Characterization of lightpipes for efficient transfer of light

R. John Koshel\textsuperscript{a} and Anurag Gupta\textsuperscript{b}

\textsuperscript{a}Lambda Research Corporation, Suite E2, 8230 East Broadway, Tucson, AZ 85710 and College of Optical Sciences, 1630 East University Blvd., University of Arizona, Tucson, AZ 85721

\textsuperscript{b}Hewlett Packard Company, 3571 SE Midvale Dr, Corvallis OR 97333-3143

\textcopyright{} 2005 Society of Photo-Optical Instrumentation Engineers. This paper will be published in the proceedings from the 2005 SPIE Optics and Photonics Meeting and is made available as an electronic preprint with permission of SPIE. One print or electronic copy may be made for personal use only. Systematic or multiple reproduction, distribution to multiple locations via electronic or other means, duplication of any material in this paper for a fee or for commercial purposes, or modification of the content of the paper are prohibited.

ABSTRACT

Lightpipes are used to transfer light from the source to a desired target. The lightpipe shape typically conforms to the necessary path, thus bending of the lightpipe is required. A number of different methods of bending the lightpipe have been developed, from linear, discontinuous bends to smooth, common circular bends to bends that expand or contract the cross-sectional size of the lightpipe over the path. In this paper we develop a set of parameters to describe the overall shape of an in-plane lightpipe section. These parameters include the thickness, radius of bend, index of refraction, and ratios of sets of these parameters. The transfer efficiency from the source to target is used to quantify the utility of parameterized lightpipes. Étendue is used to highlight the results. More complex lightpipes, such as those with several bends along their path, can be developed from the combination of parameterized sections. Finally, this parameterization can be used to automate the development of lightpipe geometry within optical analysis and design software.

Keywords: Lightpipe, illumination, light transfer, nonimaging optics, optical design, parameterization, étendue.

1. INTRODUCTION

Recently an increased amount of work in the area of lightpipe design has occurred. This work includes that of Gupta et al on the design of common-center, single bend lightpipes,\textsuperscript{1} the use of finite confinement diagrams,\textsuperscript{2} and angle-to-area conversion linear lightpipes.\textsuperscript{3} These references and the ones cited within them provide the current status of lightpipe design and theory. In this sense the lightpipe is defined as a “light conduit” that transfers light from the input port to the output port. Additionally, other characteristics of this lightpipe definition are:

- Made from a dielectric of index $n$ and surrounded by another material of index $n'$, such that $n > n'$,
- The lightpipe entrance aperture has a shape such that its thickness in two orthogonal directions are comparable, or in other words lightguides typical to the backlight display industry are not considered,
- No coatings are placed on the side walls of lightpipe so that total internal reflection is the property which transfers light from the input to the output, and
- The length of the lightpipe is greater than its cross-sectional width.

Note that these characteristics are specific to the “light conduit” pipe described herein. Other definitions for lightpipess can be developed. For example, consider the results of the SMS design process which develops hybrid optics that incorporate reflection, TIR, and refraction in a single design;\textsuperscript{4} and lightguides used for backlighting.\textsuperscript{5} Thus, the term lightpipe is broad, but herein it is only used to describe passive optical devices that transfer light from the input to the output.

Ref. [1] provides the initial treatment of determining the transfer efficiency from the input aperture to that of the output aperture for circular, single-bend lightpipes. The work is based on the principal section of the bend, which shows the cross-section of the bend. This section of the lightpipe provides the result that the bend ratio defines the base transfer efficiency for this lightpipe. The bend ratio for the common-center, single bend as shown in Fig. 1a is defined as,

$$R = \frac{r_2}{\eta},$$

\textsuperscript{*} john.koshel@osa.org; phone 1 520 721-3141; fax 1 520 721-5799; lambdares.com
where \( m \) was used for \( R \) in Ref. 1, \( r_2 \) is the outer bend radius, and \( r_1 \) is the inner bend radius. As the bend ratio is increased there is more leakage through the bend. A factor of Eq. (1) and the requirement of a common-center bend is that the defined lightpipe has a constant thickness. Ref. [2] continues with the treatment of the flux transfer efficiency from the input to the output. Finite confinement diagrams (FCDs) are phase space plots that show the spaces where the TIR condition through the lightpipe is met and where it is not obeyed. With this diagram and the inclusion of the input distribution to the lightpipe, one can quickly approximate the transfer efficiency of the lightpipe. The approximation is made by disregarding the Fresnel reflection component for any light incident at less than the critical angle. Thus, the light incident at these smaller angles is considered to leak completely from the lightpipe, while in reality there is a component that continues propagation due to the Fresnel reflection. Refs. [1] and [2] provide discussions about the uniformity of the output, but these discussions are limited in their depth. Ref. [3] provides details both about transfer efficiency and uniformity for linear lightpipes that introduce structure to the walls of the lightpipe. These lightpipes thus provide “twist” such that area-to-angle conversion is accomplished. Essentially, this design protocol addresses the skew invariant issue of optical design, or in other words, one has a limited transfer of flux from one cross-sectional distribution (e.g., circle) to that of another (e.g., square). The structure added to the sides of the lightpipes introduces a skew component to the trapped light, thus affecting this change. It should be noted that Ref. [3] is limited to linear lightpipes. The addition of a single bend makes the calculation of the uniformity quite complex, and is thus limited typically to software modeling via ray tracing.

In congruence with the earlier discussion of the definition of a lightpipe being one that is a “light conduit” from the input to the output, there are several ways to define such conduits. The common-center, single-bend one of Fig. 1a is only one such definition. However, consider those shown in Fig. 1b and Fig. 1c. Figure 1b shows a linear section, single-bend lightpipe that is presented in Ref. [2], while Fig. 1c shows a single-bend lightpipe with non-common centers. The question that often arises to new illumination-lightpipe designers is: what is the preferred definition for lightpipes? The answer is that there is no definition for the design of lightpipes, thus there remains a sizable amount of confusion about what is implied by lightpipe. Additionally, each definition leads to a different level of performance, such that the term “optimal” can be used for a number of different cases that perform the same function of light transfer from input to output. Of course, one can still make comparisons between the lightpipes as long as a standardized source is used for all models and the definition of transfer efficiency is consistent. All of these points mean that comparisons are unnecessarily difficult, are open to interpretation, confusing, and are prone to errors. The primary goal of this paper is to standardize the design, modeling, and comparison of lightpipes such that a true optimum for light transfer from the input to the output is found.
In the next section the setup for the lightpipe geometry is discussed for circular bends. Ultimately, the standardization of the design method will allow the parameterization for both linear and single-bend lightpipes, with the former being a special case when the bend center is located at infinity. In this paper only in-plane bends are considered, but out-of-plane bends is an extension of the design process. In the following section, a standard source model must be developed to allow comparison. Finally, upon successful parameterization of the lightpipe one can consider the incorporation of optimization and tolerancing algorithms. The former is presented in the Section 4 with the investigation of a spherical, single-bend lightpipe example. This paper ends with conclusions and a discussion of future work that can be performed.

2. LIGHTPIPE PARAMETRIZATION AND GEOMETRY

There are any number of methods to define a lightpipe, but we based our method on one typically mandated by design projects. For such projects, the allowed volume for the lightpipe is provided along with the desired location of the source and the target. At first this process appears counter to the design of efficient light transfer (and it often is!), but the inclusion of the optical system is often seen as a secondary goal for the overall system. The end result is that the designer must design the best system based upon the system constraints provided by the project management. Figure 2 shows a cross section of the allowed volume (i.e., the depth of the volume goes into the figure page) and the locations of the prescribed input and output. The designer must now choose the index of the lightpipe material, the entrance aperture width, the exit aperture width, the cross-sectional shape of the lightpipe, and the bend angle. These parameters and the ones prescribed are:

- Input aperture width = \( t_i \),
- Output aperture width = \( t_o \),
- Lightpipe region width = \( w \),
- Lightpipe region length = \( l \),
- Lightpipe region depth = \( d \),
- Lightpipe index = \( n \), and
- Lightpipe bend angle = \( \theta_B \).

![Figure 2: Geometry setup for the definition of a single-bend lightpipe.](image-url)
For parameters external to the lightpipe, a prime (‘) is used to denote the term. For example, the exterior index of refraction is given by $n'$. For parameters associated to the inner bend a subscript of one (1) is used and for those associated to the outer bend a subscript of two (2) is used. For the geometry definition the origin is located at the center of the lightpipe input aperture. The input is defined to lie at the lower, left-hand corner of the allowed volume, while the output is almost always located at the upper, right-hand corner of this volume. In all cases such a configuration can be enforced by truncation and rotation of the allowed volume.

Next, the input and output apertures are projected into the allowed volumes, which provides the inner and outer bend points, $B_1$ and $B_2$ respectively. These two points define the start of locus curves upon which the centers of the respective bends must be located. By mandating that bend centers must lay on these locus curves, it dictates there is no possible undercut of either the input and output legs of the single-bend lightpipe. Undercut implies that the thickness of the lightpipe decreases along linear sections of the input and output legs. Undercut leads to, at a minimum, difficult manufacture; therefore, lightpipes with undercut are not allowed in this study. Any study that would focus on them would likely be theoretical in nature since the likelihood of manufacture is limited. Figure 3 depicts the inner bend locus curve. The outer bend locus curve is analogous.

It is found that there are four regions defined by this geometry. The four regions are:

- **Region 4**: The locus curve from point $B_1$ to $A_1$. $B_1$ is the inner bend point while $A_1$ is the first point on the locus curve that intersects either with the input or output planes. In Fig. 3 $A_1$ is the intersection with the input plane. It will be shown that the locus curve in this region is linear.

- **Region 2**: The locus curve from point $A_1$ to $C_1$. $A_1$ is the point defined by Region 4, while $C_1$ is the second intercept either with the input or output planes. In Fig. 3, $C_1$ is the intersection with the output plane. It will be shown that the locus curve in this region is parabolic.

- **Region 3**: Analogous to Region 2, except the geometry shown in Fig. 3 is reversed such that the locus curve first intercepts with the output plane (defining $A_1$), and then intersects with the input plane (defining $C_1$).

- **Region 1**: The locus curve from point $C_1$ to infinity. $C_1$ is the point defined by Regions 2 or 3. It will be shown that the locus curve in this region is linear.

Any lightpipe bend has up to three regions along its locus curve. First, lightpipe bends with only two regions, 1 and 4, occur when...
Next, for lightpipe bends with three regions:

\[
\begin{align*}
\begin{cases}
    a_1 > c_1 & \text{Inner bend} \\
    a_2 > c_2 & \text{Outer bend}
\end{cases}
\end{align*}
\]  \tag{3}

there are Regions 1, 3, and 4. Analogously, for the case with Regions 1, 2, and 4:

\[
\begin{align*}
\begin{cases}
    a_1 < c_1 & \text{Inner bend} \\
    a_2 < c_2 & \text{Outer bend}
\end{cases}
\end{align*}
\]  \tag{4}

Note that there can be a lightpipe for which the inner and outer bends have differing locus bend types. The example shown in Fig. 3 has both bends such that they obey Eq. (4), so Region 3 is not present. The reasoning for defining the regions seemingly in reverse is due to the desired naming convention. A locus curve that obeys a given protocol defined in Eqs. (2) – (4), is described as “Type $N$ locus”, where $N$ is either 1, 2, or 3. Extending this argument, selection of a bend radius that locates the center of the bend to one of the prescribed $M$ regions ($M = [1..4]$) is described as a “Type $M$ bend”. Thus, for example, one can have a Type 4 bend of a Type 2 locus lightpipe bend.

In the next three sections we provide the development for Regions 1, 2, and 4 for the inner bend. Region 3 is analogous to Region 2, but the point $O_1$ is substituted for that of $I_1$. The outer bend development is analogous to the treatment provided for the inner bend.

### 2.1 Region 1 bend

Figure 4 shows the geometry specific to Region 1. Due to the demand for no undercut and the geometry developed in the previous section, both $I_1$ and $O_1$ must lie on the bend curve. Only with a bend center located at $C_1$ will this spherical curve be tangent to one of the aperture points ($O_1$ as shown in Fig. 4). At other points along the locus curve the circular bend will not be tangent to the two aperture points. Next, to find the locus curve for Region 1, consider the line segment that joins $I_1$ and $O_1$. The locus curve must bisect this
line segment, starting at point \( C \) in the prescribed geometry. Additionally, as one goes to infinity along this locus curve, it must remain linear. This result ensures that the radius of the circular bend, labeled as \( r_1 \), is equal from the point \( P_1 = (0, y', z') \) to both \( I_1 \) and \( O_1 \). The steps to finding \( P_1 \) as a function of the desired radius of the bend are:

1. The distance between points \( I_1 \) and \( O_1 \) is:
   \[
   q_1 = I_1O_1 = \sqrt{(y'_{O1} - y_{I1})^2 + z_{O1}^2} .
   \]  
   (5)

2. The intersection between the locus line projected from Region 4 intersects this line segment at:
   \[
   \left(0, \frac{y_{O1} - y_{I1}}{2}, \frac{z_{O1}}{2}\right) .
   \]  
   (6)

3. The distance along this projection line is given by:
   \[
   s_1 = \sqrt{q_1^2 - q^2} / 4 .
   \]  
   (7)

4. Using Eqs. (5) – (7), we find the Cartesian coordinates for the center of the circular bend, \( P_1 \):
   \[
   \begin{cases}
   y' = \frac{y_{O1} + y_{I1}}{2} + \frac{s_1}{q_1} y' \\
   z' = \frac{z_{O1}}{2} + \left(y_{I1} - y_{O1}\right) \frac{s_1}{q_1} .
   \end{cases}
   \]  
   (8)

2.2 Region 2 bend

Figure 5 shows the geometry specific to Region 2. For a circular bend in this region, point \( I_1 \) and \( a \) to be determined one along the output leg from \( O_1 \) to the intersection of the projection from \( A_1 \) parallel to the output plane must lie on the bend. For the example shown this latter point is labeled as \( D_1 = (0, y, z) \). First, we know that the distance from the point on the locus curve to the respective points on the input and output arms, \( r_1 = P_1I_1 = P_1D_1 \). Second, for all points along the locus curve from \( A_1 \) to \( C_1 \), \( I_1 \) must lie on the circular bend. Third, the circular bend is tangent to the output arm at its intersection point. The latter two points indicate that the point \( I_1 \) is the focus of a conic and that \( B_1O_1 \) is the directrix for this conic. Finally, the equal distances to these two conic descriptors indicates that the conic is a parabola. This parabola is rotated by the bend angle \( \theta_B \). The steps to finding \( P_1 \) as a function of the desired radius \( r_1 \) are:

1. The coordinate system is rotated by \( \theta_B \), denoted by the twiddle (~):
   \[
   \begin{cases}
   \tilde{y} = -z \sin \theta_B + y \cos \theta_B \\
   \tilde{z} = z \cos \theta_B + y \sin \theta_B .
   \end{cases}
   \]  
   (9)

2. The equation for the line joining \( B_1 \) to \( O_1 \) is:
   \[
   y_{dir} = z \tan \theta_B + b \quad \text{where}
   \]
   \[
   b = w - \frac{t_i}{2} - \left(t_i - t_o \sin \theta_B\right) \tan \theta_B .
   \]  
   (10)

3. In the rotated coordinates of Eq. (9), Eq. (10) becomes:
\[
\tilde{y}_{dir} = \left[w - \frac{t_i}{2} - (l - t_o \sin \theta_B) \tan \theta_B\right] \cos \theta_B,
\]
(11)

which is constant for all \( \tilde{z} \).

4. Using the geometry of Fig. 5, the coordinates of the point \( P_1 \) in the rotated reference are:

\[
\begin{align*}
\tilde{y}' &= r_1 + \tilde{y}_{dir} \\
\tilde{z}' &= y_{11} \sin \theta_B + \sqrt{r_1^2 - (r_1 + \tilde{y}_{dir} - y_{11} \cos \theta_B)^2}.
\end{align*}
\]
(12)

5. Rotate back to the original coordinates:

\[
\begin{align*}
y' &= \tilde{y}' \cos \theta_B + \tilde{z}' \sin \theta_B \\
z' &= -\tilde{y}' \sin \theta_B + \tilde{z}' \cos \theta_B.
\end{align*}
\]
(13)

Thus, using Eqs. (11) – (13) one can find the circular bend of radius \( r_1 \) that defines the desired inner bend. All other terms are constants, including \( \theta_B, t_i, \) and \( t_o \).

Figure 5. Lightpipe geometry for Region 2.

Figure 6. Lightpipe geometry for Region 4.
2.3 Region 4 bend

Figure 6 shows the geometry specific to Region 4. For a circular bend in this region, one point each on the input and output legs must lay on the circular bend. Additionally, due to the requirement for no undercut, the bend is tangent to the output and input legs at these two points. The locus curve bisects the angle between the input and output legs. The bisected angle is denoted as $\phi$. Because the locus curve must be equidistant from the two legs for a given bend center, the locus curve must be linear at this angle $\phi$ from $B_1$ to $A_1$. The steps to finding $P_1$ are:

1. The bisected angle is given by:
   \[ \phi = \frac{\pi - \theta_B}{2}. \]  

2. The inner bend point is given by:
   \[ \begin{align*}
   y_{B1} &= y_{H1} \\
   z_{B1} &= l - (w - t_i)\cot \theta_B - t_o \sin \theta_B.
   \end{align*} \]  

3. The coordinates for $P_1$ are found with the use of $\Delta P_1 B_1 F_1$:
   \[ \begin{align*}
   y' &= y + r_1 \\
   z' &= z + z_{B1} - \frac{r_1}{\tan \phi} = z_{B1} - r_1 \tan \left(\frac{\theta_B}{2}\right).
   \end{align*} \]

3. DEFINITION OF STANDARD LAMBERTIAN TRANSMISSION

In order to make effective comparisons of arbitrary lightpipes, a standard source and detector is required. The lightpipe references contained herein have used various source definitions to compare lightpipe performance, such that easy comparisons cannot be made. An effective solution is to use a Lambertian source and detector that span the input and output apertures respectively. In the next two subsections the source and detector are defined.

3.1 Standard Lambertian source

A Lambertian source is defined to fill the entrance aperture of the lightpipe as shown in Fig. 7. The characteristics of this source are:

- Lambertian emission from the surface closest to the entrance aperture of the lightpipe,
- The source is parallel to the entrance aperture of the lightpipe with a gap of 1E-5 mm between the two objects,
- The shape of the emitter is that of the entrance aperture of the lightpipe, but it 0.01% smaller than it.

3.2 Standard absorbing detector

A perfectly absorbing detector is defined to fill the exit aperture of the lightpipe as shown in Fig. 7. The characteristics of the detector are:

- Perfect absorption on the surface closest to the exit aperture of the lightpipe,
• The detector is parallel to the exit aperture of the lightpipe with a gap of 1E-5 mm between the two objects,
• The shape of the absorber is that of the exit aperture of the lightpipe, but it 0.01% larger than it.

3.3 Standard absorbing detector
Using the above definitions for the source and detector, the transfer efficiency from the source to detector is found. This transfer efficiency is called the Standard Lambertian Transmission (SLT), and it is defined as

$$\eta_{SLT} = \frac{P_{det}}{P_{src}}.$$  \hfill (17)

This definition, often simply called the SLT, is used for the remainder of this study.

4. TRANSFER EFFICIENCY OF SINGLE-BEND LIGHTPIPE

Using the definitions provided in the previous two sections, we investigate a lightpipe case with the following parameters:

• \( t_i = t_o = 10 \text{ mm}, \)
• \( \theta_B = 90^\circ, \)
• \( l = 50 \text{ mm}, \)
• \( w = 60 \text{ mm}, \)
• \( n = \text{Acrylic at 0.55 } \mu\text{m}, \)
• \( n' = 1.0 \text{ (Air)}, \)
• Bare surfaces: Fresnel loss, and
• Cross-sectional shape is circular.

With the above selections, we have a Type 2 locus curve. We now determine the SLT for this system with bend radii in the range of \( r_1 = [0..40] \text{ mm and } r_2 = [10..50] \text{ mm}. \) However, we use four (4) distinct lightpipe cases within this allowed lightpipe volume to illustrate the effects of the radii on the SLT. These four cases are shown in Fig. 8, and the data for the radii are shown in Table 1.

![Figure 8: Geometries for four cases to be highlighted during the determination of the SLT.](image)

<table>
<thead>
<tr>
<th>Case</th>
<th>( r_1 ) (mm)</th>
<th>( r_2 ) (mm)</th>
<th>Description</th>
<th>SLT (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td>0</td>
<td>10</td>
<td>Common bend from inner corner</td>
<td>29.8</td>
</tr>
<tr>
<td>(b)</td>
<td>15</td>
<td>20</td>
<td>Non-common bend widens lightpipe in bend</td>
<td>61.6</td>
</tr>
<tr>
<td>(c)</td>
<td>40</td>
<td>50</td>
<td>Common bend makes most effective use of volume</td>
<td>80.2</td>
</tr>
<tr>
<td>(d)</td>
<td>30</td>
<td>50</td>
<td>Non-common bend thins lightpipe in bend</td>
<td>59.7</td>
</tr>
</tbody>
</table>

Table 1: Radii, description, and SLT for the four cases shown in Fig. 8.
For cases (a) and (c) the lightpipes retain constant thickness, so étendue losses should be at a minimum; however, due to the bend ratio being large for the first case it is expected that the SLT is poor. For case (b) the pipe thickness increases through the bend. This widening assists in transfer efficiency due to étendue considerations, but the bend ratio is high such that it is expected to reduce the gains seen by étendue. Finally, case (d) shows a thinned lightpipe, which is adversely affected by étendue losses that are expected to be compensated by the low bend ratio.

4.1 Étendue considerations

As discussed in the previous section there is competition between étendue considerations and agreement to the TIR condition mandated by the lightpipe design. The latter is borne out by the bend ratio, such that an increased bend ratio value has been shown by Ref. [1] to lead to higher leakage. To illustrate the effect of étendue while reducing the effect of the bend ratio design considerations, a flared lightpipe is studied. Figure 9 shows two cases to study this effect:

- Case 1: source located at the large aperture and the detector located at the small aperture and
- Case 2: source located at the small aperture and the detector located at the large aperture.

Figure 9 shows the SLT results for varying numbers of rays traced from the source. Note the difference in the results due to the nominal direction of propagation within the lightpipe. Case 1 with the large input and small output performs poorly in comparison to the second case. This loss in SLT is attributed to étendue, since as the cross-sectional area is reduced the angular range of the trapped light is increased resulting in frustration of the TIR condition. Figure 10 also shows that the SLT is determined with a limited number of rays: 100 rays essentially computes the same SLT as 10,000 rays. However, one should error on the side of caution and trace more rays than are required to alleviate any concern of obtaining an unrepresentative result.

4.2 Case study

Finally, we test the allowed lightpipe volume as presented in Section 4. All cases are studied with radii sampling of 1 mm for both \( r_1 \) and \( r_2 \). For modeling purposes, 25,000 rays are traced within TracePro® for each case. Figure 11 shows the SLT results for this study with the horizontal axis being \( r_2 \) and the vertical axis being \( r_1 \). The SLT results for the four
cases presented previously are reported in Table 1. As expected the competition between the bend ratio and étendue provide an optimal outer radius for a given inner radius. The dotted curve in Fig. 11 represents this optimal curve. The dashed curve that goes from the lower left-hand corner to the upper right-hand corner represents the cases with a common bend center. Note that the optimal curve lies to the right of common-center curve for small inner radii, but to the left of this same curve as \( r_1 \) is increased. This result further illustrates the competition between the bend ratio and the étendue in order to increase SLT.

![SLT Results for Over the Allowed Lightpipe Volume](image)

Figure 11: SLT results for over the allowed lightpipe volume. The dashed line indicates the cases with a common bend center, while the dotted line indicates the maximum SLT for a given \( r_1 \) bend radius.

5. CONCLUSIONS AND FUTURE WORK

In conclusion a standard for the definition of the parameterization of lightpipes has been established. While this common definition may not be the best, it does provide a basis to discuss and compare different lightpipe geometries. We encourage others to refine the standard provided herein, or, alternatively, provide other definitions. Second, this standard allows the development and modeling of lightpipes in a simpler manner than previously available. The parameterization allows the implementation of optimization and tolerancing, which are required tools as the demand for illumination optics increases. Fourth, automation of lightpipe design is realizable, and, in fact, complex lightpipes comprised of several principal sections can be done.

Specifically, the SLT results of Section 4.2 show:

- Competition: between étendue and bend ratio condition,
- Higher SLT: small radii and higher bend ratio than common center bend (thinned lightpipes),
• Higher SLT: large radii and lower bend ratio than common center bend (broadened lightpipes)
• Peak SLT: near the common bend center cases, and
• SLT Increases: as \( r_1 \) and \( r_2 \) increase.

This study raises the need for much additional work in the area of lightpipe standardization, parameterization, modeling, and so forth. The potential topics of study include:

• More theoretical work required to contend with:
  o Skew bends,
  o Linear lightpipes: wedges and cones,
  o Non-common center bends,
  o Varying thickness bends, and
  o Different bend shapes: other conics, NURBS, etc.
• More integration into optical analysis and design software:
  o Better automation,
  o Overlap issues, and
  o Multiple elements for complex lightpipes.
• Connect to FCDs of Ref. [2] and their analogies

As can be seen the topic of lightpipe design and modeling is within its infancy stages, and further work should provide the tools required for integration into commercial optical design and analysis codes.

REFERENCES


