CHAPTER 4
LUMINESCENCE STUDIES OF Tb$^{3+}$ DOPED K$_3$Gd(PO$_4$)$_2$ NANOPHOSPHOR

4.1. INTRODUCTION

Luminescent properties of phosphate based phosphors attained the special attention of the researchers and therefore have been broadly investigated due to their various advantages, such as low sintering temperature, broad band gap, moderate phonon energy, high luminous efficiency, high chemical stability and exceptional optical damage threshold (Nagpure et al., 2009, Tang et al., 2007). Eu$^{2+}$ doped NaCaPO$_4$ (Yang et al., 2008, Qin et al., 2009), KBaPO$_4$ (Im et al., 2009, Lin et al., 2009), LiSrPO$_4$ (Wu et al., 2006), K$_3$Tb(PO$_4$)$_2$ (Jiang et al., 2014), Dy$^{3+}$doped NaCaPO$_4$ (Shinde et al., 2012), Tb$^{3+}$doped (La,Gd)PO$_4$ (Buddhudu et al., 2000) etc. are explored for their potential applications in white light emitting diodes (wLEDs), radiation dosimetry, solid state lighting etc. Phosphate anions do not absorb significantly in the UV-visible region and so solid phosphates can also find application as optical materials such as glasses, phosphors, nonlinear media, and lasers. Among the phosphates family, orthophosphates of the type M$_3$RE(PO$_4$)$_2$ (M= Alkali Metal ion; RE = rare earth ions) have been studied extensively as they have their absorption edge at a rather short wavelength, and are thus suitable as host lattices for various luminescent materials used in fast scintillators or ultraviolet (UV) tunable solid-state laser devices (Guzik et al., 2007). Data reported in the literature indicates that the alkaline rare earth orthophosphates crystallizes in the monoclinic phase of the P2$_1$/m and P2$_1$/n symmetry (Jungowska et al., 1991). Furthermore, the double phosphates M$_3$Y$_{1-x}$Ln$_x$(PO$_4$)$_2$ (Aitasalo et al., 2004) (Ln = Yb$^{3+}$, Nd$^{3+}$, Na$_3$Gd(PO$_4$)$_2$:Eu$^{3+}$ (Legendziewicz et al., 2009), A$_3$Lu(PO$_4$)$_2$:Yb$^{3+}$ (A = Na, Rb) (Guzik et al., 2007), K$_3$YLn(PO$_4$)$_2$ (Ln = Eu$^{3+}$, Nd$^{3+}$) (Szuila et al., 2011), K$_3$Y$_{(1-x)}$Yb$_x$(PO$_4$)$_2$ (Szuila et al., 2011), M$_1$M$_{III}$(PO$_4$)$_2$ (M$_1$ = Na, Rb; M$_{III}$ = Lu, Y) (Legendziewicz et al., 2008), have been synthesized by different techniques to investigate their dielectric, spectral, structural and optical properties.

An extensive improvement in the field of luminescent materials has been made by the introduction of rare earth ions as activators. These ions when doped into materials
possess unique optical behavior and have paved the way for the development of optical amplifiers and phosphors. The optical significance of these ions results from the electronic transitions occurring within the partially filled 4f energy shell of the lanthanide series and these 4f orbitals are not influenced by the 5s and 5p electrons. These transitions lead to narrow and intense emission bands which are useful sources of the individual colors in multi phosphor devices. Therefore, in many commercial phosphors the blue (450 nm), green (545 nm), and red (610 nm) emissions of Eu$^{2+}$, Tb$^{3+}$, and Eu$^{3+}$ have been widely used (Feldmann et al., 2003, Jüstel et al., 1998). Additionally, rare-earth activated phosphates and oxide phosphors are of interest as they are used in X-ray imaging, color display and fluorescent lamp manufacturing (Butler, 1980). Some of these phosphors do have interesting thermoluminescence (TL) properties (Bulur et al., 1996) and they might be useful in TL dosimetry applications. Phosphates and halo-phosphates of alkali and alkaline earth elements are also explored for their suitability as thermoluminescence dosimeter (TLD) materials (Welker, 1991, Band et al., 1997, Kottaiswamy et al., 1997, Sanayee et al., 1997, Dhabekar et al., 2002). Tb$^{3+}$ is a suitable choice among rare earth ions as it has a relatively large absorption and bright green emission. The optical properties of a Tb$^{3+}$ ion in different host matrices have been extensively studied (van der Weg et al., 1985; Rao et al., 1992, Nikl et al., 1996). Tb$^{3+}$ activated green phosphors have been used in three band fluorescent lamps (e.g., (Ce,Gd)MgB$_2$O$_{10}$:Tb$^{3+}$ (Jüstel et al., 1998)), projection television tubes (e.g., Y$_3$Al$_5$O$_{12}$:Tb$^{3+}$ (Ohno et al., 1986)), and X-ray intensifying screens (e.g., Gd$_2$O$_2$S:Tb$^{3+}$ (de Pooter et al., 1975)). On the other hand, Tb$^{3+}$ exhibits a relatively simple energy level structure: low-energy states, $^7$F$_J$ ($J=0$-6) and excited states, $^5$D$_3$ and $^5$D$_4$ leading to luminescence. After going through the literature, it has been found that K$_5$Gd$_{0.2}$(PO$_4$)$_2$:0.8Tb$^{3+}$ (Liu et al., 2013) and K$_3$R (PO$_4$)$_2$: Tb$^{3+}$ (R = Y and Gd) (Chen et al., 2014) phosphors were synthesized by the solid state method, sensitive to VUV radiations and had a wide range of applications in Plasma display panels (PDPs), mercury-free lamps and field emission displays (FEDs).

In this chapter, the luminescent properties of the Tb$^{3+}$ doped K$_3$Gd(PO$_4$)$_2$ phosphor (Gupta et al., 2014) prepared by the combustion method are presented. Phase and formation of the synthesized phosphor are confirmed by X-ray diffraction (XRD)
technique. The glow curves of the $K_3Gd(PO_4)_2$: Tb$^{3+}$(1.5 mole%) nanophosphors are fitted with the TLanal program, and the results are compared with those obtained by peak shape methods at different doses and different heating rates.

4.2. EXPERIMENTAL

High purity Potassium nitrate ($KNO_3$), Gadolinium oxide ($Gd_2O_3$), Ammonium dihydrogen orthophosphate ($NH_4H_2PO_4$), Urea ($NH_2CONH_2$) and Terbium oxide ($Tb_2O_3$) from Merck Chemicals are taken as the starting material for the preparation of Potassium Gadolinium Orthophosphate ($K_3Gd(PO_4)_2$) doped with Terbium ($Tb^{3+}$).

4.2.1. SYNTHESIS OF Tb$^{3+}$ DOPED $K_3Gd(PO_4)_2$

To synthesize the Tb$^{3+}$ doped $K_3Gd(PO_4)_2$ powder samples combustion method is applied. The calculated amount of reagents is taken according to the equation (4.1), by keeping the stoichometric ratio at unity, so that the heat liberated during combustion can be maximized for complete reaction. The weighed reagents are dissolved in a small amount of distilled water and are thoroughly mixed in an agate mortar to obtain a thick paste. The paste is transferred to the alumina crucible and then to a muffle furnace pre-heated to a temperature of 550°C. The combustion process occurred with the evolution of the large amount of gasses. The whole reaction takes 3–5 min to complete. The final white foamy product is cooled to room temperature and ground to obtain fine powder. The powder is then annealed at 800 °C for 2 h to improve crystallinity and optical properties.

$$3KNO_3 + 0.5(1-x)Gd_2O_3 + 2NH_4H_2PO_4 + 1.5NH_2C0NH_2 + xTb_2O_3 \rightarrow K_3Gd_{1-x}Tbx(PO_4)_2 + 9H_2O + 1.5CO_2 + 4N_2 \quad (4.1)$$

The phase purity and crystallinity of the synthesized phosphor are identified by X-ray powder diffraction (XRD) with Cu Kα ($\lambda=1.542$ Å) radiation. The photoluminescence (PL) excitation and emission spectra of the prepared phosphor are recorded by using a Cary-Eclipse Spectrofluorometer equipped with a 150W Xenon lamp as an excitation source with slit width of 5 nm. The diffuse reflectance spectra are measured by using a Shimadzu UV-VIS-2600 double beam spectrophotometer coupled with an ISR
For thermoluminescence (TL) measurements, the prepared samples were exposed to different doses of gamma rays from the gamma chamber available at the Inter-University Accelerator Centre, New Delhi having Co\textsuperscript{60} source. The TL glow curves are recorded on a Harshaw TLD reader (Model 3500) taking 5 mg of the sample which is heated every time at the heating rate of 5 Ks\textsuperscript{-1}. Furthermore, the TL glow curves for different heating rates (3Ks\textsuperscript{-1}–10Ks\textsuperscript{-1}) are also recorded.

### 4.3 RESULTS AND DISCUSSIONS

#### 4.3.1 STRUCTURAL STUDIES

Figure 4.1 shows the XRD pattern of the synthesized sample K\textsubscript{3}Gd(PO\textsubscript{4})\textsubscript{2} doped with Tb\textsuperscript{3+} along with the standard pattern of K\textsubscript{3}Gd(PO\textsubscript{4})\textsubscript{2} (JCPDS File No. 049-1085).

![XRD pattern of (a) JCPDS Card No. 049-1085 and b) K\textsubscript{3}Gd(PO\textsubscript{4})\textsubscript{2} : Tb\textsuperscript{3+} nanophosphor.](image)

Figure 4.1 XRD patterns of (a) JCPDS Card No. 049-1085 and b) K\textsubscript{3}Gd(PO\textsubscript{4})\textsubscript{2} : Tb\textsuperscript{3+} nanophosphor.
The peaks in the diffraction pattern are in agreement with the standard data, indicating the formation of the single phase $K_3Gd(PO_4)_2$ phosphor. No change in the crystal structure of the prepared phosphor occurs due to the addition of small amounts of $Tb^{3+}$ as dopant, suggesting that the $Tb^{3+}$ ion (radius = 1.09 Å) successfully replaced the $Gd^{3+}$ ion (radius = 1.10 Å) as they have approximately the same ionic radii. The crystal structure of the prepared phosphor belongs to the monoclinic crystal system with space group P2$_1$/m (Zhao, 2010). The average crystallite size of the prepared phosphor is calculated by using the Debye- Scherrer’s formula (Cullity, 1956) for the most prominent XRD peaks (001, 110, 111, 112, 020, 310, -103) and is found as 45 nm which confirms the formation of nanophosphor.

The SEM micrograph of the $Tb^{3+}$ (1.5 mol%) doped $K_3Gd(PO_4)_2$ nanophosphor is shown in Figure 4.2. The expected fluffy morphology of the particles is observed as normally obtained from the combustion synthesis. The voids are due to the large gaseous matter that escaped due to high exothermicity.

![Figure 4.2 SEM micrograph of $K_3Gd(PO_4)_2$:Tb$^{3+}$ nanophosphors.](image)

4.3.2. LUMINESCENCE STUDIES ON $Tb^{3+}$ DOPED $K_3Gd(PO_4)_2$

4.3.2.1. PL STUDY

The room temperature excitation (4.3(a)) and emission (4.3(b)) spectra of undoped $K_3Gd(PO_4)_2$ nanophosphor is recorded. Figure 4.3 shows the PL excitation and emission spectra of undoped $K_3Gd(PO_4)_2$ nanophosphor. The excitation spectrum of $K_3Gd(PO_4)_2$ is
recorded in the spectral region 200-300 nm as shown in figure 4.3(a) by monitoring the emission peak at 323 nm. The main excitation peak is located at 273 nm corresponds to the $^8S_{7/2}$→$^6I_{J(J=7/2)}$ transition of the Gd$^{3+}$ ion (Zhang et al., 2011) and some weak sharp peaks near 211 nm, 245nm and 254 nm are observed, which may be attributed to the $^8S_{7/2}$→$^6G_J$ and $^8S_{7/2}$→$^6D_{J(J=9/2,7/2)}$ transitions of the Gd$^{3+}$ (Liang et al., 2011) as shown in Figure 4.3. The emission spectrum of K$_3$Gd(PO$_4$)$_2$ at 273 nm excitation is shown in figure 4.3(b) in which a sharp peak at 323 nm attributed to the $^6P_{J(J=7/2)}$→$^8S_{7/2}$ transition of Gd$^{3+}$ (Liu et. al., 2013) is observed. The narrow emission band at 323 nm may have applications in the Ultra violet B (UVB) radiation in phototherapy lamps for treatment of various skin diseases (Mokoena et al., 2014). It is therefore important to develop high efficient phosphor material that emits in this region without the dangerous high energy UV wavelengths.

The excitation spectrum is recorded when keeping the emission wavelength as 549 nm. Figure 4.4 shows the excitation and emission spectra of the Tb$^{3+}$ ion doped K$_3$Gd(PO$_4$)$_2$ (1.5 mol%) nanophosphor. In Figure 4.4, the excitation spectrum includes three parts, one within the range of 208-268 nm corresponding to the $4f^8$→$4f^75d^1$ transitions of Tb$^{3+}$, second the sharp peaks at 273 nm and 311 nm belongs to the $^8S_{7/2}$→$^6I_{J(J=7/2)}$ and $^6P_{J(J=7/2)}$→$^8S_{7/2}$ transitions of Gd$^{3+}$ and thirdly, the $4f$→$4f$ transitions of Tb$^{3+}$, that consists of several excitation peaks at 339 nm, 350 nm, 356 nm, 368 nm and 374 nm which may be attributed to the $^7F_6$→$^5L_6$, $^7F_6$→$^5L_9$, $^7F_6$→$^5L_{10}$, $^7F_6$→$^5G_8$, $^7F_6$→$^5G_6$, transitions of Tb$^{3+}$ respectively as shown in the inset of Figure 4.4. When K$_3$Gd(PO$_4$)$_2$:Tb$^{3+}$ nanophosphor is excited with 273 nm, the characteristic emission peaks of the Tb$^{3+}$ ion occur at the Gd$^{3+}$ sites. The spin-allowed $4f$→$5d$ transition ought to be stronger with higher energy and the spin-forbidden $4f$→$5d$ transition is weak with lower energy (Wu et al., 2008). Therefore, in figure 4.4 the excitation bands at 220 nm and 255 nm are ascribed to the spin-allowed and spin-forbidden transitions of Tb$^{3+}$, respectively. The emission spectrum monitored at different excitation wavelengths in figure 4.4 consists of several peaks in the region from 406-635 nm and a prominent peak at 549 nm at 220 nm excitation wavelength occurred due to the $^5D_4$→$^7F_5$ transition, while those at 416, 436, 460, 487, 583 and 620 nm are due to the $^5D_3$→$^7F_5$, $^5D_3$→$^7F_4$, $^5D_3$→$^7F_3$, $^5D_4$→$^7F_6$, $^5D_4$→$^7F_4$ and $^5D_4$→$^7F_3$ transitions of Tb$^{3+}$, respectively (Park et al., 2010).
Figure 4.3 (a) PL excitation and (b) emission spectra of undoped K$_3$Gd(PO$_4$)$_2$ nanophosphors.

Figure 4.4 Excitation and emission spectra of Tb$^{3+}$ doped K$_3$Gd(PO$_4$)$_2$ (1.5 mole%) nanophosphor.
Figure 4.5 shows the energy level diagram of Gd$^{3+}$ ion, which reveals the possible transitions involved in the process due to the host lattice. The trivalent Gd ion (Gd$^{3+}$) has seven unpaired electrons in the unfilled 4f shell, which is shielded by the completely filled 5s and 5p shells. When the undoped K$_3$Gd(PO$_4$)$_2$ is excited with different wavelengths 212 nm, 244 nm and 273 nm, it leads to the transition of Gd$^{3+}$ ion from the ground state $^8S_{7/2}$ to the excited states $^6G_{J(7/2, 9/2, 11/2, 5/2)}$, $^6D_{J(7/2, 9/2, 11/2, 5/2, 3/2)}$, $^6I_{J(11/2, 9/2, 7/2)}$, respectively. The Gd$^{3+}$ ion from the excited state decays non-radiatively through the multiphonon relaxations up to the $^6P_{J(3/2, 5/2, 7/2)}$ level. The radiative transition from $^6P_{7/2}$ of Gd$^{3+}$ to $^8S_{7/2}$ state gives rise to the blue emission at 323 nm.

![Energy level diagram of Gd$^{3+}$ ion in the K$_3$Gd(PO$_4$)$_2$.](image)

The energy level diagram of Tb$^{3+}$ ion in the K$_3$Gd(PO$_4$)$_2$ host lattice is shown in figure 4.6, which represents the various transitions involved in the process. When the Tb$^{3+}$ doped K$_3$Gd(PO$_4$)$_2$ phosphor is excited with various wavelengths 220 nm, 339 nm, 350 nm, 356 nm, 368 nm and 374 nm, the Tb$^{3+}$ ions are raised to different excitation levels (4$f^8 \rightarrow 4f^75d^1$, $^5L_6$, $^5L_9$, $^5L_{10}$, $^5G_8$, $^5G_9$) from the ground level ($^7F_{J[0-6]}$). The Tb$^{3+}$ ions
relax non-radiatively to $^5\text{D}_3$ and further to $^5\text{D}_4$ levels. The radiative transitions from $^5\text{D}_3$ and $^5\text{D}_4$ of Tb$^{3+}$ to various $^7\text{F}_{J(J=3,4,5,6)}$ levels give rise to blue and green-red emission.

![Energy level diagram of Tb$^{3+}$ ion in the K$_2$Gd(PO$_4$)$_2$ host lattice.](image)

Figure 4.6 Energy level diagram of Tb$^{3+}$ ion in the K$_2$Gd(PO$_4$)$_2$ host lattice.

The decay curve of K$_2$Gd (PO$_4$)$_2$: Tb$^{3+}$ (1.5 mole%) phosphor is shown in figure 4.7. The phosphorescence lifetime of the prepared phosphor is probed by monitoring the excitation wavelength at 220 nm and emission wavelength at 549 nm. In figure 4.7, the decay time is determined by fitting the profile using, mono-exponential decay. The decay curves (Vij, 1998) can be represented by the equation (4.2):

$$I = I_0 \exp\left(-\frac{t}{\tau}\right)$$

(4.2)

where $I$ and $I_0$ are the luminescence intensities at time $t$ and $t_0$. $\tau$ is the radiative decay time. The decay time obtained from the fitted data of K$_2$Gd (PO$_4$)$_2$: Tb$^{3+}$ (1.5 mole%) is 5.06 ms ($^5\text{D}_4 \rightarrow ^7\text{F}_5$).
Figure 4.7: Decay Curve of K$_3$Gd(PO$_4$)$_2$:Tb$^{3+}$(1.5 mol%) phosphor by monitoring the excitation wavelength at 220 nm and emission wavelength at 549 nm.

4.3.2.2. TL STUDY

Figure 4.8 shows the deconvoluted TL glow curves of undoped K$_3$Gd (PO$_4$)$_2$ and Tb$^{3+}$ doped K$_3$Gd (PO$_4$)$_2$ nanophosphors exposed to 0.1 kGy dose of gamma rays with a linear heating rate of 5 Ks$^{-1}$. For undoped samples (as shown in Figure 4.9(a)), the main peak is located at higher temperature (575 K) with a small hump at 395 K and 535 K whereas in case of Tb$^{3+}$ doped samples (Figure 4.8(b), the main peak located at lower temperature (395 K) with two small humps located at 473 K and 579 K. Therefore, a significant change in the trap structure of the host K$_3$Gd (PO$_4$)$_2$ is observed with the addition of Tb$^{3+}$ ion. Also, it is observed that the overall TL intensity for Tb$^{3+}$ doped samples is much more than undoped sample, suggesting an increase in the density of the traps (Xu et al., 2013, Xu et. al., 2014). Furthermore, it is important to mention here that the Tb$^{3+}$ doped phosphors consists of three peaks at lower dose (as mentioned earlier) but at higher dose
the three peaks become one and they do not change further at higher dose. Therefore, the phosphor can be a good candidate for the storage of higher doses.

Figure 4.8: Deconvoluted curves of (a) Undoped K$_3$Gd(PO$_4$)$_2$ and (b) Tb$^{3+}$ doped K$_3$Gd(PO$_4$)$_2$ (1.5 mol%) nanophosphors exposed to 0.1 kGy of gamma rays at heating rate of 5 Ks$^{-1}$

Figure 4.9 shows the typical TL glow curves for the prepared K$_3$Gd (PO$_4$)$_2$: Tb$^{3+}$ (1.5 mol%) nanophosphors exposed to different doses of gamma rays from a $^{60}$Co source with a linear heating rate of 5 Ks$^{-1}$. The TL glow curve exhibits a single peak at 407 K (for higher dose). It is observed that the intensity of the peaks increases with the increase in the dose of the gamma rays (0.1 kGy – 5 kGy). The TL glow curve shape and structure does not change when exposed to higher dose of gamma rays.
Figure 4.9 TL glow curves of $K_3Gd(PO_4)_2$:$Tb^{3+}$ (1.5 mol%) nanophosphors at different doses (0.1 kGy–5 kGy) and heating rate (5Ks$^{-1}$).

4.3.2.2.1. **TL RESPONSE**

A good TL dosimeter should exhibit a linear relation between TL intensity and absorbed dose. Many TL materials show a nonlinear growth of TL intensity with absorbed dose after a certain dose ranges (McKeever, 1985). The relationship between the maximum TL intensity and gamma dose of Tb$^{3+}$ doped $K_3Gd(PO_4)_2$ phosphor is shown in Figure 4.10. In order to record the dose-response curve, the phosphor is exposed to different gamma doses at room temperature and the TL intensity is measured from the glow curve. $R^2$ value often referred as the goodness of fit. $R^2$ values range from 0 to 1, with 1 representing a perfect fit between the data and the line drawn through them, and 0 representing no statistical correlation between the data and a line. In figure 4.10, the dose-response curve fitted with a linear function and the value of $R^2$ comes to be 0.99 which means a good fit between the data and the line drawn.
Figure 4.10: Dose-response of $K_3Gd(PO_4)_2$:Tb$^{3+}$ nanophosphors.

Figure 4.11: Dose-response of the $K_3Gd(PO_4)_2$:Tb$^{3+}$(1.5 mol\%) nanophosphors using log-log scale.
There are several TL materials that exhibit nonlinear dose response over certain doses. The expression for the measured TL intensity can be expressed in the mathematical form as

\[ I = aD^k, \]

\[ \Rightarrow \log I = \log a + k \log D \]

where \( a \) is the scaling factor, \( D \) is the dose of the radiation and \( k \) is a constant. When \( I \) is plotted as a function of the dose \( D \) on a log-log scale, the above equation yields a straight line with a slope \( k \) (Pagonis, 2006). The terms superlinear, sublinear and linear dependence are attributed to the conditions when \( k > 1, k < 1 \) and \( k = 1 \), respectively. Figure 4.11 shows the dose-response of \( \text{K}_3\text{Gd(PO}_4)_2\text{):Tb}^{3+} \) phosphor using log-log scale. In figure 4.11, the slope comes to be 1.7 which is greater than 1 i.e. \( k > 1 \). From the value of \( k \), it is clear that the present phosphor exhibits a superlinear dependence. The value of the scaling factor is obtained from figure 4.11 and found to be 1.84.

4.3.2.2 HEATING RATE EFFECTS ON GLOW CURVE

The effect of different heating rates (3 K/s −10 K/s) on glow curves is studied for \( \text{K}_3\text{Gd(PO}_4)_2\text{):Tb}^{3+} \) (1.5 mole %) nanophosphor exposed to gamma radiations for a dose of 5kGy. Figure 4.12 shows the TL glow curves at heating rates 3K/s, 5K/s and 10 K/s for a dose of 5kGy. From figure 4.12, it is observed that with the increase in the heating rate the peak intensity increases and then decreases. When the heating rate is increased from 3 K/s to 5 K/s, an increase in the peak intensity is observed and the peak temperature shifts towards the higher temperature. However, with further increase in heating rate of 10 K/s, a decrease in the peak intensity is observed with a peak temperature shifting towards the higher temperature. This unusual increase and decrease in the TL intensity can be explained by the fact that at lower heating rates the charge carriers, which are responsible for producing the desired luminescence have adequate time to get trapped at the recombination centre and are not involved in producing luminescence, whereas when the heating rate is high, the phenomena such as thermal quenching of TL intensity due to higher heating rates rises (Bahl et al., 2013).
Figure 4.12: Effect of different heating rates (3 Ks\(^{-1}\) – 10 Ks\(^{-1}\)) on TL glow curve of K\(_3\)Gd(PO\(_4\))\(_2\):Tb\(^{3+}\)(1.5 mole \%) nanophosphor exposed to 5 kGy of gamma rays.

Chen’s method (Chen et al., 1981) is used to determine the kinetic parameters such as the order of kinetics (\(b\)), activation energy (\(E\)) and frequency factor (\(s\)) of each of the deconvoluted glow peaks of the TL materials. The other peak shape methods employed in this work are those of (Grossweiner, 1953) and (Lushchik, 1956). The Chen’s method is mainly based on the temperatures \(T_m\), \(T_1\) and \(T_2\), where \(T_m\) corresponds to the temperature at the maximum TL intensity while \(T_1\) and \(T_2\), are the temperatures corresponding to the half of the intensities on either side of the maximum of the glow peak, respectively. In order to determine the kinetic parameters, the following peak shape parameters are to be determined: the total half intensity width \(\omega = T_2 - T_1\), the high temperature half width \(\delta = T_2 - T_m\) and the low temperature half width \(\tau = T_m - T_1\) (Garlick et al., 1948). The peak shape method is mainly used to calculate the order of kinetics. The order of kinetics is evaluated from the geometrical factor (\(\mu_g\)) of the glow.
peak. $\mu_g$ is calculated using Eq. (4.3) from the known peak shape parameters which includes $\delta$ and $\omega$.

$$\mu_g = \frac{\delta}{\omega} = \frac{T_2 - T_m}{T_2 - T_1}$$  \hspace{1cm} (4.3)

$T_m$ corresponds to the temperature at the maximum TL intensity. The values of geometrical factor ($\mu_g$) for first- and second-order kinetics are 0.42 and 0.52, respectively. Another parameter proposed by Balarin (Balarin, 1975) gives the kinetic order as a function of the parameter

$$\gamma = \frac{\delta}{\tau} = \frac{T_2 - T_m}{T_m - T_1}$$  \hspace{1cm} (4.4)

The Balarin parameter ($\gamma$) ranges from 0.7 to 0.8 for the first order kinetics and for the second order kinetics $\gamma$ varies from 1.05 to 1.20. Commonly in the first order, the process of retrapping is negligible and the trap should be situated very close to the luminescent centre. The features of the second order peak are wider and it is more symmetric than the first order peak. The deconvolution of the glow curves was done by using the TLanal Program given by Chung et al., (2005).

The trap depth or the thermal energy ($E$) is calculated by using the following set of equations independent of the kinetic order:

$$E_\alpha = C_\alpha \left(\frac{kT_m^2}{\alpha}\right) - b_\alpha (2kT_m)$$  \hspace{1cm} (4.5)

where $\alpha$ stands for $\tau$, $\delta$, $\omega$ respectively. $C_\alpha$ and $b_\alpha$ are obtained using the expressions below:

$C_\tau = 1.51 + 3.0 (\mu_g - 0.42)$; $b_\tau = 1.58 + 4.2 (\mu_g - 0.42)$

$C_\delta = 0.976 + 7.3 (\mu_g - 0.42)$; $b_\delta = 0$

$C_\omega = 2.52 + 10.2 (\mu_g - 0.42)$; $b_\omega = 1$

General Formulae for peak shape methods (Furetta, 2003) are given as:

For First order:

$$E = 1.41 \left(\frac{T_m T_1}{\tau}\right)$$  \hspace{1cm} (Grossweiner)

$$E = 0.976 \left(\frac{T_m^2}{\delta}\right)$$  \hspace{1cm} (Lushchik)

For Second order:
\[ E_\alpha = C_\alpha \left( \frac{kT_m T_1}{\alpha} \right) \]  \hspace{1cm} \text{(Grossweiner)}

where \( \alpha = \tau, \delta, \omega \)

where \( C_\tau = 1.68 \), \( C_\delta = 1.8313 \), and \( C_\omega = 3.5217 \)

\[ E = 1.71k \left( \frac{T_m^2}{\delta} \right) \]  \hspace{1cm} \text{(Lushchik)}

Frequency factor (s) was calculated by Chen and Winer equation [Chen et al., 1970] after getting the trap depth (E) and order of kinetics (b)

\[
\left( \frac{\beta E}{kT_m^2} \right) = s \exp \left( \frac{-E}{kT} \right) \left[ 1 + (b - 1)\Delta m \right] \tag{4.6}
\]

where \( \beta \) is the linear heating rate.

Figure 4.13 shows the deconvoluted curve fitted with the original curve of the K\(_3\)Gd(PO\(_4\))\(_2\):Tb\(^{3+}\) nanophosphor exposed to gamma radiation for a dose of 5 kGy at a heating rate of 5 Ks\(^{-1}\). The curve consists of three traps having different frequency factors and energies and same kinetic orders.

Figure 4.13: Deconvoluted curve of the K\(_3\)Gd(PO\(_4\))\(_2\):Tb\(^{3+}\) nanophosphor exposed to 5 kGy gamma-rays at heating rate of 5 Ks\(^{-1}\).
The snapshot of the deconvoluted glow curve of the \( \text{K}_3\text{Gd(PO}_4\text{)}_2:\text{Tb}^{3+} \) nanophosphor with a dose of 5 kGy at 5K/s, using TLanal program is shown in figure 4.14. The goodness of fit is determined by calculating figure of merit (FOM) defined by

\[
FOM = \sum \frac{TL_{\text{Exp}} - TL_{\text{Fit}}}{TL_{\text{Fit}}}
\]

where \( TL_{\text{Exp}} \) and \( TL_{\text{Fit}} \) represent the experimental TLintensity data and the values of the fitting functions, respectively. The summation extends over all the available experimental data points. The resolution of fitting method can be refined by repeating the process of calculating the FOM for different values of \( E \) and finding the value of \( E \) that minimizes the value of FOM. In the present study, FOM is calculated to be 0.879\%, which also confirms a very good agreement between theoretical and experimental glow curves.

Figure 4.14: Snapshot of deconvoluted glow curve of the \( \text{K}_3\text{Gd(PO}_4\text{)}_2:\text{Tb}^{3+} \) nanophosphor with a dose of 5 kGy at 5 K/s, using TLanal program.
Trapping parameters of all the peaks for both undoped at 0.1 kGy dose and Tb$^{3+}$ doped K$_3$Gd(PO$_4$)$_2$ at different doses (0.1 kGy −5 kGy) are calculated by using TLaanal program are summarized in Table 4.1. The symmetric factor ($\mu_g$) and Balarin parameter ($\gamma$) are calculated for all the peaks of undoped at 0.1 kGy dose and Tb$^{3+}$ doped K$_3$Gd(PO$_4$)$_2$ phosphor at different doses (0.1 kGy −5 kGy) are listed in Table 4.2. In Table 4.2, the values of the activation energy (E) and the frequency factor (s) are compared to the different peak shape methods (Chen’s, Grossweiner and Lushchik), it is found that the values of activation energy (E) and frequency factor (s) for all the three peak shape methods are approximately the same. Furthermore, the values of the activation energy (E) calculated by the TLaanal program (Table 4.1) are also approximately closer to the values as obtained by the different peak shape methods as illustrated in Table 4.2 whereas the values of the frequency factor (s) are different. Table 4.3 summarizes the values of activation energy (E) and frequency factor (s) at different heating rates (3 K/s−10 K/s) with a dose of 5 kGy calculated by TLaanal program. The order of kinetics (b) for each peak at different heating rates (3 K/s−10 K/s) is determined from the symmetric factor ($\mu_g$) and Balarin parameter ($\gamma$) and are listed in Table 4. The mean value of ($\mu_g$) and (γ) for peak 1 at different heating rates (3 K/s -10 K/s) was 0.45 and 0.86, respectively and these parameters confirm a first order kinetic property. For peaks 2 and 3, the mean value of ($\mu_g$) and (γ) are found to be 0.51 and 1.07 and 0.51 and 1.1, respectively, and it confirms the second order kinetics. At different heating rates (3 K/s−10 K/s), the trapping parameters calculated by different peak shape methods are summarized in Table 4.4 and it is found that the values of the activation energy (E) are approximately same whereas the values of the frequency factor (s) are slightly different as compared with the TLaanal program in Table 4.3. From Table 4.1 and Table 4.2, the value of the activation energy (E) and frequency factor (s) in peak 3 with 1kGy dose found to be very large. The possibility of high frequency factor and high activation energy, a model of one trap and three recombination centers, one radiative and two non-radiative is proposed by Chen et al., (1996). Mandowski, (2006) gives another explanation related to the occurrence of high frequency factors and high activation energy, based on the concept of cascade detrapping. From Table 4.2 and Table 4.4, it is found that the maximum glow peaks obeys the second order kinetics.
Table 4.1: Kinetic parameters of the Undoped K₃Gd(PO₄)₂ (0.1 kGy) and K₃Gd(PO₄)₂:Tb³⁺ (1.5 mol%) nanophosphors using the TLanal program at different doses (0.1 kGy – 5 kGy) having heating rate 5 K s⁻¹.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Dose (kGy)</th>
<th>Peak</th>
<th>T_m(K)</th>
<th>Activation energy (eV)</th>
<th>Frequency Factor s (s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undoped K₃Gd(PO₄)₂</td>
<td>0.1</td>
<td>1</td>
<td>407</td>
<td>0.42</td>
<td>3.6 x 10⁴</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>575</td>
<td>1.40</td>
<td>3.4 x 10⁶</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>536</td>
<td>0.79</td>
<td>4.1 x 10⁶</td>
</tr>
<tr>
<td>Tb doped K₃Gd(PO₄)₂</td>
<td>0.1</td>
<td>1</td>
<td>395</td>
<td>1.06</td>
<td>4.1 x 10⁴</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>473</td>
<td>0.71</td>
<td>7.4 x 10⁶</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>579</td>
<td>0.71</td>
<td>2.0 x 10⁵</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>1</td>
<td>397</td>
<td>1.36</td>
<td>6.2 x 10¹⁰</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>427</td>
<td>1.09</td>
<td>7.6 x 10⁶</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>464</td>
<td>1.01</td>
<td>4.5 x 10⁴</td>
</tr>
<tr>
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</tr>
<tr>
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<td>450</td>
<td>1.00</td>
<td>1.4 x 10⁵</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>400</td>
<td>2.23</td>
<td>9.3 x 10⁷</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>1</td>
<td>397</td>
<td>1.41</td>
<td>1.6 x 10¹⁰</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>455</td>
<td>1.28</td>
<td>7.8 x 10⁶</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>426</td>
<td>1.25</td>
<td>1.9 x 10⁷</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1</td>
<td>396</td>
<td>1.39</td>
<td>9.1 x 10⁹</td>
</tr>
<tr>
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<td></td>
<td>2</td>
<td>412</td>
<td>1.43</td>
<td>5.9 x 10⁹</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>434</td>
<td>0.92</td>
<td>5.4 x 10³</td>
</tr>
</tbody>
</table>
Table 4.2: Trapping parameters of Undoped K$_3$Gd(PO$_4$)$_2$ (0.1 kGy) and K$_3$Gd(PO$_4$)$_2$:Tb$^{3+}$ (1.5 mol%) nanophosphors using different peak shape methods at different doses (0.1 kGy –5 kGy) having a heating rate 5 Ks$^{-1}$.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Dose (kGy)</th>
<th>Peak</th>
<th>Order of kinetics (b)</th>
<th>Chen’s Method</th>
<th>Grossweiner</th>
<th>Lushchik</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>μg</td>
<td>Γ</td>
<td>E(eV)</td>
<td>s(s$^{-1}$)</td>
<td>E(eV)</td>
</tr>
<tr>
<td>Undoped K$_3$Gd(PO$_4$)$_2$</td>
<td>0.1</td>
<td>1</td>
<td>0.53 (2)</td>
<td>1.16</td>
<td>0.42</td>
<td>2.6 x 10$^4$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.52 (2)</td>
<td>1.09</td>
<td>1.41</td>
<td>5.5 x 10$^{11}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.35 (1)</td>
<td>0.54</td>
<td>0.68</td>
<td>3.1 x 10$^5$</td>
</tr>
<tr>
<td>Tb doped K$_3$Gd(PO$_4$)$_2$</td>
<td>0.1</td>
<td>1</td>
<td>0.52 (2)</td>
<td>1.1</td>
<td>1.07</td>
<td>1.9 x 10$^{13}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.43 (1)</td>
<td>0.7</td>
<td>0.78</td>
<td>1.9 x 10$^7$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.41 (1)</td>
<td>0.7</td>
<td>0.70</td>
<td>1.7 x 10$^6$</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>1</td>
<td>0.41 (1)</td>
<td>0.72</td>
<td>1.36</td>
<td>9.8 x 10$^{16}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.52 (2)</td>
<td>1.09</td>
<td>1.07</td>
<td>1.5 x 10$^{12}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.50 (2)</td>
<td>1</td>
<td>0.99</td>
<td>1.8 x 10$^{10}$</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1</td>
<td>0.50 (2)</td>
<td>1</td>
<td>1.35</td>
<td>2.2 x 10$^{17}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.51 (2)</td>
<td>1.07</td>
<td>0.97</td>
<td>2.2 x 10$^{10}$</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>0.61 (2)</td>
<td>1.61</td>
<td>1.80</td>
<td>3.7 x 10$^{22}$</td>
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<td>3</td>
<td>1</td>
<td>0.53 (2)</td>
<td>1.13</td>
<td>1.47</td>
<td>3.2 x 10$^{16}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.52 (2)</td>
<td>1.09</td>
<td>1.29</td>
<td>8.1 x 10$^{13}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.51 (2)</td>
<td>1.05</td>
<td>1.23</td>
<td>1.8 x 10$^{14}$</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>1</td>
<td>0.51 (2)</td>
<td>1.06</td>
<td>1.35</td>
<td>8.8 x 10$^{16}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.51 (2)</td>
<td>1.05</td>
<td>1.37</td>
<td>3.3 x 10$^{16}$</td>
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<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.52 (2)</td>
<td>1.11</td>
<td>0.94</td>
<td>2.8 x 10$^{10}$</td>
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</table>
Table 4.3: Trapping parameters of various glow peaks of K$_3$Gd(PO$_4$)$_2$:Tb$^{3+}$(1.5 mol%) nanophosphors samples with 5 KGy of γ-ray radiation at different heating rates using the TLanal program.

<table>
<thead>
<tr>
<th>Dose (kGy)</th>
<th>Heating rate(K/s)</th>
<th>Peak</th>
<th>$T_m$(K)</th>
<th>Activation energy $E$( eV)</th>
<th>Frequency Factor $s$ (s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>3</td>
<td>1</td>
<td>400</td>
<td>0.82</td>
<td>5.5 x 10$^9$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>390</td>
<td>1.89</td>
<td>5.9 x 10$^{16}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>422</td>
<td>0.98</td>
<td>2.2 x 10$^3$</td>
</tr>
<tr>
<td>5</td>
<td>5</td>
<td>1</td>
<td>398</td>
<td>1.27</td>
<td>2.7 x 10$^8$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>410</td>
<td>1.46</td>
<td>1.4 x 10$^{10}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>426</td>
<td>0.84</td>
<td>7.5 x 10$^4$</td>
</tr>
<tr>
<td>5</td>
<td>10</td>
<td>1</td>
<td>402</td>
<td>0.92</td>
<td>1.8 x 10$^{14}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>422</td>
<td>1.49</td>
<td>4.4 x 10$^{10}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>439</td>
<td>0.91</td>
<td>1.8 x 10$^5$</td>
</tr>
</tbody>
</table>

Table 4.4: Trapping parameters of various glow peaks of K$_3$Gd(PO$_4$)$_2$:Tb$^{3+}$(1.5 mol%) nanophosphors with 5 kGy of γ-ray radiation at different heating rates using different peak shape methods.

<table>
<thead>
<tr>
<th>Heating rate (K/s)</th>
<th>Peak</th>
<th>Order of kinetics (b)</th>
<th>Chen’s Method</th>
<th>Grossweiner</th>
<th>Lushchik</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$\mu_g$</td>
<td>$\gamma$</td>
<td>$E$(eV)</td>
<td>$s$($s^{-1}$)</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0.42 (1)</td>
<td>0.73</td>
<td>0.81</td>
<td>3.2 x 10$^9$</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.52 (2)</td>
<td>1.09</td>
<td>1.95</td>
<td>7.9 x 10$^{24}$</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.51 (2)</td>
<td>1.17</td>
<td>0.96</td>
<td>6.1 x 10$^{10}$</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>0.52 (2)</td>
<td>1.11</td>
<td>1.29</td>
<td>1.3 x 10$^{16}$</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.52 (2)</td>
<td>1.12</td>
<td>1.47</td>
<td>6.6 x 10$^{17}$</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>0.52 (2)</td>
<td>1.10</td>
<td>0.84</td>
<td>2.3 x 10$^9$</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>0.42 (1)</td>
<td>0.75</td>
<td>0.96</td>
<td>8.2 x 10$^{11}$</td>
</tr>
<tr>
<td></td>
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<td>1</td>
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</tr>
<tr>
<td></td>
<td>3</td>
<td>0.51 (2)</td>
<td>1.06</td>
<td>0.89</td>
<td>8.6 x 10$^9$</td>
</tr>
</tbody>
</table>
4.3.3 OPTICAL STUDY

4.3.3.1. DIFFUSE REFLECTANCE

Figure 4.15 displays the diffuse reflectance spectra of undoped K$_3$Gd(PO$_4$)$_2$ and Tb$^{3+}$ doped K$_3$Gd(PO$_4$)$_2$ (1.5 mol%) phosphor from 190-1400 nm. The diffuse reflectance spectra of undoped K$_3$Gd(PO$_4$)$_2$ consists of two sharp peaks at 273 nm and 214 nm. The peak at 273 nm corresponds to the Gd$^{3+}$($^8S_{7/2} \rightarrow ^6I_{J(J=11/2,9/2,7/2)}$) transition of the Gd$^{3+}$ ion and the peak at 214 nm is due to band to band transition of the host matrix, whereas an extra peak at 223 nm is observed in the case of Tb$^{3+}$ doped K$_3$Gd(PO$_4$)$_2$ nanophosphor corresponds to Tb$^{3+}$($4f^8 \rightarrow 4f^75d^1$) of the Tb$^{3+}$ ion.

![Diffuse reflectance spectra](image)

Figure 4.15: The diffuse reflectance spectra of the undoped K$_3$Gd(PO$_4$)$_2$ and K$_3$Gd(PO$_4$)$_2$:Tb$^{3+}$ (1.5 mol%) nanophosphor.

The Kubelka Munk (Morales et al., 2007) theory is used to calculate the band gap of K$_3$Gd(PO$_4$)$_2$:Tb$^{3+}$ phosphor using diffuse reflectance spectrum. The absorption spectra (Fig. 4.15) of the phosphors is transformed from the diffuse reflectance spectra by using
Kubelka–Munk function which is given by the (equation 2.2, chapter 2). The well known Tauc’s relation is subsequently regenerated using the Kubelka–Munk relation to attain equation (equation 2.4, chapter 2) from which the energy band gap (E_g) of the material is obtained. By using equation 2.4, plot of \([F(R)hv]^2\) versus photon energy \((hv)\) is constructed from which the value of energy band gap is determined by extrapolating the linear fitted regions to \([F(R)hv]^2 = 0\). Figure 4.16 shows the plot of \([F(R)hv]^2\) versus \(hv\) of the \(K_3Gd(PO_4)_2:Tb^{3+}\) (1.5 mol\%) nanophosphors, that exhibits nonlinear and linear portions, which is the characteristic of direct allowed transitions. The nonlinear portion correlates to the unused absorption involving impurity levels and the linear portion specifies the fundamental absorption. The band gap of \(Tb^{3+}\) doped \(K_3Gd(PO_4)_2\) phosphor is thus found to be 5.87 eV.

Figure 4.16: Energy band gap in the \(K_3Gd(PO_4)_2:Tb^{3+}\) (1.5 mol\%) nanophosphors.

4.3.4. CIE STUDY
Figure 4.17 presents the Commission Internationale de l’Eclairage (CIE) 1931 color space chromaticity diagram to illustrate the chromaticity of \(K_3Gd(PO_4)_2: Tb^{3+}\) (1.5 mol\%) nanophosphors.
The chromaticity coordinates of the Tb$^{3+}$ doped K$_3$Gd(PO$_4$)$_2$ phosphors are calculated using the CIE calculator software. The CIE coordinates of K$_3$Gd(PO$_4$)$_2$:Tb$^{3+}$ are measured as $x=0.29$, $y=0.54$. These coordinates are in good agreement with the well known green phosphors (Zn,Cd)S:Ag (0.26, 0.60) and ZnS:Au$_{0.05}$, Cu$_{0.01}$ (0.267, 0.582) (Yen et. al., 2006) and exhibit green light emission in the chromaticity diagram.

**4.4. CONCLUSIONS**

In conclusion, the Tb$^{3+}$ activated K$_3$Gd(PO$_4$)$_2$ nanophosphors are successfully synthesized using combustion method. The average crystallite size and band gap of the prepared phosphor are estimated to 45 nm and 5.87 eV, respectively. The excitation spectrum of the K$_3$Gd(PO$_4$)$_2$:Tb$^{3+}$ consists of several peaks due to the $4f \rightarrow 4f$ $5d$ transitions in the shorter wavelength region and some sharp peaks due to the $4f \rightarrow 4f$ transitions in the longer wavelength region along with sharp peaks at 273 nm and 312 nm corresponds to the ($^8S_{7/2} \rightarrow ^6I_{j=7/2}$) and $^6P_{j(J=7/2)} \rightarrow ^8S_{7/2}$ transitions of Gd$^{3+}$. The emission spectrum of the prepared phosphor reveals two colors, blue due to $^5D_{3} \rightarrow ^7F_{J}$ transitions and
green due to the $^5D_{4} \rightarrow ^7F_{1}$ transitions, when excited by UV excitation (220 nm). The phosphorescence lifetime of the prepared phosphor is found to be 5.06 ms. The calculated CIE coordinates ($x = 0.29, y = 0.54$) of the prepared phosphor are in good agreement with the well known green phosphors (Zn,Cd)S:Ag (0.26, 0.60) and ZnS:Ag_{0.05}, Cu_{0.01} (0.267, 0.582). The thermoluminescence studies of undoped and Tb$^{3+}$ doped K$_3$Gd(PO$_4$)$_2$: nanophosphor exposed to different gamma doses (0.1 kGy–5 kGy) is presented. The trap parameters for the product, at a linear heating rate (5K/s) with different doses (0.1 kGy–5 kGy) and at different heating rates (3K/s–10K/s) with a dose of 5 kGy are calculated by using different peak shape methods (Chen’s, Grossweiner and Lushchik) and the obtained results are compared with that obtained by the developed TLanal program. The values of the activation energy (E) obtained by the developed TLanal program are in good agreement with those evaluated by the peak shape methods. The material exhibits a superlinear response over a wide range of gamma doses. The scaling factor is calculated for the prepared nanophosphor and it comes to be 1.84.

REFERENCES


