

Achieving high-performance far-red emission in Cr³⁺ activated garnet phosphor via Ca²⁺/Zr⁴⁺ doping toward plant lighting

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Abstract

Equimolar Ca^{2+} and Zr^{4+} doping was implemented to establish novel garnet-type $\text{Gd}_{3-x}\text{Ca}_x\text{Al}_{2.95}\text{Ga}_{2-x}\text{Zr}_x\text{O}_{12}:0.05\text{Cr}^{3+}$ ($x=0-2.0$) far-red (FR) phosphors. The quantum efficiency and temperature-dependent luminescence analysis successfully produced the optimal $x=0.5$ phosphor, which exhibited highly efficient (IQE=92.8%, EQE=31.6%) broadband FR-emission peaking at ~ 714 nm (full-width at half-maximum ~ 81 nm) and excellent thermal stability (95.5% @ 423 K) under 450 nm light excitation. Its performance is far superior to that of most reported Cr^{3+} activated FR-emitting garnet phosphors, and the emission spectrum can well superpose with the absorption band of the far-red phytochrome, making this phosphor have huge potential application in the construction of high-quality FR pc-LED used for plant lighting.

Key words: Cr^{3+} phosphor; $\text{Ca}^{2+}/\text{Zr}^{4+}$ doping; Far-red emitting; Plant lighting

In modern agriculture, indoor planting technology is a crucial development direction due to its advantages of improving crop quality/yield and reducing land/climate dependency [1, 2]. As the core technology of indoor planting, plant lighting dominates the crop's growth rhythm. Phosphor-converted light-emitting diodes (pc-LEDs) have been deemed as a prospective plant lighting source due to their small size, high luminous efficiency, and excellent durability [3, 4]. It is known that four biological pigments within plants play a significant role in the process of plant growth, wherein chlorophyll A and chlorophyll B can intensely absorb blue (400–500 nm) and red (600–700 nm) light to motivate photosynthesis. Then, the pc-LED devices applied in plant growth lighting were primarily constructed by coating the blue/red emitting phosphor on the ultraviolet/blue LED chip [5], the typical phosphors such as (Sr,Ba)LaMgTaO₆:Pr³⁺ (blue) [6], Na₂BaSr(PO₄)₂:Eu²⁺ (blue) [7], BaLaGaO₄:Eu³⁺ (red) [8], and Na₅Y(MoO₄)₄:Sm³⁺ (red) [9]. In addition, red phytochrome (P_R) and far-red phytochrome (P_{FR}), which can transform to each other under far-red (700–780 nm) or red irradiation, have a decisive influence on photomorphogenesis and photoperiod during plant growing [1, 10]. Therefore, the exploration of high-performance far-red-emitting pc-LED (FR pc-LED) is attracting growing attention.

In this respect, since transition metal Mn⁴⁺ ions are prone to achieving far-red emission via regulating the crystal field strength (D_q/B), many Mn⁴⁺ doped phosphors have been developed [11]. However, the far-red emission arising from the spin-forbidden ²E_g→⁴A_{2g} transition of Mn⁴⁺ ions commonly showed narrowband emission, poor luminescence thermal stability, and low quantum efficiency, which retard the

application of Mn^{4+} doped phosphor in FR pc-LED [12, 13]. Additionally, Cr^{3+} activated phosphors are known for absorbing blue light excitation followed by highly efficient FR- or near-infrared- (NIR, 700–1100 nm) emitting, thus the Cr^{3+} is an ideal activator for the construction of high-quality FR pc-LED [14]. As is known, the luminescence of Cr^{3+} is highly associated with the value of D_q/B and essentially dependent on its local coordination. It is commonly recognized that Cr^{3+} would exhibit broadband emission arising from the spin-allowed ${}^4\text{T}_2 \rightarrow {}^4\text{A}_2$ transition when $D_q/B < 2.3$, and otherwise narrowband emission via the spin-forbidden ${}^2\text{E} \rightarrow {}^4\text{A}_2$ transition when $D_q/B > 2.3$ [15]. Among the Cr^{3+} doped phosphors, rare-earth aluminum garnet ($\text{RE}_3\text{Al}_5\text{O}_{12}$; REAG; RE=La, Gd, Y, and Lu), in which $[\text{REO}_8]$ dodecahedron, $[\text{AlO}_6]$ octahedron, and $[\text{AlO}_4]$ tetrahedron are interconnected to each other, is the outstanding one owing to its high luminous efficiency and excellent physical/chemical stability. Whereas, the values of D_q/B for pure REAG: Cr^{3+} garnets are usually above 2.3, clarifying that the sharp-line ${}^2\text{E} \rightarrow {}^4\text{A}_2$ transition ($\sim 690\text{--}700$ nm) would dominate the emission of these phosphors [16, 17]. To achieve highly efficient broadband FR-emitting garnet phosphors, ion/ion-pair substitution (e.g., Ga^{3+} or Sc^{3+} ions, $\text{Ca}^{2+}/\text{Ge}^{4+}$ or $\text{Mg}^{2+}/\text{Si}^{4+}$ ion pairs, etc.) was implemented to regulate local coordination and tune Cr^{3+} luminescence. For example, $\text{BaY}_2\text{Ga}_{3.9}\text{GeO}_{12}:0.1\text{Cr}^{3+}$ ($\lambda_{\text{em}}=710$ nm, full-width at half-maximum (FWHM) ~ 85 nm) [18], $\text{Lu}_3\text{Sc}_2\text{Ga}_3\text{O}_{12}:\text{Cr}^{3+}$ ($\lambda_{\text{em}}=722$ nm, FWHM ~ 73 nm) [19], $\text{Y}_2\text{ZnGa}_4\text{GeO}_{12}:\text{Cr}^{3+}$ ($\lambda_{\text{em}}=708$ nm, FWHM ~ 62 nm) [20], and $\text{GdLuCaAl}_{3.95}\text{SiO}_{12}:0.05\text{Cr}^{3+}$ ($\lambda_{\text{em}}=711$ nm, FWHM ~ 73 nm) [21] garnet phosphors exhibited potential application in FR pc-LED, even though their quantum efficiency

and thermal stability need further improvement.

In this work, equimolar Ca^{2+} and Zr^{4+} doping to regulate the structure and luminescence of $\text{Gd}_3\text{Al}_3\text{Ga}_2\text{O}_{12}:\text{Cr}^{3+}$ garnet, a series of $\text{Gd}_{3-x}\text{Ca}_x\text{Al}_{2.95}\text{Ga}_{2-x}\text{Zr}_x\text{O}_{12}:0.05\text{Cr}^{3+}$ (GCAGZ:Cr; $x=0, 0.5, 1.0, 1.5$, and 2.0) phosphors with outstanding efficiency and thermal stability were successfully fabricated. The effect of $\text{Ca}^{2+}/\text{Zr}^{4+}$ doping on the structure and Cr^{3+} luminescence behaviors were investigated in detail, and the typical $x=0.5$ phosphor exhibit huge potential application in high-quality plant growth lighting.

The series of GCAGZ:Cr ($x=0-2.0$) phosphors were prepared via solid-state reaction, Gd_2O_3 (4N purity), Al_2O_3 (4N purity), Ga_2O_3 (99.9% pure), ZrO_2 (4N purity), CaCO_3 (4N purity), and Cr_2O_3 (99.95% pure) as starting materials. All the oxides were purchased from Shanghai Aladdin Bio-Chem. Tech. Co. Ltd (Shanghai, China). The reactants were weighted according to the stoichiometric composition of 1 mmol garnet product, adding 2 wt% of H_3BO_3 (4N purity, Aladdin, Shanghai) as a fluxing agent, and then mixed by grinding with an agate mortar and pestle for 30 min. The series of phosphors were directly produced via reaction at $1400\text{ }^\circ\text{C}$ for 4 h in air.

The X-ray diffraction (XRD) data for phase identification of the GCAGZ:Cr phosphors were collected in a 2θ range from 10 to 70° via continuous scan at $5^\circ 2\theta/\text{min}$ on Rigaku MiniFlex600 diffractometer (Tokyo, Japan) using Ni-filtered $\text{Cu-K}\alpha$ radiation ($\lambda=1.5406\text{ \AA}$). Structure refinement was performed with the TOPAS Version 4.2 software suite (Bruker, Germany). The morphology and elemental distribution of the phosphors were analyzed with a model Sigma 360 field-emission scanning electron

microscope (FE-SEM, Zeiss, Germany) under an acceleration voltage of 15 kV. The photoluminescence properties were measured with an FLS980 fluorescence spectrometer (Edinburgh, UK) equipped with a continuous 450 W Xe-lamp for steady excitation, and a temperature control accessory (Model MercuryITC and Optistat DN, Oxford instruments) for temperature-dependent luminescence. The quantum efficiency and absorption efficiency were measured using an absolute photoluminescence quantum yield spectrometer (Model C9920-02G, Hamamatsu Photonics, Japan) equipped with a 150 W Xe-lamp as the excitation source and a Φ 3.3-inch integrating sphere using spectralon as the standard reference.

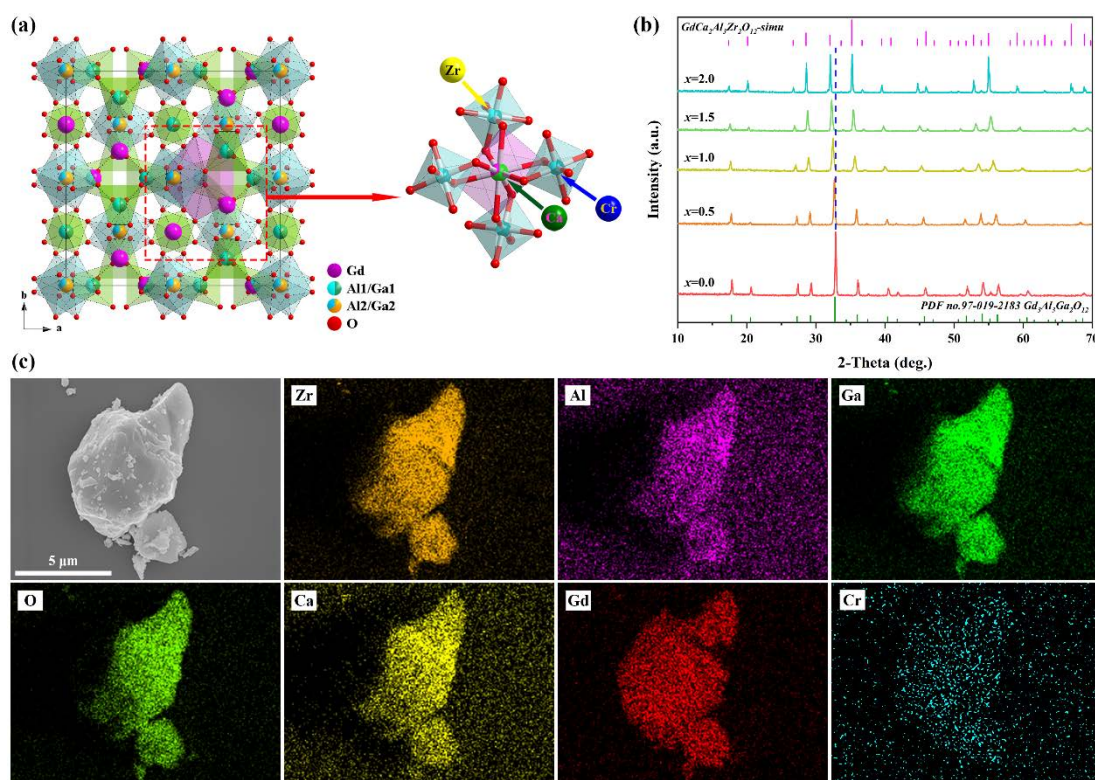


Figure 1. The crystal structure of $Gd_3Al_3Ga_2O_{12}$ garnet and the partial polyhedra of the $[(Ga,Al,Zr,Cr)O_6]$ (in aqua) and $[(Gd,Ca)O_8]$ (in purple) (a), the XRD patterns of the series of $Gd_{3-x}Al_3Ga_2O_{12}$ phosphors ($x=0-2.0$) (b). Part (c) shows the SEM morphology and EDS mapping for the $x=0.5$ sample.

As shown in Figure 1a, the framework of the $Gd_3Al_3Ga_2O_{12}$ garnet is constructed by the interconnection between the $[(Ga,Al)O_6]$ octahedrons and $[(Ga,Al)O_4]$

tetrahedrons via vertex-sharing, with Gd located at the interstitial dodecahedron. In addition, the $[\text{GdO}_8]$ are connected with another four $[\text{GdO}_8]$, four $[(\text{Ga},\text{Al})\text{O}_6]$ and two $[(\text{Ga},\text{Al})\text{O}_4]$ via edge-sharing, with four $[(\text{Ga},\text{Al})\text{O}_4]$ via vertex-sharing. XRD analysis (Figure 1b) for the GCAGZ:Cr ($x=0-2.0$) phosphors manifests that the sharp diffraction peak of the $x=0$ and 2.0 samples well conform to the $\text{Gd}_3\text{Al}_3\text{Ga}_2\text{O}_{12}$ pattern (JCPDS no. 97-019-2183) and the calculated $\text{GdCa}_2\text{Al}_3\text{Zr}_2\text{O}_{12}$ garnet [22], respectively, demonstrating that these phosphors are phase-pure garnet solid-solution and have good crystallinity. To further explore the effect of $\text{Ca}^{2+}/\text{Zr}^{4+}$ doping on the crystal structure and local coordination, Rietveld refinement of the XRD pattern was conducted for the representative GCAGZ:Cr phosphors of $x=0, 0.5$, and 1.5. Considering that Zr^{4+} ($r^{\text{VI}}=0.72 \text{ \AA}$) and Cr^{3+} ($r^{\text{VI}}=0.615 \text{ \AA}$) are close to the $\text{Al}^{3+}/\text{Ga}^{3+}$ ($r^{\text{VI}}=0.535/0.62 \text{ \AA}$) residing in the octahedra in size, the radius of Ca^{2+} ($r^{\text{VI}}=1.0 \text{ \AA}$, $r^{\text{VIII}}=1.12 \text{ \AA}$) is much larger than $\text{Al}^{3+}/\text{Ga}^{3+}$ and close to that of Gd^{3+} ($r^{\text{VIII}}=1.053 \text{ \AA}$) located in a dodecahedron, it is expected that the larger Ca^{2+} and smaller $\text{Zr}^{4+}/\text{Cr}^{3+}$ ions would occupy the dodecahedral and octahedral sites, respectively (Figure 1a) [23]. Based on these, Rietveld refinement with convergent fitting and reliable results was successfully performed, as shown in Figure S1 for the results of pattern fitting and in Table S1 for the derived crystallographic data. The lattice constant a ($=b=c$) increased from 12.2202 to 12.4566 $\text{\AA}$ with increasing x from 0 to 1.5 (Table S1), indicating that the greater incorporation of $\text{Ca}^{2+}/\text{Zr}^{4+}$ expanded the cell dimension. This is consistent with the (420) main diffraction peak gradually shifted to the lower angle side with increasing x (Figure 1b). In addition, as the x increases from 0 to 1.5, the bond length d_6 of $[(\text{Ga},\text{Al},\text{Zr},\text{Cr})\text{O}_6]$

octahedron increases from 1.9501 to 2.0795 Å, and the average bond length d_{av} of [(Gd,Ca)O₈] dodecahedron slightly increases from 2.4381 to 2.4851 Å. The results implied that the larger Ca²⁺/Zr⁴⁺ doping induced the expansion of [(Ga,Al,Zr,Cr)O₆] octahedron and [(Gd,Ca)O₈] dodecahedron, which is consistent with our previous work about Gd_{3-x}Ca_xAl_{5-x}Hf_xO₁₂ garnets [24]. Moreover, the energy dispersive spectroscopy (EDS) analysis of the $x=0.5$ sample (Figure 1c) also manifested that all the elements of concern are completely homogeneously distributed in the selected particle. The above-mentioned results clearly indicated that the phosphors were well-crystallized homogeneous solid-solution and that the results of Rietveld refinement are credible.

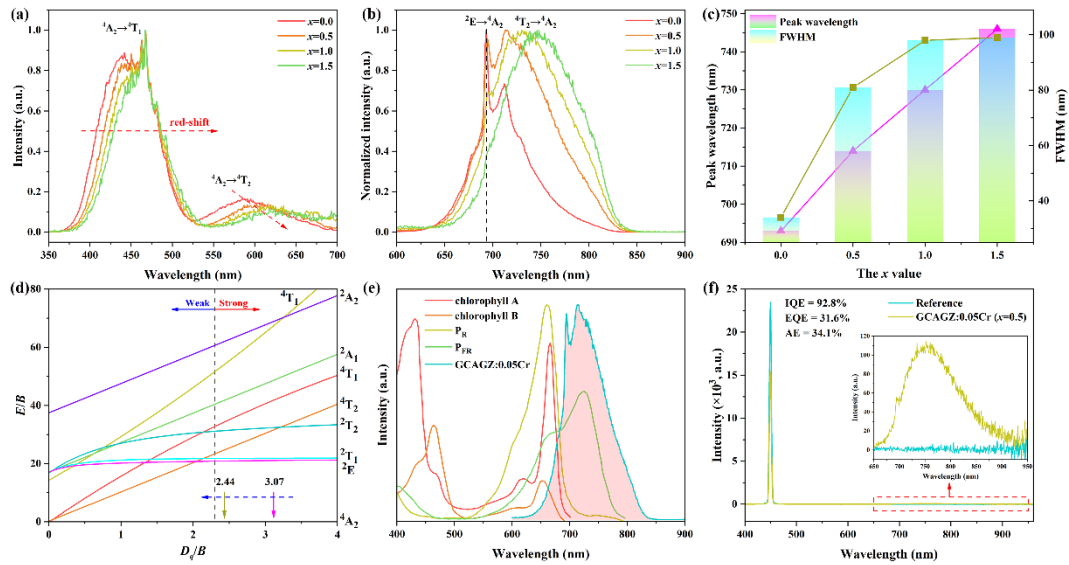


Figure 2. PLE spectra (a), PL spectra (b), the emission peak wavelength and FWHM as a function of the x value (c), and Tanabe-Sugano energy level diagram (d) for the GCAGZ:Cr ($x=0-1.5$) phosphors. The comparison between the plant pigment absorption curve and the PL spectrum (e) and the luminescence spectra for calculating quantum efficiency and absorption efficiency (f) for the $x=0.5$ phosphor.

It should be pointed out that the FR-emitting of the $x=2.0$ phosphor under blue light excitation is extremely low, so the following discussions are mainly focused on the $x=0-1.5$ phosphors. Figure 2a shows the excitation spectra (PLE) of the GCAGZ:Cr ($x=0-1.5$) phosphors, which were measured by monitoring the strongest peak

wavelength of Cr^{3+} emission. It is evident that two bands located in the 350–520 and 520–700 nm can be observed for each case, which can be ascribed to the ${}^4\text{A}_2 \rightarrow {}^4\text{T}_1$ and ${}^4\text{A}_2 \rightarrow {}^4\text{T}_2$ transitions of the Cr^{3+} activators, respectively. Moreover, the ${}^4\text{A}_2 \rightarrow {}^4\text{T}_1/{}^4\text{A}_2 \rightarrow {}^4\text{T}_2$ excitation bands were red-shifted by 10/43 nm with increasing x from 0 to 1.5, whose peak wavelengths are ~448/587, 452/604, 455/619, and 458/630 nm for $x=0, 0.5, 1.0$, and 1.5 , respectively. As seen from the photoluminescence emission spectra of the GCAGZ:Cr ($x=0-1.5$) phosphors (PL, Figure 2b) recorded under 450 nm light excitation, the spectrum for each case features an asymmetric shape in the ~650–850 nm region owing to the overlap of the broad ${}^4\text{T}_2 \rightarrow {}^4\text{A}_2$ emission and the sharp ${}^2\text{E} \rightarrow {}^4\text{A}_2$ emission of Cr^{3+} ions. The peak wavelength/FWHM of the emission bands are ~693/34, 714/81, 730/98, and 746/99 nm for $x=0, 0.5, 1.0$, and 1.5 , respectively, as shown in Figure 2c, proving that the emission band of Cr^{3+} was gradually red-shifted and broadened with increasing $\text{Ca}^{2+}/\text{Zr}^{4+}$ incorporation.

The luminescence of Cr^{3+} ions is significantly affected by its crystal field environment. The strength of the crystal field where Cr^{3+} is located can be characterized with the crystal field splitting parameter (D_q) and Racah parameter (B) by the following equations [25–27]:

$$10D_q = E({}^4\text{A}_2 - {}^4\text{T}_2) - \frac{E({}^4\text{A}_2 - {}^4\text{T}_2) - E({}^4\text{T}_2 - {}^4\text{A}_2)}{2} \quad (1)$$

$$m = \frac{E({}^4\text{A}_2 - {}^4\text{T}_1) - E({}^4\text{A}_2 - {}^4\text{T}_2)}{D_q} \quad (2)$$

$$\frac{D_q}{B} = \frac{15(m - 8)}{m^2 - 10m} \quad (3)$$

$$D_q = \frac{ze^2r^4}{6R^5} \quad (4)$$

where ΔS and E are the Stokes shift and the energy of transitions, respectively, z and e

are the charges (valence) of the oxygen anion and an electron, respectively, r presents the radius of the d wave function, R is the distance between Cr^{3+} and its O^{2-} ligands. Equation 4 clearly shows that D_q is negatively correlated with the Cr–O bond length (d_6 in this work). According to the above Rietveld refinement results, the larger Zr^{4+} substituting $\text{Ga}^{3+}/\text{Al}^{3+}$ resulted in the elongation of the (Ga,Al,Zr,Cr)–O bond, and thus decreasing the extent of crystal field splitting for Cr^{3+} . As evidenced by the D_q/B values of the GCAGZ:Cr phosphors, which were calculated to be ~ 3.07 , 2.82 , 2.58 , and 2.44 for $x=0$, 0.5 , 1.0 , and 1.5 , respectively, suggesting that the ${}^4\text{T}_{1,2}$ energy levels shifted to the lower energy side (Figure 2d). Consequently, the ${}^4\text{T}_2 \rightarrow {}^4\text{A}_2$ transitions are easier to occur, and thus the ${}^4\text{T}_2 \rightarrow {}^4\text{A}_2$ emission becomes gradually stronger. These may account for the observed red-shifting/broadening of the emission band and the red-shifting of the ${}^4\text{A}_2 \rightarrow {}^4\text{T}_{1,2}$ excitation bands with increasing x (Figures 2a and 2b).

It is noteworthy that the emission spectrum of the typical $x=0.5$ phosphor can well superpose with the absorption band of the P_{FR} (Figure 2e), signifying that this phosphor can be applied to plant lighting. Therefore, the quantum efficiency analysis was conducted for the $x=0.5$ phosphor, and the results are displayed in Figure 2f, the internal quantum efficiency (IQE), external quantum efficiency (EQE), and absorption efficiency (AE) of this phosphor are up to $\sim 92.8\%$, 31.6% , and 34.1% , respectively. According to the relationship $\text{EQE} = \text{AE} \times \text{IQE}$ (EQE and IQE are defined in the Supporting Information), the lower AE, resulting from the incident light not being able to penetrate the phosphor efficiently and being reflected away from the surface, results in a lower EQE. Even so, the EQE and AE of the $x=0.5$ phosphor are much higher than

those of many reported Cr^{3+} doped garnet phosphors (Table 1). It can be concluded that the GGAGZ:Cr ($x=0.5$) phosphor is a high-efficiency FR-emitting phosphor.

Table 1. The photoluminescence of Cr^{3+} activated FR-emitting garnet phosphors.

Phosphor	$\lambda_{\text{em}}/\text{nm}$	FWHM/nm	IQE/EQE/%	$I_{423\text{K}}/\%$	Ref.
GGAGZ:Cr ($x=0.5$)	714	81	92.8/31.6	95.5	this work
$\text{Ca}_{1.8}\text{Mg}_{1.2}\text{Al}_2\text{Ge}_3\text{O}_{12}:\text{Cr}^{3+}$	720	91	80.6/29.9	85.5	10
$\text{Y}_2\text{ZnGa}_4\text{GeO}_{12}:\text{Cr}^{3+}$	708	~62	48.1/13.3	~80	20
$\text{GdLuCaAl}_{3.95}\text{SiCr}_{0.05}\text{O}_{12}$	711	73	63.4/27.5	87.6	21
$\text{Y}_2\text{SrAl}_4\text{SiO}_{12}:\text{Ce}^{3+}, \text{Cr}^{3+}$	707	—	72.9/30.0	~38	28
$(\text{Y}, \text{Ba})_3(\text{Al}, \text{Si})_5\text{O}_{12}:\text{Ce}^{3+}, \text{Cr}^{3+}$	710	—	63.4/25.7	46	29
$\text{Gd}_{0.5}\text{Y}_{2.5}\text{Ga}_5\text{O}_{12}:\text{Cr}^{3+}$	715	64	71.8/11.9	86	30

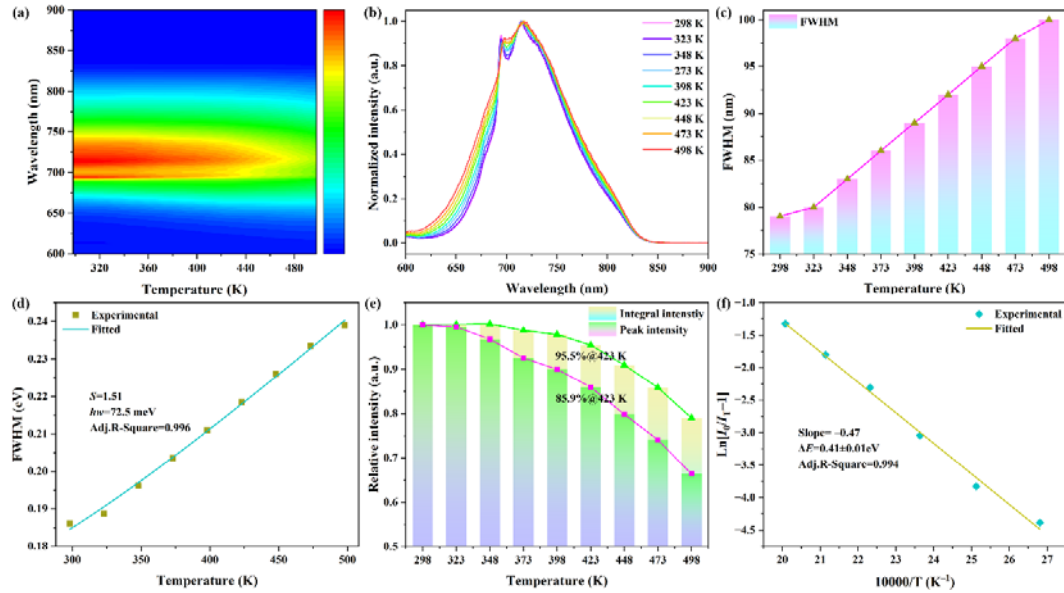


Figure 3. Contour plot (a), normalized emission spectra (b), FWHM as a function of the temperature (c), FWHM versus T plot for the calculation of the $h\nu$ and S (d), relative emission intensity as a function of the temperature (e), and $\text{Ln}[I_0/I_T - 1]$ versus $1/T$ plot for the determination of activation energy (f) for the $x=0.5$ phosphor.

To examine the thermal stability of the new FR-emitting garnet phosphor, the temperature-dependent emission spectra were recorded in Figures 3a and 3b for the

typical GGAGZ:Cr ($x=0.5$) phosphor. It is clear that the emission intensity gradually weakened due to thermal quenching while the emission wavelength remained roughly constant at ~ 714 nm with increasing temperature. Moreover, it is seen from Figure 3c that the FWHM of the emission band increases from 79 to 100 nm with increasing temperature from 298 to 498 K, which may be due to the stronger electron-phonon coupling (EPC) effect. The EPC effect can be described by the following relationship with the Huang-Rhys factor (S) and temperature T in Cr^{3+} activated phosphors [31]:

$$\text{FWHM}(T) = \sqrt{8 \ln 2} \times \sqrt{S} \times \hbar \omega \times \sqrt{\coth\left(\frac{\hbar \omega}{2kT}\right)} \quad (5)$$

where $\hbar \omega$ and k are the phonon energy and the Boltzmann constant (8.617×10^{-5} eV/K), respectively. S and $\hbar \omega$ values are calculated by fitting the relationship between the FWHM and T , as plotted in Figure 3d, to be ~ 1.51 and 72.5 meV, respectively. It is worth noting that this S value is much lower than that of reported Cr^{3+} doped garnet phosphors, such as $\text{Ca}_3\text{Sc}_2\text{Si}_3\text{O}_{12}:\text{Cr}^{3+}$ ($S=4.0$) [32], $\text{GdLuCaAl}_{3.95}\text{SiCr}_{0.05}\text{O}_{12}$ ($S=6.70$) [21] and $\text{Ca}_3\text{Sc}_2\text{Ge}_3\text{O}_{12}:\text{Cr}^{3+}$ ($S=3.38$) [33], suggesting that the EPC effect in $x=0.5$ phosphor is hugely weak. The relatively weak EPC effect generally benefits the thermal stability, as evidenced by the phosphor retaining ~ 98.6 % and 95.5% of its initial (298 K) integrated intensity at 373 and 423 K (Figure 3e), respectively. The activation energy (ΔE_a) of thermal quenching can be derived from the temperature-dependent emission spectra using the following equation [34, 35]:

$$I_T = \frac{I_0}{1 + \exp\left(-\frac{\Delta E_a}{kT}\right)} \quad (6)$$

where I_0 and I_T are the emission intensities at room-temperature (298 K) and measured

temperature T , respectively, k is the Boltzmann constant, c is a constant. As a result, the ΔE_a value was determined via linear fitting of the $\ln[I_0/I_T-1]$ versus $1/T$ plot to be ~ 0.41 eV (Figure 3f), which is much larger than the typical garnet phosphors of $\text{Y}_2\text{ZnGa}_4\text{GeO}_{12}:\text{Cr}^{3+}$ ($\Delta E_a = 0.17$ eV) [20], $\text{Ca}_{1.8}\text{Mg}_{1.2}\text{Al}_2\text{Ge}_3\text{O}_{12}:\text{Cr}^{3+}$ ($\Delta E_a = 0.233$ eV) [10] and $\text{GdLuCaAl}_{3.95}\text{SiCr}_{0.05}\text{O}_{12}$ ($\Delta E_a = 0.298$ eV) [21]. Hence, the excellent thermal stability of the $x=0.5$ phosphor can be understood by considering that the extremely weak EPC effect and the larger ΔE_a effectively suppress thermal quenching induced by nonradiative transitions.

In summary, a series of GGAGZ:Cr ($x=0-2.0$) novel garnet phosphors were prepared via solid-state reaction in this work, whose quantum efficiency and temperature-dependent luminescence were analyzed for the first time. As compared in Table 1, the optimal $x=0.5$ phosphor exhibited much higher quantum efficiencies (IQE=92.8%, EQE=31.6%) and thermal stability (95.5%@423 K) than those reported for most of the other Cr^{3+} activated FR-emitting garnet phosphors, indicating that this phosphor has huge potential application in the construction of FR pc-LED used for plant lighting.

Author contributions

Qinghong Meng: Validation, Resources, Supervision, Writing – original draft;

Jiaming Yuan: Data curation, Formal analysis, Investigation, Methodology;

Xiangming Li: Investigation, Methodology, Project administration; **Wanjun Yu:**

Investigation, Methodology; **Ji-Guang Li:** Validation, Writing – review & editing.

Conflicts of interest

There are no conflicts of interest to declare.

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