Material Research Express

**Abstract**

LaAlO$_3$: Sm$^{3+}$ (1–9 mol%) nanoparticles were synthesized using solution combustion synthesis technique. The structural analysis is carried out using different analytical techniques such as Powder X-Ray Diffraction (PXRD), Fourier Transform InfraRed spectra (FTIR), Scanning Electron Microscopy (SEM), transmission electron microscopy (TEM). The bandgap is found to be in the range $4.9–5.3$ eV. Photoluminescence and cathodoluminescence spectra are studied for the investigation of the optical property of the synthesized nanoparticles. The pure rhombohedral phase is obtained after calcination at $900 \degree C$. The agglomerated porous structure is revealed from SEM images of the nanoparticles. Under the 406 nm excitation wavelength and 10 keV accelerating voltage the PL and CL spectra are observed with characteristic emission peaks of Sm$^{3+}$ ions from $^4G_{5/2}$ to $^6H_{15/2}$ transitions with yellowish-orange color. The CIE coordinates confirm the emission of yellowish-orange luminescence from LaAlO$_3$: Sm$^{3+}$ phosphors. The results obtained reveal that these materials are potential candidates for the fabrication of field emission displays, photoluminescence liquid crystal displays, and other optical devices.

1. Introduction

Inorganic perovskite materials like lanthanide compounds are of great interest due to its significant applications in different fields as catalysis, drug delivery, battery devices, fluorescence labeling, sensors, electrical and magnetic materials, etc. [1–4]. LaAlO$_3$ (Lanthanum aluminate) is identified as a perovskite-type mixed oxide having a rhombohedral structure with a space group of R3m. Trivalent lanthanum (La$^{3+}$) ions occupy a D3 symmetry site and transform at temperatures above $530 \degree C$ into a pseudocubic lattice (Pm3 m) [5]. Because of transitions arising due to their $4f$ electronic configuration these materials display the visible range of narrow and sharp emission [6–9].

Many researchers have examined the viability of doping the lanthanides into these perovskite host materials for the enhancement of the luminescence properties for a diverse range of colors [10–12]. Diverse synthesis approaches have been used such as green combustion synthesis [13], solution combustion method [14], spray-drying technique [15], precursor decomposition approach [16], spray-pyrolysis process [17], etc among all these the solution combustion process is significant as it is easy, fast, and economical method of preparing high yield of phase pure and homogeneous nanoparticles. The photoluminescence (PL) [1], Thermoluminescence (TL) [18] and cathodoluminescence (CL) [19] studies are helpful in determining the effect of composition, structure, typo morphic details and inherited characteristics. The difference in the luminescence behavior is because of the extrinsic and intrinsic defects such as dislocations, point defects, Frenkel defects, Schottky defects, etc. created in the host lattice. Cathodoluminescence method involves the creation of light in a solid by irradiation of a high energy electron beam providing the temporary defects. From emission bands, migration and diffusion of the luminescent centers can be identified by Cathodoluminescence studies [20]. The crystalline phase directly implements its effects over luminescence phenomena like emission and excitation spectra, lifetime and efficiency, etc. Hence a minor change in the lattice parameters varied due to the added impurities, defects, inclusions, dopants and co dopants that exhibit variations in peak intensity and position of spectral wavelengths.
The magnetic and electric transitions within the 4 f orbitals cause emission of light from the rare earth activator ions [21]. Mainly these transitions involve the 4f⁴⁻¹ and 5D configurations. The outward forces are avoided by the external 5 s and 5p shells leading to sharp emission peaks. Even though transitions between f shells of lanthanide ions are forbidden, due to the lowering of selection rules from the crystal field surrounding the rare earth ions room temperature emission of luminescence can be seen [22]. Due to the structural feasibility for doping activator ions and ease in the synthesis technique aluminates are gathering huge interest. isolation of Sm³⁺ ions in the host lattice is possible using Al³⁺ ions which intern reduces the quenching in quantum luminescence and enhances the luminescence emission efficiency. Compared to other aluminates, the perovskite lanthanum aluminate nanoparticles (LaAlO₃) have shown fascinating characteristics and used as a common material for nanophosphors and solid-state lightning devices for the dosimetric applications. In order to obtain better luminescent nanomaterials, it is important to synthesize phase pure and highly crystalline nanoparticles of uniform size and shape having chemical durability. Commercial nanophosphors synthesized using solid-state methods have few inadequacies as higher synthesis temperature, lower phase purity irregular morphology and increased size. These shortcomings were overcome by using the solution combustion method in the present work [23].

In this article, we are reporting both the PL and CL properties of the Sm³⁺ doped LaAlO₃ nanoparticles prepared by using a solution combustion synthesis method with sucrose as fuel. These nanopowders are characterized using PXRD (Powder X-Ray Diffraction), FESEM (Field Emission Scanning Electron Microscopy), FTIR (Fourier Transform Infrared Spectroscopy), and UV-Visible spectroscopy to investigate their structural and morphological features.

2. Materials and methods

Lanthanum oxide (99%- La₂O₃), Aluminium nitrate (99%- Al(NO₃)₃·9H₂O), Samarium Oxide (99%- Sm₂O₃) and concentrated HNO₃ are procured from Sigma Aldrich chemicals (INDIA) and used as procured. The sucrose is used as fuel for the combustion of the nitrate precursors.

Initially, the stoichiometric amounts of lanthanum oxide and samarium oxide (1–9 mol %) were taken in a 300 ml crucible and converted into respective nitrates by adding the 1:1 HNO₃ solution (nitrating mixture) and keeping on the sand bath for forming nitrate gel. To this gel, the stoichiometric amounts of aluminium nitrate and sucrose were added along with 30 ml deionized water. This solution was made homogeneous by keeping for magnetic stirring for about 10–15 min. Then the crucible is kept into a preheated muffle furnace for combustion at 500 °C ± 10 °C for 5–10 min. The mixture boils and froths to form a fluffy mass by releasing a huge amount of heat and gases. Once the combustion is done the product is allowed to cool down to room temperature and crushed followed by the calcination for 3 h at 900 °C. The final products were collected after cooling down to room temperature, finely grind using pestle and mortar. These nanopowders were characterized using various analytical methods like XRD, SEM, TEM, FTIR, UV-Visible for the study of structural parameters. The luminescence properties were studied using photoluminescence and cathodoluminescence phenomenon.

3. Characterization

The PXRD is carried out using PANalytical X’pert Pro diffractometer, (Cu Kα λ = 1.5418 Å) with a nickel filter in the range 2θ = 20°–80°. FTIR spectra noted using Perkin Elmer Spectrometer, Frontier using the reference of KBr in the range 4000–400 cm⁻¹. The SEM (Zeiss ULTRA 55) attached with Gatan (UK) MonoCL3 system is used to note the SEM images and Cathodoluminescence properties of LaAlO₃: Sm³⁺ nanophosphors. The Photoluminescence observations are performed using a Horiba Fluorolog-3 spectrofluorometer (450 W Xenon lamp). TEM is taken with the help of a Jeol 200CX Transmission electron microscope. UV-Visible spectra is noted using Perkin Elmer Spectrometer, Frontier using the reference of

4. Results and discussion

4.1. Powder x-ray diffraction

The indexed XRD patterns as shown in figure 1(a) are consistent with the JCPDS card number 85–848 having a Rhombohedral structure with a space group R3m and lattice parameter a = 3.789 Å. It is been similar to the reviewed literature [14, 15]. There were no traces of additional peaks confirming the formation of phase pure material. The crystallite size calculated using the Debye Scherer formula (equation (1)) [24] through intensity line broadening technique for each peak and the average size is found to be in the range ~45 nm.
Figure 1. (a): XRD patterns of LaAlO₃:Sm³⁺ (1–9 mol%) nanoparticles. (b): W-H plots of LaAlO₃:Sm³⁺ + (1–9 mol%) nanoparticles.

\[ D = \frac{0.9\lambda}{\beta \cos \theta} \]  

(1)
It was also known that the FWHM can be conveyed as a direct sequence of the lattice strain and crystallite size contribution. Hence, Williamson Hall plots are used for determining the effect of lattice strain on the crystallite size as depicted in figure 1(b) using the equation [14];

$$\beta \cos \theta = \frac{0.9 \lambda}{D} + 4 \varepsilon \sin \theta$$  \hspace{1cm} (2)

Where $\beta$ is full width at half maxima, $\theta$ is the Bragg’s diffraction angle, $\lambda$ is the x-ray wavelength ($\text{Cu K}_\alpha = 1.5418 \text{ Å}$), $D$ is the crystallite size and $\varepsilon$ is the strain associated with the lattice distortions. There is a decrease in the crystallite size with increasing dopant concentration. The crystallite size is found to be in the range of ~65 nm. The minute variations in the crystallite size can be attributed to the fact that the zero strain is assumed while estimating crystallite size in Scherer’s method. The structural parameters are tabulated in table 1.

The percentage of radius difference ($Dr$) between dopant and substituted ions is calculated by using the following equation [25]:

$$Dr = \frac{R_d(CN) - R_h(CN)}{R_h(CN)} \times 100\%$$  \hspace{1cm} (3)

where $R_h$ refers effective radius of cation host, $R_d$ refers effective radius of dopant ion, and CN refers to the coordination number, respectively. The acceptable percentage of radius difference is about 30% [26]. In this case, for CN = 12, the Rh (CN) = 1.032 Å and Rd (CN) = 0.958 Å, and obtained Dr is found to be ~7.17% [27]. Hence it is evident that there are no structural changes due to the substitution of Sm$^{3+}$ ions into the La$^{3+}$ site in the host lattice and thus the structure of the compound is still in the rhombohedral phase. Owing to their small difference in the radii there is a slight shift in the diffraction peaks towards lower angles with an increase in the doping concentration. The decrease in the crystallite size with increasing dopant concentration indicates that the Sm$^{3+}$ ions are strongly overlaid inside the lattice structure of the host LaAlO$_3$. Owing to this phenomenon there occurs an expansion of the unit cell leading to the tensile stress which can be observed as the peak shift towards the lower angle side. Also, the microstrain present in the nanophosphors might be influencing the peak shift [14].

### 4.2. FTIR spectroscopy

The FTIR spectra of the prepared samples are as shown in figure 2. The broad peak at 3435 cm$^{-1}$ is ascribed to the water molecule adsorbed on the nanoparticle surface. The absorption of CO$_2$ is assigned by the peak at 2300 cm$^{-1}$. The vibrational modes of the carboxylate ions are shown by the sharp absorption bands at 1384 cm$^{-1}$. The two sharp peaks in the range 1700–1400 cm$^{-1}$ are attributed to the carboxyl group stretching and C–O bond. The peaks at 1593–1384 cm$^{-1}$ (strong bands) are evident due to the stretch vibrations of NO$_3^−$. The C–O–C crosslinking of hydrocarbon chains resembled by a peak at 1045 cm$^{-1}$. The small presence of the organic species calcined samples if refereed by the very low-intensity band at 1080 cm$^{-1}$ [15, 16]. The peaks in between 800–400 cm$^{-1}$ are due to the stretching vibrations of the M–O bonds (possible La–O and Al–O stretching frequencies) vibrations for the perovskite structure compound observed specifically at 826 and 657 cm$^{-1}$. There is no peak shift observed with the varying dopant ion concentrations. So, it confirms the formation of phase pure Sm$^{3+}$ doped LaAlO$_3$ nanoparticles.

### 4.3. Scanning electron microscopy and transmission electron microscopy

The SEM images of LaAlO$_3$: Sm$^{3+}$ (5 mol%) nanoparticles as shown in figure 3 reveals the agglomerated microgranular structures which may be due to the excess heat liberated during the combustion process. The particle sizes as seen in the images are in agreement with the PXRD results. The particle sizes vary between 41–67 nm. The SEM micrographs clearly indicate the agglomerated spherical nanostructures having various
particle sizes distribution for all samples with different concentrations of Sm$^{3+}$. Hence, we note that there is no influence on the morphology of the samples due to the dopant ion concentration.

The TEM images of LaAlO$_3$:Sm$^{3+}$ (5 mol%) nanoparticles are as shown in figure 4. The TEM pictures also reveal the agglomeration of the nanoparticles and the particle sizes are also matching with the XRD and SEM results. The SAED pattern matches the well-indexed lattice planes of the PXRD plot.
4.4. Energy band gap analysis

The UV-Visible absorption spectra of LaAlO$_3$:Sm$^{3+}$ nanoparticles is as shown in figure 5(a). The optical band gap energy of LaAlO$_3$:Sm$^{3+}$ nanoparticles were estimated from UV-Visible absorption spectroscopy by means of Wood and Tauc relation. By using the following formula, the bandgap energy is estimated with photon energy and absorbance [28]:

\[ \alpha h\nu = A(h\nu - E_g)^n \]

Where \( \alpha \) is absorption coefficient, \( h\nu \) is incident photon energy, \( E_g \) is optical band gap energy, \( A \) is proportionality constant and values of \( n \) varies with the type of electric transitions. The figure 5(b) represents the plot of \((\alpha h\nu)^2\) versus \( E_g \) for LaAlO$_3$:Sm$^{3+}$ nanoparticles. The optical band gap energies are obtained by extrapolating the curve linearly onto the x-axis. The values are found to be in the range 4.9–5.3 eV which are in agreement with the literature.
The bandgap is decreasing with the increasing Sm$^{3+}$ ion concentration indicating the effect of SmO$_8$ clusters on the electronic assembly of the host lattice.

4.5. Photoluminescence studies

The excitation spectra of the La$\textsubscript{0.99}$Sm$\textsubscript{0.01}$AlO$_3$ nanoparticles in the wavelength region 350 nm—550 nm monitored at 598 nm is as shown in figure 6(a). In this spectrum, many forbidden intra f-f transitions related to Sm$^{3+}$ ions are observed as sharp excitation peaks which are attributed to transitions between $^6\text{H}_{5/2} \rightarrow ^4\text{D}_{3/2}$, $^6\text{D}_{3/2}$, $^4\text{F}_{7/2}$, $^4\text{M}_{19/2}$, $^4\text{G}_{9/2}$, $^4\text{I}_{15/2}$, $^4\text{M}_{15/2}$ represented at 364 nm, 378 nm, 408 nm, 419 nm, 441 nm, 465 nm, 481 nm respectively. Amongst these transitions, $^6\text{H}_{5/2} \rightarrow ^4\text{F}_{7/2}$ (408 nm) transition excitation peak is more intense compared to other peaks. Therefore, these nanophosphors can be excited by NUV LEDs [29].

Figure 6(b) depicts the emission spectra of the LaAlO$_3$ nanoparticles doped with 1—9 mol% Sm$^{3+}$ ion concentration under 406 nm excitation wavelength showing four characteristic emission peaks attributed to the transitions of Sm$^{3+}$ ions. Also, figure 6(c) depicts the CIE coordinates which clearly describe that the nanophosphors emit yellowish-orange light and are better suitable for the LEDs. Using the 406 nm excitation wavelength LaAlO$_3$:Sm$^{3+}$ nanoparticles emits yellowish-orange luminescence in the region 540—740 nm. This region comprises of 4 major peaks attributed to the transitions from $^4\text{G}_{5/2}$ to $^4\text{H}_{5/2,7/2,9/2,11/2}$ levels of 4 f orbital. These characteristic peaks in the emission spectra are seen at 565 nm, 601 nm, 648 nm, and 666 nm respectively. The strongest peak is observed at 601 nm corresponding to $^4\text{G}_{5/2}$ transition of Sm$^{3+}$ ions as this transition satisfies the selection rule $\Delta J = \pm 1$. This particular transition comprises of both magnetic and electric dipole emissions. The concentration quenching occurs at 7 mol%. The maximum luminescence intensity is achieved at 5 mol% doping of Sm$^{3+}$ ions [28]. This is mainly because of the decrease in the distance
between the activator ions with an increase in the concentration of doping. When this distance is very much smaller than a particular degree, the possibility of non-radiative transfer of energy will be more between the activator ions, which is also known as cross-relaxation [30, 31]. This can be achieved by either multipole interaction or exchange interaction. Multipole interaction occurs when the critical distance ($R_c$) is greater than 5 Å. And exchange interaction occurs when $R_c$ is below 5 Å. The value of $R_c$ as proposed by Blasse and Bril [32, 33] is given as:

$$R_c = \left(\frac{3V}{4\pi Z\chi_c}\right)^{1/3}$$

(5)

Where in this particular case $V = 377.21$ Å$^3$ refers to the volume of the unit cell; $Z = 6$ refers to the number of cations in the unit cell; $\chi_c = 0.05$ (5 mol%) refers to the critical doping concentration of Sm$^{3+}$ ions. The estimated value of $R_c$ is found to be $\sim 13.4$ Å which is much greater than 5 Å hence the concentration quenching effect of LaAlO$_3$: Sm$^{3+}$ can be ascribed to multipole interaction.

The Commission de Eclairage (CIE) chromaticity coordinate diagram is helpful for determining emission color.

The correlated color temperature (CCT) is one of the important tools used for recognizing the color emergence by the light source. CCT relates the color to a reference light source when heated to a specified temperature in degree Kelvin (K).

The CCT was found by converting the ($x, y$) coordinates of the light source to ($U_0, V_0$) coordinates by using the following equations [34, 35];

$$U' = \left[\frac{4x}{-2x + 12y + 3}\right]$$

(6)

$$V' = \left[\frac{6y}{-2x + 12y + 3}\right]$$

(7)

Further, the superiority of white light was confirmed using color correlated temperature (CCT) which was given by McCamy empirical formula;

$$CCT = -437n^3 + 3601n^2 - 6861n + 5514.31 \text{ (theoretical)}$$

(8)

where $n$ is the inverse slope line given by

$$n = (x - x_c)/(y - y_c);$$

(9)

and the chromaticity epicenter was at $x_c = 0.3320$ and $y_c = 0.1858$.

The effect of Sm$^{3+}$ concentration on the color purity of the LaAlO$_3$ nanophosphors can be estimated by using the following equation,

$$\text{Colour purity} = \frac{(X_S - X_W)}{(X_D - X_W)} \times 100 \text{ or Colour purity} = \frac{(Y_S - Y_W)}{(Y_D - Y_W)} \times 100$$

(10)

where $(X_W, Y_W)$ are the coordinates of the illuminant point, $(X_S, Y_S)$ are the coordinates of the sample in CIE diagram, and $(X_D, Y_D)$ are the coordinates of the dominant wavelength. The estimated values are tabulated in table 2 and the color purity of 5 mol% Sm$^{3+}$ doped LaAlO$_3$ NPs is found to be $\sim 77\%$.

### 4.6. Cathodoluminescence studies

Using the lower voltage electron beam as an excitation source we can observe the strong yellowish-orange emission from the Sm$^{3+}$ doped LaAlO$_3$ nanophosphors. The cathodoluminescence (CL) spectra of the Sm$^{3+}$ doped LaAlO$_3$ nanophosphors are as shown in figure (7). The CL studies were carried out by keeping a working distance of 7.2 mm and 10 kV accelerating voltage.

### Table 2. CIE and CCT coordinates of the of LaAlO$_3$: Sm$^{3+}$ nanoparticles (1, 3, 5, 7 and 9 mol%).

| Sm$^{3+}$ (mol%) | CIE (1931 coordinates) | CIE (1976 coordinates) | n | CCT (K) | Colour purity (%) |
|-----------------|------------------------|------------------------|---|---------|------------------|
| 1               | 0.487 0.441            | 0.2662 0.3616          | 0.6073 | 2577    | 66               |
| 3               | 0.521 0.393            | 0.3112 0.3533          | 0.9047 | 1931    | 75               |
| 5               | 0.551 0.368            | 0.3492 0.3497          | 1.2031 | 1711    | 77               |
| 7               | 0.532 0.387            | 0.3229 0.3530          | 0.9901 | 1827    | 76               |
| 9               | 0.503 0.398            | 0.2972 0.3527          | 0.8058 | 2095    | 71               |
The corresponding characteristic emission peaks for the electron dipole transitions from $^4G_{5/2}$ to $^6H_{5/2}, ^2H_{9/2}$ of Sm$^{3+}$ ions can be seen at 563 nm, 597 nm and 641 nm respectively which agrees well with the photoluminescence spectra as shown in figure 6(a). The maximum intensity is observed at 563 nm for 7 mol% Sm$^{3+}$ doped LaAlO$_3$ nanophosphors [36]. This can be attributed to the dipole transition of the Sm$^{3+}$ ions from $^4G_{5/2}$ to $^6H_{5/2}$. The variations of the cathodoluminescence intensity and Photoluminescence intensity as a function of Sm$^{3+}$ ion concentration is as shown in figure 8. There is an increase in the CL intensity with the increasing Sm$^{3+}$ concentration till 7 mol% afterward the intensity quenches for 9 mol%. Usually, the
luminescence intensity quenching effect due to higher concentration is because of the migration of energy in between the activator ions themselves. In this process of energy migration, there occurs a loss of excitation energy at the quenching sites leading to the lowering of CL intensity [37, 38]. In this case, the quenching of the CL intensity is mainly because of the cross-relaxation process which involves energy transfer between two Sm$^{3+}$ ions of matching energies. Because of the strong CL intensity at less voltage, the Sm$^{3+}$ doped LaAlO$_3$ nanophosphors are better suited for the fabrication of FED devices.

5. Conclusions

We successfully synthesized the LaAlO$_3$ nanoparticles doped with the varying concentrations of the Sm$^{3+}$ ions (1–9 mol%) using sugar as fuel through the solution combustion synthesis method. The PXRD patterns confirm the formation of the phase pure rhombohedral perovskite structures having a crystallite size in the range 34–62 nm. The SEM and TEM images show the agglomerated granular structure of the prepared nanoparticles. The characteristic stretching vibrations are confirmed by the FTIR spectra. The PL emission spectra show the maximum optimum concentration of the Sm$^{3+}$ as 5 mol% after that the quenching occurs. The Commission de Eclairage (CIE) chromaticity coordinate diagram and correlated color temperature (CCT) diagrams show the luminescence behavior of the prepared samples. The CL emission spectra reveal that the maximum optimal concentration of Sm$^{3+}$ as 7 mol% afterward quenching is observed. The samples are capable of emitting the yellowish-orange color and hence suitable for the various display device applications such as optical storage, LCD and FED device fabrication.

ORCID iDs

N Dhananjaya @ https://orcid.org/0000-0002-7973-1353

References

[1] Foster P L et al 2013 Influence of gamma irradiation on photoluminescence properties of poly carbonate films doped with Eu$^{3+}$-bikoketonate complex Radiat. Phys. Chem. 84 47–50
[2] Caruso F et al 1998 Nanoengineering of inorganic and hybrid hollow spheres by colloidal templating Science 282 1111–4
[3] Zeng H C 2006 Synthetic architecture of interior space for inorganic nanostructures J. Mater. Chem. 16 649–62
[4] Zhou P et al 2007 A novel Heck reaction catalyzed by Co hollow nanospheres in ligand free condition Chem. Commun. 14 1418–20
[5] Randy W Set al 1999 Superconductor Josephson Junction Comprising Lanthanum Aluminate. US5906963A
[6] Fang Y P et al 2003 Systematic synthesis and characterization of single crystal lanthanide orthophosphate nanowires J. Am. Chem. Soc. 125 16025–34
[7] Zhang Q and Saito F 2000 Mechanosynthetic characterization of lanthanum aluminate by grinding lanthanum oxide with transition aluminia J. Am. Chem. Soc. 83 439–41
[8] Kaewkho J 2016 Luminescence characteristics of Dy$^{3+}$ doped Gd2O3–CaO–SiO2–B2O3 scintillating glasses J. Rare Earth 34 583–9
[9] Rajagukguk J et al 2016 Structural and optical characteristics of Eu$^{3+}$ ions in sodium lead-zinc-lithium-borate glass system J. Mol. Struct. 1121 180–7
[10] Zhang W W, Meng W, Cao L W and Liu Y L 2008 PEG assisted hydrothermal synthesis of LaPO4:Eu$^{3+}$ nanoparticles Spectrosc. Spec. Anal. 28 1023–5 Guang pu xue yu guang pu fen xi= Guang pu
[11] Bu W et al 2008 Synthesis and characterization of uniform spindle-shaped micro architectures self-assembled from aligned single-crystalline nanowires of lanthanum phosphates Cryst. Growth Des. 7 2305–5
[12] Zaman F et al 2016 Investigation of luminescence and laser transition of Dy$^{3+}$ in Li2O-Gd2O3-Bi2O3-B2O3 glasses Opt. Mater. 55 1836–44
[13] Pratibha S et al 2019 Effect of Sm$^{3+}$, Bi$^{3+}$ ion doping on the photoluminescence and dielectric properties of phytosynthesized LaAlO$_3$ nanoparticles J. Mater. Sci. Mater. Electron. 30 6745–59
[14] Manohar T, Naik R, Prashanthala S C, Nagabhushana H, Sharma S C, Nagaswarupa H P, Anantharaju K S, Pratapkumar C and Premkumar H B 2015 Photoluminescence and Judd–Ofelt analysis of Eu$^{3+}$ doped LaAlO$_3$ nanophosphors for WLEDs Dye. Pigment. 122 22–30
[15] Manjunatha C R et al 2019 Perovskite lanthanum aluminate nanoparticles applications in antimicrobial activity, adsorptive removal of Direct Blue 33 dye and fluoride Mater. Sci. Eng. C 101 674–83
[16] Rivas-Murias B et al 2011 Spray drying: an alternative synthesis method for polycationic oxide compounds J. Phys. Chem. Solids 72 158–63
[17] Pazik R et al 2011 Crystal structure and morphology evolution in the LaXO$_3$, X=Al, Ga, In nano–oxide series. consequences for the synthesis of luminescent phosphors Inorg. Chem. 50 2966–74
[18] Lux B C et al 1993 Aerosol generation of lanthanum aluminate J. Am. Ceram. Soc. 76 2669–72
[19] Isasi–Marin J, Perez–Estebanez M, Diaz–Guerra C, Castillo J F, Correcher V and Cuervo–Rodriguez M R 2009 Structural, magnetic and luminescent characteristics of Pr$^{3+}$ doped ZrO2 powders synthesized by a sol–gel method J. Phys. D: Appl. Phys. 42 075318
[20] Muhlongo G H et al 2011 The influence Pr$^{3+}$ of co-doping on the photoluminescence and cathodoluminescence properties of SiO$_2$: Eu$^{3+}$/Tb$^{3+}$ J. Lumin. 131 570–4
[21] Kacliff MA S and Phillips M R 1995 Cathodoluminescence micro characterization of the defect structure of quartz Phys. Rev. 52 3122–34
[22] Dieke G H, Crosswhite H M and Crosswhite H 1968 Spectra and energy levels of rare earth ions in crystals (NewYork: Interscience)
[23] Ankoji P and Hemalatha Budramadevi B. 2019 Structural and luminescence properties of LaAlO₃: Sm³⁺ nanophosphors synthesized via hydrothermal method. *Opt. Mater.* 95:109249

[24] García-Hipolito M et al. 2001 Cathodoluminescent and photoluminescent properties of terbium doped ZrO₂ films prepared by pneumatic spray pyrolysis technique. *J. Lumin.* 93:9–15

[25] Scherrer P. 1918 Bestimmung der inneren Struktur und der Größe von Kolloidteilchen mittels Röntgenstrahlen. *Nach Gesel Wis Gött.* 1918:98–100

[26] Chen W. 2015 Eu²⁺ and Eu³⁺ co-activated LaAlO₃ phosphor: synthesis and tuned luminescence. *Dalton Trans.* 44:17730–5

[27] Pires A M and Davolos M R. 2001 Luminescence of europium (III) and manganese (II) in barium and zinc orthosilicate. *Chem. Mater.* 13:21–7

[28] Shivakumara C et al. 2015 Synthesis of Eu³⁺-activated BaMoO₄ phosphors and their Judd–Ofelt analysis: Applications in lasers and white LEDs. *Spectrochim. Acta, Part A.* 151:141–8

[29] Halappa P, Rajashekar H M and Shivakumara C. 2019 Synthesis and structural characterization of orange red light emitting Sm³⁺ activated BiOCl phosphor for WLEDs applications. *J. Alloys Compd.* 169:77

[30] Lee S H et al. Ultraviolet radiation excited strong red-emitting LaAlO₃: Eu³⁺ nanophosphors: synthesis and luminescent properties. *Ceram. Int.* 2016:12.123

[31] Long S, Hou J, Zhang G, Huang F and Zeng Y. 2013 High quantum efficiency red-emission tungstate based phosphor Sr (La₁−xEux) 2Mg₂WO₁₂ for WLEDs applications. *Ceram. Int.* 39:6013–7

[32] Blasse G. 1986 Energy transfer between inequivalent Eu²⁺ ions. *J. Solid State Chem.* 62:207–11

[33] Blasse G and Bril A. 1969 Energy transfer in Tb³⁺-activated cerium (III) compounds. *J. Chem. Phys.* 51:3252–4

[34] Yashaswini C, Pandurangappa and Dhananjaya N. 2019 Structural and optical studies of CaSO₄:Ce³⁺ nanorods for display and dosimetric applications. *Eur. Phys. J. Plus.* 134:177

[35] Li C, Cui G, Melgosa M, Ruan X, Zhang Y, Ma L, Xiao K and Luo M R. 2016 Accurate method for computing correlated color temperature. *Opt. Express* 24:14066

[36] Liu X et al. 2009 Nanocrystalline LaAlO₃: Sm³⁺ as a promising yellow phosphor for field emission displays. *J. Electrochem. Soc.* 156:1–7

[37] Boronat C et al. 2017 Cathodoluminescence emission of REE (Dy, Pr and Eu) doped LaAlO₃ phosphors. *Radiation Phys. and Chemistry.* 130:236–42

[38] Shannon R D. 1976 Revised effective ionic radii and systematic studies of interatomic distances in halides and chalcogenides. *Acta Cryst.* A 32:751–67