Full Paper

Enhancement of up-conversion luminescence of $Y_2Ti_2O_7$;Yb$^{3+}$/Ho$^{3+}$ nanocrystals by incorporating Li$^+$ ions

Zhongsheng CHEN$^{1,2,†}$, Shuangxi XIAO$^1$, Haiqing HUANG$^1$, Jugong ZHENG$^1$, Guolin HUANG$^{1,3}$, Jianping XU$^1$, Zongbo XIE$^1$ and Zhanggao LE$^1$

1. Jiangxi Key Laboratory for Mass Spectrometry and Instrumentation, East China Institute of Technology, Nanchang, Jiangxi 330013, P.R. China
2. State Key Laboratory Breeding Base of Nuclear Resources and Environment, East China University of Technology, Nanchang, Jiangxi 330013, P.R. China
3. Engineering Research Center of Nano-Geo Materials of Ministry of Education China University of Geosciences, Wuhan, Hubei 430074, P.R. China

Key-words : Up-conversion, Luminescence enhancement, Pyrochlore, Gel-combustion, Doping

[Received July 19, 2017; Accepted October 10, 2017]

Tri-doped ($Y_{0.915}Ho_{0.01}Yb_{0.075}Li_{0.125})_2Ti_2O_7$ ($x = 0$–15.0 mol %) nanocrystals were fabricated via a facile glycine–combustion approach. The crystal structure, morphology and up-conversion spectra of the as-obtained products were investigated using X-ray powder diffractometer (XRD), transmission electron microscope (TEM), spectrophotometer pumped by 980 nm diode laser, and Fourier transform infrared spectrometer. XRD results demonstrated that, owing to the flux effect of Li$^+$ ions, the crystallization temperature of matrix $Y_2Ti_2O_7$ decreased when compared to Li$^+$-undoped samples. TEM results showed the average particle of ($Y_{0.79}Ho_{0.01}Yb_{0.075}Li_{0.125})_2Ti_2O_7$ nanocrystals calcined at 800°C for 1.0 h was estimated to be $\sim$50 nm. It was also found that up-conversion emissions were strongly dependent on the calcining temperature and Li$^+$ ion concentration. Compared with the Li$^+$-free $Y_2Ti_2O_7$:Yb$^{3+}$/Ho$^{3+}$ samples, the green and red emission intensity of nanocrystals tri-doped with 12.5 mol % Li$^+$ was enhanced by 10.2 and 4.8 times, respectively. The emission increase should be mainly ascribed to the distortion of local symmetry around Ho$^{3+}$ ions by Li$^+$-doping. In addition, the pump power dependence of integrated intensity suggested that both green and red emission was two-photon population process.

©2018 The Ceramic Society of Japan. All rights reserved.

1. Introduction

During the past decades, research on lanthanide-based up-conversion materials have attracted considerable attention owing to their potential applications in the fields of nanoscale thermometry,1) spectral converters for solar cells,2) bio-sensing, bio-imaging,3) photodynamic therapy of tumour4) and drug delivery.5) The low emission efficiency, nevertheless, has become one of the bottlenecks to hinder their practical applications due to the nanoscale particle size. How to improve the up-conversion emissions, therefore, is still one of the most significant issues. More recently, fortunately, novel approaches, such as impurities doping,6) plasmonic enhancement by noble metal,7) shell@core structure,8) and so on, have been explored to enhance up-conversion emissions. Among these strategies, impurities doping, i.e. incorporating appropriate foreign elements (such as Li$^+$, Ca$^{2+}$, Cr$^{3+}$, Gd$^{3+}$ ions, et al.) into hosts is a facile and effective method not only to tune up-conversion emissions, but also to modify the crystallographic phase, size or morphology.9)–13) For example, Cheng et al.12) demonstrated that, the green and red emission intensities of β-NaYF$_4$:Yb$^{3+}$/Er$^{3+}$ samples tridoped with 15 mol % Cr$^{3+}$ ions were enhanced by a factor of 16 and 7, respectively, in contrast to products without doping of Cr$^{3+}$ ions. Liu and his collaborators9) achieved simultaneous control over up-conversion emissions, the crystallographic phase, and particle size of the NaYF$_4$:Yb$^{3+}$/Er$^{3+}$ nanocrystals by introducing Gd$^{3+}$ ions.

Due to the fact of relatively low phonon cutoff energy (smaller than 720 cm$^{-1}$), $Y_2Ti_2O_7$ with the classical pyrochlore-type structure, is a potential and promising matrix for efficient luminescence.14)–16) In our previous report, $Y_2Ti_2O_7$:Yb$^{3+}$/Ho$^{3+}$ nanocrystals excited by 980 nm diode laser presented bright visible up-conversion emissions, and the optimal doping concentrations of Ho$^{3+}$ and Yb$^{3+}$ ion were also obtained.17) To the best of our knowledge, none of research has been reported to promote the up-conversion emissions of $Y_2Ti_2O_7$:Yb$^{3+}$/Ho$^{3+}$ by impurities doping so far. On the other hand, Li$^+$ ions with smaller ionic radius renders themselves to incorporate into host materials readily to modify the local crystal field.
around rare-earth ions, thus enhancing the up-conversion emissions.[14,18] Herein, in this report, tri-doped \(Y_2Ti_2O_7\): \(Yb^{3+}/Ho^{3+}/Li^{+}\) nanocrystals were fabricated by a facile glycine–combustion method. The effect of calcining temperature and \(Li^{+}\) ion doping concentration on the phase evolution, microstructures and up-conversion emissions, was examined in detail, and the possible mechanism for emission enhancement was also proposed.

2. Experimental

Tri-doped \((Y_{0.915}Ho_{0.01}Yb_{0.075}Li_{0.125})_2Ti_2O_7\) \((x = 0–15.0\) mol\%) samples were synthesized via a glycine–combustion approach, and the optimum conditions (i.e. the pH value of the precursor is 2.0, the fuel-to-oxidant ratio is 2.0) were employed, and the detailed procedure was given in our previous reports.[17] A variety of tri-doped \((Y_{0.915–x}Ho_{0.01}Yb_{0.075}Li_{x})_2Ti_2O_7\) \((x = 0–15.0\) mol\%) samples were prepared by fixing 7.5 mol\% \(Yb^{3+}\) and 1.0 mol\% \(Ho^{3+}\) ions, the molar ratio of \(n(Y^{3+}+Ho^{3+}+Yb^{3+})/nTi\) 1:1, and varying \(Li^{+}\) ion doping content or calcination temperatures.

The crystalline structure of as-obtained samples was determined by X-ray diffraction (XRD, D/raux2550PC, Tokyo, Japan) using Cu \(K_{\alpha}\) radiation (\(\lambda = 1.54056\) nm) over a 2\(\theta\) range from 10 to 80\(^\circ\) at a scanning rate of 4\(^\circ\)/min. The morphologies and average size of samples were observed by transmission electron microscopy (TEM, JEOI-2010F, Tokyo, Japan) operated at 200 kV. The up-conversion emission spectra were recorded by a spectrophotometer (Hitachi F-4500, Tokyo, Japan) equipped with a power-controllable 980 nm diode laser (LOS-BLD-0980-C Hite photoelectric, China). The laser was focused on the sample (spot size of \(\sim 1.0\) mm) by use of a 10-cm focal length lens and the up-conversion emission was collected in a reflection mode, in an angular direction of 45\(^\circ\) to normal incidence. All the measurements of the up-conversion emissions were carried out with the optical configuration unchanged at the room temperature. The infrared absorption spectra of samples were conducted in range of 4000–600 cm\(^{-1}\) with KBr pellet method by Avatar 380 Fourier transform infrared spectrometer (Thermo Nicolet Corporation, USA).

3. Results and discussion

The effect of the calcining temperature on the phase evolution of \((Y_{0.79}Ho_{0.01}Yb_{0.075}Li_{0.125})_2Ti_2O_7\) samples is presented in Fig. 1. Evidently, all the as-obtained powders exhibit a well-crystallized pyrochlore structure when calcined at 600\(^\circ\)C or higher temperatures for 1.0 h, and all the diffraction peaks are in good agreement with the face-centered cubic lattice (JCPDS No. 42-0413, space group \(Fd\bar{3}m\)). What’s more, the intensity of each peak increases gradually with the rise of calcining temperature, and there exists no change in the positions of 2\(\theta\) of the pyrochlore structure, which demonstrated that no other possible impure phases were detected in the calcining process. It could be safely concluded that, therefore, the component ions such as \(Y^{3+}, Ti^{4+}, Yb^{3+}, Ho^{3+}\) and \(Li^{+}\) were distributed in the xerogel homogeneously before the calcining step, ensuring that \(Ho^{3+}, Yb^{3+}\) and \(Li^{+}\) ions could be introduced into \(Y_2Ti_2O_7\) host lattice uniformly.

It is worthwhile to note that, in the case of the \((Y_{0.79}Ho_{0.01}Yb_{0.075}Li_{x})_2Ti_2O_7\) samples, well-crystallized structure could be obtained even at the calcining temperature, 600\(^\circ\)C, which is much lower than that (i.e. 800\(^\circ\)C or higher temperatures) of \(Li^{+}\)-absent \(Y_2Ti_2O_7\) powders prepared by the same procedure. It is reasonable to infer that the doping amount of \(Li^{+}\) ions would have a great influence on the crystallization temperature of samples. Herein, the effect of the \(Li^{+}\) doping concentration on the crystallinity of products \((Y_{0.79}Ho_{0.01}Yb_{0.075}Li_{x})_2Ti_2O_7\) calcined at 800\(^\circ\)C for 1.0 h, (b), (c), (d), (e) 2.5 mol\%, (f) 5.0 mol\%, (g) 7.5 mol\%, (h) 10.0 mol\%, (i) 12.5 mol\%, (j) 15.0 mol\%, (a) the standard pattern of \(Y_2Ti_2O_7\), JCPDS No. 42-0413.
introduction of Li⁺ ions help to improve the crystallinity and crystallite growth. Actually, the reduction of crystallization temperature of the samples can be ascribed to the flux effect of the introduction of hetero-atoms such as Li⁺ and Zn²⁺ ions, and this similar phenomenon was also observed by Liu et al. and our previous experiments. In the current system, no obvious change exists in the crystallinity of products when the doping concentration of Li⁺ ions is greater than 5.0 mol%.

For better understanding of the influence of the doping level of Li⁺ ions on the XRD positions, the most intensive XRD peaks (222) are displayed, as shown in Fig. 3. Clearly, the main diffraction peak shows a slight shift towards larger 2θ values as Li⁺ ion concentration increases up to 12.5 mol%, and then begins to move reversely when the Li⁺ ion concentration is greater than 12.5 mol%. The shift of the peak’s position shows that the lattice parameters changes with the different concentration of Li⁺ ions doping. The location of (222) planes, lattice constants and the average crystallite sizes estimated from the XRD planes (222) according to the Scherrer formula are listed in the Table 1.

And as indicated in the Table 1, the lattice constant decreases gradually with the increase of Li⁺ ion contents in the range of 0–12.5 mol%, and then increases slightly with the Li⁺ ions contents above 12.5 mol%, and the average crystallite size of samples increases rapidly when 2.5 mol% Li⁺ ions were introduced, and grows slightly with Li⁺ ions from 2.5 to 15.0 mol%.

The effective ionic radii for Li⁺, Ti⁴⁺ and Y³⁺ ion are 0.76, 0.61 and 1.159 Å, respectively. The difference between ionic radii of Li⁺ and Ti⁴⁺ ion is smaller, but the charge difference between them is greater. The smaller Li⁺ ions, therefore, have the tendency to replace the Y³⁺ ions to form substitution doping readily, thus giving rise to the shrinkage of the unit cell. On the other hand, the smaller Li⁺ ions can also enter the interstitial sites of the host lattice easily, bringing about the expansion of the host lattice. The aforementioned gradual shift of XRD peaks (222) demonstrates that Li⁺ ions are liable to occupy substitution sites of Y³⁺ ions for the Li⁺ ion content below 12.5 mol%, and the extra Li⁺ ions enter interstitial sites when the concentration of Li⁺ ions is greater than 12.5 mol%. What is noteworthy that, whether the substitution of Y³⁺ ions or the occupancy of interstitial sites would modify the local crystal field symmetry around Ho³⁺ ions in the host lattice and break the forbidden transitions, consequently enhancing up-conversion emissions.

The typical TEM images of (Y₀.₇₀Ho₀.₀₁Yb₀.₀₇₅Li₀.₁₂₅₂)₂Ti₂O₇ samples prepared at 800°C for 1.0 h is indicated in Fig. 4. From Fig. 4(a), it can be found that the as-obtained samples exhibit quasi-spherical or ellipsoid morphology with good dispersibility, and the average particle size is estimated to be ~50 nm, which is greater than the results calculated by XRD patterns through Scherrer equation. The typical HRTEM images in Fig. 4(b) indicate the clear and regular crystal lattice distance, which demonstrates the formation of highly crystalline host lattice. And the lattice fringes with the inter-planar distance of 0.253 nm is assigned to the crystal planes (440) of the pyrochlore-type structure.

The calcining temperature dependence of up-conversion spectra of (Y₀.₇₀Ho₀.₀₁Yb₀.₀₇₅Li₀.₁₂₅₂)₂Ti₂O₇ nanocrystals excited by the 980 nm laser diode is shown in Fig. 5. In terms of all the samples under investigation, bright up-conversion emissions could be observed with naked eyes under relatively weak 980 nm excitation, suggesting that (Y₀.₇₀Ho₀.₀₁Yb₀.₀₇₅Li₀.₁₂₅₂)₂Ti₂O₇ is a high efficient up-conversion material. As indicated in Fig. 5, the up-conversion spectra exhibit the red and green emission bands in the visible region of 500–700 nm, the former centered at ~660 nm is attributed to 5F₅ → 5I₇ radiation transitions of Ho³⁺ ions, and the latter centered at ~550 nm is ascribed to 5F₄ → 5S₂ → 5I₈ electronic transitions of Ho³⁺ ions. The two emissions are in good agreement with the up-conversion systems, NaYF₄:Yb³⁺/Ho³⁺ and Y₃Al₅O₁₂: Yb³⁺/Ho³⁺ (17,26-28).

It is evident from the Fig. 5, that the calcining temperatures had a great influence on up-conversion spectra. The emission intensity increases initially with the rise of the calcining temperature from 600 to 800°C, reaching the maximum, and then decrease from 800 to 1000°C.

Table 1. The location of (222) planes, lattice constant and average crystallite size of (Y₀.₉₁₅Ho₀.₀₁Yb₀.₀₇₅Li₀.₁₂₅₂)₂Ti₂O₇ nanocrystals calcined at 800°C for 1.0 h.

| Samples/Li⁺ (mol %) | 0 | 2.5 | 5.0 | 7.5 | 10.0 | 12.5 | 15.0 |
|---------------------|---|-----|-----|-----|------|------|------|
| Location of (222) plane (°) | 30.65 | 30.67 | 30.68 | 30.69 | 30.71 | 30.70 | 30.67 |
| Lattice constants (Å) | 10.093 | 10.091 | 10.086 | 10.079 | 10.077 | 10.074 | 10.092 |
| Average crystallite size (nm) | 24.5 | 47.7 | 48.6 | 50.5 | 51.1 | 51.4 | 51.7 |

![Fig. 3. The effect of Li⁺ concentrations on the location of (222) planes of products (Y₀.₉₁₅Ho₀.₀₁Yb₀.₀₇₅Li₀.₁₂₅₂)₂Ti₂O₇, (a) 0, (b) 2.5 mol%, (c) 5.0 mol%, (d) 7.5 mol%, (e) 10.0 mol%, (g) 12.5 mol%, (h) 15.0 mol%, (a) the standard pattern of Y₂Ti₂O₇, JCPDS No. 42-0413.](image-url)
This trend of the calcining temperature dependence of up-conversion spectra is similar to our previous findings.\textsuperscript{14,17} The initial increase of emission intensity is probably accounted for by the reduction of surface defects and higher energy contaminants (i.e. OH\textsuperscript{−} and CO\textsubscript{3}\textsuperscript{2−}) located on the surface of the samples with the rise of calcining temperature. When the samples are calcined above 800°C, the promotion of the local symmetry of Ho\textsuperscript{3+} lattice maybe counteracts the effect of reduced quenching centres, therein resulting in the decrease of emission intensity.\textsuperscript{29} Therefore, the samples calcined at 800°C gives most intense up-conversion emissions.

Figure 6 presents the dependence of up-conversion spectra of (Y\textsubscript{0.915−x}Ho\textsubscript{x}Yb\textsubscript{0.075}Li\textsubscript{x})\textsubscript{2}Ti\textsubscript{2}O\textsubscript{7} nanocrystals on the Li\textsuperscript{+} ion concentration. Apparently, the positions of emission peaks do not vary with Li\textsuperscript{+} ion concentration, while the emission intensity changes drastically. The red emission, green emission, and overall emission intensity share the same dependence on Li\textsuperscript{+} ion concentrations, albeit to a slightly different extent, as shown in Fig. 7. The emission intensity increases drastically with Li\textsuperscript{+} ion, reaching the maximum up to a critical concentration of 12.5 mol % Li\textsuperscript{+} ions, and then decreases instead at higher
doping contents of Li\textsuperscript{+} ions. Therefore, it can be concluded safely that there exists an optimal Li\textsuperscript{+} ion concentration, i.e. 12.5 mol\% that gives maximum emission. It is clearly observed from Fig. 7 that, at the introduction of 12.5 mol\% Li\textsuperscript{+} ion, the intensity of green, red and total emission is enhanced by a factor of 10.2, 4.8, and 7.1, respectively, compared with Li\textsuperscript{+}-free samples.

**Figure 8** shows the FT-IR spectra of the samples (Y\textsubscript{0.915}Ho\textsubscript{0.01}Yb\textsubscript{0.075}Li\textsubscript{x})\textsubscript{2}Ti\textsubscript{2}O\textsubscript{7} calcined at 800°C, (a) 0 mol\%, (b) 2.5 mol\%, (c) 5.0 mol\%, (d) 7.5 mol\%, (e) 10.0 mol\%, (f) 12.5 mol\%, (g) 15.0 mol\%.

The adsorption bands of impurities (i.e. OH\textsuperscript{−} groups) have been dramatically reduced and nearly disappeared. It is generally acknowledged that, for any process of up-conversion emission intensities and exciting power, and the double-logarithmic plots are as shown in **Fig. 9**. It is generally acknowledged that, for any process of up-conversion emission, the number of laser photons required, can be calculated by the following relation:

\[
I_{up} \propto P^n
\]

where \(I_{up}\) is the integrated intensity, \(P\) is the power of exciting powder, and \(n\) is the number of laser photons required to emit a visible photon. From **Fig. 8.**, at relatively low pump powers, the slope values obtained through the linear fitting are 2.20 ± 0.03 and 2.15 ± 0.05 for the red and green emissions, respectively, indicating the involvement of two NIR photons excited from \(5\)\(I_6\) and \(F_4\), \(5S_2\) to \(3F_4\) levels. According to the energy level diagrams of Ho\textsuperscript{3+} and Yb\textsuperscript{3+} ions,\textsuperscript{17} the intermediated levels \(2I_6\) and \(2I_7\) of Ho\textsuperscript{3+} ions are also involved. The result obtained is in good agreement with other up-conversion systems, such as \(Y_2\textsubscript{3}Al\textsubscript{5}O\textsubscript{12}:\text{Yb}^3+/\text{Ho}^3+\), \(\text{NaYF}_4:\text{Yb}^3+/\text{Ho}^3+\) nanocrystals.\textsuperscript{17,27,28,29,30} As the pump power increases to a relatively high region, however, there exists the so-called “saturation phenomena” for both the red and green emissions, i.e. the emission intensity decreases instead with the increase of the pump power. This effect can be originated from thermal quenching caused by the absorption of the 980-nm light when excited under too high pump power.\textsuperscript{35-37} These characteristics are well similar to our previous results obtained from Li\textsuperscript{+}-free (Y\textsubscript{0.915}Ho\textsubscript{0.01}Yb\textsubscript{0.075})\textsubscript{2}Ti\textsubscript{2}O\textsubscript{7} samples,\textsuperscript{17} which suggests the Li\textsuperscript{+} ions doping does not change the emission mechanism of Y\textsubscript{2}Ti\textsubscript{2}O\textsubscript{7}:Yb\textsuperscript{3+}/Ho\textsuperscript{3+} nanocrystals.

4. **Conclusions**

In summary, Y\textsubscript{2}Ti\textsubscript{2}O\textsubscript{7}:Yb\textsuperscript{3+}/Ho\textsuperscript{3+} nanocrystals tri-doped with various content of Li\textsuperscript{+} ions were prepared via glycine–combustion approach. An appropriate doping
of Li+ ions can lower the crystallization temperature, and improve the crystallinity of Y2Ti2O7 samples, and also, the up-conversion emissions are strongly dependent on both the calcining temperature and doping concentration of Li+ ions. Compared with Li+–free samples, the green and red emission intensity of Y2Ti2O7:Yb3+/Ho3+ nanocrystals tri-doped with 12.5 mol% Li+ ions is enhanced by a factor of 10.2 and 4.8, respectively. In addition, the pump power dependence of the integrated intensity demonstrates that both the green and red emission is a two-photon up-conversion process. This work, therefore, provides an exploration of the relationship of impurity doping, structural changes and up-conversion performance, which may be of great significance for design and synthesis of high-performance up-conversion materials.

Conflicts of Interest The authors declare that they have no conflicts of interest.

Acknowledgments This work is supported by Natural Science Foundation of China (51362002, 21462001 and 11765002), Natural Science Foundation of Jiangxi Province (20161BAB203098, 20171BAB206016), Key Research & Development Program of Jiangxi Province (2017BBH80021), Education Department of Jiangxi Province (GJJ150599, GJJ150583), and the financial supports from Jiangxi Key Laboratory for Mass Spectrometry and Instrumentation (JXMS201506) and State Key Laboratory Breeding Base of Nuclear Resources and Environment (NRE1517) are also greatly appreciated.

References
1) L. H. Fischer, G. S. Harms and O. S. Wolfbeis, Angew. Chem. Int. Ed., 50, 4546–4551 (2011).
2) J. C. Goldschmidt and S. Fischer, Adv. Opt. Mater., 3, 510–535 (2015).
3) G.-R. Tan, M. Wang, C.-Y. Hsu, N. Chen and Y. Zhang, Adv. Opt. Mater., 4, 984–997 (2016).
4) N. M. Idris, M. K. G. Jayakumar, A. Bansal and Y. Zhang, Chem. Soc. Rev., 44, 1449–1478 (2015).
5) D. Yang, P. a. Ma, Z. Hou, Z. Cheng, C. Li and J. Lin, Chem. Soc. Rev., 44, 1416–1448 (2015).
6) D. Chen and Y. Wang, Nanoscale, 5, 4621–4637 (2013).
7) W. Park, D. Lu and S. Ahn, Chem. Soc. Rev., 44, 2940–2962 (2015).
8) G. Chen, H. Agren, T. Y. Ohulchansky and P. N. Prasad, Chem. Soc. Rev., 44, 1680–1713 (2015).
9) F. Wang, Y. Han, C. S. Lim, Y. H. Lu, J. Wang, J. Xu, H. Y. Chen, C. Zhang, M. H. Hong and X. G. Liu, Nature, 463, 1061–1063 (2010).
10) M. Misiak, B. Cichy, A. Bednarkiewicz and W. Stręk, J. Lumin., 145, 956–962 (2014).
11) T. V. Gavrilović, D. J. Jovanović, L. V. Trandafilić and M. D. Dramićanin, Opt. Mater., 45, 76–81 (2015).
12) C. Wang and X. Cheng, J. Alloy. Compd., 649, 196–203 (2015).
13) M. Wang, J. Wu and Z. Chen, Key Eng. Mat., 703, 242–245 (2016).
14) Z. Chen, T. Chen, W. Gong, S. Li, W. y. Xu, D. Wang and Q. Wang, J. Am. Ceram. Soc., 96, 1857–1862 (2013).
15) B. P. Singh, A. K. Parchur, R. K. Singh, A. A. Ansari, P. Singh and S. B. Rai, Phys. Chem. Chem. Phys., 15, 3480–3489 (2013).
16) F. Wang, F. Song, G. Zhang, Y. Han, Q. Li, C. Ming and J. Tian, J. Appl. Phys., 115, 134310 (2014).
17) Z. Chen, M. Wang, H. Wang, Z. Le, G. Huang, L. Zou, Z. Liu, D. Wang, Q. Wang and W. Gong, J. Alloy. Compd., 608, 165–169 (2014).
18) M. Ding, Y. Ni, Y. Song, X. Liu, T. Cui, D. Chen, Z. Ji, F. Xu, C. Lu and Z. Xu, J. Alloy. Compd., 623, 42–48 (2015).
19) Y. Zhang, M. Wang, Z. Le, G. Huang, L. Zou and Z. Chen, Ceram. Int., 40, 5223–5230 (2014).
20) L. Brixner, Inorg. Chem., 3, 1065–1067 (1964).
21) B. J. Liu, M. Gu, X. L. Liu, C. Ni, D. Wang, L. H. Xiao and R. Zhang, J. Alloy. Compd., 440, 341–345 (2007).
22) G. Y. Chen, H. C. Liu, H. J. Liang, G. Somesfalean and Z. G. Zhang, J. Phys. Chem. C, 112, 12030–12036 (2008).
23) H. P. Klug and L. E. Alexander, “X-Ray Powder Diffraction Procedures”, Wiley (1959).
24) R. D. Shannon, Acta Crystallogr. A, A32, 751–767 (1976).
25) Y. F. Bai, Y. X. Wang, K. Yang, Y. X. Wang, X. Zhang and Y. Song, Opt. Commun., 281, 2930–2932 (2008).
26) L. Q. An, J. Zhang, M. Liu and S. W. Wang, J. Am. Ceram. Soc., 88, 1010–1012 (2005).
27) M. Liu, S. W. Wang, D. Y. Tang, L. D. Chen and J. Ma, J. Rare Earth., 27, 66–70 (2009).
28) X. P. Chen, W. J. Zhang and Q. Y. Zhang, Physica B, 406, 1248–1252 (2011).
29) C. C. Ting, Y. S. Chiu, C. W. Chang and L. C. Chuang, J. Solid State Chem., 184, 563–571 (2011).
30) Y. Bai, Y. Wang, G. Peng, K. Yang, X. Zhang and Y. Song, J. Alloy. Compd., 478, 676–678 (2009).
31) H. J. Liang, Y. D. Zheng, G. Y. Chen, L. Wu, Z. G. Zhang and W. W. Cao, J. Alloy. Compd., 509, 409–413 (2011).
32) H. Yu and J. Yu, J. Lumin., 137, 274–281 (2013).
33) M. Yang, Y. Sui, S. Wang, X. Wang, Y. Sheng, Z. Zhang, T. Lü and W. Liu, Chem. Phys. Lett., 492, 40–43 (2010).
34) M. Pollnau, D. R. Gamelin, S. R. Luthi, H. U. Gudel and M. P. Hehlen, Phys. Rev. B, 61, 3337–3346 (2000).
35) Y. Q. Lei, H. W. Song, L. M. Yang, L. X. Yu, Z. X. Liu, G. H. Pan, X. Bai and L. B. Fan, J. Phys. Chem. C, 112, 1962–1967 (2008).
36) A. H. Li and Q. Lü, J. Rare Earth., 27, 196–203 (2009).
37) J. Petit, B. Viana and P. Goldner, Opt. Express, 19, 1138–1146 (2011).