Simplifying the lightpipe design process

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Approaches that simplify the lightpipe design process will enable the widespread use of lightpipes in displays, dashboards, lighting, and light homogenizers.

Lightpipes are simple devices that transfer light, but not images. The light travels via total internal reflection along the inner surface of a solid body made from an optical-quality highly-transmissive material. Lightpipes are used in a variety of displays such as automotive dashboards and instrument panels, in lighting applications such as pools and backlights, and as light homogenizers.1 Because of the tremendous flexibility in lightpipe geometry, illumination transfer can be tightly controlled in terms of output distribution and light channeling. So far, however, very little is known about how to ease the design of such systems. We are seeking principles that simplify calculations of flux distribution across lightpipe geometry and rules to determine layout. This will make the lightpipe design process considerably easier, enabling their widespread use in many fields.

Currently, lightpipes are designed by performing Monte Carlo ray tracing on a number of trial geometries. Although this method is excellent for designing imaging systems, it is very slow at analyzing flux across the lightpipe and selecting an adequate layout. Nor does it allow for a systematic design approach towards a desired lightpipe layout and performance in a constrained space.

To simplify the design process, we believe, there are three key analytical problems to be solved. First, we must be able to lay out the lightpipe geometry in a constrained space that takes manufacturing considerations into account. Then we need to calculate the flux-transfer efficiency across a complicated light geometry. This includes checking for the possibility of a leak-free implementation, as well as locating and quantifying any leakage. Finally, we must calculate the light distribution (spatial and angular) at the lightpipe output as a function of known input.

Solving these problems will enable us to describe lightpipe performance in terms of parameters such as the refractive index, thickness, cross-section shape and size, bend radii or a description of bend curves. This will enable a faster design process via easy access to engineering trade-off variables.

We recently demonstrated a method of parameterizing the design of a single-bend lightpipe to enable designs that avoid any undercut. Undercut means that the thickness of the lightpipe decreases along linear sections of the input and output legs and leads to, at a minimum, difficult manufacture. Relevant parameters included the lightpipe region volume, the dimensions of the input/output apertures, the bend angle and the refractive index.2 The locus of the curves along which the center of inner and outer bend of the lightpipe lay have been determined. The locus curve equations can be integrated in optical CAD software to ‘draw’ lightpipes in a given space that take care of the undercut problem. It is now possible to automate the design process via bend locus parameters to evaluate the transfer efficiencies of various bends. Figure 1 shows the results.

Earlier, we described a method to simplify the design of leakage-free multiple-bend lightpipes by showing that it is suf-
cient to analyze the light rays in the principle—symmetric—
sections of a lightpipe. This result was used to show that the
refractive index and ratio of bend radii are the only dimension-
less parameters to determine the maximum acceptance angle for
a constant-cross-section right circular bend. Recently it has been
shown—by analyzing the light in the principle section of the
bend—that using a spiral curve instead of a circular curve for the
bend enables a 180° acceptance angle. Another positive develop-
ment in this direction has been made by the introduction of flux
confinement diagrams to quantify leakage across a bend. Oth-
ers have recently provided theoretical insight on how to contend
with the skew invariance by integrating surface features such as
ripples and twisting.

The knowledge of parametric equations that govern the flux
propagation will help in quantifying lightpipe performance on
the fly during the layout process, without the need for expen-
sive ray traces. A collection of such methods to analytically de-
termine the flux propagation through a lightpipe, and rules to
determine possible layouts in a constrained space will simplify
the lightpipe design, will ultimately lead to an automated design
process.

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