Method to improve spatial uniformity with lightpipes

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A heuristic method to obtain lightpipes that provide both collimation and good spatial uniformity is proposed. The change in shape that is likely to improve spatial uniformity, with minimal efficiency loss, can be predicted. Several case studies where this technique has been used are presented. © 2008 Optical Society of America

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Lightpipes are a handy tool in the illumination designer toolbox. They are ubiquitous in nonimaging optics. Straight lightpipes, sometimes called mixing rods, are commonly used to improve spatial uniformity [1]. On the other hand, lightpipes with tapered shapes can be used for light concentration (or, equivalently, for light collimation). Design techniques for concentrators have been widely investigated and are still an active area of research. Many common concentrators, such as the compound parabolic concentrator (CPC), are based on the edge-ray theorem, which provides two-dimensional étendue-limited geometries, and close to the étendue-limit for three-dimensional rotationally symmetric designs [2]. As of now, however, to our knowledge there are no methods to design single components that both collimate and homogenize light efficiently. The designer nominally relies on optimization, which can be computer intensive given that many rays must be traced to ensure good accuracy with Monte Carlo ray-tracing techniques. Optimization can be difficult when the merit function for spatial uniformity is noisy and contains multiple local minima. In this Letter, we present a simple heuristic method to obtain lightpipes that provide both collimation and good spatial uniformity. Given an illuminance distribution, we can predict the type of change in shape that is likely to improve spatial uniformity without sacrificing efficiency. This insight is valuable for both the illumination designer and for automated optimization. We present several examples where this method has been used.

We consider the case of a projector light engine using a LED as a light source. We want to use a lightpipe to efficiently couple the light emitted by the LED to a microdisplay and a projection lens. At the input, the lightpipe needs to collect the light emitted by the LED. At the output, the lightpipe must provide collimated and uniform illumination. In practice, the microdisplay can be either placed directly at the lightpipe output or the lightpipe output can be imaged onto the microdisplay. Two metrics are used to quantify the performance of these lightpipes. The *transmission efficiency* of the lightpipe is the percentage of light from the source exiting the lightpipe within a given NA. The transmission efficiency includes material absorption but does not include Fresnel losses at the input and output faces. With good antireflection coatings, Fresnel losses in the 1% to 2% range can be obtained. *Spatial nonuniformities* are measured as the relative standard deviation of illuminance at the lightpipe output. In our simulations, we used a mesh of 80×60 bins, and we traced 5 million rays. The corresponding statistical noise inherent to Monte Carlo ray tracing, given the quadrant symmetry, is about 1.5%.

Straight tapered rods were used as a starting point for our study. Straight tapered rods provide a good compromise between collimation and homogenization: Because of the taper angle, tapered rods can collimate light, and because of multiple bounces of rays inside the rod, they can homogenize the light. In contrast, most CPC-like devices attempt to collimate the light with only one bounce. To achieve a desired level of collimation with a straight tapered rod, the required length can be large [3]. Adding a lens at the output of a solid tapered rod can help overcome this drawback. Figure 1(a) shows an example of a 30 mm rectangular tapered rod with a lens made of PMMA. In this example, the LED is a Lambertian flat surface emitter with an emitting area of $2.1\,\text{mm}\times2.1\,\text{mm}$. A thin air gap is left between the LED and the input face of the lightpipe. The size of the output face of the lightpipe is $11.58\,\text{mm}\times8.68\,\text{mm}$. For this example, we consider an ideal projection lens with a NA of 0.2 ($f/2.5$), which corresponds to the minimum NA within which light can be collimated given the étendue of the source (étendue-limited case). We found an optimum radius of curvature of 14 mm for maximum transmission efficiency. To study the influence of a change in shape of the lightpipe, we model the profile shape with a rational Bezier curve. Only three control points are considered. The first and the third control points correspond to the position of the input and output face. The middle control point is used as a variable and is defined by its coordinates $y_{\rm rel}$ and $z_{\rm rel}$, where $z_{\rm rel}$ is the z coordinate of the control point relative to the length of the lightpipe, and $y_{\rm rel}=(y-y_{\rm in})/(y_{\rm out}-y_{\rm in})$, where $y_{\rm in}$ and $y_{\rm out}$ are the height of the input and output face, respectively. Figure 1 shows the general influence of the position of the con-

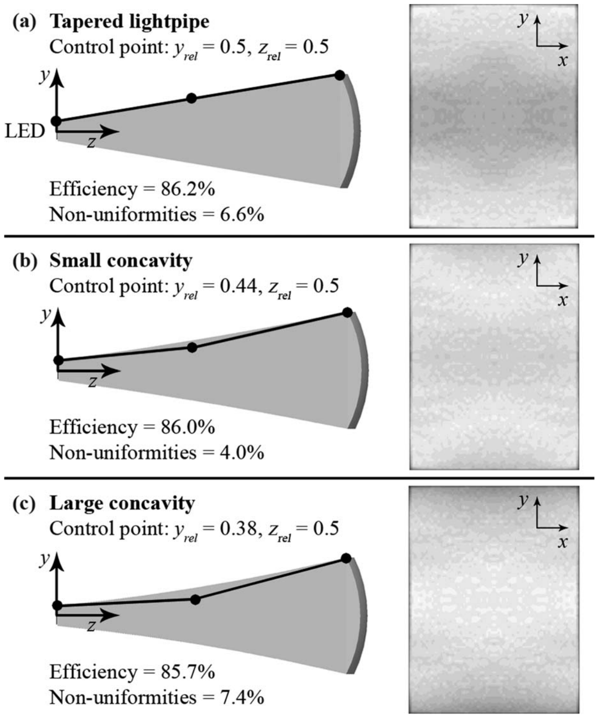

Fig. 1. Illuminance maps at the output of a 30 mm lightpipe for three different profile shapes. The change in shape is a means to spread out illuminance toward the center or the edges, without significantly changing the transmission efficiency.

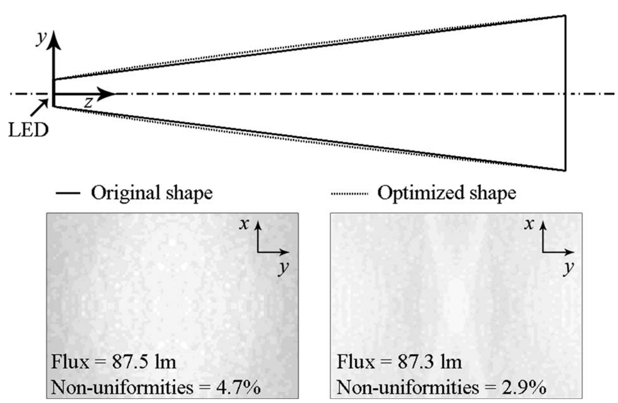

Fig. 2. 40 mm long solid tapered rod creates a peaked distribution in the center. By making the profile shape slightly convex, nonuniformities decrease by 38%.

trol point. In the straight taper case [Fig. 1(a)], a dip in illuminance is observed in the center of the distribution. The center falloff can be even more pronounced for larger aspect ratios. When the control point is moved downward, the lightpipe takes a concave shape and improved spatial uniformity is obtained [Fig. 1(b)]. As the concavity becomes more pronounced, we observe an excess illuminance in the center [Fig. 1(c)]. The opposite effect occurs when the control point is moved upward: The lightpipe takes a convex shape, and the illuminance dip in the center becomes more pronounced. In this example, the profile shape is changed along the y direction only, following the direction in which the illuminance variation for the straight taper occurs.

We see that spatial uniformity can be improved without sacrificing efficiency: Spatial nonuniformities decrease by 39.4%, while the total transmitted flux within NA=0.2 decreases by only 0.2%. Performance can be further improved by optimizing the position of the control point, in both y and z. The weight of the control point can also be used as an additional degree of freedom. In this example, we reached 3.3% nonuniformities without additional efficiency loss ($y_{\mathrm{rel}}=0.03$, $z_{\mathrm{rel}}=0.1$). In general, the optimum position of the control point is located close to the input face of the lightpipe. It is worth observing that a local change in shape close to the source has potentially more impact on the output illuminance map, as the input section of the lightpipe viewed from the source subtends a larger solid angle than the output section. The optimized lightpipe shape is similar to the dielectric totally internally reflecting concentrator (DTIRC) [4]. However, a direct comparison of the two devices is difficult, as the DTIRC is designed for rotationally symmetric configurations. The technique presented in this Letter is not restricted to "hyperbolic" shapes. When a dip in illuminance is observed in the center of the output distribution, increasing the concavity of the lightpipe helps in improving spatial uniformity. Conversely, a convex shape can "spread" a surplus of flux in the center of the output distribution. In the example in Fig. 2, we show a 40 mm tapered rod with a thin ideal Fresnel lens at the output end. The radius of curvature of the lens is 18.9 mm with a conic constant of −1; it was optimized for maximum transmission efficiency. In this case, the illuminance distribution shows a peak in the center. By making the shape more convex, the output illuminance uniformity is improved by 38%. The maximum deviation between the y coordinates of the original and optimized shape is 0.27 mm. Depending upon the configuration, the profile shape may be modified in both the x and y directions.

In the example shown in Fig. 3, we used an 18.6 mm hollow square CPC with an 8 mm × 8 mm output and a 2.1 mm × 2.1 mm Lambertian source at the input. The NA is set to 0.26 (f/1.9), which corresponds to the étendue-limited case. The original dis-

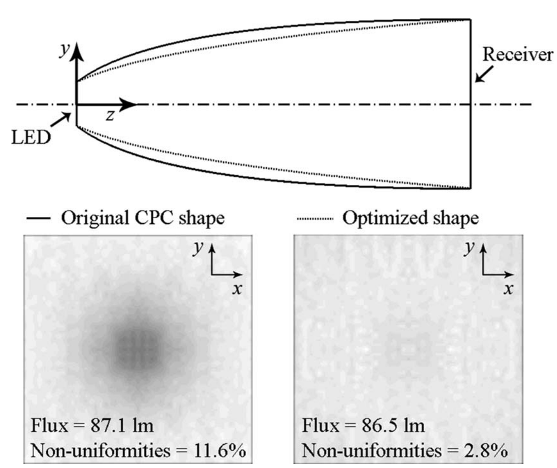

Fig. 3. 18.6 mm long hollow square CPC creates a dipped illuminance distribution. When concavity is decreased, nonuniformities decrease by 76%.

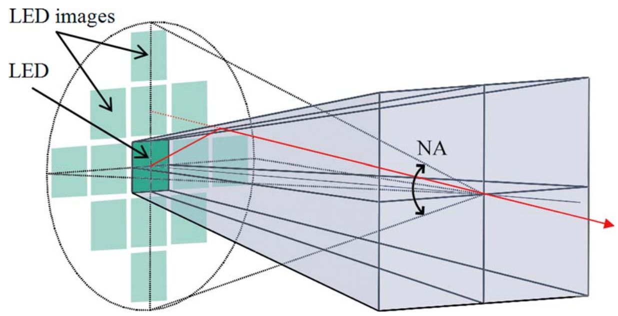

Fig. 4. (Color online) Pinhole camera images depict what is viewed from a given point within a given NA when looking through the lightpipe.

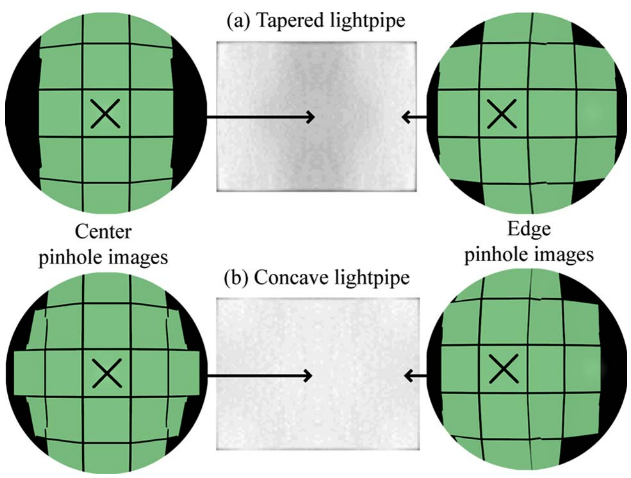

Fig. 5. (Color online) Pinhole camera images for a 30 mm lightpipe with a (a) straight taper and a (b) concave shape, taken respectively at the center and on the edge at the output face. The LED die location is indicated by an X. The other tiles are images of the LED created by the walls of the lightpipe. The concave shape creates additional images of the source at the center, thus increasing illuminance. The opposite effect is observed on the edge.

tribution has 11.6% nonuniformities and shows a dip in the center, with a transmission efficiency of 87.1%. By making the shape of the CPC less convex (the control point located at $z_{\mathrm{rel}}=0.2$ is moved from $y_{\mathrm{rel}}=1$ to $y_{\mathrm{rel}}=0.63$), nonuniformities decrease to 2.8%, while efficiency within a 0.26 NA decreases only to 86.5%. The maximum deviation between the y coordinate of the original and optimized shape is 0.55 mm. A fine tune of the shape using optimization can improve efficiency at the expense of uniformity, depending on the requirements of the application.

The spatial uniformity improvement owing to the change in shape can be understood by looking at the luminance map at the lightpipe output. At a given point on the output, we look through the lightpipe toward the source within the defined NA, as shown in Fig. 4. This shows what the source looks like when viewed through a pinhole at the lightpipe face. We call these luminance maps pinhole camera images. Examples of pinhole camera images are given in Fig. 5. The case of a straight tapered rod with an illuminance dip in the center is compared with the concave shape that provides optimum spatial uniformity. In these two cases, a pinhole image is provided at the center and the edge of the lightpipe, corresponding to locations where excess illuminance occurs with the straight tapered rod. These images show the source in the center and virtual images of the sources around it, as reflected by the walls of the lightpipe. The lightpipe shape affects the reflected images of the source. With the concave shape, more images of the source can be seen with the center pinhole camera position. The NA is more filled, therefore increasing the illuminance at this point. On the edge, the opposite phenomenon occurs: The images of the source are distorted by the concave shape so that the NA becomes less filled, thus decreasing the illuminance at this point.

It becomes increasingly difficult to optimize nonimaging systems when the number of variables is large because the solution space that the optimizer must explore also increases. Parameterization schemes that describe the geometry with fewer variables can enable faster optimization. The method outlined in this Letter allows a reduction in the solution space by giving a hint at where the shape for best uniformity is likely to be. This can quickly give insight into the problem. Given a parameterization using a quadratic rational Bezier curve, the y position of the control point is the most sensitive parameter affecting spatial uniformity. The z position and the weight of the control point have weaker influences on transmission efficiency and spatial uniformity, but they can also be used as fine tuning parameters.

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