2009) On the estimation of average crystallite size of zeolites from the Scherrer equation: a critical evaluation of its application to zeolites with one-dimensional pore systems. Microporou Microporous Mater 117:75–90
29. Zhang CM, Ma PA, Li CX, Li GG, Huang SS, Yang DM et al (2011) Controllable and white upconversion luminescence in BaYF4: Ln3+ (Ln = Yb, Er, Tm) nanocrystals. J Mater Chem 21:717–723
30. Li CX, Yang J, Quan ZW, Yang PP, Kong DY, Lin J (2007) Different microstructures of β-NaYF4 fabricated by hydrothermal process: effects of pH values and fluoride sources. Chem Mater 19:4933–4942
31. Shan JN, Uddi M, Wei R, Yao N, Ju YG (2010) The hidden effects of particle shape and criteria for evaluating the upconversion luminescence of the lanthanide doped nanophosphors. J Phys Chem C 114:2452–2461
32. Niu Y, Yang PP, Liu YC, Li CX, Wang D, Gai SL et al (2011) Controllable synthesis and up-conversion properties of trivalent BaYF4: Yb/Er (Ln= Er, Tm) nanocrystals. J Colloid Interface Sci 362:389–396
33. Tian G, Gu ZJ, Zhou LJ, Yin WY, Liu YY, Lan Y et al (2012) Mn3+ dopant-controlled synthesis of NaYF4:Yb/Er upconversion nanoparticles for in vivo imaging and drug delivery. Adv Mater 24:1226–1231