

Synthesis and Photoluminescence Characterization of Different Concentrations of Dy³⁺ Doped Na₂Sr(PO₄)F Phosphors Co-doped with (SO₄), (WO₄) and (VO₄) Ions for LED Applications

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Abstract: Compound Na₂Sr(PO₄)F doped with various concentrations as 0.1, 0.3, 0.5, 0.7 and 1 mol% of rare earth dopant Dy. These phosphors were prepared by using combustion method. Photoluminescence (PL) emission spectra shows highest intensity emission peak at 482 nm and 574 nm for 1.5 mol% Dy doped phosphor. Preliminary studies showed that the phosphor might be a promising phosphor for LED. To increase the luminescence intensity, Na₂Sr(PO₄)F: Dy 1.5 mol% phosphor was further Co-doped with various concentrations of (SO₄), (WO₄) and (VO₄) ions. Commission International de l'Eclairage (CIE) chromaticity colour coordinates of these phosphors were calculated. CIE- Chromaticity colour coordinates of this phosphor shows white emission.

Keywords: Phosphors, Synthesis, LED, Combustion method, CIE

I. INTRODUCTION

At present, solid state lighting (SSL) employs light-emitting diodes to produce white light because of their mercury-free, environmental friendliness, low energy consumption, high durability, enormously long life etc., characteristics over the conventional incandescent and halogen lamp. Solid-state lighting sources are considered to be the next generation of white light-emitting diodes (w-LED) due to their extraordinary optical properties, their extended lifetime, as well as mercury-free excitation. Dysprosium ion is vigorously studied as activator in the field of luminescence and extremely useful as a dopant in phosphors for LED and display devices, sensor [1-3].

It can exist in Dy³⁺ form. Dy³⁺ ion possesses interconfigurational 4f-4f transitions which are forbidden transitions and Dy³⁺ ion possesses 4f-5d transition which is allowed transition. 4f-4f transitions of Dy³⁺ ions are hypersensitive transition [4-6]. Depending on the chemical environment present around the crystallographic site, which is available for doping of Dy³⁺ ions, some forbidden transitions become allowed and blue-green-red emissions can be seen. Site dependent emission of Dy³⁺ ions is utilized by researchers to study local structural symmetry in host [7-10]. W-LEDs show low colour rendering index and high correlated colour temperature due to the absence of a long-wavelength red component in the visible spectrum. Red, Orange-red emitting phosphor can be used along with green and blue emitting phosphors to enhance the colour rendering index of the W-LED [11-13]. Dy³⁺ dopant ion is one of the lanthanide elements that leads to produce red luminescence.

In this work, different concentrations of Dy³⁺ doped Na₂Sr(PO₄)F phosphors with well chemical and physical stable performance were synthesized, which further co-doped with different concentrations of (SO₄) and (VO₄) ions. The photoluminescence study of these samples revealed that the phosphors can be excited by blue and emit red light.

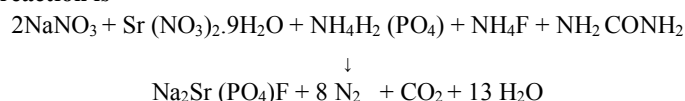


II. SYNTHESIS OF $\text{Na}_2\text{Sr}(\text{PO}_4)\text{F} : \text{Dy}$ CO-DOPED WITH (SO_4) , (VO_4) & (WO_4) -

The inorganic material $\text{Na}_2\text{Sr}(\text{PO}_4)\text{F}$ was synthesized by using solution combustion method. The A. R. Grade chemicals, Strontium nitrate $\text{Sr}(\text{NO}_3)_2$, Sodium nitrate (NaNO_3), Ammonium Fluoride (NH_4F), Diammonium Hydrogen Phosphate $[(\text{NH}_4)_2\text{HPO}_4]$, Nitric acid (HNO_3) and urea were used without further purification. All the chemicals weight per stichiometric ratio and dissolved in minimum quantity of water and mix the content in china dish. Urea is used as a fuel. The content in the China dish then kept in pre-heated vertical muffle furnace at 600°C , where auto combustion took place accompanied with evolution of brown flames. After completion of combustion process the white solid material was obtained. After cooling this material, we crushed it in fine power using mortar and pestle. In the same manner by adding different concentration Dy^{3+} in the form of Dy_2O_3 (Dysprosium oxide) dissolved in conc. Nitric acid.

The highest emission in intensity is shown by $\text{Na}_2\text{Sr}(\text{PO}_4)\text{F} : \text{Dy}$ 1.5 mol%. Therefore by keeping this doped concentration constant we further co-doped it with (SO_4) , (VO_4) & (WO_4) by using A.R Grade chemicals, Strontium nitrate $\text{Sr}(\text{NO}_3)_2$, Sodium nitrate (NaNO_3), Ammonium Fluoride (NH_4F), Diammonium Hydrogen Phosphate $[(\text{NH}_4)_2\text{HPO}_4]$, Nitric acid (HNO_3) in different concentration this co-doped phosphors were also synthesized by using the same solution combustion method. The synthesized phosphors were used for further characterization:

The proposed chemical reaction is-



Molecular Weights of the used chemicals are:

$\text{NaNO}_3 = 84.9947 \text{ g/mol}$

$\text{Sr}(\text{NO}_3)_2 = 211.63 \text{ g/mol}$

$(\text{NH}_4\text{F}) = 37.0037 \text{ g/mol}$

$\text{NH}_2\text{CONH}_2 = 60.06 \text{ g/mol}$

$\text{Dy}_2\text{O}_3 = 373 \text{ g/mol}$

Table1- Amount of chemicals (in gm) used were according to chemical reaction

For preparation of $\text{Na}_2\text{Sr}(\text{PO}_4)\text{F} : \text{Dy}$						
Mol% Dopant	Weight of Dy	Weight of $\text{NH}_4\text{H}_2(\text{PO}_4)$	Weight of NaNO_3	Weight of $\text{Sr}(\text{NO}_3)_2$	Weight of NH_4F	Weight of urea
Pure		1.5	2.2168	2.7599	0.4830	7.5
0.1 mol%	0.0048	1.5	2.2168	2.7571	0.4830	7.5
0.5 mol%	0.0243	1.5	2.2168	2.7461	0.4830	7.5
1 mol%	0.0486	1.5	2.2168	2.7323	0.4830	7.5
1.5 mol %	0.0729	1.5	2.2168	2.7185	0.4830	7.5
2 mol%	0.0972	1.5	2.2168	2.7047	0.4830	7.5



For preparation of $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{SO}_4)_x \text{ F : Dy } 1.5 \text{ mol\%}$							
Conc. of Co-dopant (SO_4)	Weight of $(\text{NH}_4)_2\text{PO}_4$	Weight of $(\text{NH}_4)_2\text{SO}_4$	Weight of $\text{Sr}(\text{NO}_3)_2$	Weight of NaNO_3	Weight of NH_4F	Weight of Dy	Weight of Urea
0.1	0.9	0.1148	1.5638	1.4777	0.3219	0.0486	4.5
0.3	0.7	0.3446	1.5638	1.4777	0.3219	0.0486	4.5
0.5	0.5	0.5743	1.5638	1.4777	0.3219	0.0486	4.5
0.7	0.3	0.8041	1.5638	1.4777	0.3219	0.0486	4.5
1	0	1.1487	1.5638	1.4777	0.3219	0.0486	4.5

For preparation of $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{VO}_4)_x \text{ F : Dy } 1.5 \text{ mol\%}$							
Conc. of Co-dopant (VO_4)	Weight of $(\text{NH}_4)_2\text{PO}_4$	Weight of $(\text{NH}_4)_2\text{VO}_4$	Weight of $\text{Sr}(\text{NO}_3)_2$	Weight of NaNO_3	Weight of NH_4F	Weight of Dy	Weight of Urea
0.1	0.9	0.1016	1.5638	1.4777	0.3219	0.0486	4.5
0.3	0.7	0.3050	1.5638	1.4777	0.3219	0.0486	4.5
0.5	0.5	0.5084	1.5638	1.4777	0.3219	0.0486	4.5
0.7	0.3	0.7118	1.5638	1.4777	0.3219	0.0486	4.5
1	-	1.0169	1.5638	1.4777	0.3219	0.0486	4.5

For preparation of $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{WO}_4)_x \text{ F : Dy } 1.5 \text{ mol\%}$							
Conc. of Co-dopant (VO_4)	Weight of $(\text{NH}_4)_2\text{PO}_4$	Weight of $(\text{NH}_4)_2\text{WO}_4$	Weight of $\text{Sr}(\text{NO}_3)_2$	Weight of NaNO_3	Weight of NH_4F	Weight of Dy	Weight of Urea
0.1	0.9	0.2172	1.5638	1.4777	0.3219	0.0486	4.5
0.3	0.7	0.6516	1.5638	1.4777	0.3219	0.0486	4.5
0.5	0.5	1.0860	1.5638	1.4777	0.3219	0.0486	4.5
0.7	0.3	1.5204	1.5638	1.4777	0.3219	0.0486	4.5
1		2.1720	1.5638	1.4777	0.3219	0.0486	4.5



Photoluminescence Study of $\text{Na}_2\text{Sr}(\text{PO}_4)\text{F}$ Doped With Different Concentrations of Dy^{3+}

Excitation and emission spectra of $\text{Na}_2\text{Sr}(\text{PO}_4)\text{F}:\text{Dy}$

The excitation spectrum of the $\text{Na}_2\text{Sr}(\text{PO}_4)\text{F}:\text{Dy}^{3+}$ phosphors show peaks which ranges between 300 to 390 nm wavelength. The peaks at 324nm, 350nm, 365nm and 388nm are due to $^6\text{H}_{15/2} \rightarrow ^4\text{M}_{17/2}$, $^6\text{H}_{15/2} \rightarrow ^6\text{P}_{7/2}$, $^6\text{H}_{15/2} \rightarrow ^6\text{P}_{5/2}$ and $^6\text{H}_{15/2} \rightarrow ^4\text{F}_{9/2}$ transitions respectively. From Fig 4.1 it has been observed that the highest intensity of excitation wavelength is at 350nm when it is monitored at 482 nm emission wavelength.

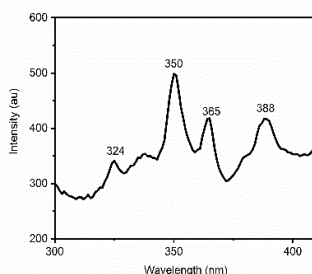


Fig.1 Excitation spectra of $\text{Na}_2\text{Sr}(\text{PO}_4)\text{F}:\text{Dy}^{3+}$ phosphor at 482 nm emission wavelength

It is well known that the colour of the luminescence in trivalent dysprosium is near to white. In present case $\text{Na}_2\text{Sr}(\text{PO}_4)\text{F}:\text{Dy}^{3+}$ have mainly two emission bands i.e., the blue band at around 482nm and yellow band at 574 nm due to the transitions $^4\text{F}_{9/2} \rightarrow ^6\text{H}_{15/2}$ (482nm) and $^4\text{F}_{9/2} \rightarrow ^6\text{H}_{13/2}$ (574nm). If the proportion of yellow to blue attained suitable value, Dy^{3+} can emit white light. Fig 4.3 shows the emission spectrum of the various concentrations of Dy doped $\text{Na}_2\text{Sr}(\text{PO}_4)\text{F}$ phosphors. A series of $\text{Na}_2\text{Sr}(\text{PO}_4)\text{F}:\text{Dy}^{3+}$ phosphors with various Dy concentrations (0.1, 0.5, 1, 1.5 & 2 mol%) are prepared and it has been observed that the maximum photoluminescence intensity is observed for 1.5 mol% of Dy^{3+} ions. Thus, the best doping concentration for Dy^{3+} ions in $\text{Na}_2\text{Sr}(\text{PO}_4)\text{F}$ host lattice is 1.5 mol%.

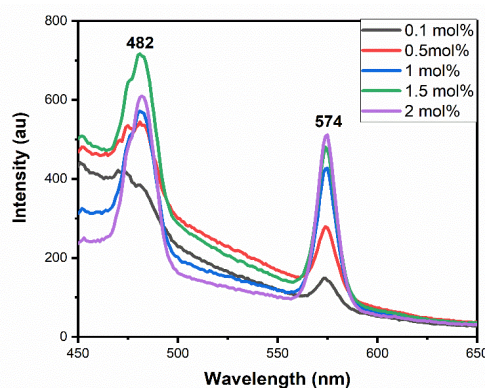
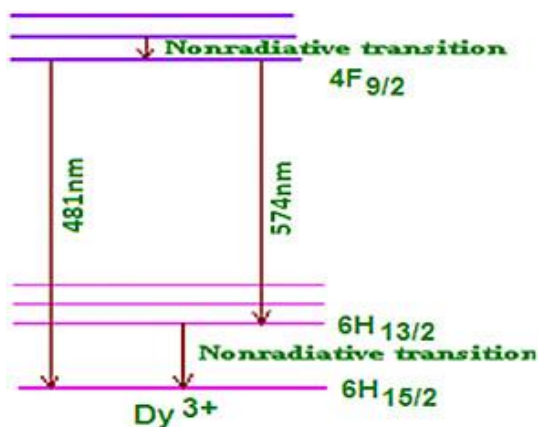


Fig. 2 Energy Level Diagram of Dy^{3+} ion Fig.3 Emission spectra of $\text{Na}_2\text{Sr}(\text{PO}_4)\text{F}:\text{Dy}^{3+}$ phosphors at 350nm excitation wavelength

Photoluminescence Study of $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{SO}_4)_x\text{F}:\text{Dy} 1.5 \text{ mol}\%$

Excitation and emission spectra of $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{SO}_4)_x\text{F}:\text{Dy} 1.5 \text{ mol}\%$ (where, $x = 0.1, 0.5, 1, 1.5 \text{ \& } 2 \text{ mol}\%$)

The excitation spectrum of the $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{SO}_4)_x\text{F}:\text{Dy} 1.5 \text{ mol}\%$ phosphors shows peaks at 324nm, 350nm, 364 nm and 387 nm are due to $^6\text{H}_{15/2} \rightarrow ^6\text{P}_{7/2}$, $^6\text{H}_{15/2} \rightarrow ^6\text{P}_{5/2}$ and $^6\text{H}_{15/2} \rightarrow ^4\text{F}_{9/2}$ transitions respectively. From Fig.4 it has been observed that the highest intensity of excitation wavelength is at 350nm when it is monitored at 481 nm emission wavelength.



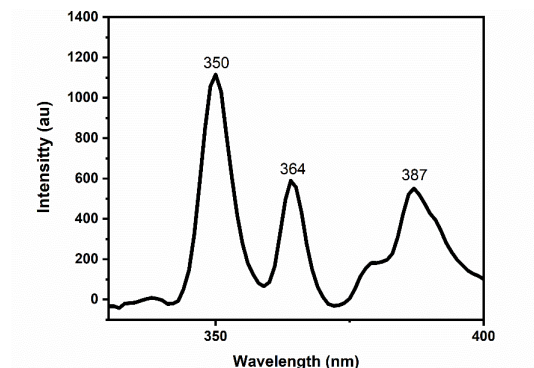


Fig.4 Excitation spectra of $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{SO}_4)_x\text{F:Dy 1.5 mol\%}$ phosphor at 481 nm emission wavelength

In present case, $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{SO}_4)_x\text{F:Dy 1.5 mol\%}$ (0.1, 0.5, 1, 1.5 & 2 mol%) have mainly two emission bands i.e., the blue band at around 481 nm and yellow band at 573 nm due to the transitions $^4\text{F}_{9/2} \rightarrow ^6\text{H}_{15/2}$ (482nm) and $^4\text{F}_{9/2} \rightarrow ^6\text{H}_{13/2}$ (574nm). Fig.5 shows the emission spectrum of the various concentrations of SO_4 co-doped $\text{Na}_2\text{Sr}(\text{PO}_4)\text{F:Dy}^{3+}$ phosphors. A series of $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{SO}_4)_x\text{F:Dy}^{3+} 1.5 \text{ mol\%}$ were prepared and it has been observed that the maximum photoluminescence intensity is observed for $\text{Na}_2\text{Sr}(\text{PO}_4)_{0.5}(\text{SO}_4)_{0.5}\text{F:Dy}^{3+} 1.5 \text{ mol\%}$. The emission intensity of both the peaks (481nm & 573 nm) were found same. As compared to $\text{Na}_2\text{Sr}(\text{PO}_4)\text{F:Dy 1.5 mol\%}$ the $\text{Na}_2\text{Sr}(\text{PO}_4)_{0.5}(\text{SO}_4)_{0.5}\text{F:Dy}^{3+} 1.5 \text{ mol\%}$ shows double emission intensity.

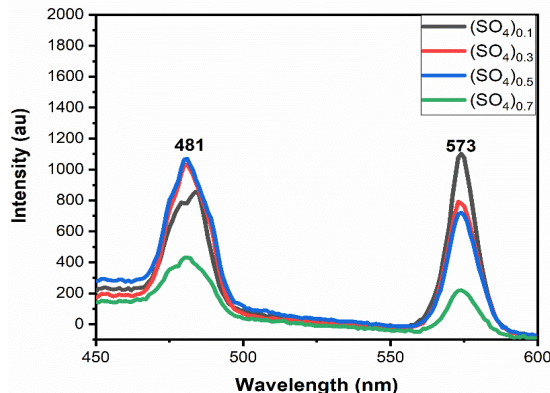


Fig.5 Emission spectra of $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{SO}_4)_x\text{F:Dy 1.5 mol\%}$ phosphor at 350 nm excitation wavelength

Photoluminescence Study of $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{WO}_4)_x\text{F:Dy 1.5 mol\%}$

Excitation and emission spectra of $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{WO}_4)_x\text{F:Dy 1.5 mol\%}$ (where, $x = 0.1, 0.5, 1, 1.5 \text{ \& } 2 \text{ mol\%}$)

The excitation spectrum of the $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{WO}_4)_x\text{F:Dy 1.5 mol\%}$ phosphors shows peaks at 325 nm, 350nm, 365 nm and 388 nm. Fig.6 shows the highest intensity excitation peak at 350nm wavelength when it is monitored at 481 nm emission wavelength.



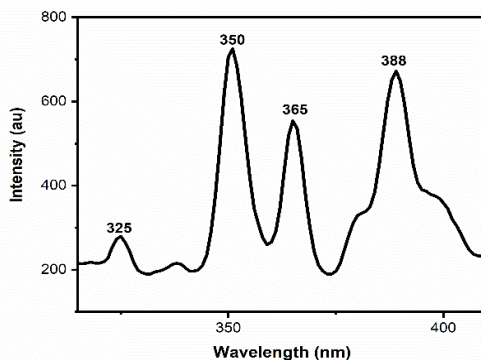


Fig.6 Excitation spectra of $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{WO}_4)_x \text{F: Dy } 1.5 \text{ mol\%}$ phosphor at 481 nm emission wavelength
 $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{WO}_4)_x \text{F: Dy } 1.5 \text{ mol\%}$ (0.1, 0.5, 1, 1.5 & 2 mol%) phosphors show two emission bands at 381 nm, 481 nm and at 574 nm. Fig.7 shows the emission spectrum of the various concentrations of WO_4 co-doped $\text{Na}_2\text{Sr}(\text{PO}_4) \text{F: Dy}^{3+}$ phosphors. A series of $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{WO}_4)_x \text{F: Dy}^{3+} 1.5 \text{ mol\%}$ were prepared and it has been observed that the maximum photoluminescence intensity is observed for $\text{Na}_2\text{Sr}(\text{PO}_4)_{0.3}(\text{WO}_4)_{0.7} \text{F: Dy}^{3+} 1.5 \text{ mol\%}$. The emission intensity of both the peaks (481 nm & 573 nm) were found same. As compared to $\text{Na}_2\text{Sr}(\text{PO}_4) \text{F: Dy } 1.5 \text{ mol\%}$ the $\text{Na}_2\text{Sr}(\text{PO}_4)_{0.3}(\text{WO}_4)_{0.7} \text{F: Dy}^{3+} 1.5 \text{ mol\%}$ shows one additional emission peak at 381 nm while the emission intensity of both the peaks (481 nm & 574 nm) are found to be twice in intensity.

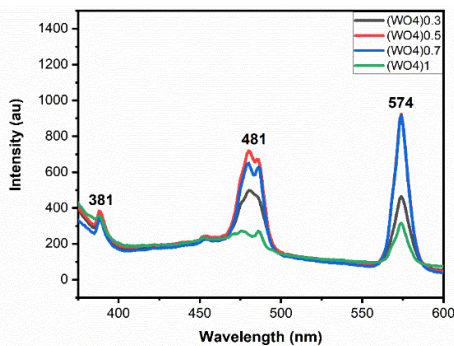


Fig.7 Emission spectra of $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{WO}_4)_x \text{F: Dy } 1.5 \text{ mol\%}$ phosphor at 350 nm excitation wavelength
Photoluminescence Study of $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{VO}_4)_x \text{F: Dy } 1.5 \text{ mol\%}$ Excitation and emission spectra of $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{VO}_4)_x \text{F: Dy } 1.5 \text{ mol\%}$ (where, $x = 0.1, 0.5, 1, 1.5 \text{ \& } 2 \text{ mol\%}$)

The excitation spectrum of the $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{VO}_4)_x \text{F: Dy } 1.5 \text{ mol\%}$ phosphors shows peaks at 350 nm, 365 nm and 389 nm. Fig.8 shows the highest intensity excitation peak at 350 nm wavelength when it is monitored at 482 nm emission wavelength.



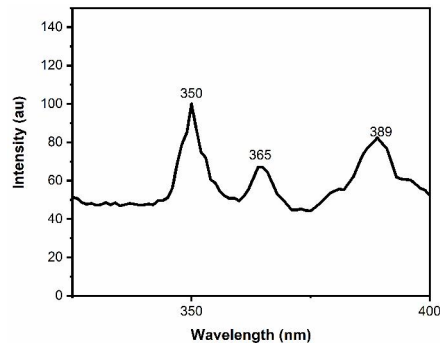


Fig.7 Excitation spectra of $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{VO}_4)_x\text{F:Dy 1.5 mol\%}$ phosphor at 481 nm emission wavelength

$\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{VO}_4)_x\text{F:Dy 1.5 mol\%}$ (0.1, 0.5, 1, 1.5 & 2 mol%) phosphors show two emission bands one at 482 nm another at 574 nm. The peak at 482 is bifurcated in two peaks as 475 & 482 nm which is not observed in other co-doped phosphors. Fig. 9 shows the emission spectrum of the various concentrations of VO_4 co-doped $\text{Na}_2\text{Sr}(\text{PO}_4)\text{F:Dy}^{3+}$ phosphors. A series of $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{VO}_4)_x\text{F:Dy}^{3+} 1.5 \text{ mol\%}$ were prepared and it has been observed that the maximum photoluminescence intensity is observed for $\text{Na}_2\text{Sr}(\text{PO}_4)_{0.7}(\text{VO}_4)_{0.3}\text{F:Dy}^{3+} 1.5 \text{ mol\%}$. As compared to $\text{Na}_2\text{Sr}(\text{PO}_4)\text{F:Dy 1.5 mol\%}$ the $\text{Na}_2\text{Sr}(\text{PO}_4)_{0.7}(\text{VO}_4)_{0.3}\text{F:Dy}^{3+} 1.5 \text{ mol\%}$ shows one additional emission peak at 381 nm while the emission peak intensity of both the peaks (481 nm & 574 nm) are found to be twice.

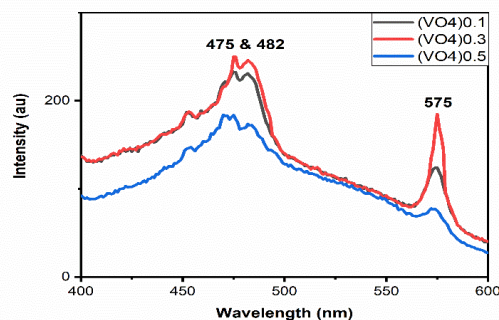


Fig.8 Emission spectra of $\text{Na}_2\text{Sr}(\text{PO}_4)_{1-x}(\text{VO}_4)_x\text{F:Dy 1.5 mol\%}$ phosphor at 350 nm excitation wavelength

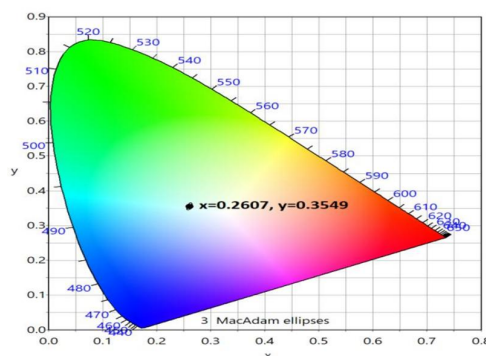


Fig.9: CIE diagram of $\text{Na}_2\text{Sr}(\text{PO}_4)_{0.5}(\text{SO}_4)_{0.5}\text{F:Dy}^{3+} 1.5 \text{ mol\%}$



The CIE diagram for $\text{Na}_2\text{Sr}(\text{PO}_4)_0.5(\text{SO}_4)_0.5\text{F:Dy}^{3+1.5}\text{mol\%}$ phosphor shows that the CIE coordinates located at $(x=0.2607)$ and $(y=0.3549)$. Fig. 9 shows that the point obtained at CIE diagram lies near white region.

CONCLUSION

$\text{Na}_2\text{Sr}(\text{PO}_4)\text{F}$ phosphors doped with dysprosium ion were prepared by solution combustion method using urea as a fuel. The prepared phosphors have been characterized for photoluminescence study. They are excited by near UV or blue light. By regulating the doping concentration of dopants and sensitizer, phosphors with high luminescent intensities were acquired.

$\text{Na}_2\text{Sr}(\text{PO}_4)\text{F}$ host material doped with different concentrations of Dy^{3+} ions, out of which $\text{Na}_2\text{Sr}(\text{PO}_4)\text{F:Dy } 1.5\text{mol\%}$ showed highest emission intensity hence this phosphor was co-doped with different concentrations of (SO_4) , (WO_4) and (VO_4) ions.

In present study, $\text{Na}_2\text{Sr}(\text{PO}_4)\text{F:Dy } 1.5\text{mol\%}$ host when co-doped with (SO_4) , (WO_4) ions, the emission peak intensities were found to be increased twice. The highest emission intensity peak was observed for $\text{Na}_2\text{Sr}(\text{PO}_4)_0.5(\text{SO}_4)_0.5\text{F:Dy } 1.5\text{mol\%}$ and $\text{Na}_2\text{Sr}(\text{PO}_4)_0.3(\text{WO}_4)_0.7\text{F:Dy } 1.5\text{mol\%}$. In case of co-doping with (VO_4) ions the highest intensity peak was observed for $\text{Na}_2\text{Sr}(\text{PO}_4)_0.7(\text{VO}_4)_0.34\text{F:Dy } 1.5\text{mol\%}$ phosphor where it shows the additional emission peak at 381 nm wavelength.

Out of all the prepared phosphors, $\text{Na}_2\text{Sr}(\text{PO}_4)_0.5(\text{SO}_4)_0.5\text{F:Dy } 1.5\text{mol\%}$ phosphor was found to be the best phosphor to be used as only component for white LED phosphor.

REFERENCES

1. Garlick, G.F.J, (1958) luminescence Encyclopedia of physics/ Handbuch Der physik, 1-128.
2. Luminescence and fluorescence, copywrite 2013. The Fluorescent Mineral Society, Inc.
3. Defect and Diffusion forum vol 347 (2014) pp 1-34 K.V.R Murthy and H.S Virk.
4. <https://www.enzolifescience.Com/science-centre/technotes/2019/december>.
5. D. A. Skoog, et al "Principles of Instrumental Analysis" 6th Edition, Thomson Brooks/Cole, 2007.
6. Justel, T; Nikol, H; Ronda, C. Angew. Chem. Int. Ed 1998, 37, 3084
7. Nakamura, S; Mukai, T,; Senoh, M. (1994), "Candela- Class High- Brightness InGaN/ AlGaIn Double – Heterostructure Blue – Light -Emitting-Diodes" Appl. Phys.Lett. 64(13): 1687. doi: 10.1063/1.111832.
8. M .A. Laughton Electrical Engineer's Reference Book Sixteenth Edition, Newness, 2003 ISBN 0-7506-4637-3, page 21-12
9. Synthesis and Luminescence properties of rare earth activated phosphors for near UV-emitting LEDs for efficacious generation of white light , Han Jinku, 2013. UC San Diego Electronic These and Dissertations.
10. An overview of LED applications for general lumination David G Pelka, Kavita Patel Design of Efficient Illumination Systems 5186, 15-26, 2003.
11. LED lighting. <https://www.energy.gov/energysaver/led-lighting>.
12. Light Emitting Diodes, [https://en.wikipedia.org/Light Emitting Diode](https://en.wikipedia.org/Light_Emitting_Diode)
13. Corazza, A.; Giorgi, S.; Massaro, V. (October 2008) Mercury dosing in Fluroscent lamp. Industry applications society annual Meeting .

