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Effects of Er\(^{3+}\) concentration on the structure and optical properties of the MgAl\(_2\)O\(_4\)/MgO/Sr\(_3\)Al\(_2\)O\(_6\)/SrAl\(_2\)O\(_4\) mixed phases prepared by the citrate sol gel method

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Abstract

The mixed phases of the un-doped MgAl\(_2\)O\(_4\)/MgO/Sr\(_3\)Al\(_2\)O\(_6\)/SrAl\(_2\)O\(_4\) (MMSS), MgAl\(_2\)O\(_4\)/MgO (MM) Sr\(_3\)Al\(_2\)O\(_6\)/SrAl\(_2\)O\(_4\) (SS), and the doped MMSSx% Er\(^{3+}\) (0 \(\leq x \leq 1.8\)) nanopowders were synthesized using the citrate sol-gel method. The effect of Er\(^{3+}\) concentration on the structure, morphology and optical properties were investigated. X-ray powder diffraction (XRD) analysis indicated the cubical MgAl\(_2\)O\(_4\), MgO and Sr\(_3\)Al\(_2\)O\(_6\) and monoclinic SrAl\(_2\)O\(_4\) phases. The scanning electron microscopic images revealed the transformation of irregular particles to rod-like structure with an increase in Er\(^{3+}\) concentration. Transmission electron microscope indicated the nanosized particles depends on Er\(^{3+}\) concentration. Several distinct absorption bands located at 444, 546, 653 and 704 nm under UV excitation (285 nm) corresponding to the defects states of the MgAl\(_2\)O\(_4\), MgO, Sr\(_3\)Al\(_2\)O\(_6\), and SrAl\(_2\)O\(_4\) phases were observed. There were traces of emission peaks at 546 and 653 nm attributed to the \(4S_{3/2} \rightarrow \) \(4I_{15/2}\) and \(4F_{9/2} \rightarrow \) \(4I_{15/2}\) transitions of Er\(^{3+}\) ion. An exponential decrease in luminescence was observed with an increase in Er\(^{3+}\) concentration.

1. Introduction

The advancement of new luminescent materials has attracted many researchers due to their compelling properties as a function of crystalline size and technological applications [1]. Among many studied luminescent materials, magnesium aluminate (MgAl\(_2\)O\(_4\)), magnesium oxide (MgO) and strontium aluminates (Sr\(_3\)Al\(_2\)O\(_6\) and SrAl\(_2\)O\(_4\)) have shown great interest to many researchers due to their fascinating properties [2–4]. MgAl\(_2\)O\(_4\) is described as an AB\(_2\)O\(_4\) spinel and exhibits a cubic structure consisting of face centred cubic (fcc) structure [5]. The MgAl\(_2\)O\(_4\) has a wide band gap \(\sim 5.82\) eV [6]. MgO with band gap of \(\sim 5.26\) eV [7] has been reported to be a promising inorganic material which can show crystallization in sodium chloride structure [7]. It has many applications such as in optical coatings, sensor, water treatment, catalysis and antimicrobial [8]. SrAl\(_2\)O\(_4\) is another interesting compound which was used to make transparent ceramics, mechanoluminescence, long lasting luminescence etc [9]. Mindru et al [10] reported cubical symmetry of SrAl\(_2\)O\(_4\) phase having wide band gap \(\sim 6.3\) eV [11]. SrAl\(_2\)O\(_4\) is considered a good luminescent material and a higher chemical stability with wide band gap \(\sim 6.5\) eV [12]. Garcia et al [13] reported that SrAl\(_2\)O\(_4\) consist of monoclinic phase structure. Different methods have been used to synthesize the bulk materials of the MgAl\(_2\)O\(_4\), MgO, Sr\(_3\)Al\(_2\)O\(_6\) and SrAl\(_2\)O\(_4\) such as hydrothermal synthesis [14], solid-state reaction [15], precipitation [16], combustion method [17] and citrate sol-gel method [18]. The citrate sol-gel method was used in this study as it is economical, low temperatures \(\sim 80^\circ\)C synthesis, less time consuming, and having good control of morphological particles. These wide band
gap materials can be made to emit emission in visible- infrared (IR) region by activating the host matrix by foreign atoms such as the lanthanide rare earth (Ln) metals [19]. One good example of the Ln is Er$^{3+}$ ion. Er$^{3+}$ is one of efficient ions to achieve IR to visible up-conversion [20]. Mironova-Ulmane et al [21] reported a study on the up and down conversion analysis of Er$^{3+}$ doped on MgAl$_2$O$_4$ spinel matrix. The emission results showed peaks at 550 and 660 nm, which were attributed to the $^4$S$_{3/2}$ $\rightarrow$ $^4$I$_{15/2}$ and $^4$F$_{9/2}$ $\rightarrow$ $^4$I$_{15/2}$ transitions of Er$^{3+}$. Balakrishnan et al [8] reported the study of optical and photocatalytic properties of MgO nanoparticles via combustion method. The PL results showed that under excitation of 385 nm three emissions were observed at 425, 461, and 495 nm which were attributed to defects band transition and oxygen vacancies. Choudhary et al [22] reported a study on effect of the Er$^{3+}$, Yb$^{3+}$ and Zn$^{2+}$ ion concentration and temperature on the up-conversion behaviour of Er$^{3+}$/Yb$^{3+}$ co-doped SrAl$_2$O$_4$ phosphor. The study of Er$^{3+}$ and Er$^{3+}$/Yb$^{3+}$ co-doped Sr$_2$Al$_2$O$_4$ phosphors was carried out by Singh et al [23], in which sample was prepared via a soft combustion synthesis route. The UV-Visible absorption results suggested that the presence of various bands correspond to the doped trivalent Ln ions. With this previous reports, it is clear that the investigations of doping the Er$^{3+}$ on the single phases or bulk materials (MgAl$_2$O$_4$, MgO, Sr$_2$Al$_2$O$_6$ and SrAl$_2$O$_4$) and other related foreign ions have

Figure 1. XRD patterns of the (a) un-doped MMSS, MM, SS phases (b) un-doped MMSS, ICSD files of MgAl$_2$O$_4$, MgO, Sr$_2$Al$_2$O$_6$, SrAl$_2$O$_4$ and (c) MMSS:x% Er$^{3+}$ (0 \leq x \leq 1.8) samples.
already been reported in literature [21–23]. However, there is no evidence on the studies of the mixed phases of MgAl₂O₄/MgO/Sr₃Al₂O₆/SrAl₂O₄ doped with Er³⁺ which have been reported to date. Thus, this study is aimed at investigating the effects of Er³⁺ concentration on the structure, morphology and optical properties of MgAl₂O₄/MgO/Sr₃Al₂O₆/SrAl₂O₄ prepared by citrate sol gel method. The main objective is to fabricate better luminescent materials for practical applications such as the light emitting diode (LED). Emission channels associated with the observed emissions are also proposed.

2. Experimental

2.1. Synthesis
The citrate sol-gel method was opted for the synthesis of various samples i.e. un-doped MMSS, MM (MgAl₂O₄ and MgO), SS (SrAl₂O₄ and Sr₃Al₂O₆) and MMSS:x% Er³⁺ (0 ≤ x ≤ 1.8). All of the chemicals used in this study
were purchased at Sigma Aldrich. The un-doped MMSS sample was prepared by mixing appropriate amount of 3.808 g Mg(NO$_3$)$_2$.6H$_2$O (98%), 3.411 g Sr(NO$_3$)$_2$.4H$_2$O (99%), 10.919 g Al(NO$_3$)$_3$.9H$_2$O (98%) and 2.328 g citric acid C$_8$H$_8$O$_7$.H$_2$O (99%), respectively in 30 ml deionized water. Similarly, for un-doped MM (MgAl$_2$O$_4$/MgO) and SS (SrAl$_2$O$_4$ and Sr$_3$Al$_2$O$_6$) samples separate bulk solutions were prepared by dissolving same desired amount of Mg(NO$_3$)$_2$.6H$_2$O (98%), Al(NO$_3$)$_3$.9H$_2$O (98%) and Sr(NO$_3$)$_2$.4H$_2$O (99%) in separate 30 ml deionized water, in which citric acid was added later on. The doped samples were prepared by adding the required amount of ErCl$_3$.6H$_2$O (99.99%) for a range ($0 \leq x \leq 1.8$) in an un-doped MMSS solution. A magnetic stirrer was used to constantly stir the different solutions which was kept at ~80 °C temperature until transparent solution gels were formed. Initially, the gels were dried in an oven for an hour at 130 °C and later on annealed at 1200 °C for 2 h until white powders were formed. The powders were taken for characterizations using different techniques.

### 2.2. Characterization

The XRD Bruker D8-Adance powder diffractometer with a Cu-K$_\alpha$ (1.5405 Å) radiation was used to characterize the crystal structure of the prepared nanopowders. The phases were identified using X’Pert Highscore plus software. The relative phase amounts (weight %) were estimated using the Rietveld method. The Zeiss Supra-55 scanning electron microscope (SEM) coupled with an energy dispersive x-ray spectroscopy (EDS) was used to analyse the surface morphology and elementary composition of the prepared nanopowders. JEOL JEM 1010 transmission electron microscopy (TEM) was used to study the particle size of the prepared nanopowder samples. The absorption characteristics of the prepared samples were investigated on the Perkin-Elmer LS-55 UV–vis spectrophotometer. The Hitachi F-7000 fluorescence spectrophotometer was used to monitor photoluminescence spectra and radiative decay curves.

### Table 2. Summary of the crystallite size estimated by considering planes of different phases.

| Sample ID | Crystal size (nm) | MgAl$_2$O$_4$ (311) | MgO (002) | Sr$_3$Al$_2$O$_6$ (044) | SrAl$_2$O$_4$ (112) |
|-----------|-------------------|----------------------|-----------|------------------------|-------------------|
| MMSS      |                    | 23                   | 40        | 60                     | 17                |
| x = 0.2%  |                    | 22                   | 38        | 59                     | 18                |
| x = 0.4%  |                    | 24                   | 37        | 51                     | 15                |
| x = 0.6%  |                    | 21                   | 37        | 46                     | 17                |
| x = 0.8%  |                    | 19                   | 41        | 56                     | 17                |
| x = 1.2%  |                    | 21                   | 38        | 49                     | 15                |
| x = 1.4%  |                    | 21                   | 40        | 51                     | 18                |
| x = 1.8%  |                    | 19                   | 43        | 45                     | 17                |

Figure 3. EDS spectrum of the un-doped MMSS.

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3. Results and discussion

3.1. XRD analysis

Figure 1(a) shows the x-ray patterns of the un-doped MMSS, MM and SS phases which correspond to the diffraction patterns of cubic MgAl2O4 and MgO samples matches well with the standard ICSD no. 77-1203 and 64 928, respectively shown in figure 1(b). On the other hand strontium aluminate sample exhibits two phases namely cubical Sr3Al2O6 (ICSD: 71860) and monoclinic SrAl2O4 (ICSD: 26466) phases. Furthermore, magnesium strontium aluminate sample co-exhibits four crystallographic phases of the MMSS. The quantification of each phase present in MMSS is presented in table 1. Figure 1(c) shows the patterns of the MMSS:x% Er3+ (0 ≤ x ≤ 1.8) samples, which revealed similar patterns as obtained in the un-doped MMSS sample shown in figure 1(a). This observation reveal that Er3+ ion doping did not affect the crystal structure of the phases within MMSS.

The analysis of the most intense peaks (311), (002), (044) and (112) of the MgAl2O4, MgO, Sr3Al2O6 and SrAl2O4 phases are shown in figure 2, respectively. Figure 2(a) shows the most intense diffraction peak (311) of MgAl2O4 phase does not have significant peak shift with the Er3+ ion doping. This is attributed to the comparison of the ionic radius of Mg2+ (0.72 Å) [5], which is comparable to the Er3+ ion size (0.88 Å) [24] and hence possibility of Mg ion substitution cannot be ruled out. Similar results were observed in our previous study of MgAl2O4:Mn2+ Dlamini et al [25]. Figure 2(b) shows the most intense peak (002) of MgO phase which generally indicates that at ≤0.6% Er3+ the peaks slightly shifted to higher angle while at the ≥0.8% Er3+ the diffraction peak was slightly shifted to lower angle. The results therefore revealed that the lattice constant in the case of MgO depends on the Er3+ concentration. In the plane (044) corresponding to the Sr3Al2O6 phase shown in figure 2(c), the results generally show that for the ≤0.6% Er3+ the diffraction peak (in comparison to the MMSS) shifted towards higher angles, while there was no shift for the ≥0.8% Er3+. Comparing the ionic radius of Er3+ (0.88 Å) with Sr2+ (1.21 Å) [26] and Al3+ (0.53 Å), the difference between the ionic radius is similar i.e. 0.33 Å and 0.35 Å for Sr2+ and Al3+ with Er3+ ion, it becomes a difficult task for the substitution of Er3+ either to Al3+ or Sr2+. Further, it is obvious that to accommodate Er3+ ion at Sr2+ site, charge compensation is required although at Al3+ ion site charge compensation is not required. Apparently Er3+ ion may substitute Al3+ ion in Sr3Al2O6 and SrAl2O4 phases. It is expected that due to the higher coordination number of Al3+ ion site in SrAl2O4 phase, Er3+ ion would prefer to accommodate in (cubical) SrAl2O4 phase rather in distorted (monoclinic) SrAl2O4 phase [27]. In the case of plane (112) of SrAl2O4 phase shown in figure 2(d), the peak slightly shifted to lower angles. This is attributed to similar observation and explanation in figure 2(b).

![Figure 4. EDS elemental map of the un-doped MMSS sample.](image-url)
The crystallite sizes of the MMSS mixed phases shown in table 2 were estimated using the Scherrer’s equation (1) [28]. The crystal sizes were estimated from the most intense diffraction peaks (311), (002) (044) and (112) of the MgAl2O4, MgO, Sr3Al2O6 and SrAl2O4 phases, respectively. It can be observed from table 2 that varying the Er3+ concentration slightly affected the size of crystallite size. Overall, the crystalline size reduces in doped than the un-doped sample. However, the crystalline size corresponding to SrAl2O4 phase is smaller than other phases.

3.2. EDS analysis

The EDS spectrum of the un-doped MMSS sample is shown in figure 3. The spectrum confirms the presence of the Mg, Sr, Al and O elements in the prepared samples. The observed extra peak of carbon (C) around 0.3 eV is

Figure 5. SEM images of the (a) un-doped MMSS, (b) x = 0.2% (c) 0.4% (d) 0.6% (e) 0.8% (f) 1.2% (g) 1.4% and (h) 1.8% Er3+.

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attributed to the carbon tape attached to the sample holder during sample preparation for the EDS measurements [29]. Note that the Er was not detected in all of the doped samples and that can possibly be attributed to the low Er$^{3+}$ concentrations, which were not sensitive to the EDS technique used in this study. Figure 4 presents the elemental map of the un-doped MMSS. The individual and layered image shows that Mg, Sr, Al and O elements are distributed all over the surface.
3.3. SEM analysis

The morphology of the un-doped and MMSS:x% Er\(^{3+}\) (0 ≤ x ≤ 1.8) samples are shown in figure 5. For the un-doped and lower concentrations 0.2 ≤ x ≤ 0.4 shown in figures 5(a)–(c), the morphology consists of the irregular particles closely packed and distributed over the sample surface. The particles are smaller and highly agglomerated to each other at x = 0.4. For the 0.6 ≤ x ≤ 0.1.2 the morphology starts to transform from irregular particles to rods-like structures. The degree of rods-like structures seem to be increasing with Er\(^{3+}\) concentration. At the higher Er\(^{3+}\) concentrations 1.4 ≤ x ≤ 1.8, the rod-like structures seem to be transforming into the bigger particles of different shapes. Therefore, the results clearly suggest that the surface morphology highly depends on the Er\(^{3+}\) doping concentration.

3.4. TEM analysis

The TEM analysis technique was further used to estimate the particle sizes of the prepared nanopowders. The image of the un-doped MMSS is illustrated in figure 6(a). It shows particles that are closely packed together with the estimated particle size around 51 nm. Generally, all other Er\(^{3+}\) doped (0.2 ≤ x ≤ 1.8) samples clearly indicate that the particle sizes are at least below 50 nm. It is interesting to realize that the rods-like structures are clearly observed at x = 0.6% Er\(^{3+}\), which agrees very well with the SEM results in figure 5(d). From x ≥ 0.6%, it can be seen that the average particle sizes get bigger as it was also observed on the SEM results shown in figure 5. The results show that varying the Er\(^{3+}\) doping concentration influences the average particle sizes and shapes.

3.5. UV-Visible reflectance analysis

Figure 7 display the UV-Visible reflectance spectra of the un-doped MMSS, SS, MM and MMSS:x% Er\(^{3+}\) (0 ≤ x ≤ 1.8) samples. From figure 7(a), it can be seen that the un-doped MMSS, SS and MM samples shows broad absorption bands at around 265 and 310 nm. The absorption band at 265 nm is related to the defect levels of the phases present in the lattice. In particular, absorption band arise from the O\(^{2-}\) → Al\(^{3+}\) charge transition in MgAl\(_2\)O\(_4\) phase during the excitation of electrons from the valence band to the conduction band [29, 30]. The observed absorption band in all four phases of MMSS at around 310 nm is attributed to the change of lamp to the other lamp during the reflectance measurement on the system [31]. When considering the Er\(^{3+}\) doped samples shown in figure 7(b), it can be seen that there are additional five sharp absorption bands located at 380, 406, 493, 524 and 652 nm. These absorption peaks are attributed to f-f transitions in Er\(^{3+}\) ions from the ground state \(^{4}I_{15/2} \rightarrow ^{2}H_{9/2}, ^{4}G_{11/2}, ^{4}F_{3/2}, ^{2}H_{11/2}\) and \(^{4}F_{9/2}\), respectively [32]. The results clearly shows that the addition of the Er\(^{3+}\) concentration to the un-doped sample results in new absorption peaks.

3.6. Photoluminescence analysis

The photoexcitation and photoluminescence (PL) spectra of the mixed phases of the un-doped MMSS, MM, SS and MMSS:x% Er\(^{3+}\) (0 ≤ x ≤ 1.8) series are presented in figure 8. PL analysis of un-doped samples revealed three excitation peaks located around 234 nm, 285 nm and 310 nm when monitoring the emission peak at 653 nm. The observed excitation peaks at 234 nm and 285 nm are certainly attributed to the band-to-band excitation [33] and neutrally charged vacancy known as F center [34], respectively. The 310 nm excitation peak
can be attributed to the defect levels within the SrAl$_2$O$_4$ of the SS phase [35]. There are four emissions peaks located at around 444, 546, 653 and 704 nm when monitoring 285 nm excitation. Peaks at 444 and 546 nm are assigned to the defect levels within the F and F$_2$—centers in pure $\alpha$-Al$_2$O$_3$ for both phases of SrAl$_2$O$_4$ and Sr$_3$Al$_2$O$_6$ phases [36], which are evidently shown by the normalized emission spectra (see figure 8(b)). It can be observed from figure 8(b) that there is a shoulder appearing at 500 nm which is attributed to the defect level within the F$_2$—center of Al$_2$O$_3$ of the SrAl$_2$O$_4$ phase [37]. Previously, Balakrishnan et al [8] reported emission peaks at 425, 432 and 495 nm to be from defect band transition and band to band transition for MgO nanoparticles, hence the observed emissions at 444 and 500 nm can also be attributed to the defect level within
the MgO phase. Emission peak observed at 653 nm is associated with the abundance of oxygen vacancy within the lattice of all phases maybe due to higher calcination temperature [33]. On the other hand, the green and red emission peaks at 546 and 653 nm, respectively are due to Er$^{3+}$ ions. These peaks are respectively attributed to $^4I_{15/2} \rightarrow ^4I_{15/2}$ and $^4I_{15/2} \rightarrow ^4I_{15/2}$ transitions of Er$^{3+}$ [38]. Similar emissions were reported by Wei et al [39]. The emission peak at 704 nm is originating from the MgAl$_2$O$_4$ defects. Taking into account the annealing temperature considered by Yoon et al [37] and this study, it is indeed reasonable to conclude that 704 nm for the un-doped sample is originating from the MgAl$_2$O$_4$. Figure 8(c) shows the excitation and emission spectra of the MMSS:x% Er$^{3+}$, it can be observed that doping the MMSS did not results in new emission peaks which is evidently shown by the normalized emission spectra in figure 8(d). The same emission peaks observed in figures 8(a) and (b) are also observed in (c) and (d). The emission intensity for the 653 nm peak as a function of Er$^{3+}$ concentration is shown in figure 8(e). For the investigated range, the results revealed an exponential decrease of emission intensity as Er$^{3+}$ concentration was increased. The decrease in luminescence with an increase in Er$^{3+}$ for the 653 nm peak is attributed to the concentration quenching [40], which is induced by the rates of non-radiative transitions known as the cross-relation or migration between the activator ions being increased [41]. In order to enhance and optimize the 653 nm emission intensity in MMSS:x% Er$^{3+}$ mixed phases, it is recommended that the window 0%–0.4% Er$^{3+}$ concentration be investigated to explore the optimum Er$^{3+}$ concentration into these mixed phases material. However, for the emission peak at 444 nm, the optimum luminescence intensity is found at $x = 0.4\%$ Er$^{3+}$ concentration.

The un-doped MMSS was excited by different wavelengths (240–300 nm) in order to obtain and confirm the optimum excitation wavelength and the results are shown in figure 9(a). The result indicate that there are five emission peaks located at 444, 486, 546, 653 and 704 nm under the excitation of 240 nm. These emissions are attributed to arise from the same notion as discussed above. The shoulder at 486 nm is in this case clearly visible, this emission may be a second order peak from the excitation of 240 nm. Figure 9(b) shows the emission intensity as a function of excitation wavelength and the results revealed the Gaussian behaviour with the maximum at 285 nm, which correspond to the excitation wavelengths used in figure 8.

Figure 10 present the proposed excitation and emission pathway mechanism of the un-doped MgAl$_2$O$_4$, MgO, SrAl$_2$O$_4$ and Sr$_3$Al$_2$O$_6$. The pathways proposed are based on the PL results displayed in figure 8. Figures 10(a) and (b) shows the mechanism for the MgAl$_2$O$_4$ and MgO. Considering the band gaps of the Sr$_3$Al$_2$O$_6$ (6.3 eV) [9] and SrAl$_2$O$_4$ (6.5 eV) [10] into account, it can be seen as shown in figures 10(b) and (c) that the 310 nm (4 eV) excitation energy is lower than the energy band gaps of both Sr$_3$Al$_2$O$_6$ and SrAl$_2$O$_4$ phases, indicating that this excitation goes to an intermediate energy level below the conduction band. The excited electrons are de-excited by non-radiative relaxation through different channels resulting in the observed emissions. Figure 10(e) shows the resulted mechanism of Er$^{3+}$ from the 285 nm excitation wavelength which produced the emissions at 546 and 653 nm.

The radiative lifetime measurements of the prepared nanopowders were undertaken at 285 nm excitation and 653 nm emission. Figure 11(a) shows the exponential decay curves of the un-doped MMSS, MM and SS, while the MMSS:x% Er$^{3+}$ ($0 \leq x \leq 2$) series is shown in figure 11(b). Generally, all of the samples exhibit the same afterglow phosphorescence mechanism and were fitted using the second order exponential decay [32],...
shown in equation (1).

\[ I(t) = I_0 + A_1 e^{-\frac{t}{\tau_1}} + A_2 e^{-\frac{t}{\tau_2}} \]  

(1)

Where \( I(t) \) represent the phosphorescent intensity, \( I_0 \) is the initial luminescence intensity, \( A_1 \) and \( A_2 \) are constants which contribute to the fast and slow decay component and \( t \) is the time of measurement. The \( \tau_1 \) and \( \tau_2 \) are the fast and slow decay time values are presented in table 3.
4. Conclusion

The undoped MMSS, SS, MM and MMSS:x% Er\(^{3+}\) (0 \(\leq x \leq 2\)) series were successfully prepared by the citrate sol-gel method. The XRD results showed that the structure of the prepared nanopowders consists of the mixture of the cubic (MgAl\(_2\)O\(_4\), MgO and Sr\(_3\)Al\(_2\)O\(_6\)) and monoclinic SrAl\(_2\)O\(_4\) phases. Varying the Er\(^{3+}\) concentration did not affect much the crystal structure of the MMSS phases. Electron microscopy results showed that doping affected the morphology of the prepared powders. The reflectance spectra showed absorption bands at 210, 265, 310, 380, 406, 493, 524 and 652 nm which were attributed to the MgAl\(_2\)O\(_4\), Sr\(_3\)Al\(_2\)O\(_6\) host and Er\(^{3+}\) ions. Varying the Er\(^{3+}\) concentration resulted in addition of absorption peaks. PL results showed four emission peaks located at 444, 500, 546, 653 and 704 nm. These peaks were attributed to the MgAl\(_2\)O\(_4\), Sr\(_3\)Al\(_2\)O\(_6\) and SrAl\(_2\)O\(_4\) phases. Increasing the Er\(^{3+}\) concentration lead to the 653 nm emission luminescence quenching.

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References

[1] Mhlongo M R, Koos I F, Kroon R E, Motaung T E and Motloung S V 2019 J. Mol. Struct. 1184 92–101
[2] Nassar Y M Y, Ahmed S I and Samir I 2014 Mol. Bio. Spectro. 131 329–34
[3] Zhang J, Zhang X, Shi J and Gong M 2011 J. Lumin. 131 2463–7
[4] Calderon-Olvera R M, Albanes-Ojeda E A, Garcia-Hipolito M, Hernandez-Alcantara J M, Alvarez-Perez M A, Falcony C and Alvarez-Fregoso O 2018 Ceram. Inter. 44 7917–25
[5] Melato L T, Motaung T E, Ntwaeaborwa O M and Motloung S V 2017 Opt. Mat. 66 319–26
[6] Motloung S V, Dejene B F, Kroon R E, Ntwaeaborwa O M, Swart H C and Motaung T E 2017 Optik 131 705–12
[7] Raghavendra M, Lalithambha H S, Sharaath B S and Rajanaika H 2017 Sciem. In. 24 3002–13 (https://www.researchgate.net/doi:http://%3A%2F%2Fdxx.doi.org%2F10.24200%2Fsci.2017.4491)
[8] Balakrishnan G, Velavan R, Bato M K and Raslan E H 2020 Res. Phy 16 103013
[9] Akinya M, Xu C N, Liu Y, Nonaka K and Watanabe T 2002 J. Lumin. 97 13–3
[10] Mindu I, Gisagau D, Patron L, Marinasus G, Culita D C, Calderon- Moreno J M, Preda S and Secu M 2017 Ceram. Inter. 43 16668–75
[11] Misievicius M, Jorgenses J and Kareiva A 2013 Mat Sci. 19 38–42
[12] Sharma S K 2014 Strontium Aluminate-from Synthesis to Applications (Lampert Academic Publishing) (https://www.morebooks. shop/store/gb/book/strontium-aluminate-phosphors-from-synthesis-to-applications/isbn/978-3-659-29605-3)
[13] Garcia C K, Diaz-Torres L A, Sala P, Guzman M and Angeles-chavez C 2015 Mat. Sci. Sem. Pro. 37 105–11
[14] Amini M M, Mirzaee M and Sepanj N 2007 Mater. Res. Bull. 42 563–70
[15] Kashi N, Maekawa H and Hinaru Y 1999 J. Am. Ceram. Soc. 82 1844–8
[16] Alvar E N, Rezaei M and Alvar H N 2010 Powder Technol. 198 275–8
[17] Zhai B, Ma Q, Xiong R and Huanga Y M 2016 Mater. Res. Bull. 75 1–6
[18] Rezgui S and Gates B C 1997 J. Non-Cryst. Solids. 210 287–97
[19] Maphiri V M, Wesley-Smith J and Motloung S V 2019 J. Lumin. 215 116710
[20] Verma S, Mishra A, Bhuie M and Singh N K 2018 Int. J. Res. Elec. Com. 6 2348–2281 (http://nebula.wsimg.com/22111770e5326ac1a7657d4e9ac167c?AccessKeyId=DFB1B1ACED7E7997D5B1&disposition=0&alloworigin=1)
[21] Mironova-Ulmane N, Sarakovskis A and Skvortsova V 2015 Phys. Pro. 76 106–10
[22] Choudhari A K, Dwivedi A, Bahadur A and Rai S B 2017 Spe. Acta. Mol. Bio. Spec. 185 155–62
[23] Singh V, Setha M and Mohapatra M 2019 J. Mater. Sci. Elec. 30 2927–34
[24] Wu S Y, Dong F N, Wei W and Naturforch Z 2004 Zeitschrift für Naturforschung A 59 341–5
[25] Dlamini C, Mhlongo M R, Koos I F, Motaung T E, Hlatshwayo T T and Motloung S V 2020 Appl. Phys. A 126 75
[26] Ayvazikl Y, Kotan Z, Ekdal F, Karabulut Y, Caminoala G, Garcia and Guine A 2013 J. Lumin 144 128–32
[27] Hou Q, Meng F and Sun J 2013 Nano Res. Let. 8 144
[28] Cullity B D and Sock R S 2001 Elements of X-Ray Diffraction 3rd edn (Reading: Pearson Education) pp 402–4 (https://www.pearsone. com/store/p6/elements-of-x-ray-diffraction-P100000151708/9780201610918)
[29] Koos I F, Dejene B F, Hone F G, Swart H C, Motloung S V, Motaung T E and Pawad V B 2018 J. Lumin. 200 205–15
[30] Mostafa Y, Nassar S I and Ahmed S A 2014 Mol. Bio. Spectro. 334 329–34 (https://www.researchgate.net/doi:http://13A%2F%2Fdx. doi.org/%210.1016%2Fsa.2014.04.040)
[31] Motloung S V, Thabala K G, Kroon R E, Hlatshwayo T E, Mlambo M and Mpelane S 2019 J. Mol. Struct. 1175 241–52
[32] Singh B P, Parchur A K, Singh R K, Ansari A A, Singh P and Rai S B 2013 Phys. Chem. Phys. 15 3480
[33] Tabaza W A I, Swart H C and Kroon R E 2014 J. Lumin. 148 192–7
[34] Maphiri V M, Dejene F B and Motloung S V 2017 Res. Phy. 7 3510–21
[35] Melato L T, Motaung T E, Ntwaeaborwa O M and Motloung S V 2017 Opt. Mat. 66 319–26
[36] Tamrakar R K and Upadhhyay K 2017 Res. J. Recent Sci. 6 28–31 (http://www.isca.in/jrs/archive/v6/14//ISCA-RJRS-2017-038.php)
[37] Mikenda W and Presingera A 1981 J. Lumin. 26 53–83
[38] Taheremunis S K, Krishna D V, Reddy K, SambasivalaKao T, Rudramamba K S, Zhaydchevskyy Y A, Sucholicki A, Paseckii and Reddy M R 2019 Opt. Mat. 13 100034
[39] Wei L, XingLeng Z, Lu H, Huiqing L, Yingjuan C, Pingguang D and Xiaowei L 2015 Inte. Jour. Photo 376202
[40] Motloung S V, Dejene B F, Kroon R E, Swart H C and Ntwaeaborwa O M 2013 Phys. B 468–469 11–20
[41] Grube J, Sarakovskis A, Doke G and Springis M 2014 Lat. Journ. Phys. Tech. Scie. N 3 0018