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Balancing Visual Comfort and Efficiency in Indoor LED Lighting: Diffusion, Cut-Off Angle, and Thermal Management

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Abstract: This paper looks at how to balance visual comfort and efficiency in indoor LED luminaires, focusing on diffusion, cut-off angle, and heat management. A diffuser smooths the emitting surface but usually costs about 5-15% light output. Adding a cut-off (θc) to block high_angle light also helps with glare (UGR).Keeping the LED junction temperature under ~85°C helps keep CCT and light output stable. For learning and office environments, moderate diffusion with a θc of approximately 30–40° is recommended, combined with a simple heat sink , to achieve a balance between UGR and efficiency.

Keywords: LOR; Light Output Ratio; θc, Cut-Off Angle; UGR; Unified Glare Rating; Tj; LED Junction Temperature; CCT; Correlated Color Temperature.

1. Introduction

Xu e t al. (2016) pointed out that LEDs have become the mainstream choice for indoor lighting due to their high energy efficiency and long lifespan, but visual comfort and color stability are often compromised by secondary light distribution and thermal management. [1] Hirn ing e t al. (2014) reported that indoor glare is related to the luminance, size, and viewing angle of light-emitting surfaces. The Unified Glare Rating (UGR) is a widely used evaluation metric and is referenced in indoor lighting standards in many countries. [2] According to T sankov e t al. (2024), increasing the effective light-emitting area and restricting the direction of high brightness through the use of diffusers , microprisms, or light-mixing chambers can effectively reduce glare , but typically results in a loss of approximately 5-15% of light output. [3] Bangali (2018) showed that the “cut-off angle” in the shielding geometry determines whether an observer can directly see a high-brightness light source or its image, thereby significantly affecting the UGR. [4] According to Kyatam et al. (2021) , an increase in LED junction temperature can lead to a decrease in luminous flux, a shift in correlated color temperature (CCT), and reduced reliability; therefore, in engineering practice, the junction temperature is typically kept below approximately 85°C to ensure both stability and longevity [5].

Learning and office environments are particularly sensitive to glare. Standards such as EN 12464-1 set upper limits-such as UGR ≤ 19-for general office spaces, requiring a balance between visual comfort and energy efficiency. [6] In practice , some low-cost indoor lighting fixtures prioritize lumens per watt (lm/W) while neglecting glare control and thermal coupling, leading to user complaints such as “blinding brightness ” and “color shift over time.” There is an urgent need for practical, low-cost optical-thermal design guidelines to guide product selection and trade-offs.

This paper focus on three levers-diffusion, cut-off angle, and junction temperature-and use simple optics and steady_state thermal estimates to sketch out a practical selection path for office/classroom luminaires: use moderate diffusion (to avoid excessive light loss), set the cut-off angle to approximately 30–40°, and control the junction temperature below approximately 85°C through appropriate thermal resistance configuration. Based on simplified light distribution models and steady-state thermal analysis, we provide quantitative selection charts and calculation steps, demonstrating that this combination can significantly reduce the predicted UGR while keeping efficiency loss within approximately 10%, without altering power consumption. Compared to simply increasing diffusion, this strategy prioritizes achieving glare reduction through geometric shading and ensures color stability via temperature control, offering a readily replicable engineering compromise for indoor LED lighting that balances comfort and efficiency.

2. Fundamental Theory

Core optics: Su e t al. (2007) described the core optical relationship as $\Phi_{out}=\tau\cdot\eta_{geom}\cdot\Phi_{LED}$ (Φ_{out} is the output luminous flux after the diffuser; τ is diffuser transmittance; η_{geom} is geometric efficiency; Φ_{LED} is the flux from the LED package.); for a Lambertian emitter $L\approx\Phi_{out}/(\pi\cdot A_{eff})$ (L is the luminance of the emitting surface; A_{eff} is the effective luminous area.) [7].

Glare trend: According to Porsch e t al. (2020), $UGR\approx 8\cdot\log_{10}[(0.25/L_b)\cdot L^2\cdot\omega]$ with $\omega\approx A_{eff}\cdot\cos\gamma/d^2 \rightarrow UGR\propto\log_{10}[\Phi_{out}^2/(A_{eff}\cdot d^2)]$ (L_b is background luminance; ω is the solid angle subtended by the source; γ is the viewing angle; d is the viewing distance. Note: This formula represents a simplified single-lumina ire evaluation model designed to highlight trends in individual design parameters. In actual indoor applications, the final UGR is the logarithmic sum of all luminaires within the field of view.). The UGR decreases when cut-off angle θ_c blocks high-angle light [8].

Cut-off by geometry: According to Roberts et al. (2021), $\boldsymbol{\theta_c}\approx\arctan(h/a)$ (h is the height of the shielding structure; a is the horizontal offset from the LED to the shielding edge.). Louvers or microprisms can realize an equivalent θ_c [9].[Figure 1]

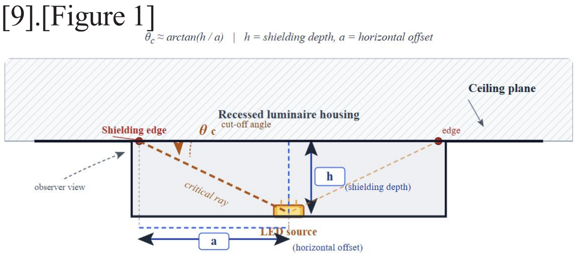

Figure 1. Cut-Off angle geometry

Thermal: According to Lasance al. (2014), $P_d\approx P_{in}\cdot(1-WPE)$ (P_d is power dissipated as heat; P_{in} is input electrical power ; WPE is wall_ plug efficiency.); $T_j=T_a+R_{\theta,ja}\cdot P_d$ (T_j is junction temperature; T_a is ambient temperature; $R_{\theta,ja}$ is the thermal resistance from junction to ambient.); Design for $T_j\leq 85°C$ for flux/color stability[10].

Quick rules: Based on Yan (2021), a practical rule is to pick A_{eff} and τ so UGR meets the target (e.g., ≤ 19) while $\Phi_{out}\geq\Phi_{min}$; set $\theta_c\approx$ 30-40°; ensure $R_{\theta,ja}\leq(T_{j,max}-T_a)/P_d$ ($T_{j,max}$ is the maximum allowed junction temperature; this inequality ensures the junction stays below the limit.) [11].

3. Thematic Review

(1)Standards and Metrics

First, let 's clarify one thing : How exactly is glare quantified in indoor lighting? What standards set the limits for office spaces-for example , what is the maximum allowable UGR value?

According to Shailesh and Raikar (2010), indoor discomfort glare is typically assessed using UGR as the primary metric, and this value has been adopted by numerous indoor lighting standards to se t upper limits for different spaces (e.g., UGR ≤ 19 is common in offices). [12] CIE. (2010) pointed out that UGR calculations are highly sensitive to room dimensions , surface reflectance, background illuminance , and viewing position. Since the scene models and location indices used in different studies often vary, it is necessary to standardize conditions or recalculate the values when comparing results across studies. [13] According to Sawicki and Wol ska (2022), DGP may be used as a supplement in daylight or mixed-light environments, while TI is commonly used for outdoor roads; however , this article focuses on the UGR framework under indoor electric lighting [14].

(2)Three Key Approaches to Reducing Glare

What practical steps can you take to reduce UGR? What is the reasoning behind each one?

There are three main approaches to reducing UGR in practice: First, according to S choett le e t al. (2004), one approach is to increase the effective luminous area by "spreading" the same luminous flux over a larger surface , thereby reducing peak surface brightness and discomfort. [15] Second,Ding et al. (2022) showed that controlling the light emission at high angles by using cut-off angles, shading structures, or angle-selective optical suppression to reduce the contribution of bright spots from oblique viewing angles. [16] Third, Yamamoto and Akashi (2016) found that increasing the proportion of ambient or indirect lighting to raise the overall brightness and reduce the brightness contrast, while ensuring energy efficiency [17].

(3)Diffusion and Microstructures

How exactly do optical components like diffuser plates and microprisms affect glare and efficiency? When should one use a diffuser, and when should one use microstructures?

G ago-Calderón et al. (2018) showed that Milky diffusion panels significantly reduce brightness peak s and improve uniformity through multi-angle scattering. They provide direct and stable glare reduction, but this is often achieved at the cost of lower transmittance, resulting in reduced system efficiency. [18] According to CIBSE Journal (2021) and Lee al. (2012),angle-selective structures such as microprisms or micro lenses suppress high-angle light while maintaining high transmittance; they are commonly used to maximize efficiency while meeting UGR limits. In short, diffusers are robust but lossy; microprisms keep more light but need care to avoid color and texture artifacts. [19-20] Kuo et al. (2015) reported that engineering solutions often employ a combination of a "diffuser + microprism" or microstructures on the light-emitting surface of the light guide plate to balance uniformity, efficiency, and glare control [21].

(4)Geometry and cut-off Angles

What is the principle behind using geometric elements such as shading structures, louvres, and reflectors to block glare? What is the typical value for the "cut-off angle" commonly referred to in engineering?

According to Chou et al. (2016),geometric shading methods, such as recessed light-emitting surfaces, reflector cups/light bowls, and louvres/blinds, primarily reduce UGR by defining the effective solid angle within the field of view and blocking high-angle light. [22] Xie (2005) suggested that literature and standard practices often set the cut-off angle at approximately 30 – 40° as a compromise: this significantly reduces glare while maintaining spatial luminance gradation and utilization factors. If the cut-off is too aggressive, you can get a 'cave' look, a darker ceiling, and more sensitivity to mounting height. [23] (5)Light Emission Forms and Light Distribution

Panel lights, down lights, linear lights, and indirect lighting-how much do these different lighting configurations affect glare and comfort?

CIE. (2019),pointed out that large-area , low-luminance surface light sources (such as panel lights and luminous ceilings) are more likely to meet UGR limits under the same illuminance targets; point or linear light sources (such as recessed lights and linear lights) typically require stronger glare control or precise light distribution control. [24] Direct-view systems primarily rely on diffusers and shading structures to suppress luminance peaks; side-entry light guide plate solutions, on the other hand , can control glare while achieving a slim profile through the design of the light-emitting angle. [25] Houser e t al. (2002) found that at the level of overall lighting design, increasing the proportion of indirect light or uplighting can raise background brightness, reduce contrast, and improve subjective comfort, but this comes at the cost of a s light reduction in energy efficiency and the utilization factor [26]

(6)Trade-offs Between Efficiency, Glare, and Uniformity

How do you balance meeting UGR standards, minimizing light loss, and ensuring uniformity? What is the most reliable order to follow when designing?

Park e t al. (2025) suggested that diffusion and shading inevitably introduce optical losses, reducing system luminous efficacy; in contrast, angle-selective microstructures typically offer a better balance between " low glare and higher efficiency". [27] According to Chiang e t al. (2015),multiple studies and field tests indicate that , given fixed geometry and luminous flux, increasing the light-emitting area and reducing high-angle light are the most direct means of lowering the UGR below the threshold; after achieving the UGR target, fine-tuning the diffusion intensity and beam angle in small increment s can often prevent efficiency losses and color rendering issues caused by excessive diffusion. [28] Therefore, the recommended engineering sequence is to first determine the area and cut-off angle, followed by the details of diffusion and microstructure.

(7)Thermal Management and Photometric Stability

What happens if the junction temperature rises? Will the luminous flux drop and the color temperature fluctuate? How do diffuser hoods and enclosed enclosures complicate heat dissipation?

Chhajed et al. (2005) reported that an increase in junction temperature causes a decrease in luminous flux, shifts in color temperature and chromatic ity coordinates, and accelerates light decay and material aging. In practice, junction temperature is often controlled at approximately 85°C or below to ensure stability and longevity [29]. Cai et al. (2019) showed that diffusion covers, sealed back cavities, and high power density elevate the internal cavity temperature and device junction temperature. This is primarily because the optical housing impedes convective heat transfer and traps radiant heat, thereby effectively increasing the system's overall thermal resistance(R^{θ}, ja). If input power is increased to maintain illuminance, heat dissipation will further increase. [30] Muthu et al. (2002) suggested that while using diffusion or shading to reduce glare, heat dissipation capacity and device efficiency should be evaluated simultaneously. If necessary, the heat sink should be optimized, the housing emi ssivity increased, or light sources with higher wall_plug efficiency selected to prevent secondary deterioration of luminous and color stability [31].

4. Results

Result 1. UGR is primarily determined by the effective luminous area and the cut-off angle.

Under typical office viewing geometry (distance from observer to luminaire d ≈ 3–5m; background luminance Lb ≈ 30–70 cd/m²), simple plots suggest that: when using a larger effective luminous area without a cut-off (Aeff ≈ 0.25 –0.35 m², Φout ≈ 1500-3000 lm), or under moderate diffusion conditions (τ ≈ 0.85–0.90) with a smaller area combined with a 30-40° cut-off angle (Aeff ≈ 0.12–0.18 m², at the same luminous flux), both can achieve the target of UGR ≤ 19 [Figure 2]. For example, assuming a typical background luminance of Lb= 50cd/m2, a lumina ire with Φout ≈ 1800 lm and Aeff ≈ 0.32 m² yields L ≈ 1.8×10^3 cd/m²; at a viewing distance of 4 m, the predicted UGR is ≈ 18-19, consistent with common "UGR < 19" office panels [Figure2].

Result 2. Trade-off Between Diffusion and Off-Axis Suppression.

A milky diffuser can reliably reduce brightness peaks, but this is typically accompanied by a τ value of approximately 0.80 –0.90 (resulting in an LOR loss of about 5-15%); in contrast, directional microprisms can maintain a τ value of ≥0.90 while more effectively suppressing light at high angles. In engineering practice, using moderate diffusion (τ ≥ 0.85) and setting a cut-off angle of 30-40° often achieves UGR ≤ 19 in office/study luminaires with a luminous flux of 1500 –3000 lm, while keeping the overall efficiency loss within approximately 10% [Figure2].

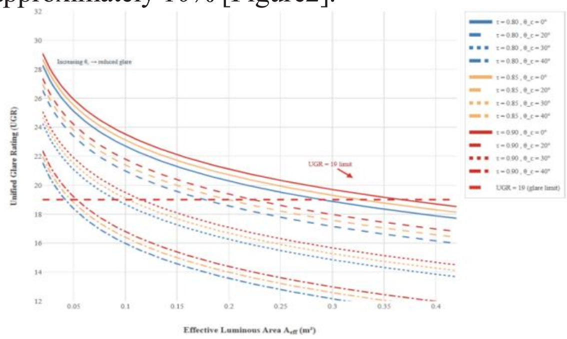

Figure 2. UGR Selection Map: Effective Luminous Area (Aeff) and Cut-Off Angle (θc) with Diffuser Transmittance (τ) Overlays.

Assumptions: d = 4m, Lb = 50 cd/m², constant pre-optics flux ΦLED (thus higher τ shifts UGR upward)

Result 3. Thermal Design Compatibility and Junction Temperature Control.

At room temperature Ta ≈ 25°C, when the power dissipation Pd of indoor lighting fixtures is ≈ 8-12W, maintaining Tj≤ 85°C typically requires Rθ, ja ≤ 5–7K/W. Enclosed diffusers and shallow back cavities often cause an additional steady-state junction temperature rise of approximately 5-10 K, which means the bare heat sink must be designed with an even lower thermal resistance (e.g., ≤ 4-6 K/W) to absorb this penalty in the overall thermal budget. Within this range, medium-diffusion and microprism designs do not prevent Tj from being controlled at ≤ 85°C, thereby supporting long-term stability of CCT and luminous flux [Figure3].

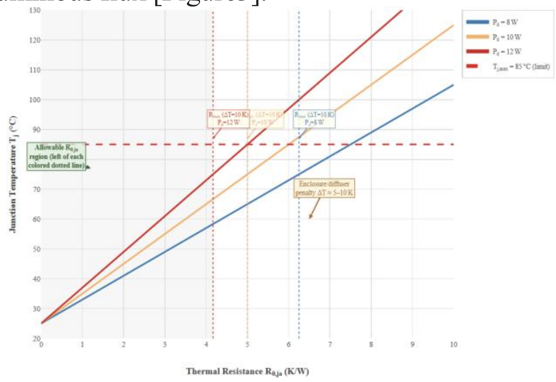

Figure 3. Thermal Budget to Maintain Tj ≤ 85°C (Ta = 25°C; Pd = 8/10/12 W; with Enclosure/Diffuser ΔT penalty)

5. Discussions

(1) Model Assumptions and Scope of Application

This paper adopts the near-Lambertian assumption and representative background illuminance/viewing distance, approximating the UGR as a function of L, Aeff, and the solid angle of observation, and expressing the effect of the cut-off angle as an equivalent suppression coefficient. This approach facilitates the determination of design corridors; however, in actual engineering practice, verification using standardized methods (such as room index, reflectance ratio, and viewing position) is still required. As recommended in CIE 117-1995, it verifies the results using standard UGR calculations or tabular methods during the completion phase and to conduct spot measurements in critical areas [32].

(2) Why area and cut-off matter

The results indicate that when meeting the same illuminance target, there are two approaches to reducing discomfort glare: the first is to increase the light-emitting area to reduce surface brightness; the second is to set a cut-off angle of approximately 30–40° under conditions of smaller area to suppress high-angle light. The former approach is beneficial for visual uniformity, while the latter is more efficient in terms of size and material usage; what they have in common is a preference for controlling glare through geometric angle selection, supplemented by moderate diffusion to suppress residual brightness peaks [33].

(3) Efficiency of Diffusion and Glare Suppression-Glare Trade-off

Milky diffusion typically results in an LOR loss of approximately 5-15%, but provides stable and reliable uniformity and suppression of luminance peaks; microprisms/micro lenses can more effectively reduce high-angle light while maintaining high transmittance (typically τ≥ 0.85-0.90), though the risk of angular chromatic ity and texture artifacts must be controlled. A practical order is set Aeff and θc first, then add just enough diffusion (τ ≥0.85) to tidy up uniformity and comfort [34-35].

(4) Thermal Budget and Luminous and Color Stability

According to Liu et al. (2024),maintaining the junction temperature below approximately 85°C is a common engineering threshold for sustaining luminous flux and CCT stability and delaying aging; For indoor lumina ires with a power consumption of approximately 8-12 W at room temperature, the thermal resistance from the device to the environment should generally be controlled within 5-7 K/W; enclosed diffusers and shallow back cavities typically introduce an additional steady-state temperature rise of about 5-10 K, which must be accounted for in the thermal budget. Also budget for hotter summer ambients, driver self-heating, dust , and radiative changes; leave a 10-15K margin [36].

(5) Limitations and Future Work

The model presented in this paper does not account for factors such as near-field non-uniform light distribution, variations in indoor reflectance distribution, and daylight interference. The thermal analysis employs a steady-state equivalent thermal resistance model and does not cover dynamic processes or long-term aging. Next steps: check the trends with a UGR table and ray tracing, build a simple prototype for joint thermal/optical tests, and add user ratings in a classroom/office [37-38].

6. Conclusion

Under typical office/study lighting conditions, there is a clear “area-cut-off angle” trade-off for achieving UGR ≤19: either use a larger effective light-emitting area, or set a cut-off angle of approximately 30 –40° with a smaller area; combined with moderate diffusion (τ ≥ 0.85), efficiency losses can typically be kept within about 10%.

Compared to “pure diffusion,” directional microstructures more effectively suppress high-angle light while maintaining high transmittance; adopting a “geometry first, diffusion second” design sequence allows for a more robust trade-off between size, efficiency, and comfort.

In room-temperature environments with a power consumption of 8-12W, controlling the junction temperature to ≤85°C generally requires R^{θ}, ja≦5-7 K/W. This must account for the 5-10K temperature rise caused by the enclosure/diffuser and allow for seasonal environmental variations to ensure stable luminous flux and color rendering throughout the product’s lifespan.

This strategy (determining Aeff and θc→selecting angular suppression+moderate diffusion→balancing the thermal budget) offers reproducibility and cost advantages, making it suitable for the development and selection of educational and office lighting products that prioritize comfort and efficiency.

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