Chapter 4

Synthesis of a novel white oxide phosphor:

$\text{ZnGa}_2\text{O}_4:\text{Dy}^{3+}$
4.1. Introduction

A major challenge in the area of flat panel display (FPD) technology is the identification of new multicolor or white light emitting phosphor materials for industrial applications. A suitable blend of the available efficient blue, green and red phosphors and light emitting diodes (LEDs) [1] is the technique adopted for white light generation in the solid state lighting industry. The combination of a blue chip with yellow emitting phosphors [2, 3] or phosphor combinations [4-6] generated white light but the output varied with the driving conditions of the LED, suffered low reproducibility and low color rendering index due to color mixing. Higher color rendering properties could be attained by using multiphosphor blends and ultraviolet (UV) LEDs [7-9]. But the luminous efficiency of such systems was low owing to the re-absorption of emission colors and blending of two or three phosphors. A combination of UV LEDs with single phased doubly activated full color emitting phosphors [10-14] was later developed to generate white light. Codoping in a single host lattice gave desirable results with better luminous efficiency but the energy transfer between the activators, and thereby the output, were found to be sensitive to the activator concentrations. Therefore, the identification of singly activated single phase phosphors capable of UV excitation would be a better alternative.

Liu et al. [15] reported on the luminescent properties of a white afterglow phosphor CdSiO₃:Dy³⁺. CaAl₂O₄:Dy³⁺ is another known white light long lasting phosphor [16]. White light emission from Eu³⁺ has been realized in the CaIn₂O₄ host lattices by suitably tuning the doping concentrations [17].
Rare earth (RE) ions serve as excellent activators in modern lighting and display fields owing to their characteristic emissions from 4f-4f or 5d-4f transitions. The phosphor hosts activated with RE ions possess a strong and broad absorption band in the UV or VUV region of the electromagnetic spectrum for efficient and effective excitation. This is because RE ions strongly absorb in the short wavelength of the UV region and weakly absorb in the near UV to blue spectral region. Trivalent dysprosium, a rare earth with 4f\(^9\) electronic configuration, is known to emit two intense fluorescence transitions, \( ^4F_{9/2} \rightarrow ^6H_{15/2} \) in the blue and \( ^4F_{9/2} \rightarrow ^6H_{13/2} \) in the yellow-orange wavelength region. The latter, being a hypersensitive transition (\( \Delta L = 2, \Delta J = 2 \)), is strongly influenced by the crystal field environment. At a suitable yellow-to-blue intensity ratio, Dy\(^{3+}\) will emit white light [18]. Unlike the RE dopants Eu\(^{3+}\) and Tb\(^{3+}\) (in oxide hosts), the luminescence of Dy\(^{3+}\) cannot be excited using the common fluorescent lamps that have a strong and broad absorption band around 254nm. This is because the charge transfer absorption band (CTB) and 4f\(^9\) - 4f\(^8\)5d excitation band of Dy\(^{3+}\) are located below 200nm. The excitation can occur only by the f-f transitions with low oscillator strength (10\(^{-6}\)) due to their forbidden features by the parity selection rule [19]. This drawback of Dy\(^{3+}\) luminescence can be overcome either by host sensitization [20, 21] or by impurity ion sensitization [19, 22]. Here, the effects of doping Dy\(^{3+}\) in ZnGa\(_2\)O\(_4\) are investigated.

**4.2. Experimental**

Stoichiometric ZnGa\(_2\)O\(_4\):Dy\(^{3+}\) powder phosphors were prepared by conventional high temperature solid state reaction. Adequate amounts of the starting
materials, namely ZnO (99.99%, Alfa Aesar), Ga₂O₃ (99.99%, Alfa Aesar) and Dy₂O₃ (99.99%, Indian Rare Earths Ltd.), weighed to an accuracy of ± 0.001 mg were hand mixed thoroughly under ethanol medium in an agate mortar and pestle and allowed to dry. The dried mixture was then placed in an alumina boat and introduced into the hot temperature zone of a horizontal tube furnace equipped with a proportional integral differential (PID) controller. The firing was done at 1350°C for 12 hours in air. The doping concentration of Dy³⁺ was varied in the range 0.25 to 3 at. %. For comparison, Zn₁₋ₓGa₂O₄:Dyₓ (x = 0, 0.02 ie. pure and 2 at. % doped sample where Dy³⁺ replaces Zn²⁺) and Ga₂(1₋ₓ)O₃:Dy₂ₓ (x = 0.02 ie. 2 at. % doped sample) phosphors were also prepared via similar routes. The crystal structure of the powder phosphors was analyzed using x-ray powder diffraction method on a Rigaku diffractometer using Cu Kα radiation (1.5414Å). The diffuse reflectance spectra (DRS) were recorded to analyze the band gap using JASCO V-570 spectrophotometer with an integrating sphere attachment, BaSO₄ being the reference. The room temperature photoluminescent emission (PL) and excitation (PLE) spectra were recorded using Spex Fluoromax-3 Spectrofluorimeter equipped with a 150W Xenon lamp as the excitation source.

4.3. Results and discussion

The x-ray diffraction patterns of the fired ZnGa₂₋ₓO₄:Dy₂ₓ samples matched well with the standard reflections of the host ZnGa₂O₄ for all dopant concentrations. The XRD patterns of ZnGa₂₋ₓO₄:Dy₂ₓ for x = 0.0025, 0.0075, 0.0125, 0.0175, 0.0225 and 0.0275 are shown in figure 4.1.
No peaks were detected that corresponded to either any of the starting materials or other allotropic forms. The absence of any secondary phase indicates that all the samples have crystallized in the spinel structure similar to that of the host and that the dopant ions have been successfully dissolved into the host lattice. Also, the structural analysis didn’t show any solubility limit of the dopant in the oxide host within the selected range. Figure 4.2 shows the XRD patterns of ZnGa$_{1.96}$O$_4$:Dy$_{0.04}$, Zn$_{0.98}$Ga$_2$O$_4$:Dy$_{0.02}$, and Ga$_{1.96}$O$_3$:Dy$_{0.04}$. The diffraction patterns of Zn$_{0.98}$Ga$_2$O$_4$:Dy$_{0.02}$ and Ga$_{1.96}$O$_3$:Dy$_{0.04}$ also resembled their respective host reflections. JCPDS data of the normal spinel ZnGa$_2$O$_4$ and monoclinic Ga$_2$O$_3$ is given for reference [23, 24].
Figure 4.2. XRD patterns of (a) JCPDS data of ZnGa$_2$O$_4$ (b) ZnGa$_{1.96}$O$_4$:Dy$_{0.04}$ (c) Zn$_{0.98}$Ga$_2$O$_4$:Dy$_{0.02}$ (d) JCPDS data of Ga$_2$O$_3$ (e) Ga$_{1.96}$O$_3$:Dy$_{0.04}$

DRS of the 2.5 at. % Dy$^{3+}$ doped sample is shown in figure 4.3. The band gap of the sample was determined to be 4.45 eV from the [(k/s) hV]$^2$ versus hV curves [25, 26] (inset of figure 4.3) obtained from diffuse reflectance measurements. The band gap values of all the doped samples fall in the range 4.48 ± 0.05 eV, close to the reported value of 4.59 eV for pure ZnGa$_2$O$_4$. Apart from the main absorption band corresponding to the valence to conduction band transition in the host, a shoulder-like absorption band appears in the Dy$^{3+}$ doped samples attributable to the 4f - 4f transitions of Dy$^{3+}$ within its 4f$^0$ ground state configuration. On increasing the dopant concentration, this shoulder-like absorption was found to increase (figure 4.4.). This ensures the fact that as x...
increases, more and more dopant ions get incorporated into the host lattice. Also, all the doped samples have their main absorption at the fundamental absorption edge of the host.

![Diffuse reflectance spectra of ZnGa\textsubscript{1.95}O\textsubscript{4}:Dy\textsubscript{0.05} powder. Inset shows the \{(k/s)hv\}\textsuperscript{2} versus hv plot used for bandgap estimation](image)

Figure 4.3. Diffuse reflectance spectra of ZnGa\textsubscript{1.95}O\textsubscript{4}:Dy\textsubscript{0.05} powder. Inset shows the \{(k/s)hv\}\textsuperscript{2} versus hv plot used for bandgap estimation

Figure 4.5 shows the PL emission spectra of pure and 2.5 at. % Dy\textsuperscript{3+} doped ZnGa\textsubscript{2}O\textsubscript{4} samples for an excitation wavelength of 270 nm. The undoped sample shows a strong broad blue luminescence with a peak at 439 nm resulting from the self-activated transition of regular O\textsubscript{h} Ga-O groups [27]. The emission spectrum of the Dy\textsuperscript{3+} doped sample exhibits both the host emission band and the characteristic fluorescence transitions \(^4\text{F}_{9/2} \rightarrow \ ^6\text{H}_j\) (\(J = 15/2, 13/2, 11/2, 9/2\)) of Dy\textsuperscript{3+} ions. The host emission band extending from UV to the blue region, with
peak maximum at 441 nm, has been very much lowered in intensity in comparison to that of the bulk.

![Figure 4.4. Diffuse reflectance spectra of bulk ZnGa$_2$O$_4$ (dotted) and ZnGa$_2$(1-$x$)O$_4$:Dy$_{2x}$ (solid) varying the dopant concentrations](image)

There are four groups of characteristic lines in the dopant emission spectra - lines in the blue region (450-510 nm), lines in the yellow region (560-610 nm) and two groups of line spectra in the red region (660-720 nm and 755-800 nm) with their peak maxima at 499 nm, 589 nm, 692 nm and 778 nm respectively. These emissions correspond to the spectral transitions $^4F_{9/2} \rightarrow {}^6H_{15/2}$, $^4F_{9/2} \rightarrow {}^6H_{13/2}$, $^4F_{9/2} \rightarrow {}^6H_{11/2}$ and $^4F_{9/2} \rightarrow {}^6H_{9/2}$ respectively, the dominant one being $^4F_{9/2} \rightarrow {}^6H_{15/2}$. The crystal field had sufficient strength to lift off the degeneracy of the free ion states of Dy$^{3+}$ in the lattice so that well resolved Stark levels of the multiplet manifolds could be observed in the spectra.
Figure 4.5. Room temperature PL emission spectra of (a) pure ZnGa$_2$O$_4$ host and (b) 2.5 at. % Dy$^{3+}$ doped sample, $\lambda_{\text{exc}} = 270\text{nm}$

The integral intensity of the blue emission ($^4F_{9/2} \rightarrow ^6H_{15/2}$) is stronger than that of the yellow ($^4F_{9/2} \rightarrow ^6H_{13/2}$) and red emissions ($^4F_{9/2} \rightarrow ^6H_{11/2}$ and $^4F_{9/2} \rightarrow ^6H_{9/2}$) for all dopant concentrations, as is evident from figure 4.6. This spectral property of Dy$^{3+}$ provides some information on the site occupation of Dy$^{3+}$ in the host lattice. It is well known that the $^4F_{9/2} \rightarrow ^6H_{13/2}$ yellow emission of Dy$^{3+}$ is a hypersensitive transition that is strongly influenced by the crystal field environment [18]. When Dy$^{3+}$ is located at a low symmetry local site (without an inversion symmetry), the yellow emission dominates the PL spectrum. On the other hand, the blue emission $^4F_{9/2} \rightarrow ^6H_{13/2}$ will be dominant in the emission spectrum if Dy$^{3+}$ occupies a high symmetry local site (with inversion symmetry) [20]. In the host lattice of ZnGa$_2$O$_4$, Zn$^{2+}$ ions occupy tetrahedral sites ($T_d$ point
symmetry without inversion center) coordinated by four oxygen atoms and Ga$^{3+}$ ions occupy octahedral sites (O$_h$ point symmetry with inversion center) coordinated by six oxygen atoms.

![Graph](image)

**Figure 4.6.** Variation of the integral intensity of the characteristic transitions of Dy$^{3+}$ with dopant concentration

Since the blue emission dominates in the spectrum of all the samples, one can be sure that Dy$^{3+}$ replaces Ga$^{3+}$ more in the spinel structured host. Moreover, the ionic radii of Dy$^{3+}$ (0.0912 nm) is more compatible with Ga$^{3+}$ (0.062 nm) for six coordination than that for four coordination (0.047 nm) [28]. Though the ionic radii of Zn$^{2+}$ is 0.074 nm for six coordination, Dy$^{3+}$ ions rarely substitutes at its tetrahedral site due to charge imbalance.
The integral intensity of the $^{4}F_{9/2} \rightarrow {}^{6}H_{j}$ transitions of Dy$^{3+}$ ions is found to vary irregularly with dopant concentration in figure 4.6. This may be because the energy levels of Dy$^{3+}$ ions in the spinel host may be highly sensitive to the lattice variations. On increasing the dopant incorporation into the host, the lattice parameter, calculated from the XRD data, was also found to vary irregularly. This will in turn influence the local field around the dopant ions and further affect other parameters such as the lifetime of excited states and transition probability [29].

![Diagram showing variation in PL peak intensities with Dy concentration](image.png)

**Figure 4.7.** Variation in the PL peak intensities $I_p$ at 441 nm, 499 nm and 589 nm with dopant concentration

The room temperature PL emission spectra of all the ZnGa$_{2-x}$O$_4$:Dy$_{2x}$ samples were recorded at an excitation wavelength of 270 nm. Figure 4.7 shows the...
variation in the PL peak intensities at 441 nm, 499 nm and 589 nm (abbreviated as $I_p(441)$, $I_p(499)$ and $I_p(589)$ respectively) with dopant concentration. For dopant concentrations at and below 1 at. %, the blue emission band of the host is more intense than the luminescent transitions of the activator. Beyond 1 at. % doping, the host emission weakens and the characteristic luminescent transitions of the activator ions predominate the PL spectrum. The peak intensity of the $\text{Dy}^{3+} \ 4F_{9/2} \rightarrow 6H_{15/2}$ transition is always greater than that of the $4F_{9/2} \rightarrow 6H_{13/2}$ fluorescent transitions for any dopant concentration. To the naked eye, these luminescent emissions from the doped samples appear blue for $x = 0.0025$ to 0.01 and white for $x = 0.0125$ to 0.03.

The PLE spectrum (figure 4.8) of the $\text{Dy}^{3+}$ doped sample, recorded at the emission wavelength of 499 nm, consists of a strong excitation band extending from 255 to 320 nm with peak maximum at 266 nm and a convolution of several weak lines (at 365, 399, 420, 425, 442 nm) in the longer wavelength region. The weak lines positioned between 320 and 445 nm are due to the f-f transitions of $\text{Dy}^{3+}$ within its $4f^9$ ground state configuration [20]. The origin of the strong band can be correlated taking into consideration the excitation of the host. The excitation spectrum of pure $\text{ZnGa}_2\text{O}_4$ is also composed of a strong broad band ranging from 220 to 320 nm with a maximum at 271 nm, whose spectral profile almost matches that of the doped sample. This indicates that the $\text{Dy}^{3+}$ doped samples strongly absorbs at the fundamental absorption edge of the host. Moreover, the emission band of the sensitizer ions (here, $\text{Ga}^{3+}$) overlaps the parity forbidden absorption band of the activator (here, $\text{Dy}^{3+}$) ions only to a small extent.
A luminescent material comprising of a sensitizer (S) and an activator (A) can exhibit either a radiative or a nonradiative energy transfer. Radiative transfer of energy is not very much efficient in the case of intrashell transitions due to the low magnitude of the oscillator strength for absorption [30]. The transfer rate of the nonradiative resonance transfer mechanism depends both on the spectral overlap of the S emission band and the A absorption band and on the interaction between the initial and final states of the transfer between the S and the A. The interaction can be either an exchange interaction or an electric multipolar interaction; the transfer rate in either case depending on the distance $R$ between S and A. The $R$ dependence is exponential for exchange interactions and $R^{-n}$ ($n = 6$ for dipole - dipole interactions and $8$ for dipole - quadrupole interactions) for

Figure 4.8. Room temperature PLE spectra of (a) pure ZnGa$_2$O$_4$ host ($\lambda_{em} = 439$nm) and (b) 2.5 at. % Dy$^{3+}$ doped sample ($\lambda_{em} = 499$nm)
electric multipolar interactions. Thus, spectral overlap and distance \( R \) significantly affects energy transfer rate [31]. The energy transfer efficiency, \( \eta_T \), was calculated using the relation [32],

\[
\eta_T = 1 - \frac{I_S}{I_{S0}}
\]  

Figure 4.9. Variation of \( \eta_T \) with dopant concentration

where, \( I_S \) and \( I_{S0} \) are the luminescence intensity of the sensitizer (Ga\(^{3+}\)) in the presence and absence of the activator (Dy\(^{3+}\)). The variation of \( \eta_T \) with dopant concentration is shown in figure 4.9. The transfer efficiency was found to increase gradually with Dy\(^{3+}\) content and reached the maximum for the sample
doped with 2.5 at. % of Dy\(^{3+}\). Hereafter, it decreased mainly due to cross-relaxation [33] i.e. energy transfer from one Dy\(^{3+}\) to another by transitions that are matched in energy. This occurs because as one increases the dopant concentration, the activator ions come more and more closer.

![Figure 4.10. A simple model illustrating the white emission from ZnGa\(_2\)O\(_4\):Dy\(^{3+}\)](image)

A simple model illustrating the luminescent process from ZnGa\(_2\)O\(_4\):Dy\(^{3+}\) is given in figure 4.10. In this phosphor system, under UV light illumination, the band-to-band transition in the host lattice gets excited. The 439 nm emission originates from the charge transfer between Ga\(^{3+}\) at regular O\(_h\) sites and its surrounding O\(^{2-}\) [34]. The energy of the emission can only be nonradiatively transferred due to the poor spectral overlap between the ZnGa\(_2\)O\(_4\) emission band and the 4f\(^5\) intraconfigurational absorption lines of Dy\(^{3+}\). Since the allowed 4f - 5d absorption band of the activator ions lie far outside the zinc gallate emission
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band, the energy transfer by electric multipolar interactions is less probable [31]. Thus, the nonradiative resonant energy transfer mechanism in Dy$^{3+}$ activated ZnGa$_2$O$_4$ is most likely to be mediated by exchange interactions. And this will be more favoured, smaller the value of R. For this, Dy$^{3+}$ ions must replace Ga$^{3+}$ at its octahedral site. The presence of the host emission band in the emission spectrum of the doped sample, with reduced intensity, suggests that the host sensitized energy transfer is incomplete in ZnGa$_2$O$_4$:Dy$^{3+}$ and that only a significant amount of the emitted energy is transferred from the sensitizer to the activator.

A comparison was made between the PL emission spectra of host ZnGa$_2$O$_4$ along with the emission spectra of Zn$_{1-x}$Ga$_2$O$_4$:Dy$_x$, ZnGa$_{2(1-x)}$:O$_4$:Dy$_{2x}$ and Ga$_{2(1-x)}$:O$_4$:Dy$_{2x}$ prepared under similar synthetic conditions for a doping concentration of 2 at.\% (figure 4.11). The emission spectra of Zn$_{0.98}$Ga$_2$O$_4$:Dy$_{0.02}$ exhibits the UV to blue emission band of the host itself whereas that of ZnGa$_{1.96}$O$_4$:Dy$_{0.04}$ includes the emission band of ZnGa$_2$O$_4$ and the characteristic fluorescence transitions $^4$F$_{9/2}$ $\rightarrow$ $^6$H$_j$ of the dopant. The blue emission of the Zn$_{0.98}$Ga$_2$O$_4$:Dy$_{0.02}$ sample is more intense than the host. But the ZnGa$_{1.96}$O$_4$:Dy$_{0.04}$ compound gives weaker ZnGa$_2$O$_4$ emission and strong dysprosium emissions. In the former case, since Dy$^{3+}$ is ought to substitute for Zn$^{2+}$ at its tetrahedral site, the energy transfer via exchange interactions is greatly reduced owing to larger S-A distance (R), thereby suppressing Dy$^{3+}$ emissions. In the latter case, Dy$^{3+}$ emission gets enhanced as R is greatly reduced. The PL emission intensity of Ga$_{1.96}$O$_4$:Dy$_{0.04}$ is much stronger than
ZnGa$_{2(1-x)}$O$_4$:Dy$_x$ indicating that host sensitization is more effective in the former.

![Figure 4.11. Room temperature PL emission spectra of (a) Zn$_{0.98}$Ga$_{0.02}$O$_4$:Dy$_{0.02}$, (b) pure ZnGa$_2$O$_4$, (c) Ga$_{1.96}$O$_4$:Dy$_{0.04}$ and (d) ZnGa$_{1.96}$O$_4$:Dy$_{0.04}$, $\lambda_{\text{exc}} = 270$nm](image)

Host sensitized white luminescence is therefore exhibited by ZnGa$_{2(1-x)}$O$_4$:Dy$_x$ for all dopant concentrations above 1 at. %. Figure 4.12 shows the variation of the integral intensity ratio for various dopant concentrations. Su et al. [18] points out that the yellow-to-blue (Y/B) intensity ratio does not vary too much with dopant concentration when Dy$^{3+}$ substitutes for an element with the same valency in the host matrix. In the case of ZnGa$_2$O$_4$:Dy$^{3+}$, the dopant ion replaces Ga$^{3+}$ ions of the host, as is evident from ionic radii considerations and PL emission spectra (explained above). The Y/B ratio, $I_{589}/I_{441}$, varies significantly.
with activator incorporation, if only the host emission was considered. But the ratio, $I_{589}/(I_{441}+I_{499})$, showed little variation with respect to dopant concentration. This asserts the fact that the white luminescence observed is due to the simultaneous occurrence of the multicolor dopant emissions on host sensitization. The Y/B ratio of Ga$_{1.96}$O$_3$:Dy$_{0.04}$, which gave white luminescence, was found to be 0.266.

![Figure 4.12. Variation of the integral intensity ratio (Y/B ratio) with dopant concentration](image)

The PL emissions of the samples were gauged employing the CIE (Commission Internationale d'Eclairage) coordinates (figure 4.13). The CIE coordinates of the Dy$^{3+}$ doped samples lie in between that of the ZnGa$_2$O$_4$ host ($x = 0.14$, $y = 0.09$) and that for achromatic white ($x = 0.33$, $y = 0.33$). The 2.5 at. % Dy$^{3+}$ doped
sample shows the best white emission and its CIE coordinates were calculated to be \( x = 0.31 \) and \( y = 0.3 \) and it lies just to the left of achromatic white in the chromaticity diagram.

![CIE chromaticity diagram](image)

**Figure 4.13.** CIE chromaticity diagram of the ZnGa\(_{2(1-x)}\)O\(_4\):Dy\(_{2x}\) (0.0025 \( \leq x \leq 0.025 \)), CIE coordinates of ZnGa\(_2\)O\(_4\) host and achromatic white is shown for comparison.

The chromaticity coordinates are better than that of the commercial Y\(_3\)Al\(_3\)O\(_{12}\):Ce phosphor (\( \lambda_{\text{ex}} = 467 \text{ nm} \)) reported to be (0.31, 0.27) [10]. The color coordinates of certain white emitting oxide phosphors like CdSiO\(_3\):Dy\(^{3+}\), CaIn\(_2\)O\(_4\):0.5\% Eu\(^{3+}\), SrIn\(_2\)O\(_4\):Dy\(^{3+}\) are found to be (0.39, 0.38) [15], (0.29, 0.31) [17], (0.3, 0.33) [21] respectively. The Ga\(_{1.96}\)O\(_3\):Dy\(_{0.04}\) sample prepared, for comparison, showed higher luminescent intensity than the Dy\(^{3+}\) doped ZnGa\(_2\)O\(_4\) sample but the CIE coordinates was calculated to be \( x = 0.26, y = 0.24 \). That is, the white emission
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of Ga₁.₉₆O₃:Dy₀.₄ phosphor is much inferior to that of ZnGa₁.₉₅O₄:Dy₀.₀₅ phosphor. The chromaticity diagram also suggests that color tuning from blue to white is possible on varying the dopant content in the spinel host.

4.4. Conclusions

ZnGa₂(1−x)O₄:Dy₂ₓ phosphors were prepared by conventional solid state reaction technique. The doped samples exhibit the normal spinel phase as the host. The photoluminescent studies reveal the fact that Dy³⁺ ions replace Ga³⁺ ions in the host lattice at their octahedral sites. For dopant concentrations above 1 at. %, the Dy³⁺ doped samples give white luminescence. This emission results from a nonradiative resonant energy transfer between the host and the activator mediated by exchange interactions. The poor spectral overlap between the sensitizer’s emission band and the activator’s forbidden absorption band accounts for the reduced PL emission intensity of the doped samples. The best white emission is obtained for the 2.5 at. % doped sample that presented the maximum energy transfer efficiency, the CIE coordinates of which is found to be (x, y) = (0.31, 0.3). The present investigation highlights the possibility of Dy³⁺ doped ZnGa₂O₄ as an active layer in white emitting oxide based alternating current thin film electroluminescent (ACTFEL) devices.

References

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