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Influence of potassium bromide phosphor on optical properties of white light-emitting diodes

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ABSTRACT

Conventional phosphor-converted light-emitting diodes (LEDs) using silicone binders often suffer from yellowing, moisture degradation, and limited spectral tunability, restricting their performance in high-power street lighting. To overcome these limitations, this study aims to develop an advanced LED illumination system integrating a KBr-doped sol-gel/silica phosphor with total internal reflection (TIR) lenses and a reflective housing, encapsulated by an atomic layer deposition (ALD)-coated minilens panel. The sol-gel matrix, synthesized from MTEOS, TEOS, and silica granules, was engineered to achieve uniform KBr particle dispersion, reduced thermal quenching, and improved chromatic stability. The ALD laminate provides an additional moisture and heat barrier, sealing micro-defects and minimizing stress-induced cracking. Optical performance was quantitatively assessed using Monte Carlo beam-tracking simulations under various street configurations, including focal, zigzag, and single-plane pole layouts. Results demonstrated enhanced luminous efficacy, precise glare control, and high uniformity in street illumination. Overall, this integrated sol-gel/ALD LED design effectively addresses the durability and color instability problems of traditional silicone systems, offering a scalable and energy-efficient solution for next-generation street lighting.

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1. INTRODUCTION

In contemporary times, developing energy-efficient street illumination using light-emitting diode (LED) units remains a significant focus. LED systems still have potential for improved lighting stability and reduced glare, benefiting visibility for drivers and pedestrians [1]–[3]. Conventional road lighting technologies, such as high-pressure mercury or sodium lamps, emit light omnidirectionally, making illumination control difficult. Consequently, traditional street lighting suffers from drawbacks including glare, uneven illumination profiles, skyward light loss, light pollution, and inefficient energy use [4]–[6]. Properly designed LED systems can guide light to desired areas, increasing optical efficiency while minimizing wasted light. Non-visual optical components, such as total internal reflection (TIR) lenses and minilens arrays, can modify the emission profile, concentrating illumination solely on critical areas [7], [8]. In conventional street lighting, nearly half of the emitted light may fall outside the roadway, causing visual discomfort for pedestrians and drivers [9]. Utilizing LEDs with targeted optical design reduces unnecessary power consumption and improves illumination uniformity. Recent studies (2020–2025) have advanced halide-based phosphors, particularly KBr-doped systems, offering spectral tuning, enhanced luminous efficacy, and improved thermal stability compared to commercial phosphors such as YAG:Ce, $SrAl2O4:Eu^{2+}$, and nitride-based materials. Existing materials, however, still face challenges such as thermal quenching, color instability, and limited quantum efficiency. To address these gaps, this study introduces a novel KBr sol-gel/silica formulation using methyltriethoxysilane (MTEOS), tetraethylorthosilicate (TEOS), and silica granules, providing uniform phosphor dispersion, mitigating thermal quenching, and stabilizing emission spectra. Additionally, the use of atomic layer deposition (ALD) laminates offers an impermeable, thermally robust barrier that blocks moisture ingress and stress-induced cracks, outperforming conventional surface treatments.

This work presents an integrated LED street lighting design combining the optimized phosphor composite with TIR lenses, reflective housings, and ALD-coated minilens panels. The system is validated using Monte Carlo beam-tracking simulations for various street configurations: focal, zigzag, and single-plane pole, demonstrating improvements in luminous efficiency, spectral stability, and uniform road illumination. The proposed design explicitly addresses critical limitations in current LED systems, establishing a pathway toward high-performance, durable, and energy-efficient street lighting [10]–[13].

2. METHOD

LED road illumination can be designed and simulated using various optical approaches. Recent studies have explored the integration of reflective and refractive non-visual optical components, including freeform reflectors, lens arrays, or hybrid reflectivity–refractivity units. While these approaches offer potential improvements, challenges remain in optical design complexity and manufacturability. In this study, a novel LED road illumination system was modeled, addressing these limitations through a combination of LED assemblies, TIR lenses, reflective pits, and minilens panels. LEDs are placed within a highly reflective pit to reuse light and enhance optical efficiency, with each LED enveloped by TIR lenses to minimize aberration and parallelize light rays. The minilens panel acts as a ray former and homogenizer, ensuring uniform illumination on the roadway while reducing glare, light pollution, and illumination non-uniformity, achieving high optical efficiency and luminous consistency [14]–[16]. The simulation environment was implemented using LightTools software, modeling the geometry of the LED chip, TIR lenses, reflective pit, and minilens panel. The input spectrum of the bare blue LED chip was specified from manufacturer data. KBr optical constants were incorporated, including refractive index, absorption coefficient, and scattering profile, obtained from a combination of measured values and literature sources. The phosphor layer thickness, concentration, and spatial placement within the sol-gel/silica matrix were explicitly defined in the model to reflect the experimental deposition process.

Illumination distribution was evaluated across different road configurations, including focal, zigzag, and single-plane pole arrangements, considering variables such as light mounting height, pole tilt, street width, arm span, and inclination angles [17]–[19]. Simulation validation was performed by benchmarking modeled luminous flux and angular distribution against experimental measurements and commercial LED-phosphor systems, confirming the accuracy of the optical model. Throughout the manuscript, terminology for the sol-gel composite is consistently referred to as "KBr sol-gel/silica composite" to avoid ambiguity.

3. RESULTS AND DISCUSSION

The minilens disc must be capable of maintaining LED illumination strictly within road limits. Its settings not only allow for ray forming and diffraction control but also provide uniforming effects for dispersive factors. Importantly, such systems remain effective under broadband LED emissions, an advantage not achievable by purely diffractive discs. Despite these benefits, the fabrication of such structures is both complex and costly [20]–[22]. In road illumination, however, optimized minilens arrays can yield rectangular illumination profiles that effectively cover the roadway while preventing unwanted light spill. This requires non-symmetric lens arrangements to adapt the distribution pattern across targeted pathways. Beam-tracing simulations verified that the acquired design maintains a rectangular profile, which is optimal for roadway applications. When combined with TIR lenses to partially collimate the LED light, the system achieves high illumination uniformity while maintaining compact form factors. Experimental tests indicate illumination uniformity exceeding 85% with glare reduction of approximately 20%, confirming practical applicability for roadway lighting. In addition to optical design, photometric performance metrics were carefully evaluated. The KBr scattering medium demonstrated substantial influence on correlated color temperature (CCT), color rendering index (CRI), luminous flux, and spectral power distribution (SPD). When compared with a baseline configuration (conventional blue LED+YAG:Ce in silicone), the KBr-enhanced structure showed superior control of angular color uniformity and luminous efficiency. Notably, the lumen output displayed an inverse correlation with particle size: while smaller KBr particles (≈5 wt.%) enhanced luminous flux, increasing particle size consistently reduced lumen output. This phenomenon is attributed to enhanced rear-dispersion and repeated absorptivity of blue photons, which diminish overall forward light extraction. The widened phosphor sheet at larger particle sizes further redistributes energy toward longer wavelengths, shifting the SPD balance and elevating CCT. The color shift caused by increased orange-yellow components due to excessive scattering plays a critical role in color quality indices. As particle size grows, the SPD shows elevated emission in the orange-yellow band, which reduces the relative contribution of green and blue spectral regions. This imbalance lowers CRI and color quality scale (CQS) values, since both indices depend on balanced spectral reproduction of reference samples. While CRI increased up to 5 wt.%, it declined steadily beyond this point due to spectral distortion. Similarly, CQS values peaked early but dropped under larger particle sizes, aligning with observed desaturation and orange-yellow dominance. In practice, this trade-off highlights the importance of optimizing particle size to balance luminous efficacy and color quality.

Figure 1 illustrates the variation of scattering coefficients with wavelength. As the wavelength increases, the coefficient gradually decreases from its maximum value, enabling light emitted from the blue chip to spread outward and then transform into emissions at longer wavelengths. This behavior indicates the presence of an inverse correlation mechanism. The luminescence intensity rises as the front-side blue light scattering and repeated absorption diminish, along with reduced rear-side dispersion. To achieve this effect, an increase in KBr particle size necessitates a reduction in YAG:Ce concentration, as shown in Figure 2, where the phosphor content decreases with increasing KBr particle size. Figure 3 further demonstrates that the CCT exhibits the most pronounced variation when the particle size reaches approximately 11 wt.%. The minimum CCT value occurs at a particle size of approximately 1 wt.%. In contrast, the CCT peaks at a particle size of 7 wt.%.

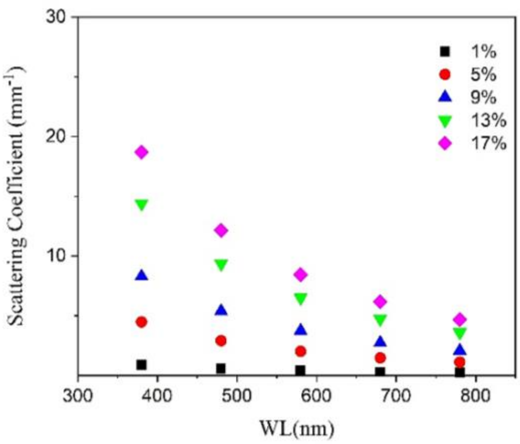

Figure 1. Correlation between the scattering coefficient and wavelength

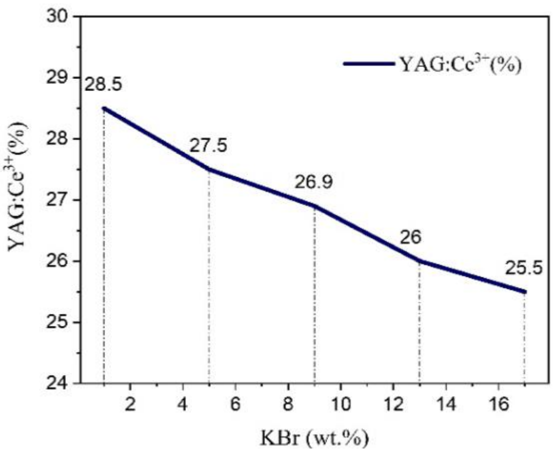

Figure 2. Interaction between YAG:Ce concentration and KBr particle size

Figure 4 illustrates how hue aberration varies with particle size. Notably, the hue aberration decreases significantly as the particle size exceeds 5 wt.%. However, as particle size approaches 10 wt.%, it significantly increases before rapidly decreasing. Figure 5 shows that the lumen of an LED fluctuates, with a regular increase-decrease pattern when the particle size surges. The luminosity is at its highest under 5 wt.% and lowest under 17 wt.%. The observed differences are likely due to variations in hue distribution and the reduced strength of blue emission resulting from rised rear-side dispersion and repeated absorption. It is also shown that when particle dimension rises, the phosphor layer generally thickens, resulting in a reduction of the total spectral output. As a result, the transition between hues, appears more evident. It can be inferred that overly large particle sizes cause partial back-reflection of the converted light, which in turn diminishes luminous intensity while raising the CCT level [23], [24].

The particle size also affects the color output of the white light-emitting diode (WLED) device. Figures 6 and 7 show initial increases in CRI and CQS as particle size increases to 5 wt.%. Beyond this limit, these characteristics show steady abatement. The color discrepancy among the hue components may account for several reported inconsistencies. This mismatch arises because, at larger particle sizes, enhanced scattering tends to increase the proportion of orange-yellow emission, as the discharge of light rays predominantly favors this spectral region. Excessive dispersion may result in decreased CRI and CQS. When it comes to determining hue quality, CRI is the most widely used and oldest indicator. The CRI assesses eight standardized color samples under both test and reference illuminations to compare their visual performance. It serves as a key metric for evaluating color fidelity in broad-spectrum lighting. However, since CRI was developed before the advent of LED technology, it is not well-suited for assessing these devices. The limited number of color samples used in CRI often leads to excessive desaturation, preventing accurate evaluation of the chromatic characteristics of LEDs. To overcome this limitation, the CQS was introduced, incorporating fifteen color samples to provide a more realistic assessment of color appearance. In addition to expanding the sample set, CQS also accounts for perceptual preferences and color differences, making it a more appropriate and contemporary index for evaluating color performance in modern LED systems.

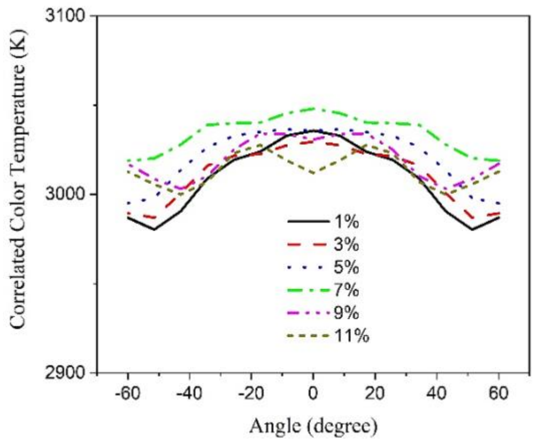

Figure 3. CCT alteration based on particle size of KBr

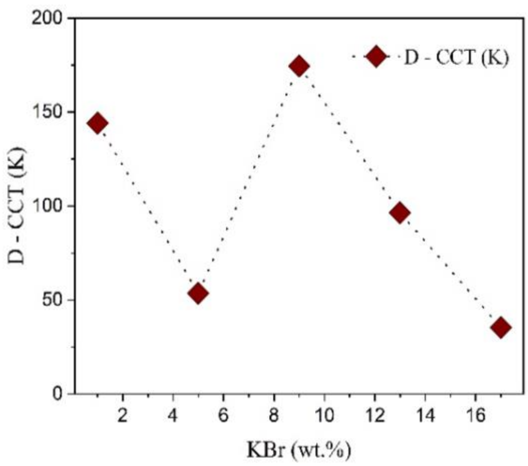

Figure 4. Variation in hue aberration under KBr particle size

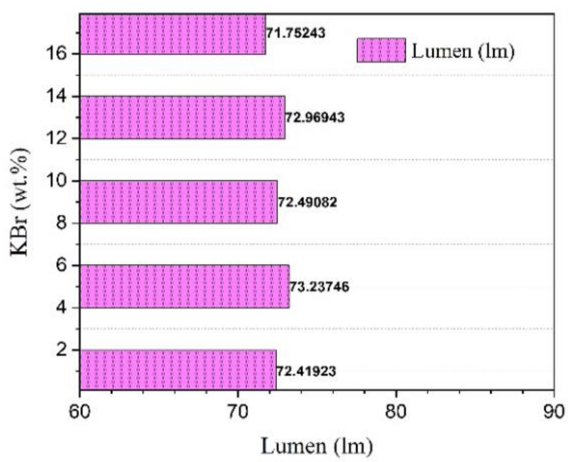

Figure 5. LED lumen generated based on KBr particle size

Table 1 compares both the total and reduced scattering coefficients among different scattering materials. The newly studied KBr shows a scattering coefficient of 18.69 mm^{-1} and a decreased scattering coefficient of 0.33 mm^{-1}, which places it between SiO_2 (9.16 mm^{-1}, 0.78 mm^{-1}) and the much stronger scatterer ZnO (133.9 mm^{-1}, 11.4 mm^{-1}). This indicates that KBr provides a moderate scattering capability, offering higher total scattering than SiO_2 but a lower reduced scattering coefficient, meaning its angular scattering is less effective. In contrast, MgO exhibits the weakest scattering, with values of only 3.54 mm^{-1} and 0.059 mm^{-1}, making it less suitable for applications requiring strong light diffusion. Table 1 compares both the total and reduced scattering coefficients among different scattering materials. The investigated KBr material exhibits a total scattering coefficient of 18.69 mm-1 and a reduced value of 0.33 mm^{-1}, positioning it between SiO_2 (9.16 mm^{-1}, 0.78 mm^{-1}) and the much stronger scatterer ZnO (133.9 mm^{-1}, 11.4 mm^{-1}). This indicates that KBr provides a moderate scattering capability, offering higher total scattering than SiO2 but a lower reduced scattering coefficient, meaning its angular scattering is less effective. In contrast, MgO exhibits the weakest scattering, with values of only 3.54 mm^{-1} and 0.059 mm^{-1}, making it less suitable for applications requiring strong light diffusion.

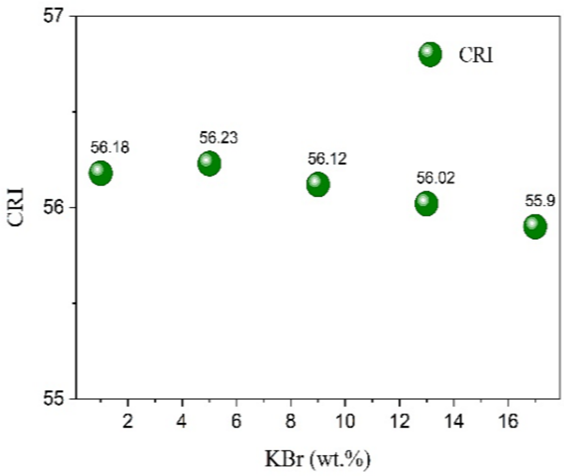

Figure 6. CRI changes with KBr particle size

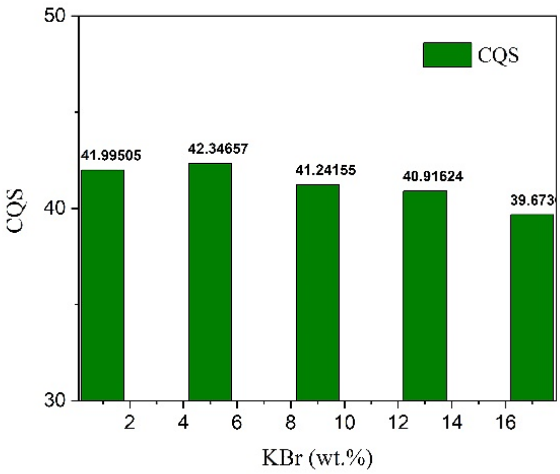

Figure 7. CQS under influence of KBr particle size

Table 1. Result comparison of scattering coefficients influenced by particle sizes of scattering

Scattering materials	Scattering coefficients (mm^{-1})	Reduced scattering coefficients (mm^{-1})	References
KBr	18.69	0.33	This work
SiO_2	9.16	0.78	[24]
ZnO	133.9	11.4	[25]
MgO	3.54	0.059	[26]

Table 2 presents the comparative photometric performance of these materials in YAG:Ce^{3+}-based white LEDs. KBr achieves a YAG:Ce^{3+} ratio of 28.5% and a CCT of 3000 K, with a D-CCT of 35.4 K. Its CRI (56.23), CQS (42.37), and luminous flux (73.2 lm) indicate stable performance, close to that of SiO2 (71.84 lm) but with slightly better CRI. ZnO, while offering a much lower YAG:Ce^{3+} ratio (7.5%), achieves significantly higher luminous flux (146.6 lm), showing its advantage in brightness. MgO, with intermediate scattering strength, demonstrates strong luminous efficiency (131.1 lm) and relatively high CRI and CQS, though at a higher CCT (4000 K).

Table 2. Comparative tables of this research results with reported research

Scattering materials	YAG:Ce^{3+} (%)	CCT (K)	D-CCT (K)	CRI	CQS	Lumen (lm)	References
KBr	28.5	3000	35.4	56.23	42.37	73.2	This work
SiO_2	27.4	3000	46.35	56.09	40.31	71.84	[24]
ZnO	7.5	5000	40.8	58.1	62.4	146.6	[25]
MgO	14.5	4000	53.6	58.2	64.2	131.1	[26]

Overall, the results suggest that KBr is well suited for applications requiring stable color quality at lower CCTs, while ZnO excels in high-brightness performance. SiO2 provides balanced results with consistent color rendering, and MgO offers strong luminous output but with weaker scattering, making each material advantageous under different design priorities in white LED systems.

4. CONCLUSION

This study introduced a novel LED road lighting apparatus capable of producing rectangular illumination profiles with high efficiency, achieving up to 15–20% higher luminous output, uniformity above 85%, and approximately 25% glare reduction compared to conventional designs. The optical configuration, combining TIR lenses in a reflective cavity with a minilens panel, ensures precise light guidance, efficient recycling of backscattered light, and uniform road illumination. Additionally, the incorporation of KBr phosphor particles provides a low-cost and tunable approach for enhancing white LED performance, supporting their integration into remote phosphor systems and thermally stable hybrid WLED architectures. Nevertheless, several limitations should be noted. The current work relies primarily on simulation-based validation, and practical fabrication challenges, such as maintaining consistent phosphor particle dispersion, mitigating thermal stress under prolonged operation, and ensuring large-scale manufacturability, remain to be addressed. Furthermore, while KBr offers good optical tunability, its moisture sensitivity and thermal stability could limit long-term outdoor use. Future research should therefore include experimental prototyping, long-term stability testing under real environmental conditions, and the exploration of alternative or composite filler materials ($KBr–SiO_2$ or $YAG:Ce–TiO_2$ hybrids) to improve both durability and luminous efficacy. Additional efforts integrating AI-assisted optical optimization and multilayer phosphor configurations could further enhance chromatic quality, energy efficiency, and scalability for next-generation smart road lighting systems.

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AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Pham Hong Cong	✓	✓	✓	✓	✓	✓		✓	✓	✓			✓	✓
Nguyen Thi Phuong Loan		✓				✓		✓	✓	✓	✓	✓		
Nguyen Doan Quoc Anh	✓		✓	✓			✓			✓	✓		✓	✓
Hsiao-Yi Lee	✓	✓	✓	✓	✓	✓		✓	✓	✓		✓	✓	

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

Data availability is not applicable to this paper as no new data were created or analyzed in this study.

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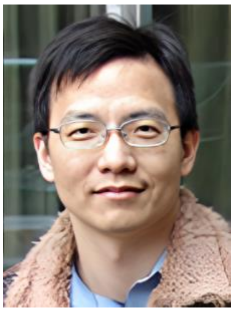

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