Investigation of Eu^{2+}–Mn^{2+} Energy Transfer and Y_2O_3 Scattering Effects in Phosphor-Converted White LEDs

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Abstract: **Phosphor-converted white light-emitting diodes (WLEDs) require both efficient luminescence conversion and effective control of photon propagation within the phosphor layer. Eu^{2+}–Mn^{2+} co-doped phosphors are of interest because Eu^{2+} can act as a sensitizer for Mn^{2+} through an energy-transfer process. In addition, scattering materials can modify photon propagation and consequently affect the optical performance of WLEDs. This work discusses the $Eu^{2+}\rightarrow Mn^{2+}$ energy-transfer process in $Ba_2MgSi_2O_7$ (BMSO) phosphors based on previously reported spectroscopic and mechanistic studies, while experimentally examining the effect of Y_2O_3 scattering conditions on WLED optical characteristics. The effects of Y_2O_3 on correlated color temperature (CCT), ΔCCT, and luminous output are analyzed, and its scattering properties are compared with those of KBr and TiO_2. The results show that Y_2O_3 produces a moderate scattering effect and influences both color characteristics and luminous output. The Y_2O_3-based WLED exhibits a CCT of 3000 K, a ΔCCT of 48.82 K, a CRI of 56.32, a CQS of 42.46, and a luminous output of 73.11 lm. Compared with the investigated scattering materials, TiO_2 provides stronger scattering and higher luminous output, whereas Y_2O_3 provides a more moderate scattering response with warm-white emission characteristics. The discussion of Eu^{2+}–Mn^{2+} energy transfer and Y_2O_3 scattering provides complementary perspectives on luminescence conversion and photon propagation in phosphor-converted WLED systems.**

Keywords: **$Ba_2MgSi_2O_7$, CCT, Eu^{2+}–Mn^{2+} energy transfer, light scattering, luminous output, phosphor-converted WLEDs, Y_2O_3.**

I. INTRODUCTION

Phosphor-converted white light-emitting diodes (WLEDs) have attracted considerable attention because of their high luminous efficiency, long operating lifetime, and flexible spectral characteristics [1,2]. The optical performance of WLEDs is determined not only by the luminescence properties of the phosphor materials but also by the propagation, scattering, and absorption of photons within the phosphor layer [3]. Therefore, both luminescence conversion and optical scattering are important factors in determining the final color and luminous performance of WLED systems [4-6].

Mn^{2+}-activated phosphors are attractive for generating orange-red emission; however, the d–d transitions of Mn^{2+} are spin- and parity-forbidden, resulting in relatively weak absorption under conventional LED excitation [7,8]. One approach to overcome this limitation is to introduce a sensitizer with stronger absorption in the ultraviolet or blue spectral region. Eu^{2+} is particularly suitable because its allowed 4f–5d transitions provide strong absorption and can facilitate energy transfer to Mn^{2+}. Consequently, the luminescence behavior of Eu^{2+}/Mn^{2+} co-doped phosphors is strongly related to the energy-transfer interaction between the donor and acceptor ions.

Energy transfer from Eu^{2+} to Mn^{2+} has been investigated in several phosphor host lattices. Depending on the donor–acceptor separation and the electronic structure of the interacting ions, the transfer process may occur through multipolar interactions or short-range exchange interactions. In particular, Dexter-type exchange interaction is highly dependent on the distance between donor and acceptor ions because it involves spatial overlap of their electronic wave functions. Previous studies of $Eu^{2+}\rightarrow Mn^{2+}$ energy transfer have shown that time-resolved photoluminescence can provide useful information about donor decay dynamics and the transfer process. For BMSO and related silicate phosphors, differences in the transfer dynamics have been associated with the separation between Eu^{2+} and Mn^{2+} ions [9-11].

$Ba_2MgSi_2O_7$ (BMSO) is a suitable silicate host for Eu^{2+}–Mn^{2+} phosphors because the incorporation of different activator ions can modify the emission characteristics and enable interaction between the luminescent centers. The energy-transfer behavior is therefore relevant to the development of phosphors capable of producing tunable emission through sensitization of Mn^{2+} by Eu^{2+}. Other activator-doped phosphor systems have also been investigated for improving the luminous and chromatic characteristics of WLEDs [12,13]. In this work, the Eu^{2+}–Mn^{2+} system is discussed based on previously reported luminescence and energy-transfer behavior, with emphasis on the possible interaction between the donor and acceptor ions.

For practical WLED applications, luminescence conversion is only one aspect of the optical process. The propagation and scattering of photons within the phosphor layer can also affect the spectral distribution, color uniformity, and luminous output. Scattering particles modify the optical path of photons and their probability of interacting with phosphor particles, thereby influencing the resulting WLED characteristics. Materials such as Y_2O_3, KBr, and TiO_2 have been investigated as scattering materials for controlling photon propagation in phosphor-converted LEDs [14-16]. Other particulate materials, including $BaSO_4$ and ZnO, have also been investigated as scattering centers in phosphor-converted WLED systems [17]. The optical response of phosphor-converted WLEDs can also depend on phosphor particle characteristics and composition, which may influence light propagation and extraction [18]. Among these materials, Y_2O_3 is of interest because it can modify photon redistribution within the phosphor layer and can also be incorporated into phosphor configurations to influence the resulting optical characteristics [19].

In addition to optical scattering and luminescence conversion, the thermal stability of phosphor materials and WLED structures is an important consideration for maintaining stable optical performance under practical operating conditions.

Y_2O_3 is of interest because its scattering properties can provide an additional means of controlling photon redistribution within the phosphor layer. Changes in scattering conditions can influence correlated color temperature (CCT), ΔCCT, and luminous output. Comparing Y_2O_3 with other scattering materials, such as KBr and TiO_2, can further clarify the relationship between scattering strength and WLED optical performance [20].

Therefore, this study considers two complementary aspects of phosphor-converted WLED systems. The first concerns the Eu^{2+}→Mn^{2+} energy-transfer process in BMSO phosphors, which is discussed based on previously reported spectroscopic and mechanistic studies. The second concerns the effect of Y_2O_3 scattering conditions on WLED optical characteristics, including CCT, ΔCCT, and luminous output. The scattering characteristics of Y_2O_3 are also compared with those of KBr and TiO_2. By considering these two aspects together, the work provides a broader discussion of luminescence conversion and photon scattering in phosphor-converted WLED systems.

II. MATERIALS AND METHODS

A. Y_2O_3 Scattering Material and WLED Configuration

Y_2O_3 was investigated as a scattering material in a phosphor-converted white light-emitting diode (WLED) configuration. Y_2O_3 particles with different particle sizes of 1–5 μm were incorporated into the investigated optical configuration to evaluate their influence on photon propagation and the resulting WLED performance.

The optical characteristics of the WLED configurations were evaluated in terms of correlated color temperature (CCT), ΔCCT, and luminous output. CCT was used to characterize the color appearance of the emitted white light, while ΔCCT was used to evaluate the deviation of the correlated color temperature. The luminous output was used to assess the effect of Y_2O_3 scattering on the extracted optical output.

The dependence of the measured optical parameters on the Y_2O_3 particle-size condition was analyzed to determine the effect of scattering on the color and luminous characteristics of the WLED.

B. Optical Scattering Characteristics

The scattering characteristics of Y_2O_3 were evaluated using the scattering coefficient and reduced scattering coefficient. The obtained values were compared with the corresponding values of KBr and TiO_2 to assess their relative scattering strength [21,22].

The comparison was used to examine the relationship between scattering strength and the optical characteristics of the corresponding WLED systems, including CCT, ΔCCT, and luminous output.

C. Evaluation of WLED Optical Performance

The optical performance of the WLED systems was evaluated using CCT, ΔCCT, color rendering index (CRI), color quality scale (CQS), and luminous output. The results obtained for the Y_2O_3-based configuration were compared with reported results for WLED systems employing KBr and TiO_2 as scattering materials.

The comparison was performed to evaluate the effect of the scattering material on color characteristics and luminous performance and to determine the relative suitability of Y_2O_3 for phosphor-converted WLED applications.

D. Literature-Based Discussion of Eu^{2+}–Mn^{2+} Energy Transfer

The Eu^{2+}–Mn^{2+} energy-transfer process in $Ba_2MgSi_2O_7$ (BMSO) was discussed based on previously reported spectroscopic and mechanistic studies [23]. Particular attention was given to the relationship between Eu^{2+} donor emission, Mn^{2+} acceptor excitation, donor–acceptor separation, and the possible contribution of short-range exchange interaction.

Because new time-resolved photoluminescence data for the Eu^{2+}–Mn^{2+} system were not available in the present study, no experimental lifetime, decay curve, or energy-transfer efficiency was determined in this work. The Eu^{2+}–Mn^{2+} discussion therefore serves as a literature-based background for understanding luminescence conversion in phosphor systems rather than as a new quantitative experimental investigation.

III. RESULTS AND DISCUSSION

A. Eu^{2+}–Mn^{2+} Energy Transfer in BMSO Phosphors

Mn^{2+}-activated phosphors have attracted considerable attention because of their potential for generating broad-band orange-red emission. However, the direct excitation of Mn^{2+} is generally inefficient because its d–d transitions are spin- and parity-forbidden. Therefore, the incorporation of a sensitizer such as Eu^{2+} provides an effective approach for enhancing Mn^{2+} emission through an energy-transfer process. In Eu^{2+}–Mn^{2+} co-doped phosphors, the broad emission band of Eu^{2+} can overlap with the absorption region of Mn^{2+}, providing a favorable condition for energy transfer between the two activator ions.

BMSO is a suitable host for investigating Eu^{2+}–Mn^{2+} interactions because Eu^{2+} and Mn^{2+} can occupy different cationic sites in the silicate lattice. The spatial distribution of these ions therefore plays an important role in determining the probability of energy transfer. Previous studies on Eu^{2+}–Mn^{2+}-activated phosphors have indicated that the transfer efficiency is strongly dependent on the Eu^{2+}–Mn^{2+} separation and can become significant when the donor and acceptor ions are located at relatively short distances.

The energy-transfer process can be described as the migration of excitation energy from an excited Eu^{2+} donor to a neighboring Mn^{2+} acceptor. In general, such transfer may occur through multipolar interactions or short-range exchange interactions, depending on the donor–acceptor distance and the electronic characteristics of the interacting ions. For closely spaced Eu^{2+} and Mn^{2+} ions, an exchange-mediated mechanism can become particularly important because of the strong dependence of the transfer probability on the spatial overlap between the electronic wave functions.

Previous studies have used steady-state and time-resolved photoluminescence to investigate Eu^{2+}–Mn^{2+} interactions in BMSO and related phosphor systems. These studies indicate that the donor–acceptor separation and the local environment of the activator ions can influence the energy-transfer behavior. However, quantitative evaluation of the Eu^{2+}–Mn^{2+} transfer efficiency requires experimental lifetime or time-resolved PL data. Since such experimental data are not available for the present study, the Eu^{2+}–Mn^{2+} energy-transfer mechanism is discussed here as a literature-supported interpretation rather than as a quantitatively demonstrated result [24].

B. Effect of Y_2O_3 Particle Size on CCT, ΔCCT, and Luminous Output

Figure 1 illustrates the variation of CCT with observation angle for Y_2O_3 particle sizes of 1–5 µm. The CCT profiles vary with both particle size and observation angle, indicating that the scattering conditions influence the angular distribution of the emitted light. The lowest CCT is observed at 5 µm, while the highest value occurs at 2 µm. These results indicate that the particle size of Y_2O_3 affects the propagation and redistribution of light within the phosphor layer and consequently modifies the spectral balance of the WLED.

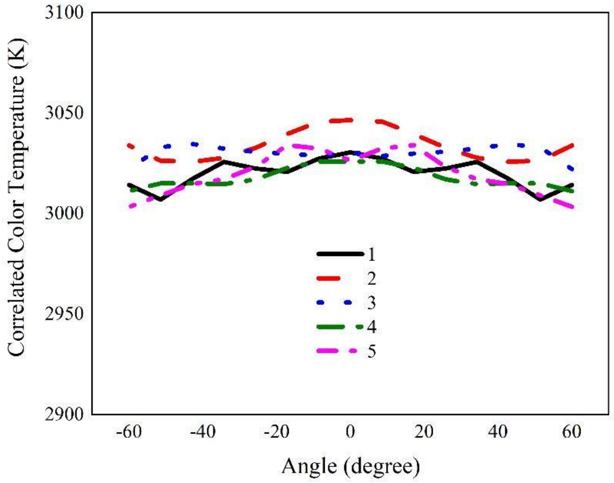

Fig. 1. CCT variation with Y_2O_3 particle size.

Figure 2 shows the variation in ΔCCT as a function of Y_2O_3 particle size. The ΔCCT remains relatively low for particle sizes of 1 and 2 µm, with values of approximately 50 and 45 K, respectively. As the particle size increases to 3 µm, ΔCCT increases to approximately 90 K. A much larger increase is observed at 4 µm, where ΔCCT reaches approximately 165 K. At 5 µm, ΔCCT decreases to approximately 120 K. These results indicate that particle size has a significant influence on the CCT deviation of the WLED. The relatively low ΔCCT obtained at 1 and 2 µm suggests more stable CCT characteristics, whereas the larger values observed at 3–5 µm indicate greater deviation in the correlated color temperature.

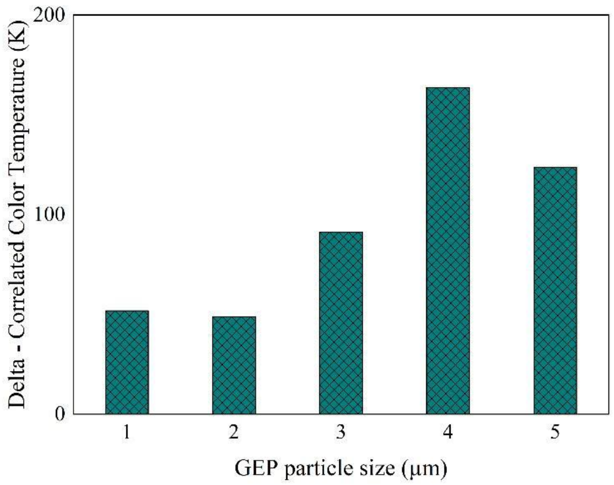

Fig. 2. Variation in ΔCCT with Y_2O_3 particle size.

Figure 3 shows the luminous output obtained with different Y_2O_3 particle sizes. The luminous output increases from approximately 70.5 lm at 1 µm to approximately 73.1 lm at 2 µm. It then decreases to approximately 72.7 lm at 3 µm and 72.1 lm at 4 µm, before remaining nearly unchanged at approximately 72.1 lm for 5 µm. This behavior suggests that the relationship between particle size and luminous output is not strictly monotonic. At an appropriate particle size, Y_2O_3 particles can promote photon scattering and redistribution within the phosphor layer. However, changes in scattering behavior at larger particle sizes may also increase backscattering and optical losses, limiting the improvement in extracted luminous output.

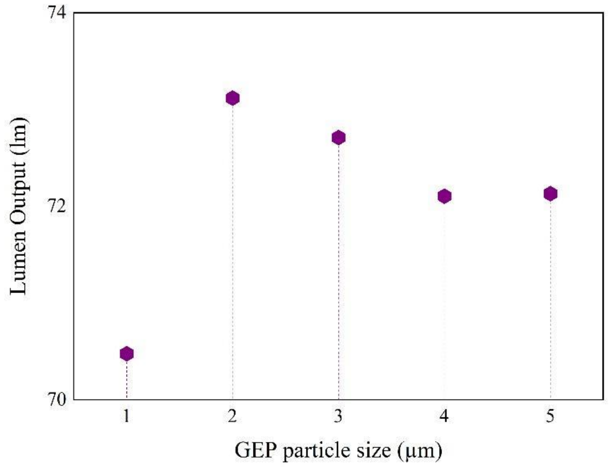

Fig. 3. Luminous output as a function of Y_2O_3 particle size.

Overall, the results from Figures 1–3 demonstrate that Y_2O_3 particle size influences both the color characteristics and luminous output of the WLED. Smaller particle sizes of 1–2 µm provide relatively low ΔCCT, while intermediate and larger particle sizes result in greater CCT deviation. The luminous output, meanwhile, reaches its highest value at 2 µm among the investigated conditions. Therefore, the particle-size effect should be considered when optimizing the balance between CCT stability and luminous output.

C. Scattering Properties of Y_2O_3 and Comparison with Other Materials

The scattering and reduced scattering coefficients of Y_2O_3, KBr, and TiO_2 are compared in Table I. Y_2O_3 exhibits a scattering coefficient of 10.11 mm^{-1} and a reduced scattering coefficient of 0.529 mm^{-1}. These values are lower than those of KBr, which are 42.5 and 13.5 mm^{-1}, respectively, and substantially lower than those of TiO_2, which reach 129.4 and 39.3 mm^{-1}. Based on the scattering coefficients listed in Table I, TiO_2 exhibits the strongest scattering, followed by KBr, whereas Y_2O_3 exhibits a more moderate scattering response.

The relatively moderate scattering strength of Y_2O_3 can be advantageous when excessive photon diffusion needs to be avoided. A scattering material with very high scattering strength can increase the probability of backscattering and repeated photon–particle interactions, which may introduce additional optical losses. In contrast, moderate scattering can provide sufficient photon redistribution while maintaining a reasonable balance between light extraction and color uniformity [25].

The difference in scattering strength also helps explain the variation in WLED performance among the investigated materials. TiO_2, with its substantially higher scattering coefficient, can provide stronger photon redirection and consequently enhance certain aspects of light extraction. However, the stronger scattering effect may also modify the spectral distribution and color characteristics of the WLED. Y_2O_3, in contrast, provides a more controlled scattering response, which may be beneficial for applications requiring balanced optical characteristics rather than maximum scattering efficiency.

TABLE I. COMPARISON OF SCATTERING AND REDUCED SCATTERING COEFFICIENTS OF THE INVESTIGATED MATERIALS

Scattering Materials	**Scattering coefficients (mm^{-1})**	**Reduced scattering coefficients (mm^{-1})**	**References**
Y_2O_3	10.11	0.529	This work
KBr	42.5	13.5	[10]
TiO_2	129.4	39.3	[11]

D. Overall WLED Optical Performance

Tables II and III summarize the reported optical characteristics of WLED configurations employing Y_2O_3, KBr, and TiO_2 as scattering materials. The YAG:Ce^{3+} concentrations are also listed to provide information on the phosphor composition of each investigated configuration. The Y_2O_3-based WLED in the present study contains 27.4% YAG:Ce^{3+}, with a CCT of 3000 K and a ΔCCT of 48.82 K. The corresponding CRI, CQS, and luminous output are 56.32, 42.46, and 73.11 lm, respectively.

Because the compared WLED configurations employ different phosphor concentrations and operating conditions, the values in Tables II and III are presented as a comparison of reported performance rather than as a strictly controlled comparison of scattering materials.

The Y_2O_3-based WLED exhibits a luminous output close to that of the KBr-based system, for which the reported luminous output is 73.7 lm. Their CRI and CQS values are also very similar, indicating comparable color-rendering characteristics. However, the ΔCCT of the Y_2O_3-based system is higher than that of KBr, indicating a somewhat larger variation in CCT. Nevertheless, Y_2O_3 maintains a warm-white CCT of 3000 K, making it suitable for applications where warm-white emission is preferred.

In comparison, the TiO_2-based WLED exhibits a substantially higher luminous output of 118.81 lm and a CQS of 63.3. The higher luminous output of the TiO_2-based WLED may be partly associated with its higher scattering coefficient shown in Table I. Stronger scattering can promote photon redistribution within the phosphor layer and may increase the probability of light extraction. However, the TiO_2-based system operates at a higher CCT of 4000 K, corresponding to a cooler white-light appearance. Its CRI is slightly lower than those of the Y_2O_3- and KBr-based systems, while its ΔCCT reaches 49.6 K.

TABLE II. COMPARISON OF CCT AND ΔCCT OF WLEDS USING DIFFERENT SCATTERING MATERIALS

Scattering Materials	**YAG:Ce^{3+} (%)**	**CCT (K)**	**ΔCCT (K)**	**References**
Y_2O_3	27.4	3000	48.82	This work
KBr	27.4	3000	35.4	[10]
TiO_2	10.6	4000	49.6	[11]

TABLE III. COMPARISON OF COLOR AND LUMINOUS PERFORMANCE OF WLEDS USING DIFFERENT SCATTERING MATERIALS

Scattering Materials	**CRI**	**CQS**	**Lumen (lm)**	**References**
Y_2O_3	56.32	42.46	73.11	This work
KBr	56.2	42.4	73.7	[10]
TiO_2	54.5	63.3	118.81	[11]

Overall, the comparison indicates that Y_2O_3 provides a moderate scattering effect together with balanced color and luminous characteristics. Although TiO_2 offers superior luminous output and stronger scattering, Y_2O_3 maintains a warm-white CCT and optical performance comparable to KBr. Therefore, Y_2O_3 can be considered a potential scattering material for WLED applications in which controlled photon redistribution, warm-white emission, and balanced color performance are more important than maximizing luminous output.

The two aspects investigated in this work—Eu^{2+}–Mn^{2+} energy transfer and Y_2O_3-assisted photon scattering—represent complementary processes in phosphor-converted WLEDs. The former concerns the generation and conversion of luminescence within the phosphor, whereas the latter concerns the subsequent propagation and redistribution of photons within the optical structure. Therefore, their discussion provides a broader view of the factors influencing the optical performance of phosphor-based WLED systems.

IV. CONCLUSIONS

This study discussed two complementary aspects of phosphor-converted WLED systems: Eu^{2+}→Mn^{2+} energy transfer in BMSO phosphors and Y_2O_3-assisted photon scattering. The Eu^{2+}–Mn^{2+} energy-transfer process was discussed based on previously reported spectroscopic and mechanistic studies. In the absence of new time-resolved photoluminescence data, the transfer mechanism was not quantitatively evaluated or experimentally confirmed in the present work. The experimental results for Y_2O_3 demonstrate that particle size influences the CCT, ΔCCT, and luminous output of the WLED. Among the investigated particle sizes, 1–2 µm produces relatively low ΔCCT, while the highest luminous output is obtained at 2 µm. The comparison of scattering coefficients shows that TiO_2 provides the strongest scattering, followed by KBr and Y_2O_3. The Y_2O_3-based WLED exhibits a warm-white CCT of 3000 K and a luminous output of 73.11 lm, with CRI and CQS values of 56.32 and 42.46, respectively. Overall, under the investigated conditions, Y_2O_3 provides moderate scattering and can be considered a potential scattering material for WLED applications where controlled photon redistribution and warm-white optical characteristics are desired.

V. ACKNOWLEDGEMENT

The authors wish to express their gratitude to the Posts and Telecommunications Institute of Technology, Vietnam, for financial support for this research.

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