Hotspot Reduction and Uniform Illumination Design

1. Abstract & Scope

In customized Human-Machine Interface (HMI), such as touch panels, medical displays, smart home controllers, and automotive center stacks – delivering seamless, uniform illumination without visible LED hotspots or dark shadows is critical for perceived build quality and usability.

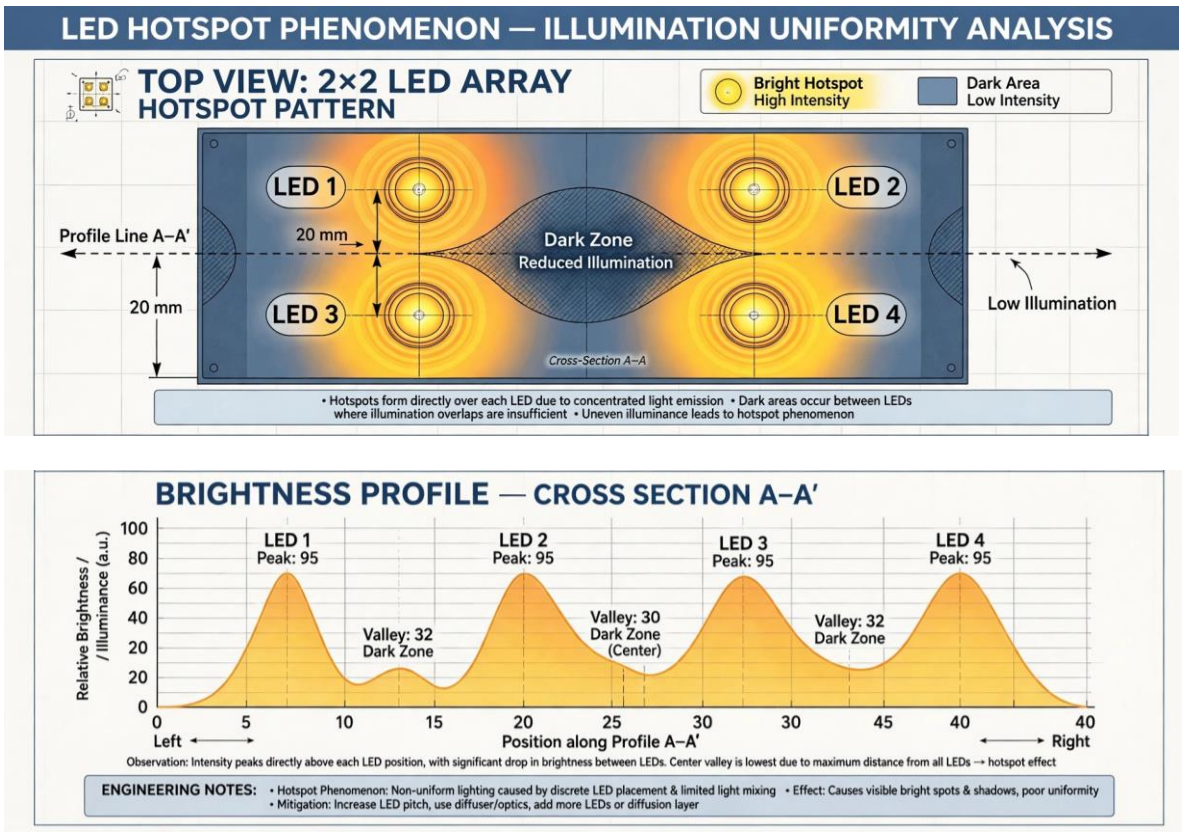
Direct-backlit configurations offer high luminance efficiency and low manufacturing complexity, but they present significant optical challenges when working within ultra-thin enclosure constraints. This application note outlines practical engineering rules, geometric formulations, optical element configurations, and LED selection strategies to achieve superior luminance uniformity in direct-backlit HMI panels.

2. Root Causes of Illumination Non-Uniformity

In direct-backlit HMI panels, Surface Mount Device (SMD) LEDs sit directly behind a translucent graphic layer or diffuser screen. Visual artifacts stem from three primary physical mechanisms:

- **Point-Source Hotspots:** Even wide-angle SMD LEDs exhibit peak intensity near the optical axis. When the LED-to-diffuser distance is too small relative to LED pitch, insufficient optical mixing can produce visible luminance peaks appear directly above the LEDs.
- **Spatial Dark Areas (Inter-LED Voids):** Gaps between adjacent LEDs receive insufficient overlapping luminous flux if the emission beam angles do not intersect prior to reaching the diffuser plane.
- **Edge Luminous Decay:** Uncoated housing walls absorb scattered light, causing noticeable luminance drop-off along the outer perimeter of the panel.

© 2013 – 2026 Inolux Corporation
All Rights Reserved

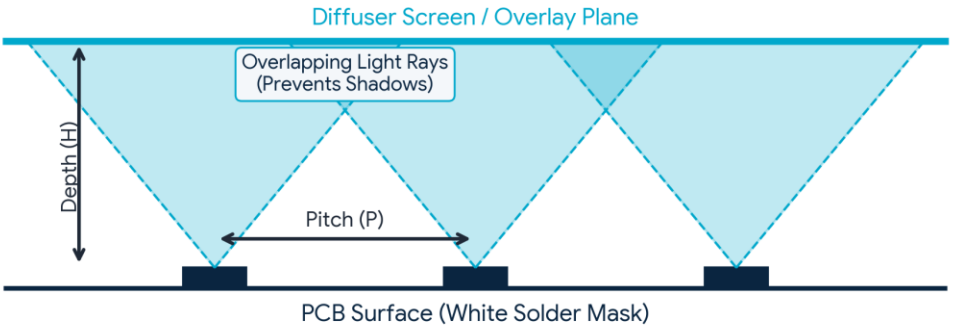


3. Geometric Optimization: The Pitch-to-Distance Ratio

P/H ≤ 1.8 may be used as an initial design guideline. Final spacing should be validated through optical simulation or prototype testing.

Initial Design Guideline : P / H ≤ 1.8

Figure 1: Direct-Backlit Geometric Parameters (Pitch P vs. Mixing Depth H)



© 2013 – 2026 Inolux Corporation

All Rights Reserved

Key Variables:

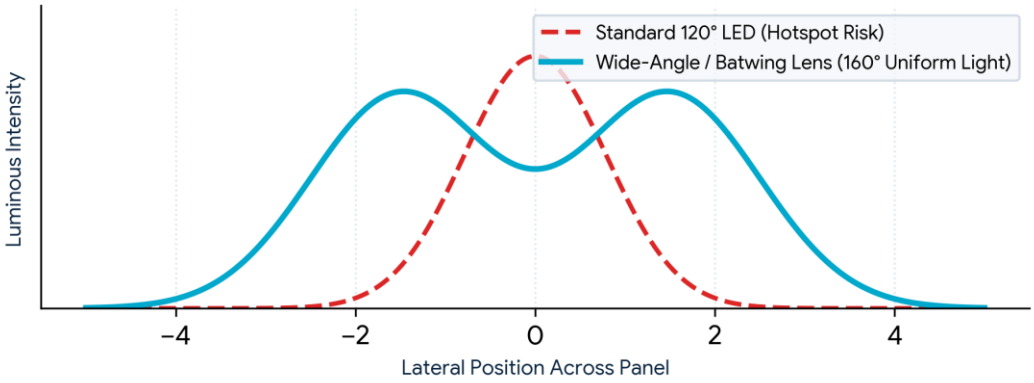
- **P (LED Pitch):** Center-to-center distance between adjacent LEDs on the PCB matrix (mm).
- **H (Mixing Distance / Cavity Depth):** Vertical distance from LED emitting plane to the rear surface of the diffuser screen (mm).

4. Design Interventions & Solution Strategies

A. Wide-Angle SMD LEDs

Standard SMD LEDs feature a 120° Lambertian emission profile. To minimize mixing depth (H), ultra wide-angle LEDs (140°–170°) or batwing secondary lenses can be selected. These spread axial intensity laterally, enabling thinner HMI structures without introducing central hotspots.

Figure 2: Angular Emission Profile Comparison Across LED Pitch Line



B. Multi-Layers Optical Diffuser Stacks

Achieving high uniformity in flat HMI enclosures requires a multi-tier optical approach:

- **High-Haze Volumetric Diffusers:** Polycarbonate (PC) or PMMA sheets infused with micro-spherical light scattering beads yield uniform distribution with > 75% optical transmission.
- **Brightness Enhancement Films (BEF):** Micro-prism structured films redirect wide-angle scattered light back toward the viewing axis, preserving central brightness.
- **Gradient Halftone Masking:** Screen-printing white/grey dot matrix patterns on the back of the overlay directly above LED positions dampens central intensity peaks.

© 2013 – 2026 Inolux Corporation
All Rights Reserved

C. Reflective Light-Box Cavities

To eliminate dark borders and maximize light efficiency, line the internal light box walls with diffuse white reflective films and specify white solder mask across the entire LED PCB surface.

5. Engineering Trade-off & Implementation Matrix

Design Approach	Uniformity Performance	Thickness Constraint (H)	Relative Cost & Complexity
Standard 120° LED + Single Diffuser	Moderate (Hotspot risk increases as P/H increases)	Requires Large H (Thick Enclosure)	Lowest Cost Simple
Wide-Angle (160°) LED / Batwing Optics	Excellent (> 85% Uniformity)	Allows Reduced H Depth	Cost Effective
High-Density Mini-LED Matrix	Very High (> 90% Uniformity)	Allows Ultra-Thin H Depth	Higher Cost Higher Power Consumption
Halftone Print Masking + White Cavity	High (> 85% Uniformity)	Moderate H Depth	Low BOM Cost Custom Mask Tooling

Note: Uniformity percentages shown above are recommended design reference values only. Actual performance may vary depending on LED type, pitch-to-distance ratio, diffuser characteristics, optical stacks, cavity reflectivity, panel size, and measurement method. Finally, uniformity should be verified by optical simulation or prototype testing.

© 2013 – 2026 Inolux Corporation
All Rights Reserved

6. Recommended Step-by-Step Design Sequence

- **Step 1: Mechanical Cavity Definition:** Determine maximum housing thickness (H) permitted by the HMI product envelope.
- **Step 2: Calculate LED Pitch (P):** Apply $P \leq 1.8 \times H$ to calculate maximum allowable LED spacing.
- **Step 3: Component Selection:** Choose appropriate wide-beam SMD LED packages based on required brightness and spatial constraints.
- **Step 4: Cavity Reflector Integration:** Incorporate white PCB solder mask and > 95% reflective cavity wall linings.
- **Step 5: Optical Stack Validation:** Verify illuminance uniformity via optical simulation software or physical mockup; adjust gradient halftone printing if necessary.

© 2013 – 2026 Inolux Corporation
All Rights Reserved