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Color homogeneity in LED spotlights

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LED is a rising technology in the field of lighting. Halogen spotlights are nowadays replaced by LED spotlights because of their energy efficiency and long lifetime. However, color variation in the light output is a common problem. Poorly designed LED spotlights tend to have yellowish or bluish rings in the beam, which is undesirable. In this article we outline a method to design an optical component that annihilates this color variation.

A schematic drawing of a typical LED spotlight is shown in Figure 1. Light is produced in several LEDs, which emit light in the direction of the right hemisphere. An optical component, the so-called TIR (Total Internal Reflection) collimator, redirects the light into a compact beam. The problem of color variation originates from the LED: light emitted in the direction of the symmetry axis is typically more bluish, while light to the sides is more yellowish. We will eliminate the color variation of the spotlight by modifying the TIR collimator.

A TIR collimator is a rotationally symmetric lens, of which a profile is shown in Figure 2. For simplicity, we assume that all the light from the LED is emitted from a point source. All light rays are described by their angle with respect to the symmetry axis. Light at small angles is refracted by the lens-like surface A and subsequently by the flat surface T. Light at large angles is first refracted by surface S, then reflected by surface B or C and finally refracted by surface T. The reflection at surface B or C is due to total internal reflection, hence the name TIR collimator.

We need to compute the location of the so-called free surfaces A, B and C, which proceeds in two stages. First, we determine transfer functions, which define the relation between the angle t of a light ray when emitted from the LED and the angle Θ when leaving the collimator at T. This step requires the solution of a set of differential equations describing conservation of luminous flux and the rules of color mixing. Our objective here is to achieve a constant chromaticity color coordinate. Second, from the transfer functions we compute the free surfaces using basic geometry and the laws of reflection and refraction.

We have computed the profile of a TIR collimator and converted into a model for Monte-Carlo ray tracing in the LightTools code. A screenshot of this collimator with a set of rays is shown in Figure 3. The numerical results in Figure 4 show an intensity profile that closely matches the intended profile and a color variation that is invisible to the human eye.

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Figure 1: Schematic drawing of an LED-based halogen spot replacement.

Figure 2: Profile of a TIR collimator, where the z-axis is the axis of symmetry.

Figure 3: Screenshot of a 3D model of the designed TIR collimator.

Figure 4: Intensity and chromaticity of the Monte-Carlo simulation and the required intensity profile.