Technical Bulletin

Color Over Angle in 1-Inch Downlights

Color Over Angle (CoA) refers to the variation in correlated color temperature (CCT) and chromaticity of light emitted from a single luminaire as a function of viewing angle. An LED source may appear, for example, 3000K when viewed on axis (0°) but shift toward 2700K, or exhibit a visible blue or amber tint, when viewed off axis. In simpler terms, CoA describes how consistently a fixture maintains its color as the viewing angle changes across its beam.

An example of poor CoA performance, in which the bottom-right portion of the beam appears significantly more yellow/amber than the rest of the beam.

CoA is distinct from fixture-to-fixture color consistency, which is influenced by LED binning and describes variation between different luminaires. CoA is a within-fixture phenomenon in which the same downlight produces different colors depending on where the observer or illuminated surface is positioned relative to the beam's optical axis. In practice, CoA can be observed in some of the following ways:

- A visible color ring at the beam edge on a wall or floor
- A cool-blue core with a warmer halo, or vice versa
- A perceptible color shift as a person moves beneath the fixture and views it from different angles
- A perceived color mismatch between adjacent adjustable/gimbal downlights aimed at different angles.

CoA in 1-Inch Downlights

While CoA may be observed in many types of lighting fixtures, ultra-small-aperture recessed fixtures can be particularly susceptible to the phenomenon, largely due to optical and packaging constraints. Fixtures with a true 1-inch aperture are limited in the light-emitting surface (LES) that can be used and must also package the LED, holders, and optics into a very confined space. These spatial constraints affect the optical system in several ways.

1) **Short mixing distance:** 1-inch fixtures typically need to package the LED, optics, and lens array(s) within a very short distance, often close to the fixture's exit aperture. This leaves very little distance for the light to blend before exiting the fixture. As a result, any angular color non-uniformity in the LED source, which is common to virtually all LEDs, can be projected out of the fixture with limited optical mixing. Larger aperture fixtures typically provide greater distance and surface area for optical mixing, making these variations less noticeable in the resulting beam.

2) **Smaller optic size:** Similarly, the overall diameter of the optics is smaller, particularly in fixtures designed to maintain an overall diameter close to their 1-inch aperture. This constrained diameter greatly reduces the surface area available within the optical system to redirect and homogenize light rays from different points on the LED package.

3) **Phosphor-converted white LED physics:** Most white LEDs produce light by pairing a blue LED die with a yellow or yellow-and-red phosphor. Light emitted near normal (0°) to the die travels through a shorter effective path in the phosphor than light emitted at more oblique angles. This difference in optical path length changes the balance between converted and unconverted blue light as a function of angle. In general, light traveling through a greater effective phosphor path undergoes more conversion, altering the spectral balance of the emitted light. This angular effect is common in phosphor-converted LEDs and can become more noticeable when combined with the small optical packages and limited mixing distances of 1-inch fixtures.

4) **Beam angle and trim geometry:** Narrow optics, typically in the sub-30° range, can make angular color shifts more visually apparent by concentrating the light into a smaller area and increasing intensity and color contrast. This can make color variation more noticeable than with a wide-flood optic, where the same angular differences are distributed across a larger area.

1-Inch Fixtures vs. 1-Inch Apertures

It is worth noting that there is a technical and practical difference between downlights with 1-inch apertures and downlights with an overall fixture diameter of 1 inch. One approach to creating a 1-inch aperture is to use a pinhole trim that reduce a larger aperture to a 1-inch visible aperture. This design allows for a larger fixture, optical system, and generally larger mixing distance, similar to what is found in traditionally sized downlights.

There are two potential trade-offs for this type of fixture design. One is that the larger fixture may require a larger trim flange, which can diminish the minimal aesthetic appeal of a 1-inch aperture. The other is that components of the fixture may be inaccessible after installation, creating significant challenges for maintenance, service, or future design changes.

A true 1-inch fixture, by contrast, maintains the minimal form factor of the 1-inch aperture throughout the fixture itself, but requires the LED, optics and other components to be engineered within a much more constrained space. This creates greater optical challenges, including the potential for increased CoA, while preserving the clean architectural appearance and compact form factor that make small-aperture lighting desirable.

Mitigation Strategies

Fixture manufacturers must carefully balance the competing demands of output, beam uniformity, glare control and aperture size when designing ultra-small-aperture fixtures. Several strategies can help reduce CoA, including:

1) **Remote phosphor design:** In remote-phosphor LEDs, the phosphor layer is physically separated from the LED die, providing greater separation between the light source and the phosphor and allowing the optical system to produce more uniform color before the light exits the package. Remote-phosphor designs can also offer benefits related to thermal management, efficiency, and LED longevity, depending on the implementation. These packages can be effective at improving color uniformity, but the additional physical space required by the technology makes it better suited to larger fixtures, such as linear lighting and soft panels used in film and television, and generally impractical for ultra-small-aperture recessed fixtures.

2) **Color mixing chambers:** Adding distance or dedicated mixing chambers within the optical system can help to mitigate CoA by allowing light rays to blend more uniformly before exiting the

fixture. This approach is somewhat inherent to larger aperture fixtures but becomes increasingly difficult to implement as the available space decreases, particularly in true 1-inch fixtures. Additional mixing can also come at the expense of lumen output and optical efficiency, making the trade-off more significant in 1-inch fixtures, where the limited LES size already places a premium on maintaining lumen output.

3) **Diffusion elements:** Adding layers of diffusion or microstructured diffusion is a common strategy for improving color uniformity across a fixture's beam. TIR and other optical elements are often used for beam control and shaping, while microstructured films or textures can be incorporated into optical elements to introduce controlled scattering. This helps blend light from different areas of the LED source and reduce visible color variation. While diffusion inherently reduces some lumen output and optical efficiency, the loss can be modest enough to justify the trade-off when improved color uniformity is the priority.

Evaluating Fixtures for CoA

CoA is not a widely discussed, tested, or reported metric for lighting fixtures, even among top-tier architectural-grade lighting fixtures. Testing CoA variation typically requires advanced photometric equipment, such as a goniophotometer paired with a spectroradiometer, to measure CCT and chromaticity at multiple angles across the beam rather than at a single normal (0°) position. Depending on the equipment and measurement protocol, this type of testing can take multiple hours to complete.

Lighting manufacturers have also not traditionally reported CoA data on spec sheets or in photometric reports. Traditional apertures of 3 inches and above generally experience less severe CoA variation than ultra-small-aperture fixtures, while 1-inch apertures can amplify the effect significantly.

When evaluating fixtures, visual inspection of a physical sample remains a practical and effective way to assess whether any CoA variation falls within an acceptable range. The intended application should also be considered when evaluating samples. An application calling for general-purpose downlighting, where individual beams blend smoothly, may have a higher tolerance for CoA variation than an accent lighting application where fixtures illuminate artwork or other highly visible surfaces.

DMF's True 1 Downlight

DMF's True 1 downlight features a true 1-inch aperture and employs a unique optical stack to achieve powerful output, extremely low glare, and excellent angular color uniformity for a fixture of its size. The True 1 optical stack utilizes non-imaging optics to create a precise cross beam focus that is highly effective at mitigating glare at the fixture's exit aperture. The final optical element in the stack features a precise level of microstructure diffusion that softens and diffuses variations in the source image. Together, these optical approaches allow the fixture to balance high output, low glare, and uniform color over angle within a minimal 1-inch form factor, while also delivering on performance, ease of installation and long-term serviceability.

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