

Luminescence characteristics of gadolinium-calcium-silicoborate glass scintillators

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ABSTRACT

Background: The research aimed to study the investigate properties of glass having increasing compositions of $(55-x) \text{B}_2\text{O}_3 : 25\text{Gd}_2\text{O}_3 : 10\text{SiO}_2 : 10\text{CaO} : x\text{A}_2\text{O}_3$ where A_2O_3 are Sm_2O_3 , Eu_2O_3 and Dy_2O_3 and $x=0.05$ to 0.50 mol%. X-ray luminescence properties of these glass samples using a BGO crystal were then compared.

Materials and methods: Glasses were prepared by conventional melt quenching technique. Density, optical properties and x-ray scintillation properties were studied and compared.

Results: The was found that density of glass increased with increasing dopant concentration. Eleven absorption bands of Sm_2O_3 were observed from the $^6\text{H}_{15/2}$ ground state to $360 (^4\text{D}_{3/2})$, $373 (^6\text{P}_{7/2})$, $403 (^6\text{P}_{3/2})$, $475 (4\text{I}_{11/2})$, $944 (^6\text{F}_{11/2})$, $1077 (^6\text{F}_{9/2})$, $1225 (^6\text{F}_{7/2})$, $1368 (^6\text{F}_{5/2})$, $1468 (^6\text{F}_{3/2})$, $1520 (^6\text{H}_{15/2})$ and $1586 (^6\text{F}_{1/2})$ nm. Two absorption bands of Eu_2O_3 were observed from the $^7\text{F}_0$ ground state to $2100 (^7\text{F}_1)$ and $2203 (^7\text{F}_6)$ nm. Nine absorption bands of Dy_2O_3 were observed to transitions from the $^6\text{H}_{15/2}$ ground state to $387 (4\text{I}_{13/2} + ^4\text{F}_{7/2} + ^4\text{M}_{21/2} + ^4\text{K}_{17/2})$, $426 (^4\text{G}_{11/2})$, $455 (4\text{I}_{15/2})$, $751 (^6\text{F}_{3/2})$, $805 (^6\text{F}_{5/2})$, $898 (^6\text{F}_{7/2})$, $1085 (^6\text{H}_{7/2} + ^6\text{F}_{9/2})$, $1261 (^6\text{F}_{11/2} + ^6\text{H}_{9/2})$ and $1672 (^6\text{H}_{11/2})$ nm. The comparisons done on x-ray luminescence properties between glass samples with BGO scintillator crystal determined that glass doped with 0.35 mol% Sm_2O_3 have four relatively strong emission peaks. Glass doped with 0.35 mol% of Eu_2O_3 have six relatively strong emission peaks. Glass doped with 0.45 mol% of Dy_2O_3 have four relatively strong emission peaks.

Conclusion: The comparisons done on x-ray luminescence properties between glass samples with the BGO scintillator crystal determined that the scintillation efficiency of glass samples doped with Sm_2O_3 , Eu_2O_3 and Dy_2O_3 was 25% that of commercial BGO scintillator crystals.

Introduction

Scintillators or Scintillation materials emit ultraviolet light (UV) or visible light after radiation interaction of ionizing radiation with a material. Scintillators are used in industry, agriculture, and medical technology. In medical professional technology, it is used in film-screens, digital

radiography, image receptors, computed tomography (CT), scintillation gamma cameras, and positron emission tomography (PET).¹⁻³

When ionizing radiation interacts with scintillation materials, electrons from ground state are raised to an excited state. Instability electrons fall back to ground state with the emission of ultraviolet or visible light having characteristic decay constants are called luminescence. The luminescence is emission of light after excitation. Scintillation materials having a prompt emission of light is called fluorescence and delayed emission of light is afterglow or phosphorescence.⁴⁻⁸

The desired properties of scintillation materials are high

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conversion efficiency, short decay time, high transparency, a frequency spectrum matching with light receptor, high detection efficiencies, high density, a large attenuation coefficient, radiation hardness, high light yield, fast decay time, they are inexpensive, and show high proficiency and stability. Additionally, most scintillation materials require high luminescence efficiencies and dopant or activators from preferred sites in inorganic scintillation for the activator excited electrons before returning to the ground state. Rare-earth ions (RE^{3+}) doped in scintillation materials has been used as photonic materials in recent years, as they have a broad emission wavelength at the visible light to the infrared region because of its 4f-5d and 4f-4f transition and fast decay time. The 4f-4f transition gives a sharp fluorescence because of the shielding effects of the outer 5s and 5p orbitals on the 4f electrons.¹⁻⁸

The rare earth oxide, intensive Gadolinium Oxide (Gd_2O_3) is the most popular substance due to the efficiencies in energy transfer from Gd^{3+} ions to the luminescence activators and increased light yield emission.^{2, 9-12} Most of the popular rare earth doped in scintillation materials have high emission efficiencies based on literature reviews such as Samarium Oxide (Sm_2O_3),¹⁰⁻¹⁸ Europium Oxide (Eu_2O_3),^{5, 6, 18, 19} and Dysprosium Oxide (Dy_2O_3).^{17, 18, 20-23}

This article focuses on rare earth doped in glass scintillator because these glasses have a wide variety of applications, have good forming ability, high optical properties, are inexpensive, are non-hygroscopic, are chemically resistant, can be produced in large volumes, and are easy to synthesize. This type of glass can also easily be fabricated into glass scintillators with doping chemical concentrations by using the melt-quenching technique.²⁻²⁸ Among the various glasses that have been used for quite some time, borate glasses play a significant role in various applications such as solid state lasers, optical and electrical applications, fiber optics, optical waveguides, and luminescence materials. Borate glasses are an especially appropriate optical material because of its high chemical resistance, high thermal stability, and high optical properties.^{10, 13, 20} Earlier, silicate glasses were used due to good mechanical and optical properties. Also, borosilicate glasses have been formally used due to their high thermal resistance and low melting point. The effects of doping concentrations can result from oxide ions in calcium oxide, as it can increase luminescence emission and are also non-hygroscopic.^{10, 20}

The purpose of this article is to demonstrate how the formula $CaO: Gd_2O_3: SiO_2: B_2O_3$ obtained by melt-quenching technique can be doped with Samarium Oxide (Sm_2O_3), Europium Oxide (Eu_2O_3) and Dysprosium Oxide (Dy_2O_3) for the desired effects. The dopant concentrations are studied regarding their physical, optical, and luminescence properties by comparing them with a standard crystal scintillator composed of Bismuth Germanate (BGO). The findings will be used for developing these glasses as candidates for glass scintillators in the future.

Materials and methods

Glass preparations

Glasses compositions of $10CaO: 25Gd_2O_3: 10SiO_2: (55-x) B_2O_3: xA_2O_3$ (where $x=0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.45$ and 0.50 %mol) and $xA_2O_3=Sm_2O_3, Eu_2O_3, Dy_2O_3$ were prepared by melt-quenching technique. The high purity chemical concentrations of $CaO, Gd_2O_3, SiO_2, H_3BO_3, Sm_2O_3, Eu_2O_3$, and Dy_2O_3 were mixed thoroughly in an aluminium crucible. About 30 gm of the each compositions were thoroughly and mixed into an aggregate and the homogeneous mixture was placed into an aluminium crucible and melted in an electrical furnace at $1400^\circ C$ for 3 hours. These melted glass samples were quenched at room temperature. The glass samples were annealed at $550^\circ C$ for 3 hrs to reduce the thermal stress and then were cut and polished into squares having dimensions of $1 \times 1.5 \times 0.3 \text{ cm}^3$.

Characterization process

Physical Properties

The density measurements were obtained by applying Archimedes' principle, the weights of the prepared glass samples were measured in air and in xylene using a 4-digit sensitive microbalance (AND, HR 200). Afterward, the density (ρ) was determined from the following equation.^{30, 31}

$$\rho = \frac{W_a}{W_a - W_b} \times \rho_b$$

Where ρ is density (g/cm^3) W_a is weight in air (g), W_b is weight in Xylene (g), and ρ_b is Xylene density (0.863 g/cm^3)

Optical properties

Absorption spectra were measured with a UV-Vis-NIR spectrophotometer (Shimadzu UV-3600) at wavelengths of 350-1800 nm.

Luminescence properties

The X-ray luminescence spectra of glass were measured with the Copper (Cu) target X-ray generator (Inel, XRG3D-E). The power setting X-ray source was operated at 50 kV, 30 mA. X-ray excitation spectra of glass samples were measured with a QE65000 fiber optics spectrometer

Results and Discussions

Physical Properties

The variation of density (g/cm^3) is a function of Sm_2O_3, Eu_2O_3 , and Dy_2O_3 concentration as shown in Figure 1. The glass samples density tends to increase with increasing of Sm_2O_3, Eu_2O_3 , and Dy_2O_3 concentrations. This means that there is change in the structural arrangement of the dopant concentration that was added to the glass sample network. It also shows that boron oxide is replaced by Sm_2O_3, Eu_2O_3 , and Dy_2O_3 concentrations. The increased density of glass samples is due to a higher molecular weight for Sm_2O_3, Eu_2O_3 , and Dy_2O_3 than any other composition found in the given glass samples system.

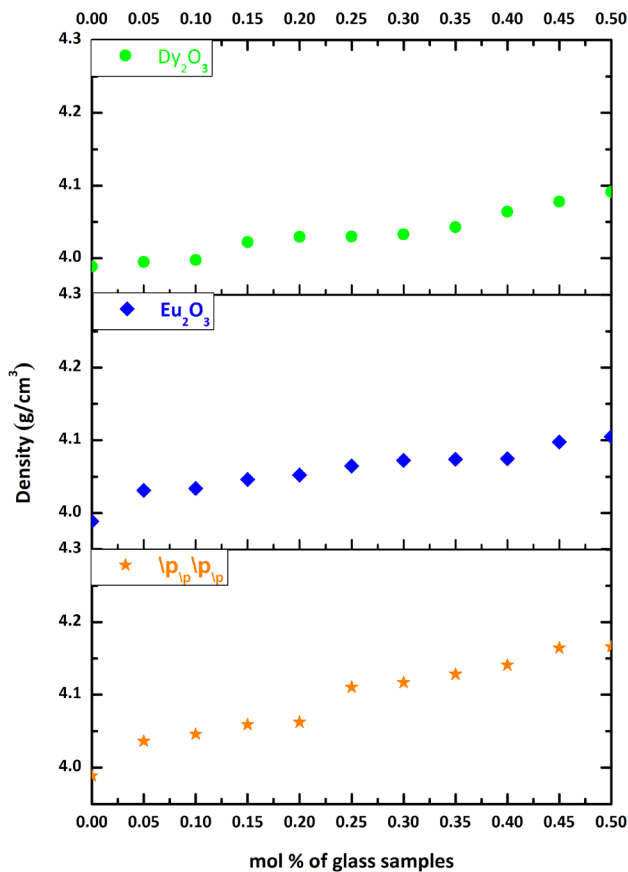
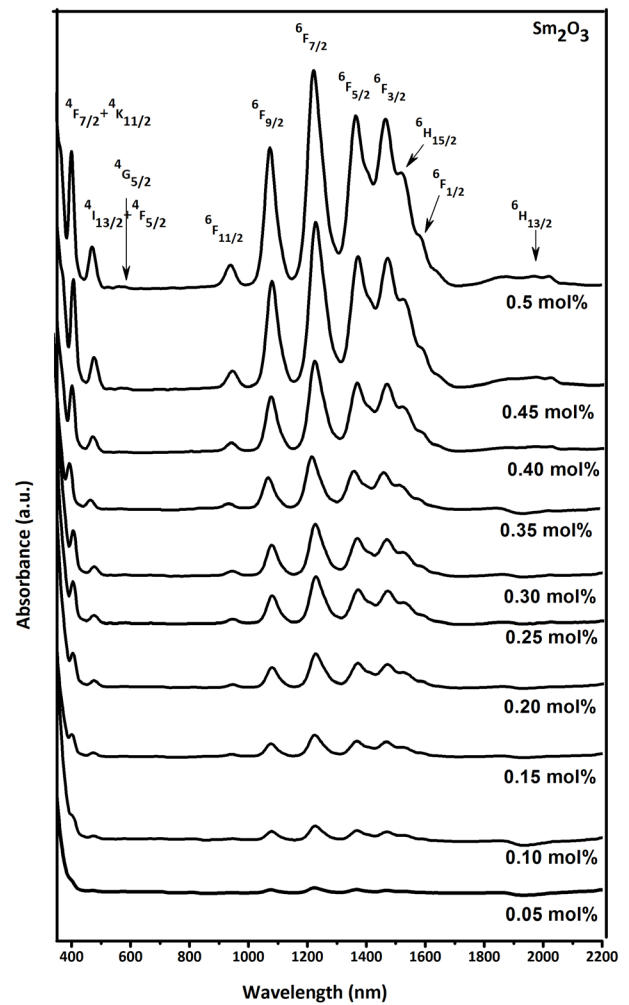
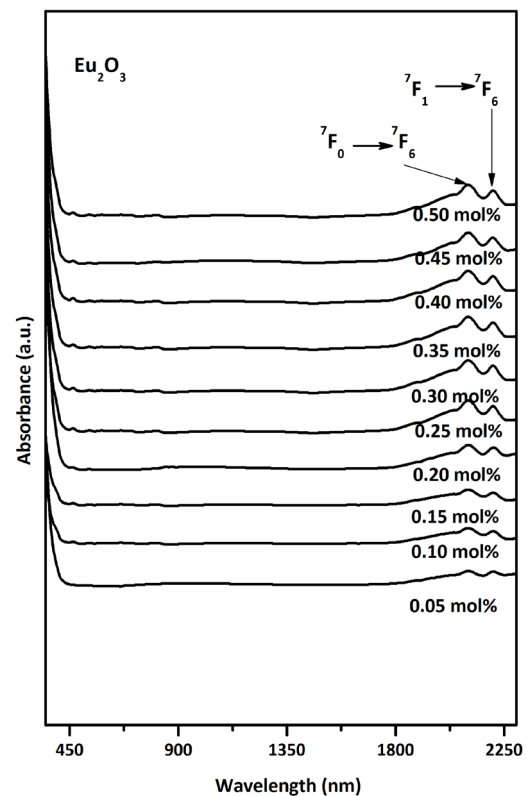


Figure 1. Density of glass samples.

Optical Properties

The absorption spectra for the Sm_2O_3 , Eu_2O_3 and Dy_2O_3 doped with $\text{CaO}:\text{Gd}_2\text{O}_3:\text{SiO}_2:\text{B}_2\text{O}_3$ glass samples. The absorption spectra of Sm^{3+} ions show eleven absorption bands at 360, 373, 403, 475, 944, 1077, 1225, 1368, 1468, 1520, and 1586 nm due to the transition spectra of $^6\text{H}_{5/2}$ to $^4\text{D}_{3/2}$, $^6\text{P}_{7/2}$, $^6\text{P}_{3/2}$, $^4\text{I}_{11/2}$, $^6\text{F}_{11/2}$, $^6\text{F}_{9/2}$, $^6\text{F}_{7/2}$, $^6\text{F}_{5/2}$, $^6\text{F}_{3/2}$, $^6\text{H}_{15/2}$ and $^6\text{F}_{1/2}$ respectively,¹⁰⁻¹⁸ as shown in Figure 2. The absorption spectra of Eu^{3+} ions show two absorption bands at 2100 and 2203 nm due to the transition spectra of $^7\text{F}_0$ and $^7\text{F}_6$ respectively,^{5, 6, 18, 19} as shown in Figure 3. The absorption spectra of Dy^{3+} ions show nine absorption bands at 387, 426, 455, 751, 805, 898, 1085, and 1261 nm due to the transition spectra of $(^4\text{I}_{13/2} + ^4\text{F}_{7/2} + ^4\text{M}_{21/2} + ^4\text{K}_{17/2})$, $^4\text{G}_{11/2}$, $^4\text{I}_{15/2}$, $^6\text{F}_{3/2}$, $^6\text{F}_{5/2}$, $^6\text{F}_{7/2}$, $(^6\text{H}_{7/2} + ^6\text{F}_{9/2})$, $(^6\text{F}_{11/2} + ^6\text{H}_{9/2})$, and $^6\text{H}_{11/2}$ respectively,^{17, 18, 20-23} as shown in Figure 4.

Figure 2. Absorption spectra of Sm_2O_3 doped GDSB Glass.Figure 3. Absorption spectra of Eu_2O_3 doped GDSB Glass.

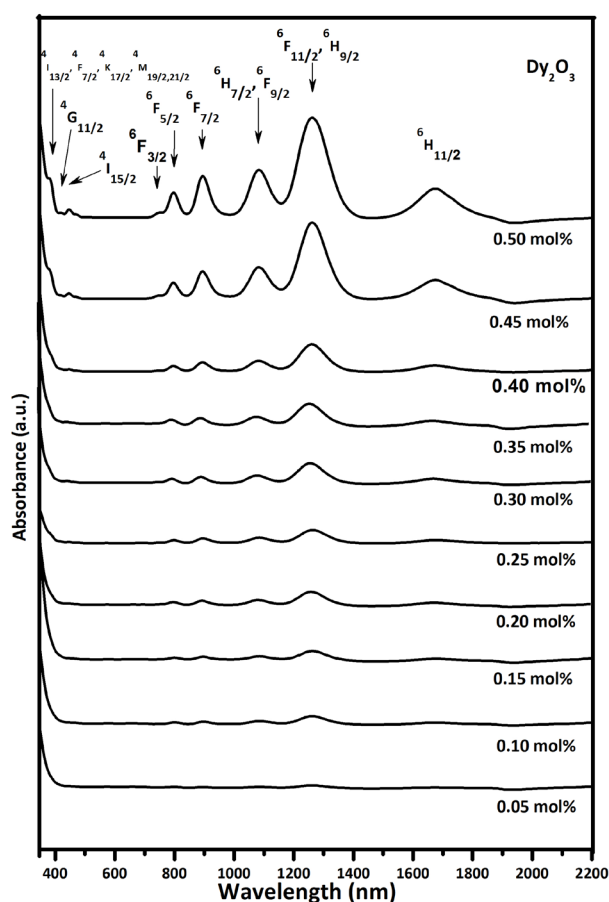


Figure 4. Absorption spectra of Dy_2O_3 doped GDSB Glass.

X-ray Luminescence properties

An X-ray of 50 kV and 30 mA were irradiated onto glass samples. The X-rays included an optical luminescence spectra of the Sm_2O_3 , Eu_2O_3 and Dy_2O_3 doped with $\text{CaO}:\text{Gd}_2\text{O}_3:\text{SiO}_2:\text{B}_2\text{O}_3$ glass samples. They were then compared with BGO scintillation crystals having the same size and shape. Glass doped with Sm_2O_3 at 0.35 mol% are shown in Figure 5. The total area under peak of spectrum, the integral scintillation efficiency of 0.35 mol% Sm^{3+} doped glass samples and found that 25% of BGO scintillation crystal. The emission peaks of Sm^{3+} ions show four emission peak at 560 ($^4\text{G}_{5/2} \rightarrow ^6\text{H}_{5/2}$), 598 ($^4\text{G}_{5/2} \rightarrow ^6\text{H}_{7/2}$), 645 ($^4\text{G}_{5/2} \rightarrow ^6\text{H}_{9/2}$) and 705 ($^4\text{G}_{5/2} \rightarrow ^6\text{H}_{11/2}$) nm respectively.¹⁰⁻¹⁸ Glass doped with Eu_2O_3 at 0.30 mol% are shown in Figure 6. The total area under peak of spectrum, the integral scintillation efficiency of 0.35 mol% Eu^{3+} doped glass samples were found to be 13% to that of BGO scintillation crystals. The emission peaks of Eu^{3+} ions show five emission peaks at 578 ($^5\text{D}_0 \rightarrow ^7\text{F}_0$), 590 ($^5\text{D}_0 \rightarrow ^7\text{F}_1$), 616 ($^5\text{D}_0 \rightarrow ^7\text{F}_2$), 652 ($^5\text{D}_0 \rightarrow ^7\text{F}_3$), and 703 ($^5\text{D}_0 \rightarrow ^7\text{F}_5$) nm respectively.^{5, 6, 18, 19} Glass doped with Dy_2O_3 at 0.45 mol% are shown in Figure 7. The total area under peak of spectrum, the integral scintillation efficiency of 0.45 mol% Dy^{3+} doped glass samples was found to 27% that of BGO scintillation crystals. The emission peaks of Dy^{3+} ions show four emission peaks at 482 ($^4\text{F}_{9/2} \rightarrow ^6\text{H}_{15/2}$), 577 ($^4\text{F}_{9/2} \rightarrow ^6\text{H}_{13/2}$), 661 ($^4\text{F}_{9/2} \rightarrow ^6\text{H}_{11/2}$), and 751 ($^4\text{F}_{9/2} \rightarrow ^6\text{H}_{9/2} + ^6\text{F}_{11/2}$) nm respectively.^{17, 18, 20-23}

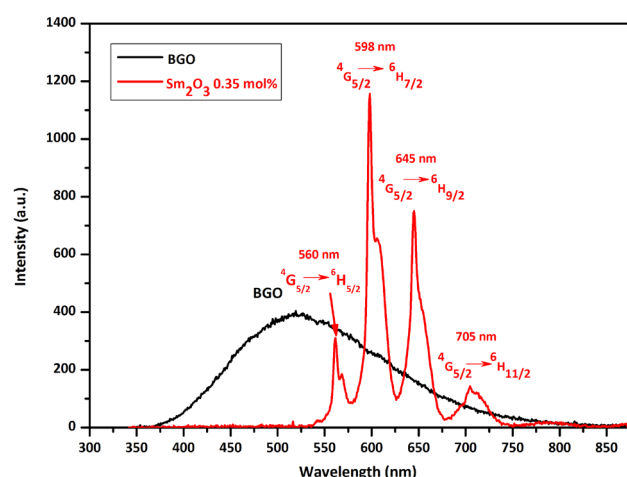


Figure 5. Comparison of X-ray luminescence of BGO with GCSB doped with Sm_2O_3 at 0.35 mol%.

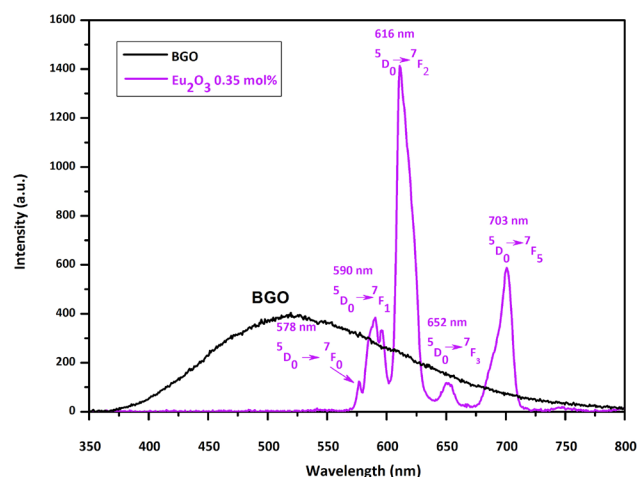


Figure 6. Comparison of X-ray luminescence of BGO with GCSB doped with Eu_2O_3 at 0.35 mol%.

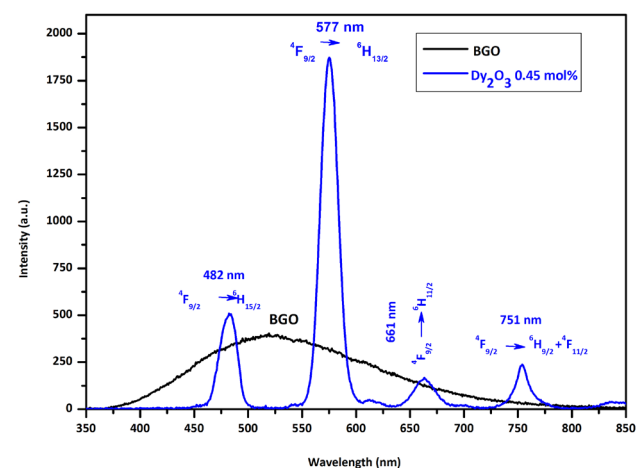


Figure 7. Comparison of X-ray luminescence of BGO with GCSB doped with Dy_2O_3 at 0.35 mol%.

Conclusions

The glass concentration in the formula $(55-x) \text{B}_2\text{O}_3 - 10\text{SiO}_2 - 25\text{Gd}_2\text{O}_3 - 10 \text{CaO} - x\text{A}_2\text{O}_3$ when $\text{A}_2\text{O}_3 = \text{Sm}_2\text{O}_3$, Eu_2O_3 and Dy_2O_3 , where $x=0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.45$, and 0.50 respectively have been grouped based on their physical, optical, and luminescence properties. The experimental results show that the glass sample densities tended to increase with an increase in Sm_2O_3 , Eu_2O_3 , and Dy_2O_3 concentration. Absorption spectra of Sm^{3+} ions show eleven absorption bands at 360, 373, 403, 475, 944, 1077, 1225, 1368, 1468, 1520, and 1586 nm due to the transition spectra of $^6\text{H}_{5/2}$ to $^4\text{D}_{3/2}$, $^6\text{P}_{7/2}$, $^6\text{P}_{3/2}$, $^4\text{I}_{11/2}$, $^6\text{F}_{11/2}$, $^6\text{F}_{9/2}$, $^6\text{F}_{7/2}$, $^6\text{F}_{5/2}$, $^6\text{F}_{3/2}$, $^6\text{H}_{15/2}$, and $^6\text{F}_{1/2}$ respectively. Absorption spectra of Eu^{3+} ions show two absorption bands at 2100 and 2203 nm due to the transition spectra of $^7\text{F}_0$ and $^7\text{F}_6$ respectively. Absorption spectra of Dy^{3+} ions show nine absorption bands at 387, 426, 455, 751, 805, 898, 1085, and 1261 nm with due to the transition spectra of $(^4\text{I}_{13/2} + ^4\text{F}_{7/2} + ^4\text{M}_{21/2} + ^4\text{K}_{17/2})$, $^4\text{G}_{11/2}$, $^4\text{I}_{15/2}$, $^6\text{F}_{3/2}$, $^6\text{F}_{5/2}$, $^6\text{F}_{7/2}$, $(^6\text{H}_{7/2} + ^6\text{F}_{9/2})$, $(^6\text{F}_{11/2} + ^6\text{H}_{9/2})$, and $^6\text{H}_{11/2}$ respectively. Emission peaks of Sm^{3+} ions show four emission peaks at 560 ($^4\text{G}_{5/2} \rightarrow ^6\text{H}_{5/2}$), 598 ($^4\text{G}_{5/2} \rightarrow ^6\text{H}_{7/2}$), 645 ($^4\text{G}_{5/2} \rightarrow ^6\text{H}_{9/2}$), and 705 ($^4\text{G}_{5/2} \rightarrow ^6\text{H}_{11/2}$) nm respectively. For glass doped with Sm_2O_3 at 0.35 mol%, the total area under peak of spectrum and the integral scintillation efficiency of 0.35 mol% Sm^{3+} doped glass samples was found to be 25% that of BGO scintillation crystals. The emission peaks of Sm^{3+} ions show four emission peaks at 560 ($^4\text{G}_{5/2} \rightarrow ^6\text{H}_{5/2}$), 598 ($^4\text{G}_{5/2} \rightarrow ^6\text{H}_{7/2}$), 645 ($^4\text{G}_{5/2} \rightarrow ^6\text{H}_{9/2}$), and 705 ($^4\text{G}_{5/2} \rightarrow ^6\text{H}_{11/2}$) nm respectively. Glass doped with Eu_2O_3 at 0.30 mol%, the total area under peak of spectrum and the integral scintillation efficiency of 0.35 mol% Eu^{3+} doped glass samples was found to be 13% to that of BGO scintillation crystals. The emission peaks of Eu^{3+} ions show five emission peaks at 578 ($^5\text{D}_0 \rightarrow ^7\text{F}_0$), 590 ($^5\text{D}_0 \rightarrow ^7\text{F}_1$), 616 ($^5\text{D}_0 \rightarrow ^7\text{F}_2$), 652 ($^5\text{D}_0 \rightarrow ^7\text{F}_3$), and 703 ($^5\text{D}_0 \rightarrow ^7\text{F}_5$) nm respectively. In Glass doped with Dy_2O_3 at 0.45 mol%, the total area under peak of spectrum and the integral scintillation efficiency of 0.45 mol% Dy^{3+} doped glass samples was found to be 27% that of BGO scintillation crystals. The emission peaks of Dy^{3+} ions show four emission peaks at 482 ($^4\text{F}_{9/2} \rightarrow ^6\text{H}_{15/2}$), 577 ($^4\text{F}_{9/2} \rightarrow ^6\text{H}_{13/2}$), 661 ($^4\text{F}_{9/2} \rightarrow ^6\text{H}_{11/2}$), and 751 ($^4\text{F}_{9/2} \rightarrow ^6\text{H}_{9/2} + ^6\text{F}_{11/2}$) nm, respectively. There is great interest in developing scintillation materials for industrial and medical use in the future.

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References

- [1] Tsoulfanidis N., Landsberger S., Measurement and Detection of Radiation 3rd United States of America. Taylor and Francis Group; 2011.
- [2] Kumar A, Rai DK, Rai SB, Luminescence of Gd^{3+} ions doped in Oxyfluoroborate glass, J Solid State Communications 117 (2001) 387-92.
- [3] Rada S, Pascuta P, Bosca M, Culea M, Pop L, Culea E, Structural properties of the boro-bismuthate glasses containing gadolinium ions, Vibrational Spectroscopy 2008; 48: 255–8.
- [4] Eilk CE, Inorganic-scintillator development. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 2001; 460: 1-14.
- [5] Fu J, Parker JM, Brown RM, Flower, PS, Eu^{2+} ions in CaF_2 -containing high Gd_2O_3 concentrations. Journal of Non-Crystalline Solids 2003; 326&327: 335–8.
- [6] Fu J, Kobayashi M, Sugimoto S, Parker JM, Eu^{3+} -activated heavy scintillating glasses. Materials Research Bulletin 2008; 43(6): 1502-8.
- [7] Iltisa A, Mayhugh MR, Mengeb P, Rozsab CM, Sellesc O, Solovyev V, Lanthanum halide scintillators: Properties and Applications. Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 2006: 359-63.
- [8] Martini M, Fasoli M, Villa I, Guibert P. Radioluminescence of synthetic and natural quartz. Radiation Measurements. 2012; 47(9): 846-50.
- [9] Jiang HD, Zhang HJ, Wang JY, Xia HR, Hu XB, Teng B, Zhang CQ, Optical and laser properties of $\text{Nd}:\text{GdVO}_4$ crystal, Optics Communication 2001; 198: 447-52.
- [10] Wantana N, Kaewjaeng S, Kothan S, Kim HJ, Kaewkhao J, Energy transfer from Gd^{3+} to Sm^{3+} and luminescence characteristics of $\text{CaO}-\text{Gd}_2\text{O}_3-\text{SiO}_2-\text{B}_2\text{O}_3$ scintillating glasses, Luminescence 2017; 181: 382–6.
- [11] Mares JA, Nikl M, Nitsch K, Solovieva N, Krasnikov A, Zazubovich S, A role of Gd^{3+} in scintillating processes in Tb-doped Na–Gd phosphate glasses. J Luminescence 2001; 94-95: 321-4.
- [12] Rodová M, Cihlar A, Kuizek K., Nitch K, Solovieva N., Preparation and properties of Ce-doped Na–Gd phosphate glasses. Radiation Measurements 2004; 38(4–6): 489-92.
- [13] Lakshminarayana G, Buddhudu S, Spectral analysis of Sm^{3+} and $\text{Dy}^{3+}:\text{B}_2\text{O}_3-\text{ZnO}-\text{PbO}$ glasses, Physica B 2006; 373: 100–6.
- [14] Som T, Karmakar B, Infrared-to-red upconversion luminescence in samarium-doped antimony glasses, Journal of Luminescence 2008; 128: 1989–96.
- [15] Biju PR, Ajithkumar G, Jose G, Unnikrishnan NV, Spectroscopic studies of Sm^{3+} -doped phosphate glasses, Bull. Mater. Sci. 1998; 21: 415-9.

- [16] Praveena R, Venkatramu V, Babu P, Jayasankar CK, Fluorescence spectroscopy of Sm^{3+} ions in P_2O_5 – PbO – Nb_2O_5 glasses, *Physica B* 2008; 403: 3527.
- [17] Zhang J, Wang Y, Wen Y, Zhang F, Liu B, Luminescence properties of $\text{Ca}_{10}\text{K}(\text{PO}_4)_7:\text{RE}^{3+}$ ($\text{RE}=\text{Ce}$, Tb , Dy , Tm and Sm) under vacuum ultraviolet excitation, *Journal of Alloys and Compounds* 2011; 509: 4649–52.
- [18] Mohitkar AS, Kalpana G, Vidyasagar K, Syntheses, structure and rare earth metal photoluminescence of new and known isostructural $\text{A}_2\text{Mo}_4\text{Sb}_2\text{O}_{18}$ ($\text{A}=\text{Ce}$, Pr , Sm , Eu , Gd , Tb , Dy , Ho , Er , Tm , Yb , Lu) compounds, *Journal of Solid State Chemistry* 2011; 184: 735–40.
- [19] Mohan BA, Jamalaiah BC, Suhasini T, Srinivasa RT, Rama MT, Optical properties of Eu^{3+} ions in lead tungstate tellurite glasses, *Solid State Sciences* 2011; 13: 574–8
- [20] Santiago M, Marcuzzó J, Grasselli C, Lavat A, Molina P, Spano F, Caselli E, Thermo- and radioluminescence of undoped and Dy-doped strontium borates prepared by sol-gel method. *Radiation Measurements* 2011; 46(12): 1488–91.
- [21] Zhang F, Xiao Z, Yan L, Zhu F, Huang A, Visible luminescence properties of Er^{3+} – Dy^{3+} codoped tellurite glasses, *Appl Phys A* 2010; 101: 77–80.
- [22] Yan Z, Chunhua L, Yaru N, Qitu Z, Zhongzi X, Optical Properties of Dy^{3+} Doped in Boroaluminasilicate Glass, *Journal of Rare Earth* 2007; 25: 99–103.
- [23] Insiripong S, Kaewkhao J, Ratanae T, Limsuwan P, Optical and Structural Investigation of Bismuth Borate Glasses Doped With Dy^{3+} , *Procedia Engineering* 2011; 8: 195–9.
- [24] Chewpraditkul W, Shen Y, Chen D, Yu B, Prusa P, Nik M, Beitlerova A., Wanarak C., Luminescence and scintillation of Ce^{3+} -doped high silica glass. *Optical materials* 2012; 34 (11): 1762–6.
- [25] Chewpraditkul W, Shen Y, Chen D, Beitlerova A, Nik M, Luminescence of Tb^{3+} -doped high silica glass under UV and X-ray excitation. *Optical Materials* 2013; 35(3): 426–30.
26. Fukabori A, Yanagida, Chani V, Moretti F, Pejchal J, Yokota Y, Kawaguchi N, Kamada K, Watanabe K, Murata T, Arikawa Y, Yamanoi K, Shimizu T, Sarukura N, Nakai M, Norimatsu T, Azechi H, Fujino S, Yoshida H, Yoshikawa A, Optical and scintillation properties of Pr-doped Li-glass for neutron detection in inertial confinement fusion process. *Journal of Non-Crystalline Solids* 2011; 357(3): 911–4.
- [27] He D, Yu D, Cheng J, Li S, Hu L, Effect of Tb^{3+} concentration and sensitization of Ce^{3+} on luminescence properties of terbium doped phosphate scintillating glass. *Journal of Alloys and Compounds* 2011; 509(5): 1906–9.
- [28] Pan Z, James K, Cui Y, Burger A, Cherepy N, Payne SA, Mu R, Morgan SH, Terbium-activated lithium–lanthanum–aluminosilicate oxyfluoride scintillating glass and glass-ceramic. *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 2008; 594(2): 215–9.
- [29] D.A. Kilymis, J.M. Delaye, S. Ispas, Density effects on the structure of irradiated sodium borosilicate glass: A molecular dynamics study, *J. Non-Cryst. Solids* 2016; 432: 354.
- [30] Kirdsiri, K., Kaewkhao, J., Limsuwan, P. Photon Interaction in Borate Glass Doped with Bi_2O_3 at Different Energies. *Procedia Engineering* 2012; 32: 727–33.
- [31] Limkitjaroenpoma, P., Kaewkhao, J., Chewpraditkul, W., Limsuwan, P., (2012) Mass Attenuation Coefficient and Effective Atomic Number of Ag/Cu/Zn Alloy at Different Photon Energy by Compton Scattering Technique, *Procedia Engineering* 2012; 32): 847–54.