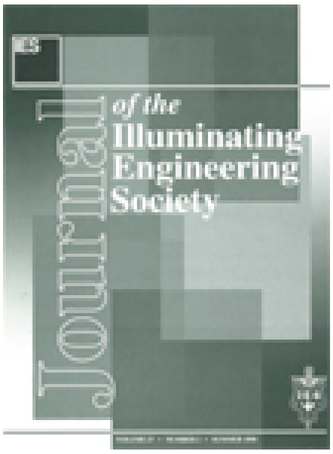

Journal of the Illuminating Engineering Society
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/uzie20

New Simplified Design Procedures for Prism Light Guide Luminaires

Lorne A. Whitehead[a]
[a] Department of Physics, and Astronomy, University of British Columbia, Vancouver, BC, Canada
Published online: 19 Sep 2013.

New Simplified Design Procedures for Prism Light Guide Luminaires

Lorne A. Whitehead

A prism light guide luminaire is an illumination system in which light from a localized source is guided and emitted along the length of a prism light guide. Such devices are made in a wide variety of sizes and shapes, and can exhibit a large range of photometric characteristics. There are several standard ways to predict the resultant photometric performance of prism light guide luminaires, such as photometric testing of optical mock-ups, or Monte Carlo ray tracing. These methods work well, but require considerable effort, and they do not provide much guidance in creating an initial design for testing. Persons new to the field may find it particularly difficult to devise an initial design as a starting point for subsequent investigation.

In view of this problem, the purpose of this paper is to provide a simple, widely applicable procedure for making an initial design for a prism light guide luminaire. The intention is that the resultant design should be a good starting point for developing an optimized design, and should be sufficiently close to the fully optimized design that it will be useful in initially establishing the feasibility of a proposed light guide luminaire for a proposed application.

The paper begins by reviewing the concept of prism light guide luminaires and characterizing the design problem. Several useful approximations are then presented which make the problem amenable to analytic solution, yielding useful design relationships. Two examples are then provided which show the role of these relationships in devising actual prism light guide luminaire designs.

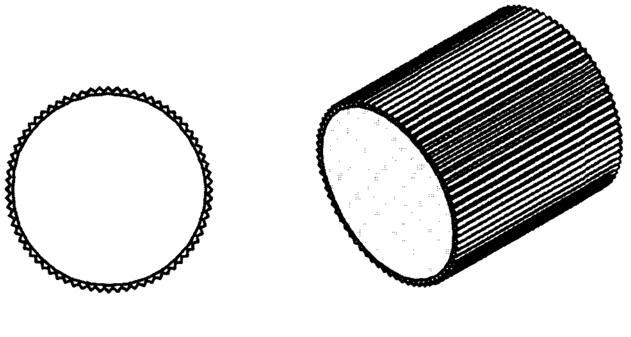

Figure 1— Prism light guide cross section and isometric view.

Author's affiliation: Department of Physics, and Astronomy, University of British Columbia, Vancouver, BC, Canada

Background

Prism light guide luminaires are based on the principal of the prism light guide,[1,2] a simple version of which is shown in **Figure 1**. In essence, the prism light guide is a hollow pipe made of transparent material in which one or more of the surfaces of the pipe contain longitudinal prisms which cause the light in the inner air space to be reflected by total internal reflection at the outside surfaces of the guide walls such that they are returned to the inner air space for further propagation. In most prism light guides the inner surface of the guide is smooth, and the cross sectional shape of the prisms running on the outside parallel to the guide axis is that of an isosceles right angle triangle. Generally such guides are formed of a flexible prismatic sheet,[3] and the guide itself is housed within a protective outer structure to keep it clean and to prevent abrasion of the optical quality surfaces.

Prism light guides can be made with a wide variety of cross section sizes and shapes, all of which can efficiently guide incident light rays whose angular deviation, θ, from the guide axis is less than a value θ_c, where θ_c depends on the refractive index n, of the pipe material, in the following manner:

$$\theta_c = \arcsin\sqrt{(3 - 2\sqrt{2})(n^2 - 1)} \qquad (1)$$

The basic idea of a prism light guide luminaire[4,5] is to collimate the light from a lamp such that most of the emitted rays lie within the acceptance angle of a prism light guide, to then direct this light into a prism light guide so that it is guided along the length of the guide, and to introduce into the guide some kind of escape mechanism[6] which causes the light to be emitted from the guide fairly evenly along its length. The device that sends partially collimated light into the prism light guide is known as the light injector[7] and the mechanism that causes such light to escape is known as the light extractor.[7]

The light extractor often consists of a light scattering material which deflects light rays to directions outside the angular transport range for the guide. The key to achieving a relatively uniform output is to have the density of the extraction material increase with distance from the source, in order to compensate for the decreasing light intensity caused by the induced escape. In essence we want the product of the extraction rate and luminous flux in the guide to remain constant, which is a difficult non-linear design problem.

In addition to this general concept, there are other constraints which affect overall design. First, it is generally desired to achieve a certain luminance, luminous exitance, or luminous flux per unit length from the guide. Next there are constraints on the guide length. If the guide is too short, it serves no useful purpose relative to conventional lighting methods. If it is too long, it is impossible to achieve sufficient uniformity. Additionally, there are usually other constraints regarding available sources and other allowable dimensions. What we seek is a general method of dealing with all these factors, to select the number and types of lamps to use, the dimensions for the guide, and to work out approximately how the amount of extractor should increase with length.

General characterization of the prism light guide luminaire design problem

Figure 2 is a pictorial representation of a general prism light guide luminaire. In this case the light injector is a reflector lamp, but it could equally well be a non-reflector lamp mounted in a separate reflector. The characteristics of the light injector can usually be adequately summarized by two numbers, Φin, the luminous flux directed into the prism light guide by the light injector, and $\theta_{1/2}$, the off axis angle at which the luminous intensity of the lamp output has dropped to one half of its value in the axial direction. In the case of reflector lamps, these values are the two most commonly stated values in the lamp catalogues. For injectors with discrete reflectors, it may be necessary to measure or estimate these values, but generally this is not difficult.

As shown, the prism light guide has an arbitrary cross section shape, and a specified length, L. A portion of the cover of the light guide is generally composed of opaque, reflective material which causes light to leave from the selected escape region having width W_e. The area, A, of this region should be at least 25 percent of the overall guide surface area, to allow efficient escape of light. As depicted in the figure, the cross sectional shape of the guide is not critical. The key defining feature of the cross section is the minimum cross section width, labeled W_g. In a circular guide this is the diameter. In an elliptical guide, it is the minor axis, and in a rectangular guide, it is the smaller edge length.

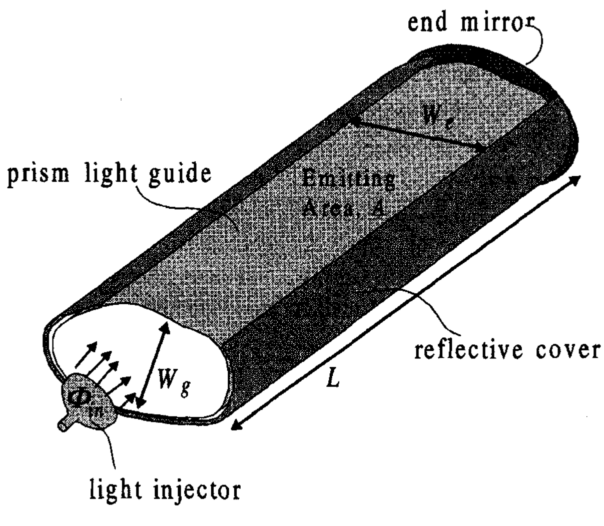

Figure 2— Prism light guide luminaire.

The ratio of the length L, to the minimum cross sectional width, W_g, is known as the aspect ratio, AR:

$$AR = \frac{L}{W_g} \tag{2}$$

A common error in making general statements about prism light guides is to try to characterize them by their length, L, or their aspect ratio, AR. Neither of these are useful in the sense that light guide systems having similar lengths or aspect ratios can behave very differently. Fortunately, there is a simple non-dimensional value that is useful for characterization, which we believe is introduced in the literature here for the first time. This parameter, N_g, is the approximate number of times an average light ray would reflect off the wall of the prism light guide in traveling from the light injector to the opposite end in the absence of any extraction. This is a useful parameter because it relates directly to the role of the prism light guide wall material in efficiently reflecting light. Roughly speaking if N is smaller than about 3, a prism light guide is not needed because conventional reflective materials could guide the light reasonably well, and if N is greater than 30, the intrinsic loss per reflection of even the best prism light guide films would cause prohibitive loss of light. However, if N is between roughly 3 and 30, the prism light guide is the best solution.

The precise value of N_g is rather difficult to work out, but for the purposes of this paper a suitable estimate is provided by the following formula:

$$N_g \cong \frac{\theta_{1/2}}{50} \frac{L}{W_g} \tag{3}$$

where $\theta_{1/2}$ is measured in degrees. The value of N_g is of central importance in the rest of this paper, but fortunately none of the results depend critically on this value, so that it is not unreasonable to use this simple estimate. A more accurate measure of N_g would be obtained by determining the average tangent of the off axis angle of the light distribution ($\theta_{1/2}/50$ is an estimate of this), then multiplying by the average inverse cross sectional width ($1/W_g$ is an estimate of this) and multiplying by the length. Our experience is that the estimate represented in **Equation 3** is quite adequate for practical light guides.

As already mentioned, the key to achieving uniform light emission is to have the correct amount of light extractor as a function of length. The light extractor can take a variety of forms, the most common of which involves the application of a diffusing sheet on a portion of the interior of the non-emitting portion of the prism light guide. The extractor may consist of various materials, and can even be incorporated into the prism light guide film. It can consist of one strip, or multiple strips or patches.

Figure 3 shows a general way of specifying the magnitude of the extractor as a function of length. We introduce here a non-dimensional length fraction, x, which is defined to be the fraction of the distance from the light injector to the end of the guide. In some cases the light injector will direct light in two directions from the center of a length of a prism light guide, in which case x is 0 at the injector and it is 1 at either end. In other cases a single length of a prism light guide will have a light injector at each end. In this case, x is 0 at the injector and is 1 at the center. In all cases, x represents the fraction of the total distance the light must travel in the prism light guide.

We also introduce a non-dimensional extractor magnitude, $E(x)$, which is equal to the width of the extractor at a given point divided by the perimeter length of the rear half of the guide. In other words, $E(x)=1$ when the entire rear half of the guide is covered with scattering material. In the case where the prism light guide has a wide rectangular cross section, as is often the case in signs, $E(x)=1$ corresponds to the entire back of the sign being covered. In a circular guide, this would represent the rear 180 degrees of the guide being covered. Generally, $E(x)$ should vary between 0 and 1.

With these definitions, we can now work out the extractor profile in completely general terms.

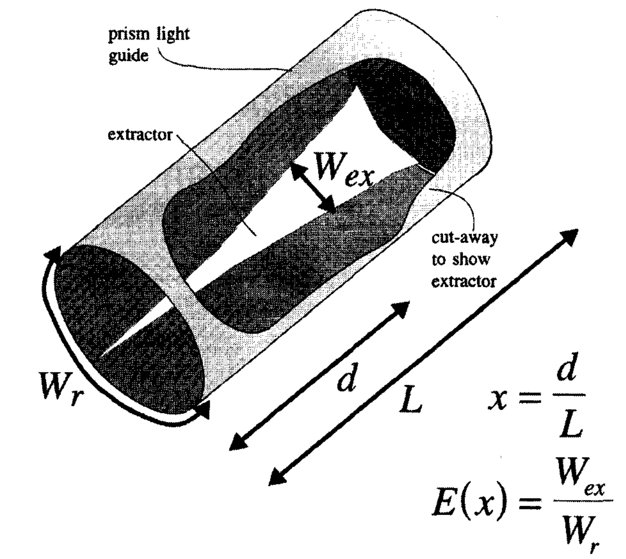

Figure 3— Fractional extrator width E(x) versus fractional length, x.

Design of the light extractor

The best extractor design will depend on many details of design, as well as the detailed preferences of the user in terms of the trade-off between the level of uniformity, level of efficiency, and manufacturing cost. However, the procedure outlined below will provide a design which is sufficiently similar to the best design to allow feasibility estimates, and to initiate the process of finding the best design. In some cases, where the design is not too critical, this first design will be sufficient.

We present here an approximate treatment for determining the extraction value E as a function of x, for any given value of the parameter N_g. A key initial approximation is to assume that the relative amount of flux in the guide, $F(x)$, will decrease linearly from its maximum value $F(0)=1$ to a minimum value $F(1)=0.25$. Although somewhat arbitrary, it is highly desirable that about 25 percent of the light reach the end of the guide, where it is not lost, but instead reflects an end mirror and heads back toward the injector. If $F(1)$ is substantially less than 0.25, it has been found to be very difficult to achieve extraction with sufficient control, intensity, and efficiency to maintain reasonable uniformity. On the other hand, if $F(1)$ is much greater than 0.25, the average light ray reflects more times than necessary, which increases absorption loss, and also some of the light reflected by the end mirror will return all the way to the light injector where it is mainly lost. The reason we can expect the flux level to drop linearly with distance is that with a good design the light will be extracted at a uniform rate by the extractor. To summarize, we have that:

$$F(x) \cong 1 - (0.75)x \tag{4}$$

The following calculation treats only the light coming directly from the injector and ignores the light reflected off the end mirror. This ignored light tends to preferentially brighten the far end of the prism light guide relative to this calculation. On the other hand, another effect, namely the enhanced escape rate of large angle rays, tends to dim the far end relative to this calculation, and so these two minor effects largely cancel. Any small residual error is of the same order as many other detailed effects which will influence the final precise design, but are not a concern at the accuracy level of this basic calculation.

As mentioned earlier, in the absence of extraction, a light ray would reflect approximately N_g times in traveling the length of the guide. In terms of the dimensionless distance measure x introduced above, in which the guide has unity length, we can say that the

Table 1— $E(x)$ values for various ranges of N_g.

N_g range x values>>	0.00	0.25	0.5	0.75	1.00
3 to 6	0.27	0.35	0.48	0.71	1.00
6 to 12	0.11	0.15	0.21	0.32	0.61
12 to 18	0.04	0.06	0.10	0.17	0.34
18 to 24	0.01	0.03	0.05	0.10	0.23
24 to 30	0.00	0.01	0.03	0.07	0.16

number of reflections per unit distance is

$$\frac{dn}{dx} \cong N_g \tag{5}$$

If we define F_e to be the average fraction of flux lost per reflection, this will be given by

$$F_e \cong \frac{E(x)}{2} + F_0 \tag{6}$$

where the denominator of 2 results from our definition of $E(x)$ in which a value of 1 corresponds to half of the interior being covered. F_0 is an intrinsic loss rate associated with defects in the film, and typically has a value of about 0.03 in actual light guides, although it can be as low as 0.02 in guides which are assembled with utmost care.

Differentiating **Equation 4**, we obtain the rate of loss of flux per unit length:

$$\frac{dF(x)}{dx} \cong -0.75 \tag{7}$$

Now this loss rate should be the product of the fractional loss per reflection, the amount of flux at the point in question, and the number of reflections per unit distance:

$$\frac{dF(x)}{dx} = -F_e(x)F(x)\frac{dn}{dx} \tag{8}$$

Substituting **Equations 4 – 7** into **8**, we obtain:

$$-0.75 \cong -\left(\frac{E(x)}{2} + F_0\right)[1 - (0.75)x]N_g \tag{9}$$

solving for $E(x)$, and using a typical value of 0.025 for F_0, we obtain:

$$E(x) \cong \frac{2}{(1.33 - x)N_g} - 0.05 \tag{10}$$

Equation 10 has general applicability and is simple to use. It is interesting to recall that the value of $E(x)$ should lie between 0 and 1 for all values of x between 0 and 1. This implies that N_g must be greater than approximately 6 (otherwise the value of $E(1)$ needs to be greater than 1, which means that light will be lost by traveling back to the light injector), and N must be less than 24, (otherwise the value of $E(0)$ must be less than 0, which means that good uniformity cannot be achieved). Of course values just outside the 6–24 range will not be too bad, and it may not be unreasonable to have N values in the range 3–6 or 24–30, as long as the shortcomings are taken into account. In terms of extractor design in these cases, simply set $E(x)=0$ if the formula gives a negative value, and similarly set $E(x)=1$ if the formula gives a value in excess of 1.

Although the formula gives values $E(x)$ which form a smooth curve, it is possible to approximate this curve sufficiently accurately by straight lines. For this purpose, **Table 1** shows values for $E(x)$ at x=0, 0.25, 0.50, 0.75, and 1.00. These are calculated using values for N_g at the center of the five N_g ranges shown in the table. To use the table, determine the N_g value for the design in question, and use the values for $E(x)$ from the appropriate row in **Table 1**.

In making the extractor, the x values must be translated into actual distance from the light injector by multiplying by the light guide length, L, and the values $E(x)$ must be translated into actual extractor widths by multiplying by one half of the perimeter of the interior of the guide, or by the distance between strips, if multiple extractor strips are used. Once this has been done, one can determine the intermediate widths by simply connecting with straight lines.

Other design considerations

Generally, the performance requirement for a prism light guide luminaire will be expressed in terms of its total flux output, its flux output per unit length, or the luminance or luminous exitance of the light emitting area. We begin by defining the efficiency of the prism light guide by the following relations:

$$\Phi_{out} = \eta\Phi_{in} \text{ or } \Phi_{in} = \frac{\Phi_{out}}{\eta} \tag{11}$$

where Φ_{out} is the flux exiting from the guide and Φ_{in} is the flux injected into the guide. Often there is only one source, but in some cases there may be more. Generally, let there be N_s source, each injecting flux Φ_s, so that $\Phi_{in}=N_s\Phi_s$. For luminance, assuming the usual approximately Lambertian output angular distribution, these relations require that:

$$L \cong \frac{\eta N\Phi_s}{\pi A} \text{ or } N\Phi_s \cong \frac{\pi LA}{\eta} \tag{12}$$

where A is the area of emission of the light guide.

For luminous exitance, we have that:

$$E \cong \frac{\eta N\Phi_s}{A} \text{ or } N\Phi_s \cong \frac{EA}{\eta} \tag{13}$$

Although the precise value of η can only be determined by detailed modelling, if the guidelines in this paper are followed, and reasonably efficient optical components are used, the value will usually be in the 0.5–0.7 range. For the purposes of rough design, a value of 0.6 is a reasonable approximation.

In working out a specific design, generally one begins with certain desirable design parameters, and works out a self-consistent solution for the others. Two examples will be given here to help elucidate this approach.

Example 1

Consider as a first example an indoor illumination situation in which the prism light guide luminaire must be 15 m long, and there is a requirement that the guide emit a total luminous flux of 45,000 lm.

Using **Equation 11** we determine that the required flux from the light injector is 75,000 lm for the estimated efficiency value of 0.6. There are no reflector lamps with this magnitude of output, so a separate reflector will be required to partially collimate the output of a non-reflector lamp. The efficiency of the reflector will likely be of order 0.8, implying that the lamp used must produce about 94,000 lm. The best candidate for this would be a 1000 W metal halide lamp, having an arc length, l_a, about 80 mm.

Unless other special requirements exist, it is generally least expensive to make the guide circular in cross section as this achieves the largest value of W_g with the least amount of material. Again, to minimize material cost, we would normally make W_g as small as possible while avoiding having N_g too large, so it is reasonable to make N_g approximately 24. According to **Equation 3** N_g depends inversely with W_g, but it turns out that W_g also has an effect on N_g in another way—the half angle of the reflector light output is larger for smaller reflector diameters. Roughly, a good reflector design will have an output half angle, measured in degrees, given by:

$$\theta_{1/2} \cong \frac{50L_a}{D} \tag{13}$$

where L_a is the length of the lamp arc tube, and D is the reflector diameter, which for a circular cross section system will be the same as W_g. Substituting this in **Equation 3** we get:

$$N_g \cong \frac{\left(\frac{50L_a}{D}\right)}{50} \frac{L}{W_g} = \frac{L_a L}{DW_g} = \frac{L_a L}{W_g^2} \tag{14}$$

solving for W and setting L_a = 80 mm, L = 15 m, and N_g=24, we obtain

$$W_g \cong \sqrt{\frac{L_a L}{N}} = \sqrt{\frac{(0.08\text{m})(15\text{m})}{(24)}} = 0.22 \text{ m} \tag{15}$$

Typically we would select a slightly larger diameter which is a conventional tubing size, for example 0.25 m.

To design the extractor, we will use the "N= 18 to 24" row of **Table 1**. We must convert the x values into actual distances down the guide by multiplying by 15 m, and we must convert the extractor values to actual extractor widths by multiplying by one half the circumference, 393 mm. The resultant values are shown in **Table 2**. A fixture of this type would provide much the same quality of light as would a row of two-tube fluorescent fixtures.

Example 2

In a second example, consider a backlighted display which is to have an emitting surface 1 m wide by 2 m long, and it is to consist of a prism light guide propagating light in the direction of the 2 m length. The desired luminance of the surface, L_v, is roughly 1000 cd/m² The guide should have a minimum possible cross sectional width, W, and should be illuminated with 50 W quartz halogen MR16 reflector lamps having 50 mm diameter, and output flux of 1000 lm. We must determine the prism light guide depth, W_g, the number of lamps required to produce the desired luminance, and the design for the extractor.

Using **Equation 12**, and estimating the efficiency to be about 0.6, we obtain the following estimate for the required light injector light input:

$$N_s\Phi_s \cong \frac{\pi L_v A}{\eta} = \frac{\pi L_v A}{\eta} =$$

$$\frac{\pi \text{ lm} \bullet \text{cd}^{-1}\, 1000\text{cd} \bullet \text{m}^{-2}\, 2\text{m}^2}{0.6} \cong 10{,}5001 \text{ m} \tag{16}$$

Since each lamp injects 1000 lm into the guide, the desired luminance could be obtained by equally spacing 11 lamps along the 1 m input cross section of the guide.

Since we know the value of $\theta_{1/2}$ and L, we can determine from **Equation 3** the necessary value of W_g to obtain a desired value of N. Solving **Equation 3** for W_g, we obtain

$$W_g \cong \frac{\theta_{1/2}}{50} \frac{L}{N} \tag{17}$$

For the maximum desirable N value of 24, we would obtain:

$$W_g \cong \frac{20}{50} \frac{2\text{m}}{24} = 0.033 \text{ m} \tag{18}$$

Table 2— Extractor widths for Example 1.

Distance	Width
0.00 m	4 mm
3.75 m	12 mm
7.50 m	20 mm
11.25 m	39 mm
15.00 m	90 mm

This means that W_g must be at least 33 mm.

For a minimum desirable N_g value of 6, we obtain:

$$W_g \cong \frac{20}{50}\frac{2\text{m}}{6} = 0.133\text{ m} \quad (18)$$

This means W must also be less than 133 mm, so that W must be in the 33–133 mm range. There is no advantage in making W larger than necessary, but it must be at least as large as the diameter of the lamps, so 50 mm will be used. This yields a value of N_g given by **Equation 3** of:

$$N_g \cong \frac{\theta_{1/2}}{50}\frac{L}{W}\frac{20}{50}\frac{2}{0.05} = 16 \quad (19)$$

The front emitting surface of the cover will be diffusely transmissive so that the extractor pattern on the back surface will be diffused. In order for the diffusion to be sufficient that the luminance of the emitting surface will appear uniform, the extractor strips should be separated by no more than about one half the distance from the extractor to the front surface. Since in this case that distance is 50 mm, the extractor strips should be placed on 25 mm centers, so that there will be 40 equally spaced extractor strips on the back of the guide.

To design the extractor, we will use the "N= 12 to 18" row of **Table 1**. We must convert the x values into actual distances down the guide by multiplying by 2000 mm, and we must convert the extractor values to actual extractor widths by multiplying by the extractor strips' center-to-center spacing of 25 mm. The resultant values are shown in **Table 3**.

Table 3— Extractor widths for Example 2.

Distance	Width
0 mm	1.0 mm
500 mm	1.5 mm
1000 mm	2.5 mm
1500 mm	4.3 mm
2000 mm	8.5 mm

In other examples, other combinations of parameters may be specified, but the general approach is much the same. In some cases, it may be found that no self-consistent solution is possible with available light sources. In such cases, it is often possible to reconfigure the problem into one that is easier to solve, e.g., by reducing the required length of the light guides, or reducing the required output flux by increasing the number of guides in a lighting system. In almost all cases, a self-consistent design based on the above approach should be a good starting point.

The above design approach can be facilitated by the use of a simple computer program to keep track of the various simultaneous relations which must be satisfied. Such a program is freely available on the World Wide Web for this purpose.[8]

Conclusions

This paper provides a simple method for creating a first design for a prism light guide luminaire. It will be a rare situation where such a design is the best that can be made, but in most cases it will be close enough to such an ideal design that it should be fairly simple to iterate to that best design in a quick and simple manner. Depending on the size and complexity of the system, it may be best to carry out such iteration by means of computer Monte-Carlo ray tracing or by constructing optical mock-ups. In any case, it is expected that the differences between the resultant final design and the initial design will be small enough that the initial design can be safely used for initial feasibility estimates for performance and cost.

Acknowledgments

The author thanks Klaus Beihl and Arno Eberwein of the 3M Company, for pointing out the need for this work, and gratefully acknowledges the advice provided by Harry Anderson, Ric Dryer, and Ken Kneipp, also of the 3M Company. This work was partially supported by the Natural Sciences and Engineering Research Council of Canada, and 3M Canada Inc.

Appendix

Glossary of symbols used in this paper length of the prism light guide luminaire

- θ — angle between light guide axis and light ray direction
- θ_c — maximum value of θ for which prism light guide carries all rays
- Φ_{in} — luminous flux injected into prism light guide
- Φ_{out} — luminous flux emitted along length of prism light guide
- L_v — visible luminance of the light emitting surface
- η — efficiency of prism light guide luminare
- N_s — number of sources emitting light into prism light guide
- Φ_s — luminous flux injected by each source
- $\theta_{1/2}$ — the angle at which the light injectors intensity has dropped to half
- L — the length of the prism light guide luminare
- W_e — width of luminaire emitting region
- A — prism light guide luminaire emitting area
- W_g — minimum cross sectional width of prism light guide
- AR — aspect ratio of prism light guide
- x — dimensionless fractional distance down prism

light guide

W_{ex} width of light guide extractor material

W_r width of rear half of the perimeter of prism light guide cross section

$E(x)$ dimensionless ratio of extractor width to rear half perimeter

$F(x)$ fraction of initial flux reaching point x

F_0 intrinsic loss per reflection of prism light guide wall material

L_a length of light emitting portion of lamp

D diameter of lamp reflector

References

1. Whitehead, L.A. 1982. US Patent No. 4,260,220.
2. Whitehead, L.A., Nodwell, R.A., and Curzon, F.L. 1982. New efficient light guide for interior illumination. *Applied Optics* 21:15.
3. Saxe, S.G., Whitehead, L.A,, and Cobb Jr, S. 1984. Progress in development of prism light guides. *SPIE Proceedings* 692: 235–240.
4. Whitehead, L.A. 1986. U.S. Patent No. 4,750,798.
5. Whitehead, L.A., Scott, J.E. 1984. Distribution of light with prism light guides. *Proceedings of the 1984 Annual Conference of the IESNA.* Vol.1: 128-143
6. Whitehead, L.A. 1988. U.S. Patent No. 4,787,708.
7. CIE TC 3-30. 1995. Hollow Light Guide Applications *Publication of CIE TC 3-30.*
8. Program PLG.EXE designed by Hoffman, K., and Whitehead, L., 1997. *http://ssp.physics.ubc.ca/download.html*

Discussion

We were very pleased with this paper. It proves to be very useful as a tool to create the first iteration in a prism light guide design.

We have one question about **Equation 6**. This equation defines F_e, the fraction of flux lost per reflection to be

$$F_e \cong \frac{E(x)}{2} + F_0$$

This implies that all of the light that encounters the extractor at x is lost. However, the guide can guide a significant portion of the light that reflects off of the extractor. That is, some of the light that reflects off the extractor makes an angle with the axis of the guide that is less than the value of θ_c given by **Equation 1**. We would like to know if the author has considered this fact. If not, does he think that it would significantly improve his model? As well, does he think that it could be easily incorporated into his model?

B. York and M. Donaldson
TIR Systems Ltd.

This paper fills a need. The design procedures are clear, easy to understand, and will be useful to the novice designer. The examples will be helpful. Limitations are pointed out by the authors.

Only one design method, the diffusing extractor, is presented. Are there any plans for the authors to present other design methods, such as the prismatic extractor?

D.A. MacLennan
FusionLighting Inc.

Author's response

To B. York and M. Donaldson

It is true that in general some of the light scattered by the extractor will have a direction within the acceptance range of the guide. For an isotropic radiator, this fraction is about 13 percent for a prism light guide having a refractive index of about 1.6 and a resultant acceptance angle of about 30 degrees. However, the light scattered from the extractor is not isotropic. Typically it has the directional distribution of a Lambertian radiator, with its peak intensity in the direction perpendicular to the guide axis. This reduces the fraction of this scattered light that is subsequently guided to about 2 percent, which we suggest is negligible at the level of approximation presented in this paper.

To D. MacLennan

Although diffuse extractors are most common, and are therefore used in the two examples given, the results of this paper are not restricted to such extractors. The extraction width W_{ex} can generally be interpreted as the "equivalent width" of the extraction mechanism.

For example, if the extraction mechanism were holes in the prismatic film, W_{ex} would represent of the area of holes per unit length of guide, which could vary as a function of distance down the guide.