Color patterns in a tapered lightpipe with RGB LEDs

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ABSTRACT

There is an enormous range of possible color distributions that may be created with a light cone when the primary source is an array of multicolor light-emitting diodes (LEDs). If one looks through a lightpipe toward an LED array, multiple images of the color LEDs can be observed as in a kaleidoscope. A tapered lightpipe behaves as a three-dimensional kaleidoscope, and then, by changing the position and orientation of the red-green-blue LEDs can produce a plenty of amazing illumination patterns. We analytically calculate this color spatial distribution of the illumination pattern produced by a tapered lightpipe. Moreover, we simulate these color illumination patterns, and analyze their structure and symmetry.

Key words: Multicolor, Lightpipe, Light-Emitting Diodes, LED array, color distribution.

1. INTRODUCTION

Lightpipes are very useful components in solid-state lighting, solar technology, and in other important fields [1-4]. They are optical transmission elements that utilize reflection to reduce light losses and to distribute the radiation. If one looks through a lightpipe toward the input, multiple images of the entrance can be observed as in a kaleidoscope. In a tapered lightpipe the input and output ends have different sizes, and then the multiple images lies over a three-dimensional surface (Fig. 1). This surface may be a sphere, torus, or cylinder depending on the proportion of the cross section of the tube [4]. If an array of multicolor LEDs is placed at the input, then a colorful illumination pattern may be produced at the output. In principle, by changing the position and orientation of the red-green-blue (RGB) LEDs, a plenty of different color patterns can be produced at the output.

We believe these unusual color patterns of tapered lightpipes would find applications, perhaps in human vision studies, maybe in imaging, lighting therapy, and most likely as visual toys. A tapered lightpipe could create amazing color patterns by modulating each color LED of the incorporated multicolor LED array. We illustrate some of these color

Fig 1. (a) Schematic that depicts what is viewed from the output of the lightpipe, and array of virtual images of the light source. (b) and (c) shows the three-dimensional locus of the virtual sources of a lightpipe with square and rectangular cross section.

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distributions with simulated color images, and we analyze some of their features. In this work we focus on lightpipes whose exit face is larger than the entrance aperture. We analytically calculate the color spatial distribution by using the radiometric theory of tapered lightpipes [4], and by using a color theory of LED arrays [5]. Moreover, we analyze the structure and symmetry of the color illumination patterns by changing the tube parameters and LED array configuration. The analysis of this work also is useful for color uniformity optimization, which is an important issue that must be addressed in SSL design [5].

2. COLOR PATTERN CALCULATION

Here we analytically calculate the color distribution at the output of a tapered lightpipe when the input source is a multicolor LED array. The output color distribution is the combined visual response to the output irradiance due to each color LED. In particular for the CIE 1931 \(xy\) chromaticity coordinates, the additive color mixing is a function of the relative irradiance contribution of each color LED. The color spatial pattern is calculated by the superposition of the light pattern of each color LED. And it can be determined by the spatial distribution \((x,y)\) of chromaticity coordinates \((x_o,y_o)\) over the lightpipe output. Note that \((x, y)\) are Cartesian coordinates, and \((x_o, y_o)\) are color coordinates. The chromaticity coordinates, when using a RGB LED array, are [5]

\[
x_o(x, y) = \frac{\bar{X}_R + \bar{X}_G \epsilon_{GR}(x, y) + \bar{X}_B \epsilon_{BR}(x, y)}{(\bar{X}_R + \bar{Y}_R + \bar{X}_R) + (\bar{X}_G + \bar{Y}_G + \bar{X}_G) \epsilon_{GR}(x, y) + (\bar{X}_B + \bar{Y}_B + \bar{X}_B) \epsilon_{BR}(x, y)},
\]

\[
y_o(x, y) = \frac{\bar{Y}_R + \bar{Y}_G \epsilon_{GR}(x, y) + \bar{Y}_B \epsilon_{BR}(x, y)}{(\bar{X}_R + \bar{Y}_R + \bar{X}_R) + (\bar{X}_G + \bar{Y}_G + \bar{X}_G) \epsilon_{GR}(x, y) + (\bar{X}_B + \bar{Y}_B + \bar{X}_B) \epsilon_{BR}(x, y)}.
\]

Here \(\bar{X}_i, \bar{Y}_i, \bar{Z}_i\) are the normalized tristimulus values for the each color LED, \(i=R,G,B\), given by

\[
\bar{X}_i = \int_{400nm}^{700nm} U_i(\lambda) \bar{x}(\lambda) d\lambda, \quad \bar{Y}_i = \int_{400nm}^{700nm} U_i(\lambda) \bar{y}(\lambda) d\lambda, \quad \bar{Z}_i = \int_{400nm}^{700nm} U_i(\lambda) \bar{z}(\lambda) d\lambda,
\]

where \(\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)\) are the color-matching functions. \(U_i(\lambda)\) is the normalized spectrum of each color LED (see Eq. (4) in reference [5]). The terms \(\epsilon_{BR}(x, y)\) and \(\epsilon_{GR}(x, y)\) are the relative irradiances of the blue and green light with respect to red light,

\[
\epsilon_{BR}(x, y) = \frac{E_B(x, y)}{E_R(x, y)}, \quad \text{and} \quad \epsilon_{GR}(x, y) = \frac{E_G(x, y)}{E_R(x, y)}.
\]

Here \(E_i(x, y)\) is the output irradiance of the tapered lightpipe for each color LED \((i=R,G,B)\) [4]. These irradiance distributions are the key to simulate the color patterns (see Section 3).

We display the color pattern by calculating the correlated color temperature (CCT) [5]. Because there is a broad CCT range for light from multicolor LEDs, we recommend using [5]:

\[
CCT(x, y) = \begin{cases} 
A_0 + \sum_{m=1}^{3} A_m \exp \left( \frac{-n(x, y)}{t_m} \right) & \text{if } CCT > 4000K \\
A_0 + \sum_{m=1}^{3} a_m [n(x, y)]^m & \text{if } CCT < 4000K
\end{cases}
\]

where \(A_0=949.86315, A_1=6253.80338, A_2=28.70599, A_3=0.92159, t_1=0.92159, t_2=0.20039\) and \(t_3=0.07125\) and \(a_0=5520.33, a_1=-6823.3, a_2=3525, a_3=-449\). Parameter \(n\) is given by:

\[
n(x, y) = \frac{x_o(x, y) - x_e}{y_o(x, y) - y_e},
\]
where \( x_e = 0.3320 \), and \( y_e = 0.1858 \) for \( \text{CCT} < 4000 \text{ K} \); \( x_e = 0.3366 \), and \( y_e = 0.1735 \) for \( 4000-50000 \text{ K} \); and \( x_e = 0.3356 \), and \( y_e = 0.17691 \) for \( 50000-800000 \text{ K} \).

3. ABOUT THE OUTPUT IRRADIANCE OF TAPERED LIGHTPIPES

The output irradiance (W/m\(^2\)) is the power distribution that illuminates the exit face of the lightpipe. To compute the output irradiance for each LED, we use an analytical approach [4]. It models the lightpipe as an array of light sources composed of real and virtual emitters. The virtual sources are the multiple images of the real source that can be observed if one looks through the lightpipe. In this way, the irradiance distribution \( E \) is the superposition of irradiances due to each real and image source, i.e. it is the sum of the irradiances due to the “sources” that are visible from the output:

\[
E = \sum E_{\text{sources}} + \sum E_{\text{images}}
\]

There is an equation of irradiance distribution for each one of the three basic tube geometries (Fig. 2): Square cross-section, rectangular cross-section, and when two walls are parallel.

The simplest case is for a lightpipe with only two tapered walls (Fig. 2a). As we explained in Ref. [4], a 3D tunnel construction shows that the array of images lies over a cylinder. For this tube geometry the irradiance pattern is very smooth, and is the simplest to calculate (see Eq. (7) in Ref. [4]).

If the shape of the input and output faces is squared (Fig 2b), the array of source images is a sphere. For this type of geometry the irradiance pattern is highly structured because a windows effect [4]. As an observer views the sphere of images through the lightpipe, each image can be seen only through a specific wall or through a group of virtual walls. The result is a set of windows allowing visualization of each image source rather than a virtual space freely showing all image sources. This leads to abstract irradiance patterns, which can be used to produce unique color patterns if a multicolor LED array is used as light source.

![Fig 2. Basic geometries of tapered lightpipes. (a) Two walls are parallel, (b) square cross-section, and (c) rectangular cross-section.](image)

4. COLOR PATTERN SIMULATIONS

In this section we present several simulations of the color patterns at the exit face of a tapered lightpipe. Several configurations of RGB LED arrays are considered. We use a simple RGB array with only three LEDs, i.e. the array is configured with one LED for each color. Each LED has a simple Lambertian radiation pattern. We set the same light flux for the three color LEDs.

We begin with the simplest case, a lightpipe with only two tapered walls (cylinder of images). The tube length is 4 in arbitrary units (a.u.), the input size is 3×3 a.u., and the output size is 3×6 a.u. We simulate the color pattern for four different RGB LED configurations (see Fig. 3). The CCT pattern is calculated for LEDs that emit light with peak...
wavelengths and half spectral widths (typical parameters of Luxon® emitters): \( \lambda_{\text{R}}=625\text{nm} \) and \( \Delta \lambda_{\text{R}}=20\text{nm} \) (red); \( \lambda_{\text{G}}=530\text{nm} \) and \( \Delta \lambda_{\text{G}}=35\text{nm} \) (green); and \( \lambda_{\text{B}}=470\text{nm} \) and \( \Delta \lambda_{\text{B}}=25\text{nm} \) (blue). For this tube geometry the color patterns are very smooth, without complex spatial structure.

Now let us consider a lightpipe with square-cross section (sphere of images). The tube length is 18 a.u., the input size is \( 3 \times 3 \) a.u., and the output size is \( 6 \times 6 \) a.u. We simulate the color pattern for three different RGB LED configurations (see Fig. 4). The CCT pattern is calculated for LEDs with the same spectral characteristics than in Fig. 3. The color pattern shows a complex structure. For this tube geometry the color patterns are highly structured because the windows effect [4]. Because this lightpipe is long, the color mixing is high and the color contrast is low. Color separation increases if the tube is not so long.

Figs. 5-8 show the color patterns of a short lightpipe with square-cross section. The tube length is 4 a.u., the input size is \( 3 \times 3 \) a.u., and the output size is \( 6 \times 6 \) a.u. In Figs. 7(right) and 8 the tube length is 5 a.u. The CCT pattern is calculated with the same LED characteristics than in previous figures. The color patterns show symmetric structures with high color separation and high color contrast.

The main organizing principle of these color patterns is the symmetry. The concept of symmetry conveys two meanings. One is the subjective sense of harmonious or aesthetically pleasing proportionality and balance. The other meaning follows from the concept of balance and similarity in a pattern that can be analyzed according to formal mathematical rules [6]. Symmetry may be observed in the time and space through geometric transformations such as scaling, reflection, and rotation. The color patterns in Figs. 4-8 show reflection and rotation symmetries. In its simplest form, its symmetry consists of a pair of radial bands that run perpendicular to each other from one corner to the other of the exit face of the lightpipe. In most cases, these bands display a star. Geometric structures of patterns for different LED array configurations are low correlated; this increases the variety of possible color patterns. Also, the variety of patterns can be dramatically increased if more primary colors are used instead of only RGB, for example an array of R-G-YG-B LEDs.

Fig 3. (Color Online) Color patterns of the simplest tapered lightpipe. It is a tube with two parallel walls, and does not show complex structure. Left side shows the configuration of the LED array shining at the input of the lightpipe. The color pattern is displayed in the center column. The right side shows the spatial distribution of correlated color temperatures.
Fig 4. (Color Online) Color patterns of a tapered lightpipe with square-cross section. Because this lightpipe is long, the color mixing is high and the color contrast is low. The color pattern shows an abstract structure.

Fig 5. (Color Online) Color patterns of a tapered lightpipe with square-cross section. Because this lightpipe is short, the color separation is high and the color contrast is high.
Fig 6. (Color Online) Color patterns of the tapered lightpipe of Fig. 5, but with different LED array configuration. If the tube length is a little changed, the color pattern changes (right).

Fig 7. (Color Online) Color patterns of the tapered lightpipe of Fig. 5, but with different LED array configuration. If the tube length is a little changed, the color pattern changes (right).
5. SUMMARY

We analyzed some of the many possible color distributions that may be created with a light cone when the primary source is a cluster of RGB LEDs. Because a tapered lightpipe behaves as a 3D kaleidoscope, by changing the position and orientation of the color LEDs can produce a plenty of amazing illumination patterns. We believe these unusual color patterns would find applications, perhaps in human vision studies, maybe in imaging, lighting therapy, and most likely as visual toys [7].

We analytically calculated these color spatial distributions, which was a practical tool for computer simulations. Several color patterns were simulated, and its structure and symmetry were analyzed. In analogy with kaleidoscopes, the variety of patterns could be dramatically increased if more primary colors are used instead of only RGB, for example an array of R-G-YG-B LEDs [8].

REFERENCES