Technical Bulletin

Recessed LED Optics and Glare

The architectural lighting industry has witnessed a pronounced shift toward increasingly compact luminaire apertures, driven by the aesthetic demand for minimalist ceiling planes and the rapid advancement of high-efficacy LED light sources capable of delivering meaningful lumen output from ever-smaller optical packages. Where fixtures with 4-inch and 6-inch apertures were once standard for architectural downlighting, today's projects routinely specify 2-inch and sub-2-inch aperture fixtures.

This pursuit of visually quiet ceilings, however, carries a significant photometric challenge: as aperture size decreases and light level targets remain constant, brightness at the aperture rises sharply, increasing the potential for discomfort glare and disability glare within the spaces these fixtures are meant to serve. This concentration of light output into a smaller emitting surface fundamentally complicates glare control, challenging fixture designers and manufacturers to develop increasingly sophisticated optical systems that minimize unwanted glare while retaining high levels of light output.

The Role of Optics

Recessed LED downlights, without optical control, emit light according to a Lambertian distribution, a natural emission pattern in which light radiates with equal luminous intensity in all directions from the source. While this spread may be broad and even, in practice it is poorly suited to most architectural and task lighting applications. The raw output of an LED chip is diffuse and uncontrolled, flooding the ceiling cavity and spilling light across wide, unintended angles. In a recessed fixture, this means a significant portion of generated light is either absorbed by the housing before it even exits the aperture or escapes at such oblique angles that it contributes little useful illumination to the space below while simultaneously exposing the high-luminance source to anyone in the room.

This is where optics become essential. Reflectors, lenses and diffusers give designers precise control over how light leaving the fixture is shaped and directed. A well-designed reflector or lens can transform the wide Lambertian emission into anything from a narrow accent beam to a broad, controlled distribution suitable for general ambient illumination. By shaping the beam in a controlled manner, optics concentrate output toward intended targets, reducing wasted light and improving luminaire efficiency.

Critically, optics also address one of the most persistent problems with recessed downlights: glare. Without optical treatment, the bare LED source remains directly visible from wide viewing angles, producing uncomfortable or even disabling glare that undermines visual comfort and the quality of the lit environment. Optics work to obscure the source and restrict light emission to controlled angles, ensuring the fixture delivers its output where it is needed while remaining visually comfortable to occupants throughout the space.

Achieving meaningful glare control in recessed LED downlights requires deliberate and exacting optical design, especially as products move toward smaller apertures. Small aperture fixtures, generally 2 inches and below, concentrate the same high-luminance source behind a far narrower exit, dramatically increasing perceived aperture brightness and making the fixture significantly more visually aggressive from oblique sightlines. Unlike larger downlights, where aperture size and reflector depth naturally assist in shielding the source, small aperture fixtures offer little physical room for the baffles or layered optical assemblies that would ordinarily manage glare, placing far greater demands on the precision and efficiency of whatever optical elements can be accommodated within the constrained housing.

Product designers and engineers may utilize a variety of optical approaches, including precision reflectors, refractive lens elements and diffusing or micro-structured optical films to shape and control light emitted from an LED source. Each of these approaches has distinct advantages and limitations depending on the application and, most importantly, the aperture size of the fixture. As aperture dimensions decrease, optical systems must balance beam control, efficiency and glare reduction within an increasingly constrained physical envelope, making optical design one of the most critical aspects of small-aperture luminaire performance.

Cutoff Angles

The cutoff angle of a recessed LED downlight is the angle, measured from the nadir (the point directly below the fixture), at which the bare LED source is no longer visible to an observer (see Figure 1). Above this angle, the optical assembly, whether a reflector wall, baffle, or lens housing, successfully shields the source from view, presenting only a controlled, low-luminance aperture to anyone in the room. As the observer's sightline falls below the cutoff angle toward nadir, the source becomes progressively more visible, and the risk of direct glare increases correspondingly. In practical terms, the cutoff angle defines the boundary between the glare-controlled zone of a luminaire and the zone of potential visual discomfort, and it is a key metric by which the glare performance of a downlight is evaluated and specified.

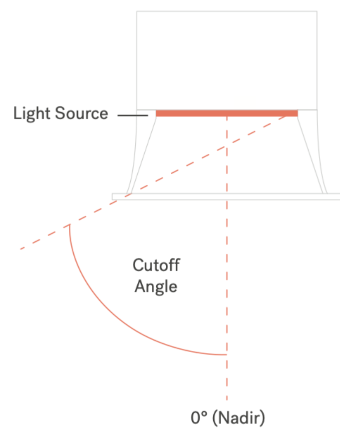

Figure 1 - A diagram showing the cutoff angle of a recessed downlight.

A fixture with a narrow cutoff angle, which shields the source from a wider range of viewing positions, is generally preferable and will perform well in environments where occupants are seated or reclined and their natural sightlines frequently intersect the ceiling at steeper angles, such as in hospitality, healthcare and residential settings. Conversely, a wider cutoff angle may be acceptable in spaces where ceiling heights are higher and occupants are unlikely to approach the fixture aperture within their normal field of view, such as commercial real estate lobbies. For recessed downlights, and particularly for small aperture fixtures where the luminance of the source behind the restricted opening is inherently high, achieving a sufficiently narrow cutoff angle is one of the primary objectives of optical design, and it is the interplay between aperture diameter, optical depth, reflector geometry and lens or baffle configuration that ultimately determines the fixture’s cutoff angle.

Reflectors

Reflectors are among the oldest and most widely used forms of optical control in luminaire design and remain highly relevant in recessed LED downlights despite the emergence of more sophisticated refractive and film-based alternatives. In principle, a reflector works by intercepting light emitted at wide or upward angles from the LED source and redirecting it downward through specular or semi-specular reflection, with the geometry of the reflector surface — its depth, curvature and cross-sectional profile — determining the resulting beam angle and intensity distribution. Parabolic profiles are commonly used where a narrow, collimated beam is desired, as they can redirect rays from a point source into near-parallel output with high efficiency, while elliptical and conical profiles offer broader, more diffuse distributions suited to general ambient applications. Reflectors are also favored in deep-format architectural downlights where the physical depth of the reflector itself contributes to shielding the source from view, naturally limiting the angles at which the LED is visible and providing an inherent degree of glare control simply through geometry.

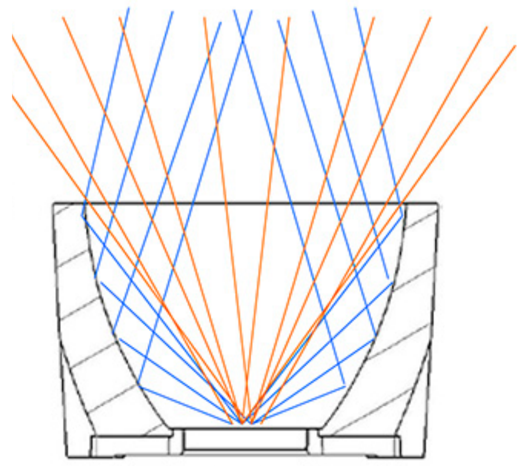

Figure 2 - An example of light beams that escape a reflector without hitting any surface, causing unwanted glare.

Despite their advantages, reflectors also present several limitations. Even high-quality specular anodized aluminum or vacuum-metalized surfaces introduce optical losses through absorption, and multiple reflections within a deep housing can accumulate these losses significantly, reducing overall luminaire efficacy. Surface imperfections, contamination over time, or manufacturing tolerances in the reflector profile can introduce unwanted artifacts such as striations, beam irregularities, color fringing, or uneven beam edges. Furthermore, reflectors are inherently less effective at controlling very wide-angle or Lambertian emitters unless combined with a secondary optical element, as rays emitted nearly parallel to the reflector surface may escape without being intercepted, contributing to residual spill and glare around the aperture. Figure 2 diagrams this, as the beams drawn in orange escape the reflector without touching the reflector surface itself.[1]

Refraction Lenses

Refractive lenses control light in recessed LED downlights by exploiting the principle of refraction — the bending of light rays as they pass from one optical medium into another of different refractive index, governed by Snell's Law[2] — to redirect and reshape the emission from the LED source with a high degree of precision. Unlike reflectors, which intercept and bounce light through geometry alone, refractive lenses act directly on rays as they transmit through the optical element, using carefully engineered surface curvatures, facet angles, and profiles to bend each ray bundle toward a desired trajectory. The most common forms used in LED downlight applications are total internal reflection (TIR) lenses, which combine a refractive entry surface with a reflective outer wall that captures wide-angle rays and redirects them forward through total internal reflection before they exit through a collimating front face. Fresnel lenses represent another refractive optical approach, using a series of concentric stepped facets to approximate the curvature of a conventional lens while reducing thickness and weight, although they are less commonly employed in

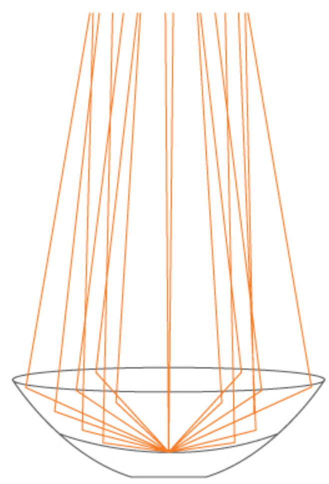

Figure 3 - A diagram of a TIR optic, which concentrates light to a tight, narrow beam.

[1] Image from LEDiL - https://www.ledil.com/support/guide-to-tir-lenses/
[2] Snell's Law describes the relationship between the path taken by a ray of light crossing the boundary between two mediums, such as air and a lens - https://www.britannica.com/science/Snells-law

architectural recessed downlights than TIR optics.

Refractive lenses are particularly well suited to compact, low-profile downlights where the shallow ceiling void makes the deep housings required by reflector-based systems impractical, and they excel in applications demanding tight, precise beam control such as accent lighting, retail display illumination, and gallery or museum fixtures where beam angle consistency and optical cleanliness are critical. Their primary benefits lie in their efficiency, as a well-designed TIR lens can capture and redirect a very high proportion of LED output with minimal loss. They also produce sharply defined, uniform beams with smooth intensity profiles and controlled cutoff.

Refractive lenses do, however, present several limitations. They are typically designed around a specific LED source geometry, meaning they are sensitive to tolerances in LED placement and perform poorly if the source shifts even fractionally from the design position, which can introduce beam asymmetry or hotspots. They are also more susceptible to visible chromatic effects at beam edges, where dispersion at the lens surfaces can produce color fringing, and in applications requiring very wide, diffuse distributions they offer less flexibility than reflector or film-based approaches. Most often, TIR lenses require additional diffusion elements to soften the output to an acceptable level.

Microstructure Optical Films

Microstructure optical films control light in recessed LED downlights through the manipulation of ray trajectories at a microscopic surface level, using precisely engineered repeating geometric structures, such as prismatic arrays, lenticular profiles, pyramidal facets or moth-eye patterns, which are embossed or etched onto a thin plastic or glass substrate. These microstructures redirect, diffuse or homogenize light as it passes through or reflects from the film. Unlike reflectors or refractive lenses, which rely on macroscopic optical geometry, microstructure films function as a continuous surface treatment applied across the exit aperture of a luminaire. Rather than using the curvature of a lens or reflector to redirect light, they derive their optical effect from the geometry, pitch and orientation of microscopic surface features.

Figure 4 - DMF's 4-inch downlights utilize microstructure lenses placed in front of TIR lenses for final shaping and beam spread.

In recessed LED downlights, microstructures are most commonly employed as a final optical stage positioned at or near the aperture plane, where they receive the partially shaped output of an upstream reflector or lens system and perform the last stage of beam shaping, often softening hard edges, eliminating source imaging, spreading or redirecting light across a controlled angular range, and presenting a large, uniform, low-luminance emitting surface to the room. Microstructure films are particularly well suited to shallow, low-profile downlights where there is insufficient depth for meaningful reflector geometry or bulky lens assemblies, where they are successful at creating soft and diffused, yet controlled beams of light. Their benefits are considerable: they are thin, lightweight, and cost-effective relative to precision-molded lens elements; they can be tuned through variation of the microstructure geometry to achieve a wide range of beam spreading and redirecting effects; and they are highly effective at concealing the discrete nature of the LED source and eliminating possible imperfections such as hotspots, LED imaging and phosphor non-uniformity.

However, microstructure films carry inherent drawbacks. Any diffusing or scattering element introduces optical loss through absorption and back-scatter, reducing the proportion of light that exits the luminaire in the intended direction and lowering overall system efficacy. Films that produce wide, Lambertian-like diffusion can also partially negate the beam-shaping work of upstream optics, reintroducing the broad, uncontrolled distribution that the reflector or lens was designed to control. Achieving both meaningful diffusion and tight beam control simultaneously therefore requires careful optical system design rather than reliance on the film alone.

Cross Beam Optics

The term cross beam optics generally refers to a focusing technique that is utilized in downlights to reduce glare and excess spill onto trims. Cross beam focuses can be produced through a number of different optical devices, including refraction and TIR lenses. When two or more such refractive elements are oriented in opposition or at calculated angles to one another, they create what is effectively a cross beam focus. Ray bundles from opposite sides of the LED source are bent inward and caused to intersect at a defined point or plane in space. For recessed downlights, this convergence is typically engineered to occur near the ceiling plane aperture, which concentrates useful light output while suppressing low-angle rays that would otherwise strike the fixture trim.

This cross beam focusing principle has a significant practical consequence for luminaire design: by forcing incidental and peripheral light rays to converge rather than scatter, it reduces the proportion of output that reaches the trim ring, ceiling aperture and surrounding surface at shallow angles. In conventional downlights without such control, these stray rays can create bright halo or wash of light around the fixture aperture. This effect not only draws unwanted attention to the fitting itself but also contributes to veiling luminance across the ceiling plane, reducing perceived contrast and decreasing visual comfort. A well-executed cross beam refractive design intercepts these rays before they can illuminate the trim, redirecting their energy into the useful beam cone. The result is a cleaner, crisper aperture appearance with a visually dark surround that allows the fixture to recede into the ceiling rather than stand out as a bright source.

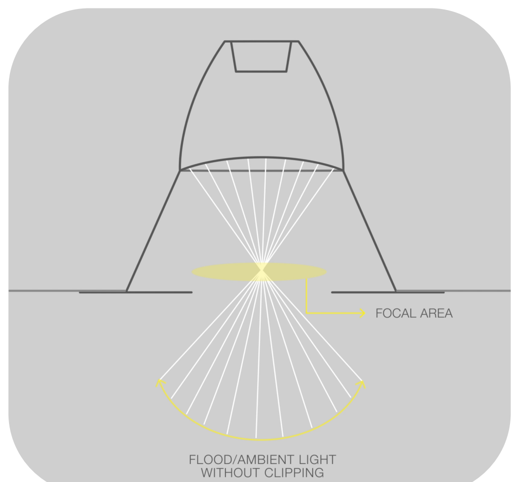

Figure 5 - An example of a regressed TIR cross beam optic and the effect on rays of light, utilized in DMF's 3-inch downlights.

Scattering and Non-Scattering Optics

Optical systems can generally be categorized as either scattering or non-scattering. Scattering optics, such as frosted lenses/TIR optics, diffusers, and certain microstructure films, deliberately introduce controlled randomness into ray trajectories to homogenize the beam and suppress source imaging. These non-scattering optics can also be referred to as non-imaging optics. Non-scattering optics on the other hand, including specular reflectors, polished refractive lenses and smooth TIR optics, redirect light through deterministic optical laws while preserving the spatial relationship between source and output. Some more familiar examples of non-scattering optics include camera and telescope lenses, and lenses used in image projector light fixtures. This characteristic property of non-scattering optics to faithfully reproduce source imaging means they can also be referred to as imaging optics.

The first category of scattering optics encompasses many different optical systems currently in use for recessed downlights. These optical systems, as previously outlined, work well in many instances, however the trade-off is that scattering inevitably broadens the beam to some degree, and creates some inherent unpredictability. Aside from optical losses that decrease efficiency, these scattering features allow some light rays to hit trims, which contribute greatly to glare.

In contrast, a non-scattering optic such as a precision-ground converging lens or a smooth, specular reflector preserves the coherence and directionality of individual ray bundles as it redirects them, bending each ray according to deterministic geometric or refractive laws without introducing any randomness into their trajectories. The result is a beam of high optical quality in which the intensity profile is a direct and predictable function of the source geometry and the lens prescription; in other words, non-scattering optics faithfully reproduce the source image and intensity profile. Its optical characteristics are sharp, well-defined, and capable of forming a crisp image of the source at a focal plane.

This characteristic property makes non-scattering optics the preferred choice where precise beam control, hard cutoff and maximum intensity concentration are required, such as in image projectors and hard-edge spotlights. The tradeoff is that any non-uniformities in the source, such as phosphor granularity, die structure or variations in flux across the LED surface, are faithfully reproduced in the beam, potentially producing visible structure, color variation, or hotspots within the pool of light.

Optics for Ultra-Small Aperture Fixtures

As fixtures trend towards ultra-small aperture sizes, at or below 1 inch at the ceiling plane, greatly reducing excess light spill on trims and reflectors becomes critically important in reducing glare and creating a visually comfortable ceiling and fixture. Traditional downlight optical systems, including combinations of reflectors, TIR lenses and microstructure films, all pose significant challenges in meeting this goal of reducing light spill and glare. In such a small format, achieving a true cross beam focus, in which all light rays meet at a secondary point, is imperative in achieving the lowest possible glare.

Figure 6 – DMF's True 1 optical stack and resulting cross beam focus

To meet this challenge, DMF's optical engineers designed a patent-pending optical stack that primarily utilizes non-scattering optical elements to create a true cross beam focus. This optical stack design features a glass primary lens followed by two silicone lenses arranged in opposition to precisely control beam spread and virtually eliminate excess light spill on the trim of the fixture. The exit side of the final silicone optical element features a precise microstructure film that softens the beam and reduces unwanted source imaging. The result is a soft-edge beam of light that effectively blends between fixtures and beautifully illuminates a space.

The True 1 optical stack was also chosen to allow for a relatively narrow cutoff angle, given the small aperture size. The position of the final lens behind the fixture's trim creates a relatively narrow 53-degree cutoff angle, greatly reducing positions where a direct view of the brightest portion of the fixture – the optical elements – can be seen.

Optic Systems for DMF Lighting Fixtures

	True 1 Downlight	3-Inch Downlights	4-Inch Downlights
Optic System	3 Stage Optical Stack: Non-Scattering Optical Elements and Microstructure film	Regressed TIR Optic: Cross Beam Focus and Diffusion Lenses for Beam Softening	Proprietary Folded TIR Optic and Microdiffusion Lenses for Beam Angle Control
Light Focus	Cross Beam	Cross Beam	Traditional Cone
Reason for Use	- Ultra-small aperture requires ultimate glare control and minimal spill -Traditional TIR lenses can't create a true cross beam focus	- Smaller aperture fixture requires cross beam focus for reduced glare and increased performance - Diffusion lenses allow for additional beam softening	- Ability to achieve a very shallow optical package - Wider 4-inch aperture doesn't require cross beam focus, as the larger aperture is inherently less glare-prone