INFLUENCES ON LED OPTICAL CHARACTERISTICS WHEN VARYING ZNS PARTICLE SIZES IMPACTING SCATTERING COEFFICIENTS

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Abstract. *This study investigates the influence of zinc sulfide (ZnS) particle size variation on the optical and colorimetric performance of white light-emitting diodes (LEDs), with particular attention to parameters including luminous flux, correlated color temperature (CCT), color rendering index (CRI), and color quality scale (CQS). ZnS, a high-refractive-index scattering medium, was selected as a secondary phosphor encapsulant to modulate photon transport within the LED package. Mie scattering theory, implemented through MATLAB-based numerical simulations, was employed to systematically evaluate the optical behavior of LEDs incorporating ZnS particles of various diameters. By modeling scattering efficiency, angular light distribution, and chromatic response, the study quantitatively assesses the trade-offs between luminous efficacy and color fidelity. The simulation results reveal that increasing ZnS particle size enhances light scattering and spatial uniformity but leads to a reduction in overall luminous output and an increase in CCT deviation. Larger particles also result in a modest decrease in CRI and CQS values, indicating partial spectral distortion due to excessive backscattering. These findings highlight the critical role of particle size optimization in achieving balanced optical performance, where medium-sized ZnS particles provide the best compromise between color accuracy and luminous efficiency. The outcomes of this work offer valuable design insights for developing high-quality, color-stable, and energy-efficient white LEDs suitable for both general illumination and specialized optical applications.*

Keywords: *Double-layer phosphor; WLEDs; Monte Carlo theory; color homogeneity; luminous flux.*

1. Introduction

Light-emitting diodes (LEDs) have gained widespread adoption in modern lighting solutions due to their exceptional energy efficiency, durability, and versatility across a broad spectrum of applications [1–3]. Unlike traditional incandescent and fluorescent lighting systems, LEDs convert electrical energy into light through direct electron–hole recombination within semiconductor junctions, resulting in minimal energy loss and extended operational lifetime. Their unique characteristics, such as tunable spectral properties, compact form factor, and low environmental impact, make them well-suited not only for general illumination but also for specialized lighting systems in automotive headlamps, medical diagnostics, horticultural growth lighting, and architectural design [4, 5]. These diverse applications demand precise control over photometric and colorimetric parameters—including brightness, color uniformity, correlated color temperature (CCT), and color rendering index (CRI)—to ensure optimal visual comfort and functional performance [6–9].

Despite remarkable advancements in LED chip fabrication and phosphor-conversion technologies, achieving both high luminous efficiency and uniform chromatic distribution remains a persistent challenge. Light emitted from the LED chip often exhibits angular color variation due to nonuniform phosphor distribution and limited light scattering within the encapsulant layer. As a result, considerable research has focused on engineering scattering and diffusive structures to improve light extraction, color mixing, and angular uniformity. One promising and widely adopted approach is the incorporation of scattering particles into the LED structure—either within the encapsulant or the phosphor composite layer—to promote multiple light scattering events. These embedded particles enhance light diffusion, homogenize the emitted beam, and mitigate color separation, thereby improving overall visual performance without sacrificing luminous efficiency.

Among the various scattering materials investigated, zinc sulfide (ZnS) has emerged as a particularly effective candidate for LED applications. ZnS is a II–VI semiconductor characterized by a high refractive index, wide bandgap, and strong optical scattering properties, making it ideal for controlling photon propagation within LED structures [10, 11]. When embedded into the phosphor layer or encapsulant, ZnS particles can redistribute light uniformly, enhance luminous flux, and reduce angular color deviation. Beyond scattering enhancement, ZnS possesses tunable optical properties that make it valuable for a range of optoelectronic applications, including photodetectors, electroluminescent devices, and display technologies.

Recent studies have demonstrated ZnS's capability to improve both light extraction and chromatic uniformity in LED systems. For instance, ZnS-based nanocomposites and coatings have been shown to increase photon escape probability by reducing total internal reflection, thereby boosting external quantum efficiency [12–14]. In addition, ZnS's role as a scattering medium in display technologies and backlighting systems contributes to enhanced visual clarity and reduced glare by controlling directional light propagation [15, 16]. These attributes highlight ZnS's versatility as a multifunctional optical material capable of bridging performance and stability in solid-state lighting applications. Consequently, understanding and optimizing the incorporation of ZnS within LED phosphor structures remain vital for advancing next-generation illumination systems with superior efficiency, spectral balance, and color uniformity.

With that potential in the optics field—particularly in LED technology—this study aims to deepen the understanding of how ZnS particle size affects LED performance through a simulation-based analysis. Building upon prior findings on scattering-enhanced phosphor structures, we employ Mie scattering theory, a well-established model for analyzing light interaction with spherical particles, in conjunction with MATLAB simulations. This approach enables precise calculation of scattering coefficients and phase functions across a wide spectral range, providing insights into how particle size influences light diffusion, spectral balance, and color stability.

By systematically varying ZnS particle dimensions, the simulation clarifies the relationship between particle morphology and key LED optical parameters, including luminous efficacy, correlated color temperature (CCT), and chromatic uniformity. The use of Mie theory provides a controlled framework to predict how scattering efficiency and angular light distribution evolve with particle size and refractive index contrast. This simulation-driven method allows detailed examination of optical behavior without the limitations of experimental variability [17], offering valuable guidance for optimizing ZnS integration in high-performance, color-stable LED systems.

The remainder of this paper is structured as follows: first, we detail the simulation methods and assumptions, including the implementation of Mie scattering calculations in MATLAB. We then present the simulation results, analyzing the influence of ZnS particle size on scattering coefficient, CCT deviation, lumen output, CRI, and CQS. The discussion addresses the implications of ZnS particle size selection in LED design and suggests potential applications based on the simulation findings. This research contributes to the field of LED optimization by providing a theoretical foundation and practical insights for enhancing LED performance through tailored scattering particle sizes [18–21].

2. Experimental

The scattering analysis was performed based on Mie scattering theory to simulate the light-scattering behavior of ZnS particles with different radii [22–24]. The purpose of employing Mie scattering theory is to investigate variations in scattering efficiency corresponding to varying particle sizes of the ZnS, from which the impacts on LED light properties can be discussed. The following Equation (1) describes the wavelength-dependent scattering coefficient $\mu_{\mathrm{sca}}(\lambda)$:

$$\mu_{\mathrm{sca}}(\lambda) = \int N(r)\, C_{\mathrm{sca}}(\lambda, r)\, dr \quad (1)$$

where $\mu_{\mathrm{sca}}(\lambda)$ is the wavelength-dependent scattering coefficient, λ denotes the incident wavelength, $N(r)$ represents the number density of ZnS particles with radius r, and $C_{\mathrm{sca}}(\lambda, r)$ is the scattering cross-section of a single particle. According to Mie theory, the scattering cross-section C_{sca} is calculated as expressed in Equation (2), while the Mie coefficients a_n and b_n are obtained from Equations (3) and (4):

$$C_{\mathrm{sca}} = \frac{2\pi}{k^2} \sum_{0}^{\infty} (2n-1) \left(|a_n|^2 + |b_n|^2\right) \quad (2)$$

where k is the wave number defined as $k = 2\pi/\lambda$, λ is the wavelength in vacuum, and n denotes the order of the spherical harmonic expansion in Mie scattering theory. a_n and b_n are parity symmetric expansion coefficients and are calculated by:

$$a_n(x,m) = \frac{\psi_n'(mx)\,\psi_n(x) - m\,\psi_n(mx)\,\psi_n'(x)}{\psi_n'(mx)\,\xi_n(x) - m\,\psi_n(mx)\,\xi_n'(x)} \quad (3)$$

$$b_n(x,m) = \frac{m\,\psi_n'(mx)\,\psi_n(x) - \psi_n(mx)\,\psi_n'(x)}{m\,\psi_n'(mx)\,\xi_n(x) - \psi_n(mx)\,\xi_n'(x)} \quad (4)$$

where $x = k.r$, r is the particle radius, m is the refractive index, and $\psi_n(x)$ and $\xi_n(x)$ are the Riccati - Bessel functions of the first and third kinds, respectively.

The angular scattering amplitudes $S_1(\theta)$ and $S_2(\theta)$ are obtained from Equations (5) and (6), representing the angular distribution of the scattered fields predicted by Mie scattering theory:

$$S_1 = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \left[\begin{array}{l} a_n(x,m)\,\pi_n(\cos\theta) \\ + b_n(x,m)\,\tau_n(\cos\theta) \end{array} \right] \quad (5)$$

$$S_2 = \sum_{n=1}^{\infty} \frac{2n+1}{n(n+1)} \left[\begin{array}{l} a_n(x,m)\,\tau_n(\cos\theta) \\ + b_n(x,m)\,\pi_n(\cos\theta) \end{array} \right] \quad (6)$$

where $S_1(\theta)$ and $S_2(\theta)$ are the angular scattering amplitude functions, θ denotes the scattering angle, and τ_n and π_n are angular functions associated with Legendre polynomials in Mie theory.

3. Results and Discussion

Figure 1 illustrates the simulated wavelength-dependent scattering coefficients corresponding to different ZnS particle sizes. Figure 1a shows the scattering coefficient for smaller ZnS particle sizes (1, 3, 5, 7, 9, and 11 µm) across different wavelengths (300–800 nm). Figure 1b displays the scattering coefficient for larger ZnS particles, from 13 to 21 µm, with the same wavelength range. The data reveal that the scattering coefficient increases with larger particle sizes across all wavelengths, with the most pronounced scattering occurring at shorter wavelengths. This behavior is consistent with Mie scattering theory, where larger particles induce greater scattering, especially at shorter wavelengths, due to their comparable size to the wavelength of visible light. Besides, in Mie scattering, the scattering coefficients increase with particle size because larger particles have more surface area and volume to interact with the light. As a consequence, the scattering is not only stronger but also more forward-directed and also significantly back-scattered [25–27], which increases the overall scattering coefficient. The increased scattering with larger ZnS particles enhances light diffusion within the LED, potentially improving uniformity and reducing glare. However, excessive scattering can reduce light transmission, impacting lumen output. Thus, the selection of ZnS particle size represents a balance between enhancing diffusion and maintaining brightness. Beyond the overall increase in scattering coefficient with particle size, it is important to emphasize the wavelength-selective nature of ZnS-induced scattering. As shown in Figure 1, shorter wavelengths experience substantially stronger scattering than longer wavelengths, particularly for particle diameters exceeding 7 µm. This behavior is intrinsic to Mie scattering, where the scattering efficiency peaks when the particle diameter becomes comparable to the incident wavelength.

From an LED packaging perspective, this wavelength-dependent scattering plays a critical role in shaping the final spectral power distribution. Blue photons emitted from the LED chip are scattered more intensively than yellow phosphor-converted photons, leading to spatial redistribution of excitation energy within the phosphor layer. While moderate redistribution enhances color mixing and angular uniformity, excessive short-wavelength scattering can induce spectral imbalance and contribute to CCT deviation, as observed in later results.

Figure 2 demonstrates the effect of ZnS particle size on the required amount of YAG:Ce^{3+} phosphor in the LED configuration. As ZnS particle size increases, the amount of YAG:Ce^{3+} phosphor decreases significantly. This trend suggests that larger ZnS particles, due to their enhanced scattering, compensate for some of the color-mixing properties typically achieved by the phosphor [28]. By increasing light diffusion, larger ZnS particles help blend the

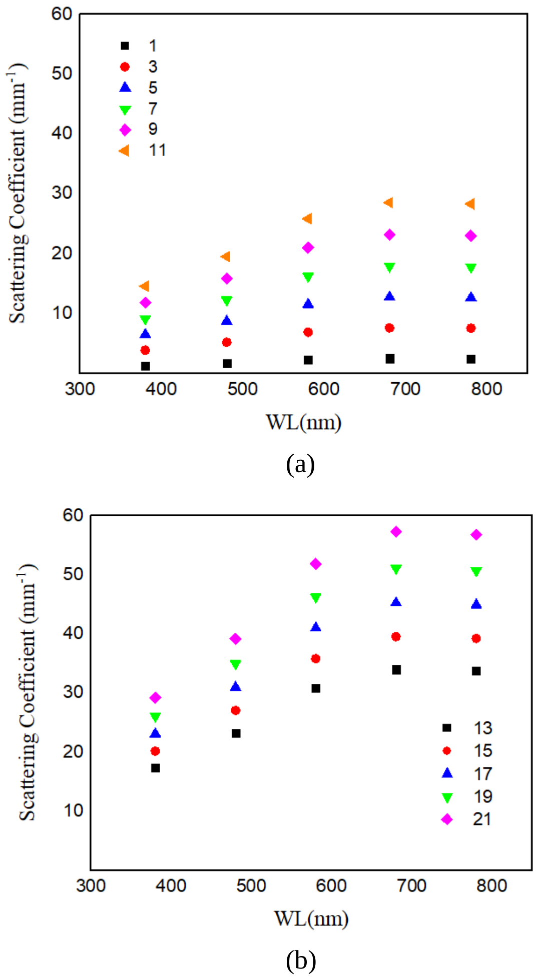


Figure 1. Scattering coefficients with different particle sizes of ZnS: (a) 1–11 μm and (b) 13–21 μm.

emitted light, reducing the need for YAG:Ce^{3+} to achieve a uniform and desirable color output. This reduction in phosphor content not only lowers material costs but also can potentially reduce thermal loads within the LED, improving efficiency and lifespan. Physically, the reduced YAG:Ce^{3+} requirement can be attributed to scattering-induced photon path elongation inside the phosphor layer. Larger ZnS particles increase the probability of multiple scattering events, effectively extending the optical path length of blue photons. This prolonged interaction enhances phosphor excitation efficiency, allowing equivalent chromatic output to be achieved with lower phosphor concentration. However, this mechanism introduces an intrinsic

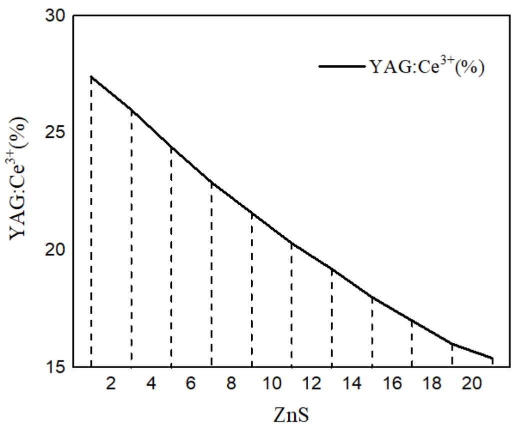
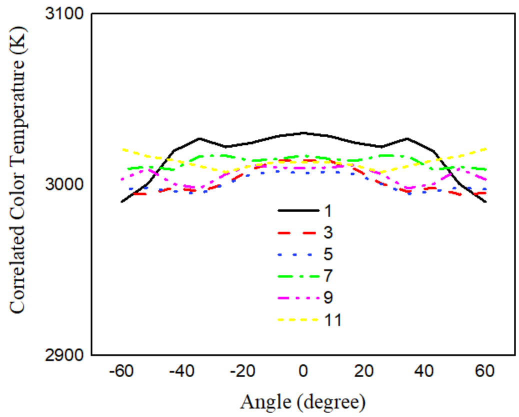
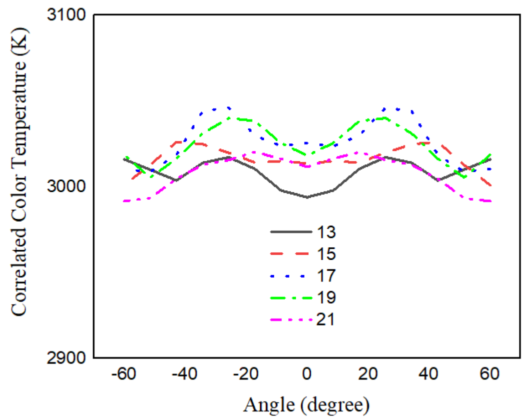


Figure 2. YAG:Ce^{3+} amount with different ZnS particle sizes.



(a)



(b)

Figure 3. CCT across the angles with different ZnS particle sizes: (a) 1–11 μm and (b) 13–21 μm.

trade-off. Excessive scattering also increases backward photon flux toward the LED chip and encapsulant interfaces, leading to partial photon recycling and absorption losses. Consequently, phosphor reduction driven purely by scattering enhancement must be optimized carefully to avoid sacrificing luminous efficiency. However, in applications where color fidelity and precision are critical, maintaining a balance between ZnS particle size and phosphor concentration is essential to avoid compromising on color quality.

Figure 3 shows the correlated color temperature (CCT) behavior across varying angles for different ZnS particle sizes. The plot in Figure 3a focuses on smaller particle sizes, ranging from 1 µm to 11 µm while that in Figure 3b is with the ZnS radius range of 13 – 21 µm. With the smaller particles, the CCT remains relatively stable, with only minor fluctuations across angles. However, larger particles exhibit slightly higher CCT values, indicating a shift towards cooler color temperatures. Moreover, the larger sizes of ZnS in Figure 3b displays the decrease in the CCT strength at the center (zero degree viewing angle), while the wider angles present the higher CCT intensity. Such data hint that the light distribution in the rear of the LED package is likely to be stronger, due to the increasing scattering coefficients [29, 30].

The angular asymmetry observed for larger ZnS particle sizes originates from enhanced backward and lateral scattering components. As particle size increases, scattering transitions from quasi-isotropic to strongly anisotropic behavior, redistributing a larger fraction of short-wavelength photons toward oblique and backward directions.

This redistribution alters local phosphor excitation conditions and produces angular-dependent spectral imbalance. Consequently, the perceived color temperature increases at larger viewing angles, particularly for particle sizes exceeding 11 µm. These results confirm that particle-size-induced scattering anisotropy is a dominant factor governing angular color stability in ZnS-assisted LED systems.

The stability of CCT across different angles is beneficial for LED applications, as it ensures consistent color perception from various viewing perspectives. The slight increase in CCT with larger ZnS particle sizes may be attributed to the enhanced scattering effect, which can shift the light output towards the blue end of the spectrum. This shift is particularly useful in applications where cooler light is desired, as it allows for color temperature tuning through particle size selection. For applications needing warm or neutral light, smaller ZnS particles may be preferable to avoid unintended shifts toward cooler tones [31].

The deviated CCT level in Figure 4 is used to further validate the impacts of various ZnS radii on the color stability of the LED light. The data shows an oscillating pattern in the CCT deviation as a function of ZnS particle size, with values rising and falling unpredictably as particle size increases. This deviation suggests that larger ZnS particles introduce inconsistencies in color temperature, leading to fluctuations in the perceived color of the LED output.

Specifically, smaller ZnS particles of around 1-5 µm exhibit relatively low CCT deviations, suggesting that they contribute to more stable color temperatures. However, as the ZnS is larger within 7-11 µm, the CCT deviation shows a sudden surge, which is nearly double that with 5 µm ZnS particle. As the particle reach 13 µm, a notable drop in deviated CCT level is recorded. This decline marks a nearly three-time lower CCT deviation at 13 µm, turning out to be the lowest point. Then, when the size is bigger, the CCT deviation gradually increases again [6].

Larger particle sizes introduce greater fluctuation in CCT values, likely due to increased scattering, especially at shorter wavelengths, and complex light interactions within the LED matrix. The variation in scattering can affect how different wavelengths of light are dispersed, leading to uneven color mixing, causing the color temperature to vary across different points in the light output. Since CCT is calculated based on the spectral balance of light, any inconsistency in the spectrum due to excessive or uneven scattering can shift the CCT, creating deviations.

Besides, larger particles scatter shorter (blue) wavelengths more than longer (red) wavelengths. This wavelength-dependent scattering (chromatic aberration) can cause certain colors to scatter more, effectively shifting the CCT towards a cooler (higher) temperature or warmer (lower) temperature based on the spectral composition at different points. As particle size varies, this selective scattering effect intensifies, leading to fluctuations in the color balance of the emitted light, and hence, an increase in CCT deviation.

On the other hands, when using the significantly large ZnS particles, it can interfere with how uniformly the phosphor layer is excited by the LED's blue light. If the excitation is uneven, it can lead to color temperature inconsistencies because the phosphor may not emit uniformly across the LED's surface. This variability could impair color consistency, making larger particles less ideal for applications requiring precise color stability. Thus, for LEDs targeting uniform color temperature across various viewing angles or operating conditions, selecting smaller ZnS particle sizes appears preferable. In this case, the advisable size for ZnS is 13 µm (optimal), or within 1-5 µm.

Notably, the non-monotonic trend of CCT deviation as a function of particle size indicates the presence of an optimal scattering regime. Intermediate ZnS particle sizes, particularly around 13 µm, minimize CCT deviation by balancing forward diffusion and backward scattering.

Below this regime, scattering strength is insufficient to fully homogenize spectral distribution, whereas above it, wavelength-selective scattering dominates and destabilizes color balance. This observation highlights that color stability in phosphor-converted LEDs is governed not by maximum scattering strength, but by optimized scattering balance.

Figure 4 illustrates the deviation of correlated color temperature (CCT) as a function of ZnS particle size. Smaller ZnS particles exhibit lower CCT deviation, indicating improved color stability, whereas larger particles introduce stronger wavelength-dependent scattering, leading to increased CCT fluctuation.

Figure 5 exhibits the lumen intensity of the LED in connection to the change in ZnS particle sizes. The inverse relationship between ZnS particle size and lumen output is evident in the decreasing lumen values as particle size increases. This observation aligns with Mie scattering theory, where larger particles scatter light more intensely, thus reducing its transmission through

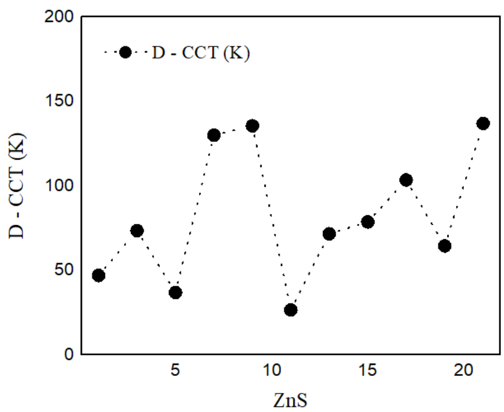


Figure 4. Deviated CCT values with different ZnS particle sizes.

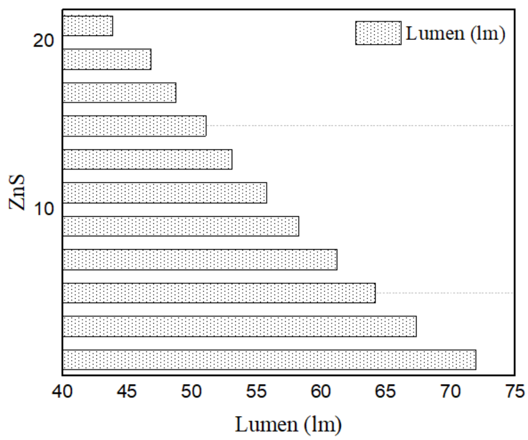


Figure 5. Lumen values with different ZnS particle sizes.

the LED medium. Larger particles also scatter light more, which can cause more light to be lost within the material rather than being emitted outwards. This reduces the overall lumen output [32].

In contrast, the efficiency of converting absorbed light into emitted light (luminous efficacy) can be higher with smaller particles due to better interaction with the excitation light. To put it differently, smaller particles can improve the light conversion efficiency and reduce scattering losses, leading to higher lumen output. The findings here emphasize a key trade-off: while larger particles improve light diffusion and reduce glare, they diminish overall brightness. This balance is crucial in LED design, as applications prioritizing brightness may benefit from smaller ZnS particles, whereas those focusing on uniform light diffusion might tolerate some reduction in lumen output.

Figure 6 shows the variation of color render-

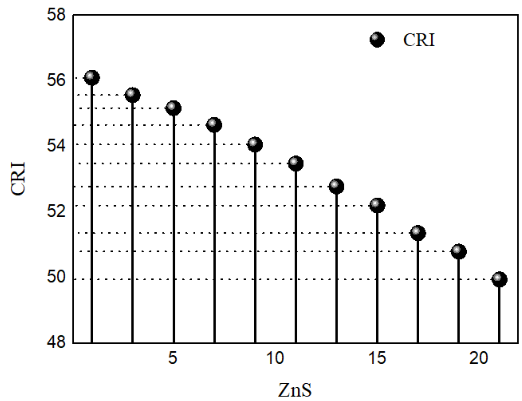


Figure 6. CRI values with different ZnS particle sizes.

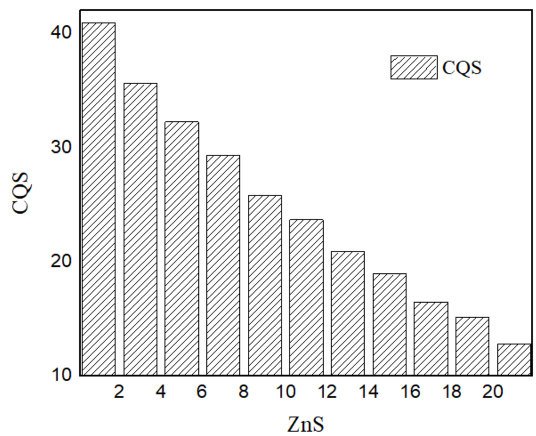


Figure 7. CQS values with different ZnS particle sizes.

ing index (CRI) with different ZnS particle sizes. Figure 6 depicts the downward trend in CRI with increasing ZnS particle size, highlighting the impact of particle scattering on color rendering fidelity. Higher CRI values, which are preferable for accurate color reproduction, are observed with smaller ZnS particles. As particle size increases, the CRI decreases, suggesting that larger particles introduce more significant scattering and absorption effects, which distort color representation. For applications like display lighting, retail lighting, or any environment where accurate color reproduction is essential, the use of smaller ZnS particles could enhance the CRI, offering a more natural light output. Larger particles, while potentially beneficial for light diffusion, may compromise color accuracy and are therefore less desirable for high-CRI applications [29, 30].

Figure 7 presents the color quality scale (CQS) as a function of ZnS particle size. Similar to CRI, CQS also declines with larger ZnS particle sizes, emphasizing the role of particle-induced scattering on perceived color quality. CQS considers additional factors beyond fidelity, such as saturation and viewer preference, making it a comprehensive measure of color quality. The findings show that smaller ZnS particles yield higher CQS values, which are indicative of more vibrant and preferred color output. As particle size increases, CQS decreases, reflecting reduced color saturation and visual appeal. For LED lighting solutions where color quality and appeal are crucial (e.g., architectural or ambient lighting), smaller particle sizes may be advantageous in providing vivid and attractive lighting [33].

The combined results of lumen output, CRI, and CQS reveal a fundamental trade-off between scattering-induced uniformity and spectral fidelity. While increasing ZnS particle size enhances diffusion and angular homogenization, it simultaneously introduces spectral distortion and photon trapping losses.

These competing effects define a constrained design space for ZnS-assisted LEDs. Optimal performance is achieved when scattering strength is sufficient to homogenize angular emission without excessively altering wavelength-dependent photon transport. The intermediate particle size regime satisfies this condition, offering a balanced compromise among brightness, color stability, and visual quality.

4. Conclusion

This study demonstrates the significant impact of ZnS particle size on the optical properties and overall performance of LEDs, with particular focus on scattering behavior, lumen output, correlated color temperature (CCT), color rendering index (CRI), and color quality scale (CQS). The results indicate that ZnS particle size plays a critical role in shaping key LED characteristics, presenting both benefits and trade-offs depending on the application requirements.

Smaller ZnS particles were shown to enhance lumen output, provide higher CRI and CQS values, and reduce CCT deviation, making them suitable for applications requiring high brightness and precise color rendering. However, the moderate scattering provided by smaller particles may be insufficient for applications demanding extensive light diffusion. Conversely, larger ZnS particles increased scattering coefficients and reduced the required YAG:Ce3+ phosphor content, effectively enhancing light diffusion and reducing glare. Nonetheless, larger particles also introduced greater CCT deviations and reduced lumen output, potentially compromising color stability and brightness.

These findings suggest that LED performance can be optimized by tailoring ZnS particle size based on the specific requirements of the application. For high-brightness, color-accurate lighting, smaller ZnS particles are preferable, while larger particles may be suitable for ambient or general lighting applications where uniform diffusion is prioritized over color accuracy. Future research could explore hybrid approaches that combine multiple particle sizes or materials to achieve customizable lighting properties, advancing the development of LEDs that meet a broader range of lighting demands.

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