Blue emission of Eu^{2+} -doped translucent alumina

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Abstract

Inorganic scintillators are very important in medical and industrial measuring systems in the detection and measurement of ionizing radiation. In addition to Ce^{3+} , a widely used dopant ion in oxide scintillators, divalent Europium (Eu^{2+}) has shown promise as a high-luminescence, fast-response luminescence center useful in the detection of ionizing radiation. In this research, aluminum oxide (Al_2O_3) was studied as a host material for the divalent europium ion. Polycrystalline samples of Eu^{2+} -doped translucent Al_2O_3 were fabricated, and room temperature luminescence behavior was observed. Al_2O_3 ceramics doped with 0.1 at% Eu^{2+} were fabricated with a relative density of 99.75% theoretical density and in-line transmittance of 22% at a wavelength of 800nm. The ceramics were processed by a gel-casting method, followed by sintering under high vacuum. The gelling agent, a copolymer of isobutylene and maleic anhydride, is marketed under the commercial name ISOBAM, and has the advantage of simultaneously acting as both a gelling agent and as a dispersant. The microstructure and composition of the vacuum-sintered $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ were characterized by Scanning Electric Microscopy (SEM), Transmission Electron Microscopy (TEM), and Energy-dispersive X-ray spectroscopy (EDS). The phase composition was determined by X-Ray diffraction measurements (XRD) combined with Rietveld analysis. The photoluminescence behavior of the $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ was characterized using UV light as the excitation source, which emitted blue emission at 440nm. The radio-luminescence of $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ was investigated by illumination with X-ray radiation, showing three emission bands at 376nm, 575nm and 698nm. Multiple level traps at different depths were detected in the $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ by employing thermoluminescence measurements.

Keywords: Blue emission, Eu^{2+} -doped translucent Alumina, Gelcasting, photoluminescence, radio-luminescence, thermoluminescence

1. Introduction

In radiation detection, inorganic scintillators play an important role in all medical diagnostic imaging modalities that use X-rays or γ -rays, as well as in many industrial measurement systems[1, 2]. The criterion of a promising scintillator includes high luminosity (high brightness) and a fast response of the scintillator to radiation exposure. Recently, the application of the Ce^{3+} emission center within different matrices has attracted much attention due to its useful 5d-4f transition[3], very fast decay time (38ns)[4], and the largest radioactive transition probability in the rare-earth ions[5]. With increasing research into

the rare-earth elements, Eu^{2+} is a promising choice as a emission center, as it possesses a highly efficient and relatively fast 5d-4f luminescence.

The electronic transitions of the divalent Europium ($4f^7$) Eu^{2+} ion have many potential applications in optical applications, such as in phosphors[6], lasers[7], and scintillators for detecting ionizing radiation [8] due to its function as an efficient luminescence center. High luminosity and fast decay time are mainly decided by the host matrix and specific emission center. Recently, Eu^{2+} has been explored as a dopant in various materials, such as SrI_2 [9], CsBa_2Br_5 [10], BaFI [11], Ba_2CsI_5 [12], LiCaAlF_6 and LiSrAlF_6 [13], and high light output and acceptable scintillation decay time being reported. However, the application of halide-based materials as scintillators suffers from major disadvantages, stemming from their sensitivity to moisture and low mechanical strength. Oxide ceramics, on the other hand, hold the advantages of high strength and chemical stability, high transparency, and the relative ease of doping with rare-earth elements as luminescence centers, and as such are ideal candidates for the new generation of scintillation materials. Different compounds of aluminum oxide have been studied as host matrices, including Eu-doped Garnet ($\text{Y}_3\text{Al}_5\text{O}_{12}$), which has been shown to have promising scintillation behavior[14]. $\alpha\text{-Al}_2\text{O}_3$ was the material studied here, which commonly sees application as a optical host crystal, and is a promising candidate for new generation emissive optical materials, which makes use of isolated impurities incorporated into ceramic matrices.

There are multiple methods to achieve the reduction of Eu^{3+} to form Eu^{2+} in solid samples, including reduction of Eu^{3+} to Eu^{2+} by laser induction[15], pulsed-laser deposition[16], wet chemistry methods to precipitate the desired valency of the ion, [17] and annealing under reducing atmospheres [18, 19]. Recently, researchers have reported with the assumption that the presence of Al^{3+} is a key factor in the reduction of Eu^{3+} to Eu^{2+} [14]. In the processing of $\text{Eu}:\text{Al}_2\text{O}_3$, the valence state of the Eu ion is strongly affected by oxygen partial pressure. It has been observed that at low oxygen partial pressures ($\sim 10^{-3}\text{Pa}$), the desired divalent ($2+$) oxidation state of the Eu ion becomes the stable valence state, while Eu^{3+} is reduced. [20].

In this study, Eu^{2+} -doped translucent Al_2O_3 was prepared by gel-casting and high vacuum ($10^{-3}\text{-}10^{-5}\text{Pa}$) sintering. Eu_2O_3 was doped into Al_2O_3 , and then subsequently reduced to form luminescent $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ with a blue emission at 440nm and radio-luminescence emissions located at 376nm, 575nm and 698nm.

2. Experimental Section

2.1 Materials:

All chemicals used in this study were reagent-grade quality materials supplied by commercial vendors. Eu_2O_3 (99.99%, Sigma, USA) was used as the source for Eu^{2+} . High-purity $\alpha\text{-Al}_2\text{O}_3$ powder (>99%) (CR-10, Baikowski, Annecy, France, $D_{50} = 0.45\mu\text{m}$) was used as the matrix material. ISOBAM (Kuraray Co., Osaka, Japan) was used as spontaneous gelling agent and dispersant, the use of which has been detailed in similar applications by other authors, [21-26] with de-ionized water as the solvent.

2.2 $\text{Eu}_2\text{O}_3\text{-Al}_2\text{O}_3$ slurry fabrication and gelcasting process

A homogeneous slurry with a solids loading of 38 vol% was obtained by ball milling Eu_2O_3 , Al_2O_3 , and ISOBAM together with de-ionized water for 5 hours with ZrO_2 grinding media. Bubble removal was performed before casting using a custom-made vacuum degassing system with an ultimate pressure less

than 10Pa, while the slurry was simultaneously stirred at 250 r/min. The resultant slurry was cast into plastic molds with diameters ranging from 4 to 9 cm; sizes similar to that used in the procedures of other authors [22-24]. Using this process, green bodies of Al_2O_3 intimately mixed with different concentrations of Eu_2O_3 were formed. The compositions were designed for the end ceramics to have compositions with dopant levels of 0 at%, 0.1 at%, 0.2 at%, and 0.5 at% Eu^{2+} .

2.3 De-binder and sintering

After gelling and demolding, the green bodies were dried in air for 24 hours at room temperature with no applied heat or humidity control. Organics and water were removed by pre-sintering at 973-1273K in air with dwell times ranging from 3-5 hours and heating rates of 3-10 K/min. The final ceramics were obtained by high vacuum sintering at 2073K-2173K for 5hrs at a heating rate of 3-10 K/min.

2.4 Characterization

The microstructures of the vacuum-sintered $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ were characterized by SEM (FEI Quanta 200, USA) and TEM (JEOL2100F, Japan). Chemical composition was measured using EDS (JEOL2100F, Japan). Phase composition of the ceramics was measured by X-ray diffraction (XRD) (Bruker D2 Phaser, Germany) equipped with Cu radiation ($\lambda = 0.154 \text{ nm}$) in the range of $10^\circ 2\theta$ - $75^\circ 2\theta$. Unit cell parameters were determined from analysis of the XRD measurements using Rietveld analysis performed with TOPAS pattern fitting software. The in-line transmittance in the UV-VIS region (Perkin Elmer Lambda 1050, USA) of the sintered doped Al_2O_3 bodies was measured to be 22% at a wavelength of 800nm. The relative densities of the sintered bodies were measured using Archimedes' principle density measurements, with the following average results: dry green body: 49.50% of theoretical density; pre-sintered green body: 76.80%, vacuum sintered ceramic: 99.75%. Photoluminescence (PL) spectra were obtained using a fluorescence spectrophotometer (JobinYvon Fluorolog-3spectrofluorometer, Horiba, USA) with a Xenon lamp as the excitation source. The luminescence decay curve was recorded using a pulsed Nd:YAG laser source at 266nm (Spectron Laser System SL802G, Rugby, UK) with a pulse energy of approximately 5 mJ, at a frequency of 10 Hz, with a pulse duration of 5 ns. The radio-luminescence spectra of the $\text{Eu}:\text{Al}_2\text{O}_3$ were recorded at room temperature (Acton Spectropro 2150i, CMX003 X-ray generator (35kV, 0.1mA)). Thermoluminescence behavior was characterized in the temperature range of 10K-550K, using Advanced Research Systems DE-202 for cooling and heating and CMX003 X-ray as the energy source.

3. Results and Discussion

3.1 Microstructure

Figure 1 shows the microstructure of pure Al_2O_3 (Fig. 1(a)) and 0.1at% $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ (Fig. 1(b)) after vacuum sintering. It can be readily observed that the 0.1at% $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ sample has a larger average grain size than the pure Al_2O_3 sample, which may indicate that europium facilitates grain growth in Al_2O_3 during vacuum sintering, similar to the phenomenon observed in $\text{Eu}:\text{Y}_2\text{O}_3$ [27]. Figure 2 shows a surface microstructure [Fig.2 (a) (c)] and grain size distribution [Fig.2 (b) (d)] of vacuum-sintered $\text{Eu}:\text{Al}_2\text{O}_3$ and undoped Al_2O_3 fitted to a polynomial curve in the range of 20-105 μm . The grains stack closely together with only a few isolated pores apparent, confirming that the samples are high density. The average grain size of vacuum-sintered $\text{Eu}:\text{Al}_2\text{O}_3$ is approximately 63 μm , as determined from a statistical and mean

value grain size calculation using software (Nano Measurer, Version 1.2, Fudan University, Shanghai, China) shown in Fig. 2(b), which is larger than that of vacuum-sintered undoped Al_2O_3 shown in Fig. 2(d). An impurity phase was observed in a cross-section of the $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ ceramic, as shown in the TEM images in Fig. 3. The elemental composition of the impurity phase measured by EDS is shown in Fig. 4. Strong peaks from Eu were detected, indicating that the impurities are Eu-rich clusters. The segregation of undissolved europium may come from the large difference in ionic radii of Eu^{2+} (120pm) relative to Al^{3+} (67.5pm), causing a solubility limit of Eu^{3+} in Al_2O_3 to be reached, causing precipitation of Eu at the grain boundaries. The Eu-rich segregates can be observed entangled together with Al_2O_3 grains and appear to grow along or through the grain boundaries of the Al_2O_3 . The segregation of europium at Al_2O_3 grain boundaries has been observed and reported by other authors [28, 29].

3.2 Phase Identification

The phase composition and lattice parameters of the translucent Al_2O_3 with and without Eu doping were determined by analysis of XRD measurements performed at room temperature, as shown in Fig. 5. Phase identification was performed using Diffrac EVA XRD data analysis software. It can be clearly observed that when the concentration of Eu^{2+} dopant is lower than 0.2 at%, the pattern can be well indexed as undoped Al_2O_3 , consistent with standard hexagonal $\alpha\text{-Al}_2\text{O}_3$ (JCPDS # 00-042-1468). Although SEM images show that there are impurities present, these impurities are present below the level which can be detected by XRD. In samples with higher Eu^{2+} levels, Jade 9.0 XRD analysis software was employed to identify the impurity peaks as $\text{EuAl}_{12}\text{O}_{19}$ (JCPDS # 00-026-1125). However, a small shift in the position of the diffraction peaks of the corundum phase towards lower 2θ values was also observed relative to the un-doped Al_2O_3 , which is a result of an increase of the lattice parameters. Lattice parameter refinement was performed using the Rietveld method in TOPAS phase analysis software. Lattice parameters were also calculated directly from the measured peak positions as summarized in Table 1. The lattice parameter calculation results are in agreement with the software analysis of the XRD data, which revealed that Eu doping causes a significant increase in the a and c lattice parameters, as well as the overall cell volume. This reinforces the idea that the most of the Eu^{2+} dopant is substituted into the Al_2O_3 lattice. Higher Eu levels were doped into the samples shown in Fig. 5, with Eu^{2+} levels of 0.2 at% and 0.5 at%. The XRD patterns in Fig. 5 show the existence of $\text{EuAl}_{12}\text{O}_{19}$ impurity phase.-

3.3 Transmittance of vacuum-sintered $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$

Fig. 6 shows the in-line transmittance of final mirror-polished $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ ceramic in the UV-VIS region from 300nm-800nm with its image shown in the inset. The end thickness of the samples was 1.1mm, at which thickness the samples are translucent and letters can be clearly resolved through the sample with the naked eye. The in-line transmittance is 22% at a wavelength of 800nm, which decreases gradually to zero at around 300nm. The transmittance is relatively low compared with other translucent ceramics [30, 31]. As reported before[32, 33], there are many possible reasons for the low measured transmittance. The birefringent nature of the host Al_2O_3 crystal structure, absorption and grain-boundary scattering (reflection, refraction) by the host materials and impurities, scattering from porosity, as well as the quality of the surface polish, can all affect transmittance. Also observed was a sharp decrease in transmittance in the 300-400nm range. For this reason, this region was also investigated in the reflectance mode of the spectrometer. Fig. 7 shows the UV-VIS diffuse reflectance spectrum of 0.1 at% $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$. The measured sample shows strong absorption bands in the range of 320nm-380nm, with the maximum

absorption peak centered at ~340nm, resulting from the energy absorption by the electron transition between $4f^7 (^8S_{7/2})$ and $4f^6 5d^1$ of doped Eu^{2+} in the host materials.

3.4 Photoluminescence behavior

The measured photoluminescence, excitation, and emission spectra are shown in Figs. 8 and 9. Under UV excitation in reflectance mode, with the emitted light vertical to the excitation light, the only detected broad peak sits in the range of 330nm-600nm with a peak center at 440nm. This indicates that the reduction of Eu^{3+} to Eu^{2+} in the Al_2O_3 host was successful, as Eu^{3+} has two main emission peaks at 598nm and 614nm, neither of which are present [34-36]. The photoluminescence excitation spectrum of 0.1 at% $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ was recorded at 440nm, as shown in Fig. 8. Two broad excitations of the 440nm band occurred at wavelengths of 280nm and 330nm, which indicate that the splitting of Eu^{2+} ion's 5d band in the Al_2O_3 matrix [19]. Eu^{2+} has complex energy levels with the peaks observed in optical spectra generally being a result of f-d transitions, which are usually dependent on the coordination environment of the Eu^{2+} . The room temperature photoluminescence spectrum shown in Fig. 9 displays a broad emission band with a peak center at 440nm, leading to a blue emission. The emission is presumably a result of the Eu^{2+} electronic transition from $4f^6 5d^1$ to $4f^7 (^8S_{7/2})$ in the low symmetry coordination environment of Al_2O_3 . The emission spectra are different for $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ powder[19] and consolidated $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ samples [16], which may result from the Eu^{2+} existing in different coordination environments, resulting from the differences in processing. Europium ions prefer to coordinate in Al-O-Eu polyhedral, where the stronger strength of the Al-O bond leads to a decrease in the covalency of the Eu-O bond from the higher field strength of the Al^{3+} ion, and an increase in the probability of the f-d radiative relaxation[37].

The luminescence decay curve of 0.1 at% $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ measured at 10K is depicted in Fig. 10, with an excitation wavelength of 266nm and a measured luminescence wavelength of 490nm. The luminescence decay is described well by double-exponentials ($I = A_1 * \exp(-t/\tau_1) + A_2 * \exp(-t/\tau_2)$) with the fitting parameters shown in the Fig. 10. The d-f transition of Eu^{2+} is parity and spin allowed with a lifetime on the order of sub-microseconds. The average decay time calculated from the fitted values is about ~0.177 μs .

3.5 Radio-luminescence Properties

Fig. 11 presents the radio-luminescence properties of vacuum-sintered 0.1 at% $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ under X-ray excitation, at emission wavelengths measured from 200nm to 800nm at 1nm/step. Multiple-peak Gaussian fitting was applied to the recorded radio-luminescence spectrum in Fig. 11, and it was determined that the original curves could be well fit into four Gaussian bands with peak positions located at 300nm, 376nm, 575nm, and 720nm. In Fig. 11, the radio-luminescence peak at 376nm and 575nm is associated with the $\text{Eu}^{2+} 4f^6 5d (^6P_J)$ to $4f^7 (^8S_{7/2})$ transition, similar to the transition observed in $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ thin films excited with UV light[16]. The two emission positions may come from different coordination of the Eu^{2+} in the Al_2O_3 host material, which will experience different crystal field splitting effects [16]. Compared with the photoluminescence results in Fig. 9, the number and positions of the emission peaks has changed. An explanation for this behavior is that the higher energy of X-ray radiation relative to UV radiation increases the possibility of defect (F^+ -center) emission and changes the energy transition behavior of the Eu^{2+} ion. The emission peak located at 300nm is caused by excited F^+ -center defects (an oxygen vacancy with one trapped electron) in the Al_2O_3 . F^+ -center defects are formed by the

low O₂ partial pressure during the vacuum sintering process, and emit a photon when electron-hole pairs recombine at shallow traps in the vicinity of an oxygen vacancy[38-40]. The peak located at 720nm may come from Cr³⁺ impurity ions in Al₂O₃ [41, 42].

3.6 Thermoluminescence property under X-Ray excitation.

The thermoluminescence (TL) glow curve of vacuum-sintered 0.1 at% Eu²⁺:Al₂O₃ is shown in Fig. 12, which provide the evidence the formation of trapping levels within the system. The glow peak temperatures of 0.1 at% Eu²⁺:Al₂O₃ are 97K, 243K, and 422K with the heating rate of 9K/min in the temperature region 10K to 450K. This indicates the existence of a multilevel trapping system in the ceramic. The peak at 97K is very small and supplies a shallow trap of electrons, which normally do not affect scintillation behavior at room temperature. The peak at 200-300K has very high intensity and a broader shape compared with other peaks, indicating the existence of multiple level and intensive traps at different depths. Because these traps are located near room temperature, it should be noted that they could impact scintillation light yield dramatically. The detection of traps near room temperature also explains why under Cs-137 γ -ray excitation at room temperature, no full-energy photoluminescence peak can be detected. The peak position at 422K provides evidence that even deeper traps of electrons exist in this system. These traps could prevent electrons from recombining with holes, preventing photon production and emission.

3.7 Dependence of luminescence behavior under UV

The return to the ground state of Eu²⁺ under UV light excitation is influenced by the thermo-activated promotion [43]. It is supposed that the photo-excitation of Eu²⁺ experience an energy transfer within the return of electron trapped at the certain defect levels of unknown origin or oxygen vacancy levels back to the ground state [44]. The luminescence behavior of 0.1 at% Eu²⁺:Al₂O₃ under the excitation of UV light is found as a function of temperature in Fig. 13(a). The 0.1 at% Eu²⁺:Al₂O₃ shows a blue light during the heating process from 10K to 300K with a peak center near 430nm, which is similar to Fig. 9. As the sample temperature increases, the intensities of emission peak decrease, which results from the thermal quenching process of 5d-4f emission of Eu²⁺ in solids. It was proposed that the thermal quenching of Eu results from an ionization of the electrons from the lowest energy level of the relaxed Eu²⁺ 4f⁶5d¹ electronic configuration onto the host lattice conduction band level[45]. It indicates a thermally activated ionization of Eu²⁺ excited state competes with a nonradioactive recombination process during the temperature quenching process. A weak redshift was detected as temperature increased. The emission spectra show a slight peak broadening at the temperature about 150K, which may come from the two recombination process. There is one predominant at the temperature lower than 150K and another being dominant at the higher temperature.

The luminescence intensity of 0.1 at% Eu²⁺:Al₂O₃ as a function of reciprocal temperature in the range of 10-300K is plotted in Fig.13 (b). The emission intensity slightly decreases as the temperature increases to approximately 100K, followed by a fast decrease in the range 150-300K due to the activation of nonradioactive process. It represents two different nonradioactive processes within the two temperature regions. The process could be described by the following Arrhenius equation [46-48]

$$I(T) = \frac{I_0}{1 + c \exp \left(-\frac{E_a}{kT} \right)} \quad \text{Eq. (1)}$$

Where I_0 is the initial intensity, $I(T)$ is the luminescence intensity at temperature T , c is a constant, E_a is the activation energy related to the thermal process, k is the Boltzmann constant. The intensity at 10K was set to 1. The photoluminescence data are well-expressed by Equation 1. It was determined from the plot that the quenching temperature, at which the intensity drops to 50% of the original value[49], of 0.1at% Eu: Al₂O₃ is around 250K in the region of 10-300K.

4 Conclusions

Eu²⁺ doped translucent polycrystalline Al₂O₃ ceramics were prepared by gel-casting and vacuum sintering with Eu₂O₃ as the source of Eu²⁺. The combined effects of the presence of the Al³⁺ ion and low oxygen partial pressure (<100Pa) during the sintering process cause the reduction of Eu³⁺ to Eu²⁺ in the sintered ceramic. The grain size of the sintered Al₂O₃ bodies increased with the introduction of Eu²⁺ into the material. The phase composition of 0.1 at% Eu²⁺:Al₂O₃ is mainly hexagonal α -Al₂O₃ with enlarged lattice parameters relative to pure corundum. The in-line transmittance of the 0.1 at% Eu²⁺:Al₂O₃ is about 22% at 800nm. Emission of blue light with a center at 440nm was obtained by excitation with 278nm and 330nm UV radiation ($4f^65d^1 \rightarrow 4f^7$ (⁸S_{7/2})). Under X-ray excitation, emission peaks were generated at 376nm and 575nm, as a result of the d-f electronic transition ($4f^65d \rightarrow 4f^7$) of Eu²⁺. The broad thermoluminescence peak at 243K under the excitation of X-Ray indicates that multiple level traps at different depths exist within the Eu²⁺-doped Al₂O₃ ceramics. The luminescence intensity of 0.1 at% Eu²⁺:Al₂O₃ decreases in the heating process in the temperature region of 10-300K with a quenching temperature around 250K.

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Figure Captions:

Fig. 1 Fracture surface images of (a) undoped Al_2O_3 (b) 0.1 at% $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ after vacuum sintering at 2073-2173K for 3-5 hours.

Fig. 2 Surface SEM images and grain size distribution of the 0.1 at% $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ ceramic (a, b) and undoped Al_2O_3 (c, d) after a vacuum-sintering at 2073-2173K for 3-5hours.

Fig. 3 High resolution TEM image of a vacuum-sintered 0.1 at% $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ (2073-2173K for 3-5hour).

Fig. 4 EDS spectrum of a vacuum-sintered 0.1 at% $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ (2073-2173K for 3-5hour).

Fig. 5 XRD patterns of vacuum sintered Al_2O_3 with different Eu concentrations (a) un-doped Al_2O_3 , (b) 0.1 at% $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$, (c) 0.2 at% $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$, (d) 0.5 at% $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$.

Fig.6 The in-line transmittance of mirror-polished translucent 0.1 at% $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ ceramic (vacuum sintered at 2073-2173K for 3-5 hours, thickness: 1.1mm) in the UV-VIS region from 300nm-800nm with its image shown in the inset.

Fig.7 UV-VIS reflectance spectrum of a vacuum-sintered 0.1at% $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ (2073-2173K for 3-5hour).

Fig.8 Photoluminescence excitation spectrum of 0.1 at% $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ (vacuum sintered at 2073-2173K for 3-5hours) monitored at 440nm (dashed line: Gaussian-fitted curves).

Fig.9 Photoluminescence emission spectrum of a vacuum-sintered 0.1 at% $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ (2073-2173K for 3-5hour).

Fig.10 Decay curves of a vacuum-sintered 0.1 at% $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ (2073-2173K for 3-5hour) at an excitation wavelength of 266 nm and measured emission wavelength of 490nm, at 10K.

Fig.11 Radioluminescence spectrum of a vacuum-sintered 0.1 at% $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ (2073-2173K for 3-5hour) under X-ray irradiation (35 KeV, 0.1 mA for 15 min).

Fig.12 Thermoluminescence glow curves of a vacuum-sintered 0.1% $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ (2073-2173K for 3-5hour) in the temperature range of 10-550K under an excitation of X-Ray.

Fig.13 Temperature response of a vacuum-sintered 0.1% $\text{Eu}^{2+}:\text{Al}_2\text{O}_3$ (2073-2173K for 3-5hour) emission spectra in the range of 10 to 300K under UV light excitation.

Tables:

Table 1 Comparison of lattice parameters before and after Eu doping

Samples	Lattice parameters (Å)		Cell volume(Å ³)
	a	c	
Undoped Al ₂ O ₃	4.757	12.989	254.602
0.1at%Eu doped Al ₂ O ₃	4.761	13.000	255.202

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10

Figure 11

Figure 12

Figure 13