

Article

Exploring Asymmetric Lens–Total Internal Reflection (AL–TIR) Optics for Uniform Ceiling Illumination in Interior Lighting

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Abstract: This study presents a significant advancement in LED interior lighting through the development and application of Asymmetric Lens–Total Internal Reflection (AL–TIR) optics, with a focus on enhancing lighting uniformity and indoor comfort by simulating sky-like lighting distribution. AL–TIR technology employs asymmetric lenses combined with total internal reflection to efficiently redirect and spread light, achieving a controlled and even ceiling illumination suitable for various interior applications. This research explored the establishment of ideal luminous intensity curves, devised practical AL–TIR optical designs through numerical calculations, and conducted extensive simulations to assess performance in typical indoor environments. Our findings demonstrated substantial improvements in lighting uniformity, with the AL and AL–TIR systems achieving direct illuminance uniformities of 0.78 and 0.83, respectively, compared to traditional tube LEDs at 0.25. These results, validated in several office rooms, highlight the efficacy of AL–TIR optics in revolutionizing indoor lighting design by balancing optimal lighting distribution with occupant comfort and well-being.

Keywords: asymmetric lens; total internal reflection; uniform illumination; sky-like ceiling; washing LED luminaire



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1. Introduction

Human-centric lighting (HCL) seeks to improve human health and productivity by closely mimicking natural light, a goal that has driven significant innovations in lighting technology. As House (2021) [1] and Ticleanu (2021) [2] explain, HCL differentiates itself from traditional lighting by integrating a comprehensive understanding of light's influence on circadian rhythms and cognitive functions. Knoop (2020) [3] emphasizes the importance of replicating a sun-like spectrum and aligning lighting with human circadian rhythms, further refined by Sánchez-Cano (2020) [4] through the considerations of photopic and melanopic effects. In addition to these biological aspects, spatial comfort and visual impressions—achieved by mimicking sky-like light distribution—are critical for enhancing occupant well-being and aligning with the aesthetic goals of HCL principles, as noted by Münch (2020) [5] and De Vries (2021) [6]. Chraibi et al. (2017) [7] demonstrated that uniform wall luminance enhances visual comfort, highlighting the importance of consistent lighting distribution in interior environments. The study by Klir et al. (2023) [8] highlighted that sky-like interior lighting settings are preferred by users, as they enhance visual comfort and well-being. Zielinska-Dabkowska (2022) [9] advocates sustainable urban illumination that prioritizes human health, well-being, and environmental responsibility. Yang et al. (2022) [10] reported that a 3D uniform light field effectively supports health by facilitating SAD therapy and circadian rhythm adjustment, enhancing user convenience and comfort in a healthy residential environment.

While alternative solutions like Barrisol stretch ceilings and Philips lightboxes can provide uniform lighting distribution, they are limited by challenges in optical utilization factor (OUF), heat management, and the flexibility to integrate other fixtures or focus on specific areas. These constraints limit the versatility and usability of ceiling space in various lighting scenarios.

Building on the foundational work by Fang et al. (2013) [11], which detailed intricate freeform optical surface designs, subsequent research has expanded on these technologies. Lai et al. (2016) [12] advanced the field by improving glare reduction in LED streetlights using asymmetric TIR lenses, eliminating the need for luminaire inclining. Zhu ZM et al. (2017) [13] and Zhu ZB et al. (2018) [14] extended these designs to include off-axis and catadioptric systems for complex road layouts. Sorgato et al. (2017) [15] and (2019) [16] further optimized LED lighting optics, enhancing light distribution and OU, and extending these improvements to human-centric applications.

Babadi et al. (2020) [17] discussed designing symmetric and asymmetric freeform lenses for uniform illumination, while Yang et al. (2020) [18] developed lenses for lighting hard-to-reach areas, beneficial in medical and industrial settings. He et al. (2020) [19] focused on educational settings, improving blackboard visibility. Kang (2020) [20] improved visibility and OU by enhancing asymmetric lighting optics for large-area illumination at short distances. Giang et al. (2020) [21] and Li et al. (2021) [22] explored cost-effective and efficient designs for general and specialized LED applications.

Our research builds upon these studies by exploring theoretical luminous intensity curves as benchmarks for LED performance, employing asymmetric lens (AL) and total internal reflection (TIR) optics for optimal lighting redistribution. Through comprehensive simulations, we identify linear Asymmetric Lens–Total Internal Reflection (AL–TIR) optics as the optimal form factor for achieving superior ceiling illuminance uniformity. This approach not only mimics natural sky-like conditions but also enhances OU and versatility, significantly improving indoor lighting quality. While not a comprehensive HCL system, this work contributes to HCL principles by fostering visual comfort and spatial impressions through sky-like, uniform ceiling illumination. By aiming to achieve sky-like, uniform ceiling illumination, this work enhances human-centric lighting quality by fostering visual comfort and spatial impressions that align with natural lighting distribution, supporting human well-being and productivity in interior spaces.

2. Design Method

This design method, built on the theoretical model from Giang et al. [23], aims to create uniform ceiling illumination that emulates a natural sky-like light source, aligning with the principles of HCL. The process for developing the AL–TIR optics LED luminaire is illustrated in Figure 1, outlining the objective of engineering a luminaire that replicates the near-ideal luminous intensity curve presented in Giang’s study. The flowchart details the steps from the initial concept based on ideal luminous intensity curves through simulations and the comparisons of these curves with the ideal. Following successful simulation, the design considers room and installation parameters, leading to ceiling illumination simulation and uniformity comparisons. Positive outcomes in these areas advance to a significant assessment, ensuring the final design meets environmental integration and luminance effectiveness.

In the lighting model, the intensity of light at various points along the x -axis on the ceiling is represented by two logistic functions. As depicted in Figure 2a, two extensive linear light sources are mounted on opposite sides of a lengthy ceiling at a height H below the ceiling surface. Due to the significant length of the ceiling relative to its width W , our 3D model has been simplified into a 2D representation by adopting the concept of linear illuminance (measured in lm/m) rather than the conventional area-based illuminance (measured in $\text{lx} = \text{lm}/\text{m}^2$). This approach allows for a more focused analysis of light distribution along the ceiling’s length without the complexity of a full three-dimensional model.

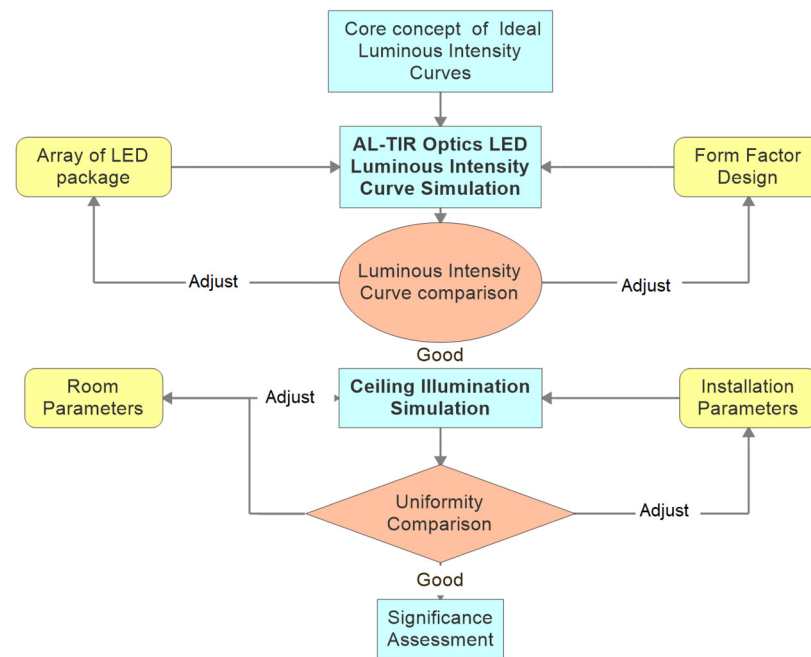


Figure 1. The design flow chart of the proposed AL-TIR LED luminaires.

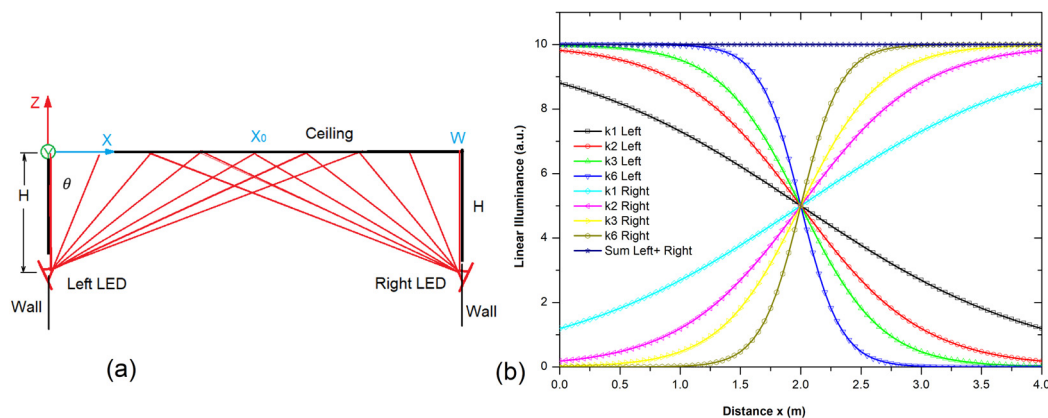


Figure 2. (a) Schematic diagram of the lighting system with two LED arrays mounted on the walls; (b) the linear illuminance $E_R(x)$, $E_L(x)$ along the ceiling line x calculated for various logistic growth rates $k = 1, 2, 3, 6$, with $E_m = 10$, $H = 0.3$ m, and $W = 4$ m.

In the 2D model, as illustrated in Figure 2a, the linear illuminance along the ceiling line x is generated by light sources positioned on both the right (R) and left (L) sides. The expressions for the linear illuminance from these sources are defined as follows:

Linear illuminance from the right light source:

$$E_R(x) = \frac{E_m}{1 + e^{-k(x-x_0)}} \quad (1)$$

Linear illuminance from the left light source:

$$E_L(x) = \frac{E_m}{1 + e^{k(x-x_0)}} \quad (2)$$

where E_m represents the maximum linear illuminance, k is the logistic growth rate, x denotes the position on the ceiling (in meters), and x_0 is the midpoint of the ceiling's x -value (in meters). Importantly, at any position x along the ceiling, the sum of $E_R(x)$ and $E_L(x)$ remains equal to E_m as shown in Figure 2b.

As the value of k increases, the distribution pattern sharpens, indicating that the illuminance decreases more rapidly beyond x_0 . A preliminary value of $k = 3$ has been chosen, with further discussion on this selection to follow.

In this model, the angular luminous intensity distribution is defined as the ratio of the logistic intensity to the change in angle $\Delta\theta$, where θ is the angle between the light ray and the vertical axis, calculated as follows:

$$\theta(x) \approx \arctan\left(\frac{x}{H}\right) \quad (3)$$

$$D(\theta) = \frac{E(x)}{\Delta\theta(x)} = \frac{E_m}{(1 + e^{-k(x-x_0)})\Delta\theta(x)} \quad (4)$$

$$\Delta\theta(x) \approx \frac{d\theta}{dx}\Delta x = \frac{d}{dx}\arctan\left(\frac{x}{H}\right) \approx \frac{1}{H\left(1 + \frac{x^2}{H^2}\right)}\Delta x \quad (5)$$

where $\Delta\theta$ is the change in angle; H is the height from the light source to the ceiling; and Δx is the change in horizontal distance along the ceiling. Equation (5) assumes Δx is small, allowing the approximation to hold.

Figure 2b displays the linear illuminance $E_R(x)$, $E_L(x)$, and $E_R(x) + E_L(x)$ calculated for various values of the parameter k , with the light source mounted on the left wall. Uniform illumination across the ceiling is achieved when these profiles are combined with their counterparts from the opposite wall. A profile that incorporates the most beneficial aspects of the distribution will be selected for further development to optimize the lighting design. As illustrated in Figure 2b, the logistic curves $E_L(x)$ for $k = 1$ and $k = 2$ exceed the ceiling boundary, resulting in light spillage beyond the target area. Consequently, the configurations leading to such spillage have been excluded from further consideration.

In the subsequent phase of the design, careful assessment is conducted to align the array of LED packages with the ideal luminous intensity curve concept, prioritizing compact source sizes throughout the collimation system design. The finite size of the LED's emissive surface in relation to the lens size introduces complexities in closely mirroring the ideal luminous intensity curve. Conventionally, LED packages exhibit a Lambertian angular distribution, typified by a circular form in 2D and a spherical form in 3D distribution plots. This inherent distribution diverges significantly from the ideal luminous intensity curve, thereby necessitating the incorporation of secondary optics to redistribute lighting effectively.

A linear AL was designed using SolidWorks as the initial redistributive optic. The lens' outer shape has been crafted as a semicircle centered at the LED package, while the inner shape has been divided into two distinct parts: a non-converging circular arc and a strongly converging straight line, both of which are centered at the LED package. An additional TIR component is necessitated by the wide angle of the LED's Lambertian luminous intensity curve. This TIR part is designed not only to effectively utilize the entire LED light beam but also to minimize glare when illuminating the ceiling.

The AL–TIR design was optimized using ray-tracing software, which was employed to simulate the luminous intensity curves and conduct comparisons with the theoretical ideal. The luminous intensity curves were plotted in rectangular coordinates, and the design iteration continued until the difference ratio in each angular region was reduced to a saturated change of about 15%.

Upon finalizing the AL–TIR optics design combined with the LED array, the ceiling illumination uniformity was evaluated using lighting simulations. The Dialux software was chosen due to its capacity for simulating large rooms with multiple luminaires.

3. Calculation and Simulation Results

3.1. Calculation of Ideal Luminous Intensity Curves

In the calculations and simulations conducted, a ceiling width $W = 4$ m and the distance between the LED luminaire position and the ceiling $H = 0.3$ m were chosen,

aiming for uniform illumination, which reflects common specifications in interior lighting installations (Figure 2b).

The profile $E_L(x)$ for $k = 1$ and $k = 2$ is observed to be relatively flat across the ceiling, although a portion of the light beam extends beyond the ceiling boundary. The sharpness of $E_L(x)$ for $k = 6$ is significant around the midpoint $x_0 = 2$ m, resulting in a non-uniform distribution if only one LED luminaire is installed on a single side.

In Figure 3, the luminous intensity curves $D(\theta)$ are depicted, having been calculated based on the $E(x)$ for various values of k (where $k = 1, 2, 3, 6$), utilizing Formulas (2)–(5). It is observed that the maximum of the luminous intensity curves varies between 80° and 84° . For $k = 1$ and $k = 2$, the maximum angle, corresponding to the end of the ceiling, is determined to be 86° ; hence, luminous intensity values are not obtained for larger angles.

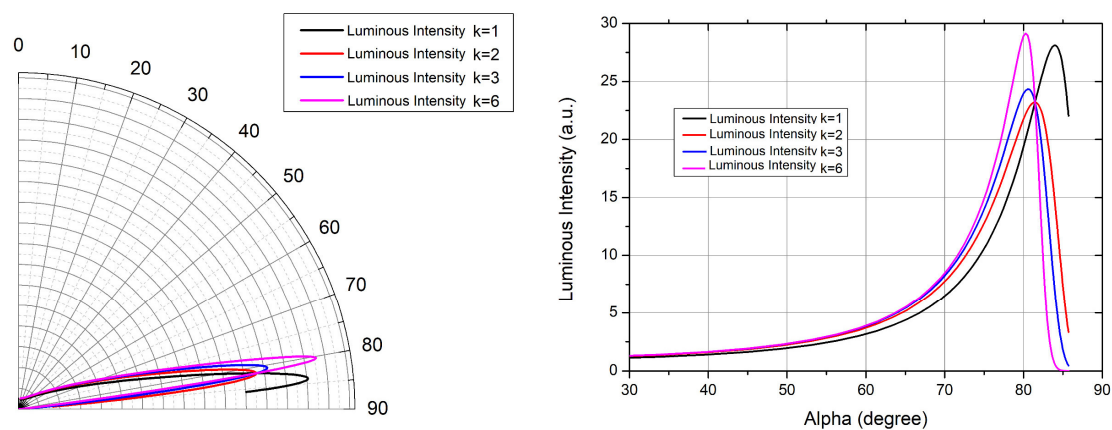


Figure 3. The luminous intensity curves $D(\theta)$ for various values of the parameter k (1, 2, 3, 6), with $H = 0.3$ m and $W = 4$ m, in polar (left) and rectangular plots (right).

It is noted that the shape of the luminous intensity curve and the width of the distribution angle at half maximum are exceedingly narrow (approximately 15°), presenting a significant challenge for lens designers, particularly when a primary lens system is required for simplicity.

3.2. Lens Form Factor Design and Luminous Intensity Curve Comparison

For practical application in interior lighting, a linear LED luminaire measuring 1200 mm in length was initially selected, utilizing an AL for the preliminary design. During the early stages of the design process, a very thin LED strip served as the light source. The dimensions of the lens were determined to be 1200 mm in length, approximately 10 mm in height, and 20 mm in width.

To demonstrate the merits of the design methodology grounded on ideal luminous distribution curves, four distinct AL-TIR LED luminaire configurations, as depicted in Figure 4, were evaluated. The L1-AL0 luminaire, developed empirically prior to the formulation of ideal luminous intensity curves, serves as a foundational reference. In contrast, the L2-AL6 luminaire, conceptualized with the ideal luminous intensity curves in mind, showcased improved light beam utilization, albeit not fully optimized due to the absence of TIR optics. The lens profiles of L2-AL6, observed in the section perpendicular to the lens axis, exhibit an asymmetric shape. It consists of a semi-circular arc on the exterior, transitioning into linear segments to form the asymmetry, while the interior cross-section is segmented into distinct subsections, crafting a composite lens with convergent, divergent, and non-refractive zones. The precise placement of a thin LED strip at the lens' center, at variable distances, and the subsequent selection of configurations based on maximum intensity in the luminous intensity plot ensured optimal lighting distribution.

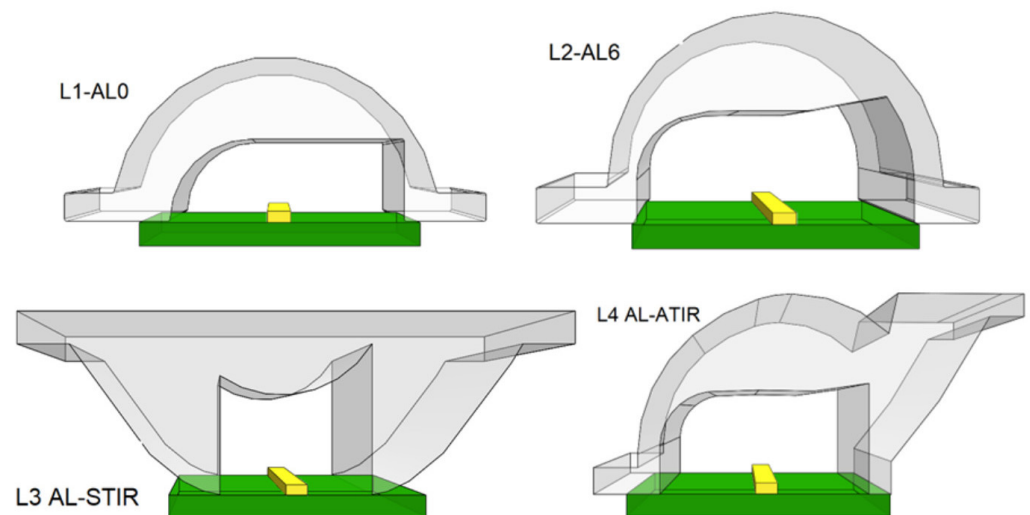


Figure 4. LED luminaire configurations: L1–AL0 with AL segmented into non-refractive (**left**) and refractive (**right**) sections; L2–AL6 with progressively increasing refraction; L3 AL–STIR with two symmetric total internal reflection (STIR) optics; L4 AL–ATIR with a gradient in refraction paired with ATIR optics for enhanced light control. The width of the LED bar is 1 mm.

The prevalent design by He et al. [19], represented by L3 AL–STIR, features a central convergent lens flanked by TIR parabolic prisms on either side. However, a comprehensive analysis of these configurations necessitates a comparison against the ideal luminous intensity angular distribution requirements. The epitome of this evolution is seen in L4 AL–ATIR, which is benchmarked against the ideal luminous intensity curve K3. This optimal design, which will be detailed in the subsequent section, highlights how meticulous optics engineering can culminate in achieving uniform ceiling light distribution and enhanced efficacy.

3.3. Simulation Results

Figure 5 shows a graphical representation of the calculation results for four different LED luminaire configurations. On the left, there is a tracing diagram showing random red, green, and blue rays emanating from the LED sources, illustrating the path, and the spread of light in various directions. In the middle, lighting distribution curves are depicted, likely in the form of graphs or charts, demonstrating how the luminous intensity varies in different directions. On the right, there is a 3D distribution curve, which provides a three-dimensional representation of the light spread, showing both the intensity and the spatial distribution of the light from the LED luminaires.

As illustrated in Figure 5, the emission angles on plane C90 for all the luminaires are notably narrow, enhancing luminous intensity on distant ceiling areas when aligned correctly. Conversely, the wider emission angles on plane C0 facilitate sufficient overlap in the proximity of the ceiling, ensuring uniform illumination. The colors in Figure 5 are used solely for visualization purposes to differentiate individual light rays within the optical path and do not indicate specific wavelengths or intensities.

In the ray tracing diagram for luminaires L1–AL0 and L2–AL6 with only AL in use, it is observed that a segment of the light beam on the right side significantly deviates from the main beam. This deviation could cause glare for the observer unless mitigated by an extra barrier.

Upon integrating total internal reflective components, as depicted in luminaires L3 AL–STIR and L4 AL–ATIR, the previously mentioned light beam segments were redirected towards the intended target. This modification not only reduced glare but also improved the overall luminous efficacy of the luminaires.

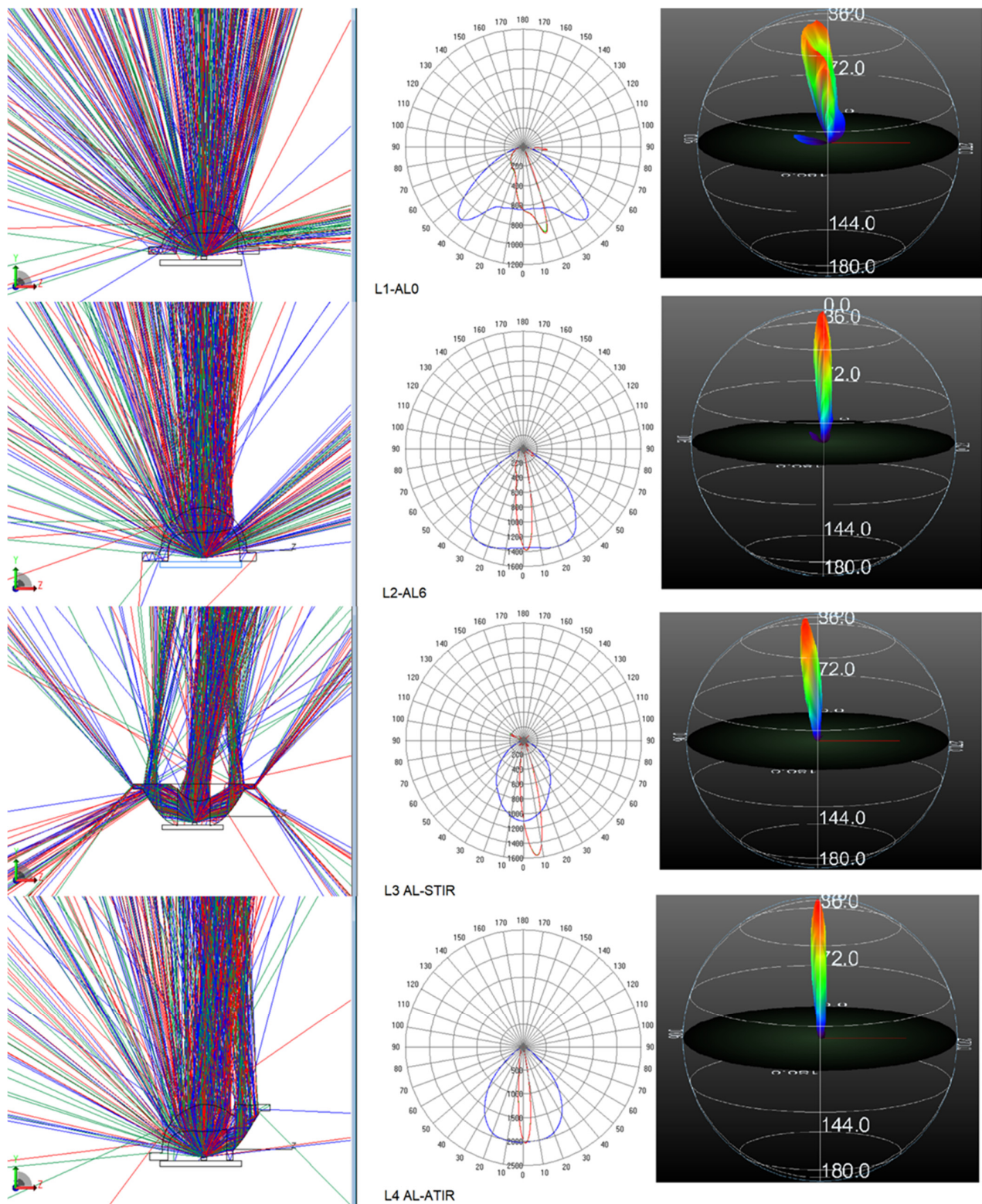


Figure 5. Photometric analysis of luminaires L1-AL0, L2-AL6, L3-AL STIR, and L4-AL ATIR. **(Left)** Ray tracing visualization with RGB light rays illustrating the directional spread of light for each design. **(Middle)** Polar luminous intensity distribution plots showing angle-based light intensity variation, revealing beam shape and spread. **(Right)** 3D polar distribution maps depicting spatial intensity in color-coded format, highlighting regions of high and low intensity. These visualizations enable comparison of each luminaire's light distribution characteristics, including directionality, uniformity, and intensity control.

It is important to note that the lens designs were tailored for practical application, incorporating lens fixation elements at the cost of minor light losses, as can be observed in the tracing diagrams.

To navigate this complexity, the ensuing section will introduce the use of rectangular luminous intensity curves as a more efficacious approach for analyzing and evaluating the diverse luminaire configurations. This methodology will facilitate a comprehensive comparison, underpinning a deeper understanding of each design's merits and limitations. Furthermore, the practicality and impact of our design recommendations will be substantiated through case studies, meticulously examining their efficacy in real-world ceiling illumination scenarios. The two lighting researchers De Boer and Fischer stated in 1978 that at a horizontal illuminance of 1000 lx, a luminance for the ceiling of 200 cd/m² and for the walls of 100 cd/m² are preferred [24]. At a horizontal illuminance of 500 lx (as defined as a minimum by EN 12464-1:2021 [25]), the above values can be estimated as about 210 cd/m² (ceiling) and 70 cd/m² (walls). For a possible control of the next generation of intelligent luminaires, this means that ceiling luminance should remain almost constant at 200–210 cd/m².

4. Discussion

4.1. Comparison of Luminous Intensity Distribution Curves

In Figure 6, the luminous intensity curves for luminaires L1–AL0 and L2–AL6, as well as the ideal luminous intensity curve (K3 LOG) defined by $k = 3$ are illustrated. The luminous intensities of these curves have been normalized, implying that the total fluxes of these luminaires are equivalent. The integral of the luminous intensity values across all the angles, ranging from 0° to 360°, was calculated and employed as a division factor.

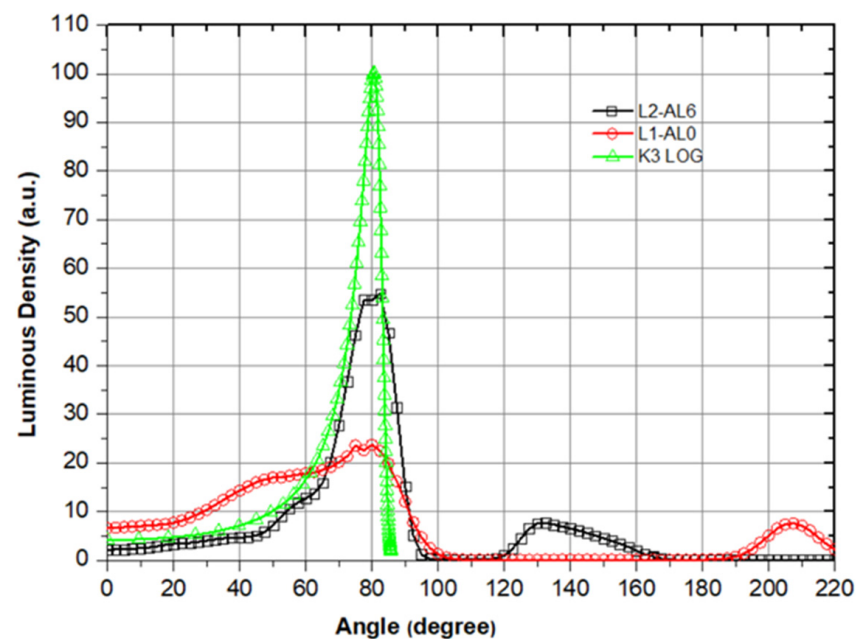


Figure 6. Normalized luminous intensity distribution curves for the L1–AL0 luminaire with AL0 lens, the L2–AL6 luminaire with AL6 lens, and the ideal $k = 3$ curve. The peak intensities are aligned at 80 degrees to compare OUF and uniformity.

The angles at which the maximum luminous intensities occur were aligned to be at 80°, matching the angle of maximum intensity for the ideal luminous intensity curve to facilitate the comparison. The luminous intensities have been adjusted to reflect equal total fluxes across the luminaires, meaning their outputs are comparable. To normalize these curves, the area under the luminous intensity distribution from 0° to 360° was calculated and used as a normalization factor. The peak luminous intensities for each curve have been synchronized

to occur at 80° to align with the peak of the ideal luminous intensity curve, enhancing the clarity of comparison. The maximum intensity of the L1–AL0 luminaire with an AL0 lens at this position is only a fourth of the ideal curve’s peak intensity. This reduction is attributed to the light that is distributed in less efficient angular regions, specifically from 0° to 60° , 85° to 90° , and 190° to 220° . Conversely, the luminous intensity in the range of 0° to 60° for the L1–AL0 luminaire is higher than that of the ideal curve, leading to a less uniform lighting distribution on the ceiling, which will be demonstrated in the forthcoming calculations of ceiling lighting distribution.

In Figure 7, the graphical representation showcases the normalized luminous intensity distribution curves for two different luminaires, L3 AL–STIR equipped with an AL–STIR optic and L4 AL–ATIR with an AL–ATIR optic, alongside the luminous intensity curve termed K3 LOG, which is derived using a k -value of three. The normalization process applied here mirrors that utilized for the L1–AL0 and L2–AL6 luminaires, ensuring that the total light output, quantified as the integral of luminous intensity values over a full 360° range, is consistent across all the luminaires, thereby enabling a fair comparison of their lighting distribution profiles.

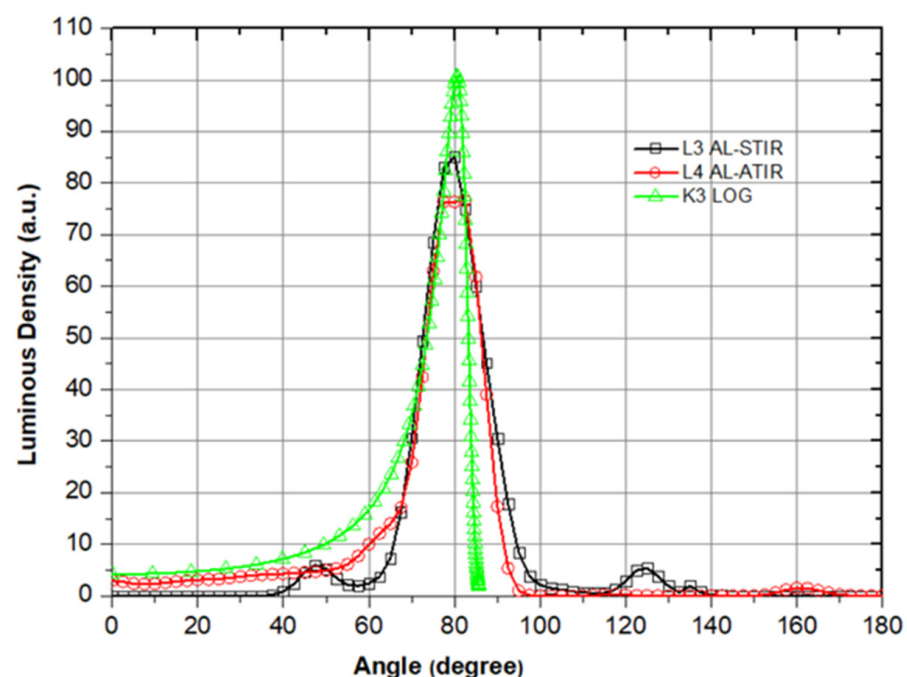


Figure 7. Comparison of the normalized luminous intensity curves for the L3 AL–STIR luminaire with AL–STIR lens, L4 AL–ATIR luminaire with AL–ATIR lens, and the ideal $k = 3$ curve (K3 LOG). The peak intensities for L3 AL–STIR and L4 AL–ATIR are slightly below the ideal curve’s peak, demonstrating the beneficial effect of using TIR segments in the luminaire design.

From the graph, it is noticeable that both the L3 AL–STIR and L4 AL–ATIR luminaires exhibit peak lighting intensities that are slightly lower than the peak of the ideal K3 LOG curve. This subtle deviation indicates a marginally reduced luminous intensity at the angle of maximum emission when compared to the theoretical optimum modeled by the K3 LOG curve. The inclusion of TIR elements in the luminaire designs, as indicated by the AL–STIR and AL–ATIR nomenclature, appears to have contributed to an improved luminous intensity distribution, drawing it closer to the ideal curve’s distribution.

The curves for L3 AL–STIR and L4 AL–ATIR also suggest a good alignment with the shape of the K3 LOG curve, particularly around the peak, which implies that the TIR components in their lenses are effective in directing the light towards the target angle. However, the L3 AL–STIR luminaire’s curve indicates insufficient lighting intensity from 0° to approximately 80° , suggesting a lack of illumination in the ceiling’s proximal area.

After considering the overall analysis, the L4 AL–ATIR luminaire with AL–ATIR optics emerges as the right choice for achieving uniform ceiling illumination.

4.2. Comparison of Ceiling Light Distribution Uniformity

Calculations were conducted using the Dialux 9.1 software (DIAL GmbH, Bahnhof-sallee 18, 58507 Lüdenscheid, Germany) and the relevant IES files for the luminous intensity curves to assess ceiling illumination uniformity and intensity. A virtual room, 6 m long, 4 m wide, and 3 m high, was created for the simulation. Typical materials for the ceiling, wall, and floor were chosen with reflectance values of 85%, 70%, and 60%, respectively, to accurately visualize the ceiling’s appearance in the simulation. However, these reflectance values were not factored into the direct illuminance calculations, ensuring that only the direct illumination component was analyzed.

Two sets of six luminaires (a total of twelve) were mounted on opposite sides of the room, positioned 0.3 m below the ceiling ($H = 0.3$ m). The luminaires were aligned such that their maximum intensity rays formed an 80° angle with the vertical. The total LED luminous flux for the simulation was 19,200 lm (12×1600 lm).

Two types of average illuminance $\bar{E}$ measurements across the ceiling were determined. The first type, $\bar{E}_{ceiling}^{direct}$, accounted solely for direct light from the light sources to the ceiling, aiding in the comparison of different luminaires for ceiling illumination. The second type, $\bar{E}_{ceiling}^{total}$, included all light rays—both direct and reflected from surrounding surfaces—offering a realistic view for practical installations that consider the complete interplay of light with the environment. The illuminance uniformity U_o was employed as a measure of lighting quality, defined by the ratio of minimum to average illuminance $E_{min}/\bar{E}$.

Tube LEDs are commonly utilized for ceiling and wall lighting and act as reference points for evaluating advanced AL–TIR LED luminaires. Figure 8a presents a 3D rendering of the ceiling illuminated by tube LEDs, with the associated illuminance color map shown in Figure 8b. Their extensive Lambertian luminous intensity distribution results in a concentration of light near the fixtures, leading to a low direct illuminance uniformity $U_{TLED}^{direct} = 0.25$. While tube LEDs offer simplicity and cost-effectiveness, their use in ceiling applications, particularly within decorative ceiling boxes, often results in light being trapped and wasted.

Wall-washing LED luminaires, noted for their narrow-spread angles, provide an alternative method for ceiling illumination. Figure 8c illustrates a 3D view of a ceiling lit by NF301 LED (NVC Lighting Inc., Ruhe, Huizhou, Guangdong, China), while Figure 8d displays the corresponding illuminance color map. These LEDs achieve a $U_{NVLED}^{direct} = 0.56$ for direct illumination. Despite the improved U_o , diminished light levels are still discernible in the vicinity of the luminaires.

Figure 8e,f reveal the lighting impact of the L1–AL0 luminaire equipped with an AL0 lens. The L1–AL0 luminaire’s $U_{AL0}^{direct} = 0.57$, matching the $U_{NVLED}^{direct} = 0.56$ of the NF301 luminaire and indicating an improved overall lighting intensity. The direct ceiling illuminance $\bar{E}_{ceiling}^{direct}$ provided by the L1–AL0 luminaire is 366 lx, which exceeds the 292 lx provided by the NF301 luminaires.

Figure 9a,b present the influence of the L2–AL6 luminaire, featuring an AL6 lens, on ceiling brightness, showcasing a significant rise in direct U_{AL6}^{direct} to 0.78. The average direct illuminance $\bar{E}_{ceiling}^{direct}$ for the L2–AL6 luminaire is equivalent to that of the L1–AL0 luminaire, rendering the L2–AL6 design a promising option for widespread production.

Figure 9c–f illustrate the ceiling illuminated by the L3 AL–STIR and L4 AL–ATIR luminaires, which incorporate ALs with TIR optics. The L3 AL–STIR luminaire combines two symmetric TIR optics with an AL, constituting an AL–STIR system, and achieves a $U_{NVLED}^{direct} = 0.63$. Notably, the L4 AL–ATIR luminaire, which integrates an AL with asymmetric TIR elements (AL–ATIR), attains the highest uniformity with a $U_{ALATIR}^{direct} = 0.83$ and an average illuminance of 429 lx, as depicted in (c) and (d).

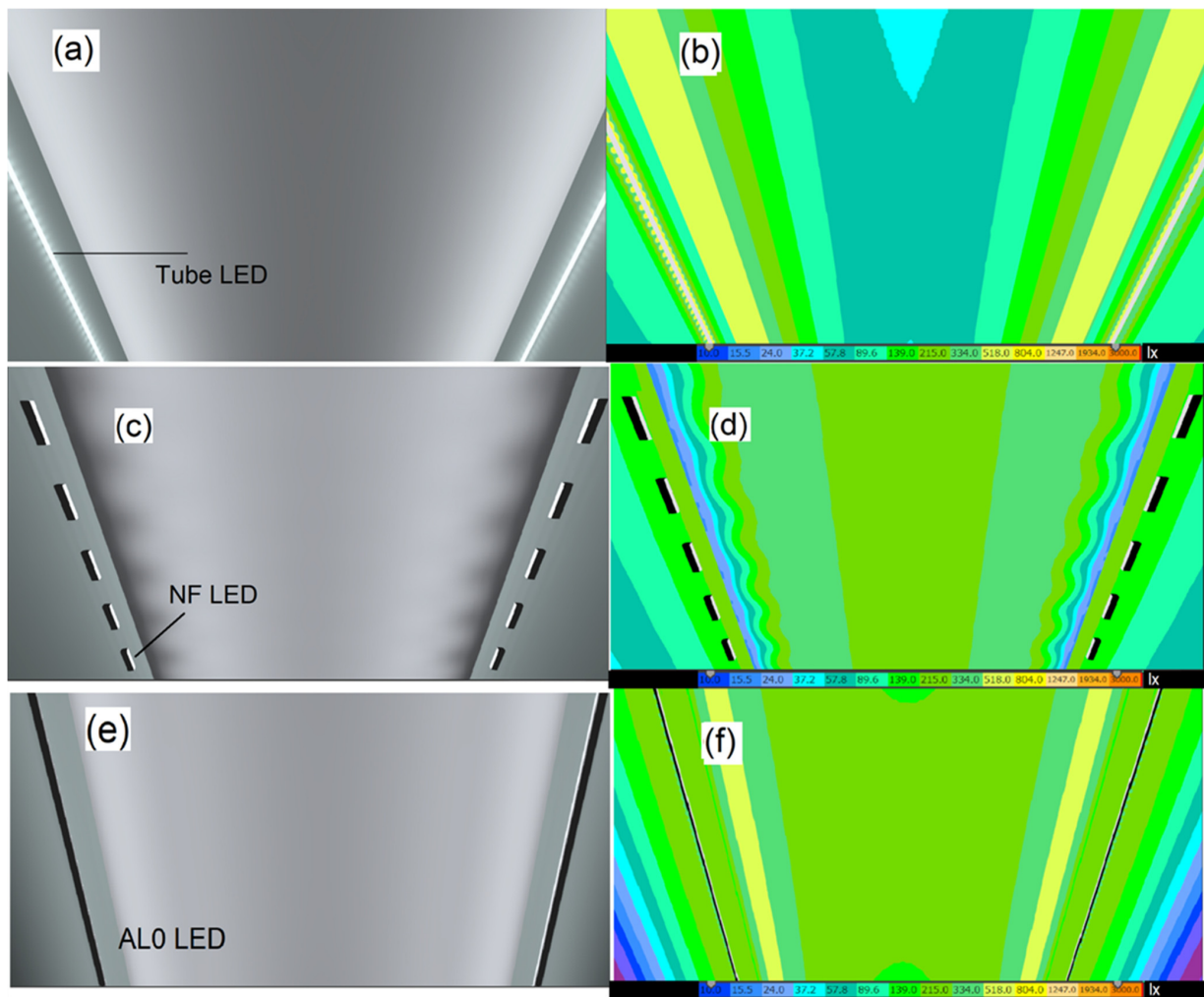


Figure 8. Comprehensive 3D renderings and illuminance color maps for diverse LED luminaire configurations illustrating their effects on direct ceiling illumination: (a,b) feature 12 tube LEDs with a direct illuminance uniformity U_{TLED}^{direct} of 0.25; (c,d) display 24 NVC NF301 LEDs achieving a U_{NVCLED}^{direct} of 0.56 for improved uniformity; (e,f) show ceiling illumination by an AL0 LED (L1–AL0 luminaire) with a U_{AL0}^{direct} of 0.57.

These findings align with the analysis of rectangular luminous intensity curves in Figure 7, which juxtaposes the AL–ATIR with the ideal K3 LOG curve. The inability of the L4 AL–ATIR luminaire to reach perfect direct illuminance uniformity $U_{ideal}^{direct} = 1$ may be attributed to factors such as the intricacies of the optical design and the physical dimensions of the LED packages. Moreover, the necessity for complex thermal management with smaller LED packages makes them less viable for HCL applications.

The findings from the ceiling illumination analysis are consolidated in Table 1. $\bar{E}_{ceiling}^{direct}$ denotes the average direct illuminance on the ceiling. Direct optical utilization factor (DOUF) represents the ratio of direct luminous flux to total flux; $\bar{E}_{ceiling}^{total}$ signifies the average total illuminance on the ceiling, factoring in the reflected light from surrounding surfaces. Notably, the total optical utilization factor (TOUF) can exceed 100% due to the substantial contribution from reflected light.

In summary, we selected the tube LED as a reference configuration due to its popularity and widespread use as a standard luminaire. The NFLED was chosen for its reputation as one of the top-performing wall-washing luminaires. The AL0 and AL6 LED luminaires were included based on their use in previous projects, allowing for direct and straightforward

comparison. Finally, the AL-STIR LED was included based on recent advancements proposed by He et al. [19] in asymmetric lighting design.

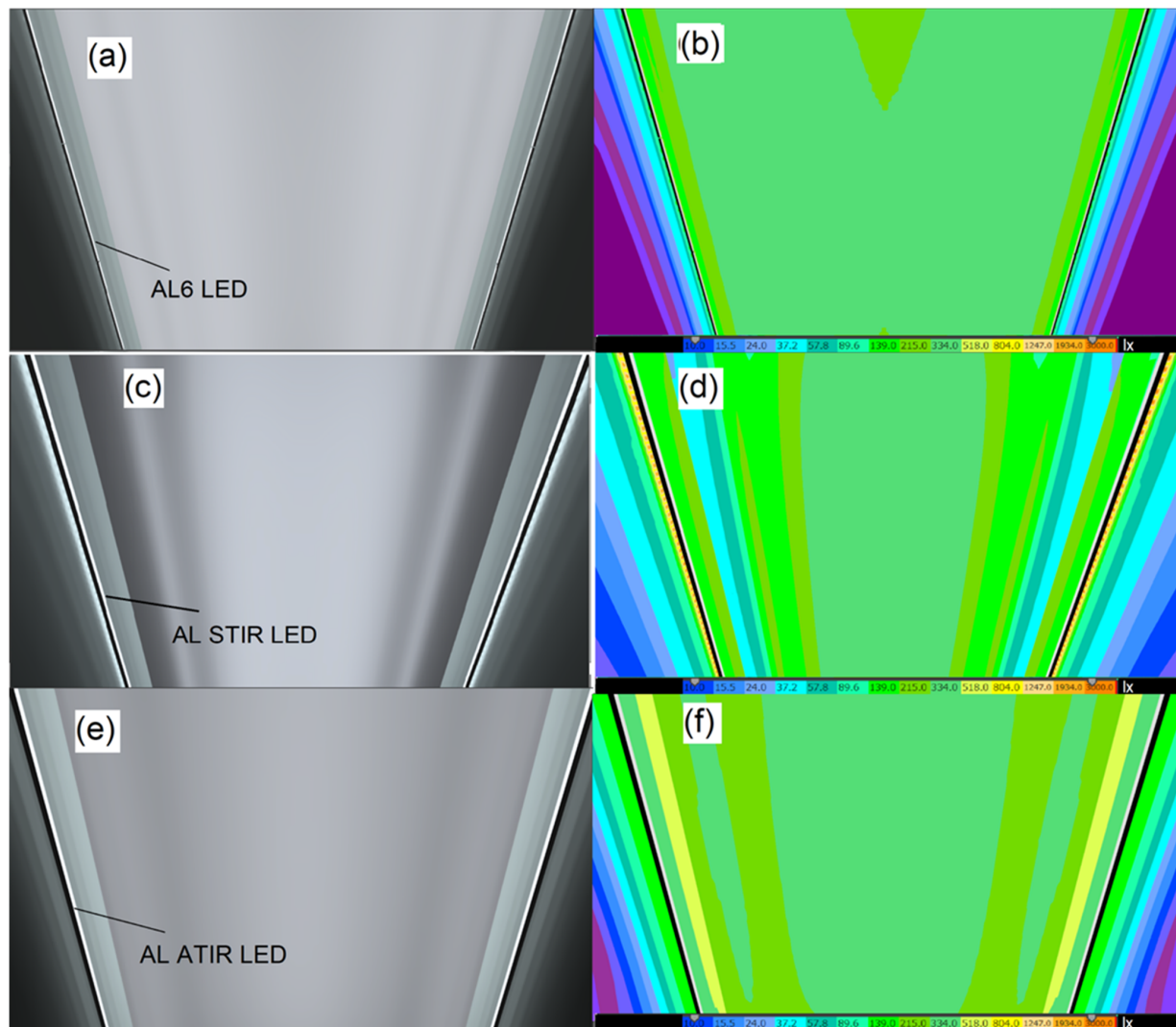


Figure 9. Three-dimensional renderings and illuminance color maps of advanced AL LED luminaires demonstrating their impact on ceiling illumination: (a,b) AL6 LED configuration provides a uniformity U_{AL6}^{direct} of 0.78, depicting efficient light distribution; (c,d) AL-STIR LED setup, achieving a uniformity U_{NVLED}^{direct} of 0.63, combines optics for balanced illumination; (e,f) AL-ATIR LED arrangement reaches the highest uniformity U_{ALATIR}^{direct} of 0.83, showcasing optimal uniformity and intensity control across the ceiling.

Table 1. Ceiling illumination analysis results.

Luminaires	Optics	Illuminance —direct $E_{ceiling}$ (lx)	Dir. Util. Factor DOUF	Direct Uniform U_0^{direct}	Illuminance —total $E_{ceiling}$ (lx)	Total Uniform U_0^{total}	Total Util. Factor TOUF
12 × TLED	Diffuser	252	36%	0.25	483	0.42	70%
24 × NF301	Sym. Lens	292	43%	0.56	404	0.76	57%
12 × L1-AL0	AL0 Lens	366	53%	0.64	606	0.75	88%
12 × L2-AL6	AL6 Lens	362	53%	0.78	556	0.90	81%
12 × L3-AL STIR	AL STIR	354	51%	0.63	487	0.87	71%
12 × L4-AL ATIR	AL ATIR	429	63%	0.83	700	0.91	100%

4.3. Comparison with Real Lighting Scenario

Our findings were validated by producing linear luminaires modeled on the L2–AL6 design and using them to illuminate the ceilings of several office rooms. While the specifics of the luminaire design are not covered in this work, the simulation followed the same procedure described for the L2–AL6. Notably, the real luminaires used LED packages and power supply that delivered a higher luminous flux (1700 lm), but this did not affect the OUF and U_o generated by the luminaires. For comparison, a typical office space measuring $6 \times 3 \times 3.8$ m (length $\times$ width $\times$ height), with reflectance values of 85% for the ceiling, 70% for the walls, and 50% for the floor was selected. Ten L2–AL6-based luminaires were mounted 0.225 m from the ceiling, maintaining the previously calculated H/W (0.3/4) ratio, and were positioned on opposite sides along the ceiling.

The comparison between the simulated and actual ceiling luminance is presented in Figure 10a–d. Figure 10a displays a simulated ceiling image with calculated luminance values based on the total illuminance figures detailed in Figure 10b. The values in parentheses indicate the luminance corresponding to the illuminance at each ceiling position, averaging 234 cd/m^2 . Figure 10c features a real ceiling image with measured luminance values, captured using a Konica-Minolta LS-150 Luminance Meter, arranged in a grid that mirrors the simulation grid. The minimal differences in average ceiling luminance (234 vs. 232 cd/m^2) and total uniformity U_o^{total} values (0.85 vs. 0.82) validate our model and design approach, confirming their applicability in LED luminaire development.

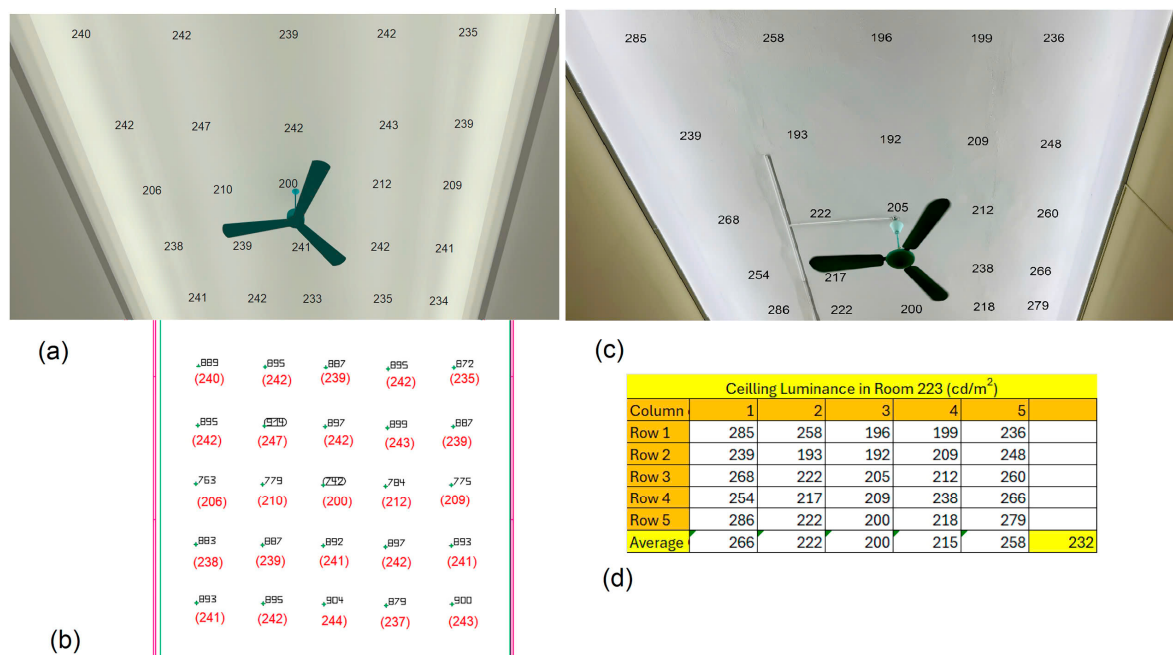


Figure 10. Comparison of simulated and actual ceiling luminance: (a) simulated ceiling image with calculated luminance values; (b) detailed luminance values with corresponding illuminance; (c) real ceiling image with measured luminance; (d) tabulated luminance measurements across a grid in Room 223, illustrating the correlation between simulation and reality, validating the luminaire design process.

5. Conclusions

This research introduces an advanced AL–ATIR LED system that sets new standards for ceiling illumination. The main findings highlight the successful design and implementation of LED luminaires tailored for ceiling-washing applications, particularly the L4 AL–ATIR luminaire, which achieved nearly ideal performance and cost-effectiveness. With a direct illuminance uniformity of 0.83 and an optical utilization factor of 63%, the system optimally distributes light, achieving a total ceiling illumination of 700 lx with highly re-

flective surfaces. This design also reduces shadows from ceiling fixtures and floor-standing objects, enhancing spatial comfort by using a uniformly illuminated large-area ceiling as an indirect light source.

An optimal floor illuminance of 433 lx is achieved, resulting in a high level of uniformity that ensures a conducive environment for various interior spaces. Furthermore, the AL-TIR LED system surpasses traditional solutions like stretch ceilings and lightboxes by offering unparalleled adaptability and efficiency. The integration of even ceiling lighting with adjustable LED spectra, color-correlated temperature, and high color rendering index creates a lighting environment that closely mimics natural conditions, supporting HCL solutions.

The potential of this system to improve lighting design, closely emulate natural lighting conditions, and enhance spatial quality underscores its significance in promoting human well-being and productivity. Future work will explore the scalability of this system across different architectural styles and its integration with smart lighting technologies, enhancing its impact on human psychological and physiological well-being in long-term studies.

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Abbreviations

AL	Asymmetric lens
AL-STIR	Asymmetric Lens-Symmetric Total Internal Reflection
AL-ATIR	Asymmetric Lens-Asymmetric Total Internal Reflection
TOUF	Total optical utilization factor (including multiple reflections)
$\bar{E}$	Average illuminance
$\bar{E}_{ceiling}$	Average Illuminance on Ceiling
$\bar{E}_{ceiling}^{direct}$	Average Direct Illuminance on Ceiling
$\bar{E}_{ceiling}^{total}$	Average Total Illuminance on Ceiling
HCL	Human-centric lighting
TIR	Total internal reflection
U_0^{direct}	Direct illuminance uniformity
U_0^{total}	Total Illuminance Uniformity
U_o	Illuminance uniformity

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