Color-tunable photoluminescence and persistent luminescence in a single LiYGeO₄:Tb³⁺ phosphor

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Abstract
Persistent luminescence (PerL) phosphors have been widely applied in many advanced applications in the field of emergency lighting, safety signage, and ornaments. Recently, the PerL phosphors based on germanates have attracted great attention owing to their excellent PerL performance. However, the design and development of excellent germanates-based PerL materials with full spectral emissions remain challenging due to the lack of color-tunable PerL, especially in the blue and green regions (400–600 nm). Herein, we develop a new type of Tb³⁺-activated LiYGeO₄ PerL phosphor with real-time adjusting the photoluminescence (PL) and PerL color, which can be effectively excited by a 254 UV light. Both blue and green PerL are realized simultaneously in a single phosphor. When LiYGeO₄:Tb³⁺ doped with lower concentrations of Tb³⁺ ions, phosphors emit blue PL and PerL. With increasing Tb³⁺ concentration, the PL and PerL colors of LiYGeO₄:Tb³⁺ PerL phosphor are gradually regulated from blue to green. Besides, LiYGeO₄:Tb³⁺ exhibits temperature-dependent luminescence property, whose PL and PerL colors can also be successively widely tuned by various temperature. This stable and tunable color in real-time PL and PerL property promote the as-designed LiYGeO₄:Tb³⁺ phosphor to have potential applications in advanced anti-counterfeiting and display devices.

1. Introduction
PerL materials can continue emitting light for a period of time after removal of the excitation source [1–3]. In recent decades, visible PerL materials have been rapidly developed and widely applied in commercial fields, such as traffic signs, decorations, and emergency lighting [4, 5]. The representative visible PerL materials includes Y₂O₂S:Eu²⁺, Mg²⁺, Ti³⁺ [6], SrAl₂O₄:Eu²⁺, Dy³⁺ [7] and CaAl₂O₄:Eu³⁺, Nd³⁺ [8], exhibiting bright blue, green, and red PersL, respectively. However, there are still some problems in this research field including type of host material and adjustable emitting colors. It is well known that suitable matrices can improve the performances of PerL materials. The germanates with olivine structure (space group Pbnm) with the general formulas XeMeGeO₄ (Xe = Li, Na; Me = Y, Er, Nd, Sc) have high-density trap energy levels that are favor to produce PerL [9, 10]. In recent years, researches on XeMeGeO₄-based PerL materials suggested that they have excellent PerL with afterglow time ranging from dozens of hours to hundred of hours after irradiation by high-energy x-ray or UV light [11]. The XeMeGeO₄-based PerL materials with a strong emission peak in the wavelength range of 315–400 nm, named the ultraviolet A (UVA) region, have been extensively reported. For example, Zhang et al [12] reported that LiYGeO₄:Bi³⁺ phosphor shows super-long PerL in the UVA region peaking at 350 nm. Liang group [13] and Peng group [14] have realized persistent luminescence in the UVA region in Bi³⁺-doped LiScGeO₄ phosphor peaking at ~360 nm. Liu et al [15] reported that LiLuGeO₄:Bi³⁺, Yb³⁺...
phosphor exhibits prominent UVA PersL peaking at 350 nm. In addition to UVA PerL, Wang et al. [16] observed blue PersL in the NaLuGeO$_4$:Bi$^{3+}$,Eu$^{3+}$ material peaking at 400 nm, but half of its PerL emission was located in the UVA region. Recently, Hu et al. [17] reported red PerL peaking at 611 nm in LiYGeO$_4$:Eu$^{3+}$ phosphor. Although some promising XeMeGeO$_4$-based persistent materials have been reported, the design and development of excellent germanates-based PerL materials with full spectral emissions remain challenging due to the lack of flexible blue and green PerL.

In this work, we design an excellent LiYGeO$_4$:Tb$^{3+}$ material with tunable PL and PerL emitting at excitation of a 254 nm UV light. The LiYGeO$_4$:Tb$^{3+}$ phosphors show blue PerL in the case of low doping level of Tb$^{3+}$ ions, while exhibit green PerL for the samples doped with higher Tb$^{3+}$ concentration. The tunable emission colors is caused by the cross-relaxation interaction between Tb$^{3+}$ ions. Furthermore, the as-designed LiYGeO$_4$:Tb$^{3+}$ PerL phosphor simultaneously possesses temperature-dependent luminescence property. The PL and PerL colors continuously changes as temperature increasing. The proposed LiYGeO$_4$:Tb$^{3+}$ PerL phosphor with adjusting the emitting color would be a promising candidate for advanced anti-counterfeiting applications.

2. Experimental

2.1. Materials and preparation

A series of LiYGeO$_4$:x%Tb$^{3+}$ (x = 0.001, 0.003, 0.005, 0.008, 0.01, 0.02, 0.04, 0.06, 0.08, 0.2, 0.3) samples were synthesized via a solid-state reaction [18]. The starting raw materials of Li$_2$CO$_3$ (99.5%), Y$_2$O$_3$ (99.99%), GeO$_2$ (99.99%), and Tb$_2$O$_3$ (99.9%) were measured and weighed according to the designed compositions. According to each given stoichiometric proportion, the raw materials were weighed and fully ground in an agate mortar for 30 min. A crucible containing the mixtures were pre-heated at 800 °C for 2 h. The samples were cooled to room temperature and thoroughly ground. These pre-sintered samples were further annealed at 1100 °C for 5 h. Finally, the samples were cooled to room temperature and re-ground for subsequent characterization.

2.2. Characterization

X-ray diffraction (XRD) analysis was carried out using a D/Max-Ultima x-ray diffractometer. The PL spectra and afterglow time of the samples were measured via employing a Hitachi F-4600 fluorescence spectrometer equipped with a 150 W xenon lamp as an excitation source. The thermoluminescence (TL) curve and temperature dependent PL spectra were obtained using a Hitachi F-4600 fluorescence spectrometer equipped with a temperature-controlled system (DMU-TC450). For the TL curve, the sample was heated from room temperature to 300 °C with heating rate of 60 °C min$^{-1}$. Before measuring the TL curves and afterglow time decay curves, the sample was irradiated at 254 nm for 10 min, and then, the light source was blocked. The photographs of the samples were recorded by Canon EOS 5D Mark III.

3. Results and discussion

The XRD patterns of LiYGeO$_4$:x%Tb$^{3+}$ (x = 0.01, 0.06, 0.3) samples as the representative are depicted in figure 1(a). All diffraction peaks are well consistent with the standard ICDS card No.02–3479, indicating that the as-synthesized materials are pure LiYGeO$_4$ phase. Compared with the diffraction pattern of standard card of LiYGeO$_4$ (No. 47–0461), the diffraction peaks of the Tb$^{3+}$ ions doped samples are shifted to the high angle direction. It suggests that the Tb$^{3+}$ activators have been successfully incorporated into the host lattice, and does not affect the crystal structure. The diffraction peaks are shifted to the high angle direction. This is contributed by the replacement of Y$^{3+}$ by the dopants of Tb$^{3+}$ ions with smaller radius, making the host lattice shrinkage. The crystal structure diagram of LiYGeO$_4$ is shown in figure 1(b). The LiYGeO$_4$ crystal belongs to the orthorhombic structure with the space group of Pnam. In this crystal structure, Li$^{+}$ and Y$^{3+}$ ions are both coordinated by six O atoms to form octahedrons (LiO$_6$ and YO$_6$), and Ge$^{4+}$ ions is coordinated by four O atoms to form tetrahedra (GeO$_4$). The ion radius of different cation are as follows: Li$^+$ (CN = 6, 0.76 Å), Y$^{3+}$ (CN = 6, 0.9 Å), Ge$^{4+}$ (CN = 4, 0.39 Å), and Tb$^{3+}$ (CN = 6, 0.92 Å). On account of considering the ion radius, coordination condition and electrovalence balance, it further suggest that the Tb$^{3+}$ dopant ions occupies the Y$^{3+}$ sites in the LiYGeO$_4$ host lattice.

Figure 2(a) and b show the excitation and emission spectra of LiYGeO$_4$:x%Tb$^{3+}$ (x = 0.001, 0.003, 0.005, 0.008, 0.01, 0.02, 0.04, 0.06, 0.08, 0.2, 0.3) samples at room temperature, respectively. By monitoring the characteristic emission of Tb$^{3+}$ ions at 550 nm, the excitation spectra of the as-prepared samples were measured in the range of 200–400 nm (figure 2(a)). The excitation band centered at 293 nm can be attributed to the self-trapped excitation (STE) band of the LiYGeO$_4$ host according to the previous researches [19]. An intense and broad absorption band in the range of 210–280 nm is ascribed to the 4F $\rightarrow$ 5d transition of Tb$^{3+}$ ions. This indicates that the LiYGeO$_4$:Tb$^{3+}$ phosphors can be effectively excited by excitation wavelengths within 250–300 nm. The other weak absorption peaks located at 317 nm ($^7F_6 \rightarrow ^3D_0$), 335 nm ($^7F_6 \rightarrow ^3D_1$), 343 nm...
UV, blue, green, and red emissions. The intensity of main emission band centers Tb$^{3+}$ concentration. The PerL colors coincides with PL colors, indicating that the PerL originates from the emitting concentration, and the corresponding photographs exhibit in the concentrations, while the emission intensity of spectral region in the range of 475$–$650 nm increases gradually. As a result, the LiYGeO$_4$:0.001%Tb$^{3+}$ phosphor shows PerL after cutting off the 254 nm UV light. As shown in figure 2(c), the emission colors of LiYGeO$_4$:Tb$^{3+}$ samples shifting from bright blue light to bright green light can be observed with the naked eyes in the daytime as the Tb$^{3+}$ excitation peaks, which is due to the fact that parity-forbidden 4f-$\rightarrow$4f transitions of Tb$^{3+}$ ions result in the UV-visible emissions. Here, when the maximum at Tb$^{3+}$ concentration of 0.005%, and then decreases with the further increase of Tb$^{3+}$ concentrations, while the emission intensity of spectral region in the range of 475–650 nm increases gradually. When doping concentration of Tb$^{3+}$ increases to 0.2%, the emissions ranging from 300 to 475 nm quench, and emissions as a function of Tb$^{3+}$ ions concentration are presented in the inset of figure 2(b). Figure 2(c) shows the proposed luminescent processes for the LiYGeO$_4$:Tb$^{3+}$ sample under 254 nm excitation. The electrons are excited to the 4f$^5$5d$^1$ levels by absorbing of a 254 nm photon. After sequential nonradiative relaxations, the excited states of $^5$D$_3$ and $^5$D$_4$ are populated. The radiative transitions from the two excited states to the 7F$^g$ multiplet ground state result in the UV-visible emissions. Here, when the Tb$^{3+}$ concentrations beyond 0.008 mol%, the cross-relaxation process of $^5$D$_3$ $\rightarrow$ $^5$D$_4$ may occur, which results in luminescence quenching of the emissions from $^5$D$_3$ excited state. Consequently, a very wide range of emission colors can be continuously tuned by the altered composition. As shown in figure 2(d), the CIE chromaticity coordinates ($x$, $y$) shift from the blue region to the green region with the increase of Tb$^{3+}$ concentration, and the corresponding photographs exhibit in the figure 2(e). Under excitation of 254 nm, the emission colors of LiYGeO$_4$:Tb$^{3+}$ samples shifting from bright blue light to bright green light can be observed with the naked eyes in the daytime as the Tb$^{3+}$ doping concentration increases.

Excitingly, LiYGeO$_4$:Tb$^{3+}$ phosphors show PerL after cutting off the 254 nm UV light. As shown in figure 2(e), the PerL colors of LiYGeO$_4$:Tb$^{3+}$ are gradually regulated from blue to green with increasing Tb$^{3+}$ concentration. The PerL colors coincides with PL colors, indicating that the PerL originates from the emitting centers Tb$^{3+}$. Figure 3(a) illustrates the temperature-dependent PL spectra of LiYGeO$_4$:0.001%Tb$^{3+}$ phosphor under 254 nm excitation. With the temperature increases from 303 to 723 K, the relative PL intensity gradually decreases induced by a thermal quenching effect, but the position and shape of emission peaks remain unchanged. However, the intensity of the UV and blue emissions decreases more quickly with an increase in temperature than that of green emission. As a result, the LiYGeO$_4$:0.001%Tb$^{3+}$ exhibits temperature-dependent

![Figure 1](image1.png)
tunable colors. The color coordinates have a constant shift with increasing temperature, as shown in the inset of figure 3(a).

The PerL decay curves of LiYGeO₄ₓTb₃⁺ (x = 0.003, 0.08, 0.2) phosphors by monitoring at 550 nm emission were investigated after excitation by a 254 nm UV light for 10 min (figure 3(b)). The decay curves decreases quickly and then decays slowly. With increasing Tb³⁺ concentration, the afterglow lifetime decreases remarkably, especially for initial stage. Detailed mechanisms will be discussed later. It is well known that the trapping centers play an essential role for photo energy storage in persistent phosphors [21]. To identify the trap properties in LiYGeO₄:Tb³⁺ persistent phosphor, TL measurement was conducted at temperatures from 295 to 573 K. Figure 3(c) shows the TL curve of LiYGeO₄:Tb³⁺ by monitoring the 550 nm emission after irradiation by 254 nm UV light for 10 min. The TL curve exhibits two strong emission bands peaking at 329 and 393 K (the shallow trap), and a weak band peaking at 527 K (the deep trap). The energy depths of the trapping centers can be estimated by the following equation [22]:

\[
E = \frac{\hbar c}{\lambda} - h
\]

Figure 2. (a) Excitation and (b) emission spectra of LiYGeO₄ₓ%Tb³⁺ (x = 0.001, 0.003, 0.005, 0.008, 0.01, 0.02, 0.04, 0.06, 0.08, 0.2, 0.3) samples. The excitation spectrum is obtained by monitoring at 550 nm emission, and the emission spectrum is measured under 254 nm UV light excitation. (c) A schematic representation of the PL mechanism for LiYGeO₄:Tb³⁺ phosphors at excitation of 254 nm. (d) CIE chromaticity diagram for all the designed samples excited at 254 nm. (e) PL and PerL images of all the LiYGeO₄:Tb³⁺ sample under/after irradiation by 254 nm UV light.
where \( E \) is the trap depth, \( T_m \) is the temperature of the TL emission peaks. Therefore, the corresponding trap depths are determined to be 0.658, 0.786, and 1.054 eV, respectively. These energy traps in LiYGeO\(_4\):Tb\(^{3+}\) can be generated by the following possible reasons. At a high-temperature sintering environment, the oxygen vacancy (VO\(^{2+}\)) can be produced in the phosphor \([1]\). In addition, Li\(^{+}\) can escape easily from the crystal lattice under an oxygenic atmosphere at high sintering temperatures, which creates traps \([11, 12, 23]\). According to reported work, a trap depth between 0.5 eV and 0.7 eV is usually suitable for PerL \([24]\). The trap depth of low temperature TL peak for LiYGeO\(_4\):Tb\(^{3+}\) locates in these values range, which would be beneficial to the PerL at room temperature.

The possible PerL mechanism of LiYGeO\(_4\):Tb\(^{3+}\) phosphor is proposed, as shown in figure 3(d). Under 254 nm UV light excitation, some electrons are excited to the 4f\(^5\) 5d\(^1\) excited states of Tb\(^{3+}\) ions (process 1). Since these excited levels are in the conduction band (CB) of LiYGeO\(_4\), some electrons is favorable to escape into the host’s CB \([25]\). Meanwhile, some other electrons are excited into the CB from the valence band (VB) (process 2). The excited electrons in the CB can move freely and are caught by the shallow traps (process 3) and deep traps (process 4). With low energy barrier, a lot of electrons captured in the shallow traps can easily escape to the CB through thermal stimulation at room temperature (process 5), and then populate excited states of Tb\(^{3+}\) ions through the CB. The electrons in the shallow traps contribute to the initial strong-intensity PerL emission, resulting in the fast decay process of the PerL. While the electrons in the deep traps are slow to be released to CB at ambient temperature. These electrons would generally contribute to the long duration PerL. However, the number of electrons in the deep trap is small in as-prepared LiYGeO\(_4\):Tb\(^{3+}\) phosphors. Therefore, LiYGeO\(_4\):Tb\(^{3+}\) does not show the ideal decay time. When increasing temperature, some electrons in the deep traps can be caught by the shallow traps (process 6), or release to CB (process 9). The CIE chromaticity coordinates \((x, y)\) shift from the blue region to the green region with the temperature increasing, indicating that the electrons in the deep traps prefer to be trapped by the shallow traps and fall into \(^5D_4\) level of Tb\(^{3+}\) (process 7 or 8). The concentration quenching of PerL of Tb\(^{3+}\) ions was attributed to electron transfer from the shallow traps to the \(^5D_4\) level. The concentration quenching of PerL of Tb\(^{3+}\) ions was attributed to electron transfer from the shallow traps to the \(^5D_4\) level.
migration among traps via tunneling \cite{17, 26}. With the Tb$^{3+}$ concentration increasing, the distance (the width of the potential barrier) between the vacancy trap and the nearby charged trap become shorter compared with at low concentrations. This allows the electrons in the traps to rapidly tunnel a short distance to the nearby traps and be captured into the energy-matched Tb$^{3+}$ energy levels (process 7 or 8). The quick tunneling process can greatly reduce the afterglow lifetime of Tb$^{3+}$ ions, which is consistent with the PerL decay curves.

4. Conclusions

In summary, we have developed a series of new tunable emission Tb$^{3+}$-doped LiYGeO$_4$ phosphors that can be effectively activated by 254 nm UV light. The LiYGeO$_4$:Tb$^{3+}$ phosphor emits bright PL originating from emitting centers Tb$^{3+}$. The PL colors of LiYGeO$_4$:Tb$^{3+}$ phosphor gradually shift from blue to green with increasing Tb$^{3+}$ concentration and temperature. Besides this, LiYGeO$_4$:Tb$^{3+}$ phosphors also show PerL after the stoppage of 254 nm power source. The PerL colors of LiYGeO$_4$:Tb$^{3+}$ coincides with PL colors, and can be finely regulated by adjusting the Tb$^{3+}$ doping concentrations and ambient temperature. We anticipate that future investigations will optimize afterglow time, develop LiYGeO$_4$:Tb$^{3+}$ with long PerL. This newly as-designed LiYGeO$_4$:Tb$^{3+}$ phosphor possessing excellent luminescent properties including PL and PerL with stable and tunable color, is a promising phosphor candidate for multifunctional applications of anti-counterfeiting and display.

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Data availability statement

The data generated and/or analysed during the current study are not publicly available for legal/ethical reasons but are available from the corresponding author on reasonable request.

Conflicts of interest

There are no conflicts to declare.

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References

\cite{1} Pan Z W, Lu Y Y and Liu F 2012 Sunlight-activated long-persistent luminescence in the near-infrared from Cr$^{3+}$-doped zinc gallogermanates Nat. Mater. 11 58–63
\cite{2} Qu B Y, Zhang B, Wang L, Zhou R L and Zeng X C 2015 Mechanistic study of the persistent luminescence of CaAl$_2$O$_4$:Eu,Nd Chem. Mater. 271155 2195–202
\cite{3} Huang K, Le N, Wang J S, Huang L, Zeng L, Xu W C, Li Z J, Li Y and Han G 2022 Designing next generation of persistent luminescence: recent advances in uniform persistent luminescence nanoparticles Adv. Mater. 34 2107962
\cite{4} Jiang K, Wang Y C, Lin C J, Zheng L C, Du J R, Zhuang Y X, Xie R J, Li Z J and Lin H W 2022 Enabling robust and hour-level organic long persistent luminescence from carbon dots by covalent fixation Light Sci. Appl. 11 80
\cite{5} Yuan W H, Tan T, Wu H Y, Pang R, Zhang S, Jiang L H, Li D, Wu Z J, Li C Y and Zhang H J 2021 Intense UV long persistent luminescence benefiting from the coexistence of Pr$^{3+}$/Pr$^{4+}$ in a praseodymium-doped Ba$_5$Al$_2$Al$_2$Si$_2$O$_{12}$ phosphor J. Mater. Chem. C 9 5206–16
\cite{6} Zhou X L, Xing M M, Jiang T, Fu Y, Peng Y, Wang H and Luo X X 2014 Afterglow performance enhancement and mechanism studies on Y$_2$O$_3$:Eu,Mg,Ti prepared via cold isostatic pressing J. Alloys Compd. 585 376–83
\cite{7} Urakawa K, Miyasato K, Totani K and Watanabe T 2020 Emission increase in persistent inorganic phosphor improving absorption property by surface chemical modification J. Lumin. 217 116772
\cite{8} Xia Y, Huang X Q, Wu W F, Li W B, Li Z J and Han G 2019 Multicolor persistent luminescence realized by persistent color conversion J. Lumin. 207 53–7
\cite{9} Sharonov M Y, Bykov A B, Rojas P, Petricevic V and Alfano R R 2005 Spectroscopy of chromium centers in LiScGeO$_4$ and LiInGeO$_4$ single crystals. Phys. Rev. B 72 115111
[10] Koseva I, Nikolov V, Petrova N, Tzvetkov P and Marychev M 2016 Thermal behavior of germanates with olivine structure Thermochim. Acta 646 1–7
[11] Liu L, Yu K X, Ming L Y, Sheng Y Y, Zheng S H, Song L, Shi J P and Zhang Y 2021 A novel Gd-based phosphor NaGdGeO₄:Bi³⁺,Li⁺ with super-long ultraviolet-A persistent luminescence J. Rare Earths
[12] Shi J P, Sun X, Zheng S H, Fu X Y, Yang Y, Wang J N and Zhang H W 2019 Super-long persistent luminescence in the ultraviolet A region from a Bi³⁺-doped LiYGeO₄ phosphor Adv. Opt. Mater. 7 1900526
[13] Zhang Y, Chen D X, Wang W L, Yan S, Liu J W and Liang Y J 2020 Long-lasting ultraviolet-A persistent luminescence and photostimulated persistent luminescence in Bi³⁺-doped LiScGeO₄ phosphor Inorg. Chem. Front. 7 3063–71
[14] Zhou Z H, Xiong P X, Liu H L and Peng M Y 2020 Ultraviolet-a persistent luminescence of a Bi³⁺-activated LiScGeO₄ material Inorg. Chem. 59 12920–7
[15] Cai H, Song Z and Liu Q L 2021 Infrared-photostimulable and long-persistent ultraviolet-emitting phosphor LiLuGeO₄:Bi³⁺,Yb³⁺ for biophotonic applications Mater. Chem. Front. 5 14310–8
[16] Dai T S, Ju G F, Lv Y, Jin Y H, Wu H Y and Hu Y H 2021 Luminescence properties of novel dual-emission (UV/red) long afterglow phosphor LiYGeO₄:Eu³⁺ J. Lumin. 237 118193
[17] Cheng K, Li C C, Xiang H C, Sun Y H and Fang L 2018 LiYGeO₄: Novel low-permittivity microwave dielectric ceramics with intrinsic low sintering temperature Mater. Lett. 228 96–9
[18] Fan B, Zhou W X, Qi S M and Zhao W Y 2020 Eu³⁺-doped NaYGeO₄: a novel red-emitting phosphors for ultraviolet or blue chips excited white LEDs J. Solid State Chem. 283 121158
[19] Huang Z X, Yang Y, Gong L J, Ma M and Xu C F 2016 Sr²⁺ and Tb³⁺ doping tuning the size, morphology, and photoluminescence of NaCeF₆ nanorods via solvothermal method Chem. Eng. J. 286 692–9
[20] Li G, Wang Y H, Zeng W, Chen W B, Han S C, Guo H J and Liu J 2016 Effects of Nd³⁺ co-doping on the long lasting phosphorescence and optically stimulated luminescence properties of green emitting NaBaSi₃O₆:Eu²⁺⁺ phosphor Mater. Res. Bull. 84 1–6
[21] Shalgaonkar C S and Narlikar A V 1972 Review of recent methods for determining trap depth from glow curves J. Mater. Sci. 7 1465
[22] Zhao L, Zhang B P, Zhou P F, Zhu L F and Wang N 2016 Piezoelectric and ferroelectric properties of (Ba,Ca)(Ti,Sn)O₃ lead-free ceramics sintered with Li₂O additives: Analysis of point defects and phase structures Ceram. Int. 42 1086
[23] Matsuzawa T, Apki Y, Takeuchi N and Murayama Y 1996 A new long phosphorescent phosphor with high brightness, SrAl₂O₄:Eu²⁺, Dy³⁺ J. Electrochem. Soc. 143 2670–3
[24] Rodrigues L C V, Brito H F, Holza J, Stefani R, Felinto M C F C, Lastusaari M, Laamanen T and Nunes L A O 2012 Discovery of the persistent luminescence mechanism of CdSiO₃: Tb³⁺ The J. Phys. Chem. C 116 11323–40
[25] Ju G F, Hu Y H, Chen L, Wang X J and Mu Z F 2013 Concentration quenching of persistent luminescence Physica B 415 1–4