New efficient light guide for interior illumination

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Experimental and theoretical studies of the recently patented prism light guide are described [L. A. Whitehead, U.S. Patent 4,260,220 (7 Apr. 1981)]. This device combines the total internal reflection of optical fibers with the low attenuation of air transmission of light. Since it can be moulded from acrylic plastic, the cost of the guide is low enough to make large-scale interior illumination with piped light feasible.

I. Introduction

The idea of piping light from a remote source to an interior space for illumination purposes is not new.[1] There are a number of advantages in this concept, such as the economies of scale with larger light sources and the ability to remove electrical connections from explosive atmospheres to keep waste heat out of air-conditioned areas and even to employ sunlight for interior lighting.[2–4] In spite of these advantages, large-scale light piping has not become common mainly because of the difficulties outlined below.

Solid dielectric light guides are impractical because reasonably priced dielectric materials have absorption coefficients which exceed 0.1 m^{-1} so that efficiency is low. Furthermore, practical power density limits require that the light pipes be fairly large making even the cheapest materials prohibitively expensive.

In more practicable light guides, light is transmitted with low loss through air, while mirrors or lenses confine the light within the guide dimensions. In one system, the beam waveguide, regularly spaced confocal lenses or mirror equivalents are employed.[4–6] Unfortunately low-cost lenses and mirrors entail excessive losses of the transmitted light. In another device, the metal waveguide, the light strikes the metal-coated walls of the guide and is thereby reflected down the guide.[2] In this case absorption of light at the metal walls is too large for a practicable system.

The recently patented prism light guide offers a solution to these problems.[7,8] This device is basically a transparent pipe whose walls have prism-shaped outer facets which act as total internal reflection mirrors. For this special geometry, it is thus possible to have at reasonable cost the efficiency of total internal reflection combined with low attenuation of light.

In this paper a description of a ray tracing analysis of an imperfect prism light guide is presented. A method of making sections of prism light guide is then presented together with measurements of its light propagation characteristics. Finally the possible immediate and future uses for the device are discussed.

II. Ray Tracing Analysis of Prism Light Guide

Figure 1 shows the cross-sectional shape of the prism light guide as well as an oblique view. In the ideal guide, all the internal surfaces are either parallel or perpendicular to one another. In addition, the external surfaces are either parallel or perpendicular to one another and are inclined at 45° relative to the inner surfaces. Finally the cross-sectional shape of the guide is constant along its length. If a ray enters the air space of a guide with wall refractive index n with an angular deviation θ from the axial direction, it is fairly easy to show that providing θ is less than θ_{max}, where

$$\theta_{max} = \cos^{-1}\left[\frac{1 - n^2 \sin^2(\pi/8)}{1 - \sin^2(\pi/8)}\right]^{1/2}, \tag{1}$$

the ray will be confined to travel down the guide.[7,8] This confinement occurs as follows: when a ray strikes the inner surface of the guide, it will be partially reflected back into the air space and partially transmitted into the wall material. The transmitted ray will then strike one or more of the outer surfaces of the wall, undergoing total internal reflection. Eventually the ray will strike an internal surface of the wall, where it may be partially transmitted back into the air space. The ray which is reflected back into the wall material simply undergoes a repeat of the total internal reflection at the outer surfaces, and eventually all the light energy is thus able to return to the air space. Even the ideal light guide cannot be perfect because of diffraction effects which are ignored in the ray tracing analysis presented

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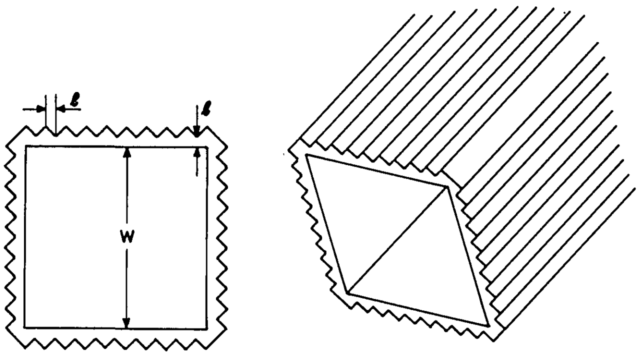

Fig. 1. Cross-sectional and isometric views of the prism light guide.

here. However, with typical facet sizes of several millimeters, such losses will be negligible relative to the other forms of loss found in the imperfect guides produced in practice.

The guide imperfections are due to errors in the shape of the guide walls and to absorption of light traveling in the wall material. A Monte Carlo computer ray tracing program was developed to study propagation of rays down a model of an imperfect guide. Each ray is given a random initial position and direction in the guide interior subject to the constraint that the angular deviation from the axial direction be less than an angle θ_c, where θ_c is the collimation angle of the incident light. The program then traces the ray's path through the system.

At an interface the incident ray divides into a reflected ray and a transmitted ray. It would be prohibitively expensive to follow an exponentially growing number of such rays. Therefore, at each interface the path of only one of the rays created is followed to the next interface. This is done by a random selection process in which the probability of selecting the reflected or transmitted ray is equal to the corresponding reflection or transmission coefficients which are determined by the Fresnel equations.

Angular errors in the wall surfaces are modeled by assigning a 2-D probability distribution for the direction of the normal vector to the surface. In reality this distribution is quite complex and is a function of position on the surface. We have modeled this dependence by dividing the wall surface into two types of regions—the jagged corner regions shown in Fig. 2 being the first and all other regions being the second. In the corner regions, over a distance of $\pm c/2$ from the vertex, the normal vector probability distribution is modeled to be uniform over all possible angles. In the other regions, the distribution is modeled to be Gaussian, with standard deviation σ_z for angular variation of the normal vector in the transverse plane and σ_p for variation perpendicular to that plane. In addition, a small fraction of probability s is assigned uniformly over all possible angles. In this way, the Gaussian part of the distribution models the effect of slight errors in shape in the guide wall, while the uniform part models the effect

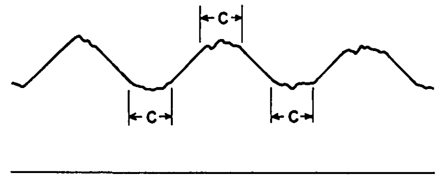

Fig. 2. Enlarged view of cross section of prism light guide wall.

of small surface scratches and marks which cause wide-angle scattering.

Absorptivity of the wall material is taken into account by assigning a probability per unit length k of complete annihilation of a ray, which is equal to the bulk absorptivity. Small- and wide-angle scattering of the light ray in the bulk material was not modeled because these effects were very small relative to the analogous surface scattering and would be similar in effect.

For sufficiently small values of c, σ_z, σ_p, and s, the loss mechanisms contribute independently to the attenuation of light. With the pipe dimensions specified by l and w in Fig. 2 and assuming that θ_c is small, the resulting attenuation per unit length can be summarized in the approximate empirical formula

$$\frac{d\ln I}{dz} = (0.55)\frac{c\theta_c}{lw} + (2.9)\frac{lk\theta_c}{w} + (2.0)\frac{\sigma_z\theta_c}{w} + (20)\frac{\sigma_p\theta_c}{w} + (1.7)\frac{s\theta_c}{w}. \quad (2)$$

A more convenient way to describe this attenuation is in terms of the loss of light per reflection off the guide wall. The mean number of reflections per unit length can easily be shown to be

$$\frac{d\langle N\rangle}{dz} = \frac{8}{3\pi}\frac{\theta_c}{w}, \quad (3)$$

and the fraction of light lost per reflection L_r can then be determined from Eq. (2) to be

$$L_r = (0.65)\frac{c}{l} + (3.4)lk + (2.3)\sigma_z + (24)\sigma_p + (2.0)s. \quad (4)$$

It is interesting that the coefficient of σ_p is about ten times larger than that of σ_z, indicating that angular variations stemming from waviness down the length of the guide are correspondingly more deleterious than variations of the angles in the cross-sectional plane.

For parameters resulting in values of L_r of more than a few percent, Eqs. (2) and (4) become inaccurate, chiefly because of interactions between various types of loss. Angular errors in the surfaces, for example, tend to increase the time a ray spends in the wall, and this changes the importance of the bulk absorptivity of the wall material. For such cases it is simplest to just run the program for the parameters of the guide to be studied. An example of such a study is presented in Sec. IV with the attenuation measurements made for samples of prism light guide.

III. Experimental Production of Prism Light Guide

We have constructed a number of lengths of prism light guide, each 1.1 m long and 130 × 130 mm in cross section with the dimension l in Fig. 1 being 4.5 mm. The guides were constructed by gluing together four wall sections which had been produced by press-moulding commercial grade acrylic plastic sheet with refractive index $n = 1.5$.

Our mould was composed of laminated strips of polished stainless steel, which were bolted to an aluminum backing containing forced hot air heating channels. With mould pressures of 20 atm at 200°C and a cycle time of 4 h/segment, we obtained excellent reproduction of the mould surface. As a result, most of the errors in the plastic shape stemmed from inaccuracies in the mould itself which would be reduced with better mould fabrication techniques.

Optical testing of the moulded plastic yielded the following approximate values for the loss parameters described in Sec. II:

$$k = 0.15\ \text{m}^{-1}; \quad c = 10\ \mu\text{m};$$
$$\sigma_z = 0.019\ \text{rad}; \quad W = 130\ \text{mm};$$
$$\sigma_p = 0.001\ \text{rad}; \quad l = 4.5\ \text{mm}.$$
$$f = 0.02;$$

If these values are used in Eq. (4), the predicted loss per reflection is found to be ~10%, of which only ~0.2% result from absorption and scattering from incorrectly shaped corners. Thus with improvements in moulding techniques highly efficient guides can be expected. Even the present loss is comparable with the best metal mirrored light pipes. Moreover, in contrast to metal-walled guides, most of the light not transmitted down the prism light guide escapes from it with little absorption and can be used for illumination purposes. This feature is being used by the authors in developing a prototype facility for illuminating a solvent storage area.

IV. Measurements of Guide Efficiency

The guides were tested by butting six 1.1-m long sections end to end and shining white light collimated to ±10° in one end. Figure 3 shows the apparatus used to measure the luminous flux arriving at various points along the guide. A fiber-optic cable was used to sample light from the integrating cube. We had verified experimentally that this light sample weighted all regions of the front of the cube equally to within a few percent, so that a photomultiplier connected to the cable would give an accurate proportional reading of total light flux in the guide's air space at the point of measurement. Since the guides were only butted together, some light loss occurred at the joints. This was taken into account in the ray tracing program used to predict the decrease of light intensity with distance.

Figure 4 shows a graph of the logarithm of the light flux level as a function of position down the guide as well as the predicted value obtained from the ray tracing program. The agreement is quite good. From the data in Fig. 4, we were able to determine an accurate value for light lost per reflection off the wall to be 8%. The ray tracing program shows that of this loss, 6% is light escaping from the pipe, and 2% is absorption loss in the plastic. In addition to reflection losses, 5% of the light escapes at each joint.

Further ray tracing studies showed that these values are relatively insensitive to collimation angle θ_c as long as this is <27.6° the maximum value for proper operation of an acrylic plastic guide. Thus one can calculate the average number of reflections per unit length for an arbitrary size of guide and collimation angle and multiply this by the known loss per reflection to predict the loss per unit length.

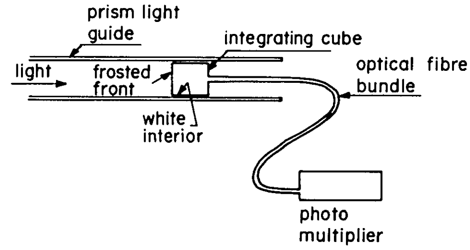

Fig. 3. Apparatus for measuring luminous flux at various points in the light guide.

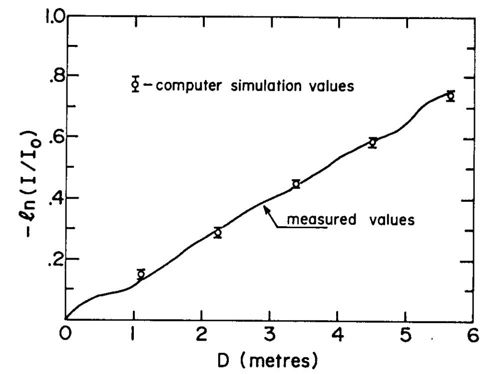

Fig. 4. Graph of $-\ln(I/I_0)$ vs distance D down the pipe. I = luminous flux at D; I_0 = luminous flux at $D = 0$; collimation angle = 10°.

V. Conclusions

The operation of the prism light guide has been demonstrated experimentally in complete agreement with a simple theoretical model. Moreover, the quality of pipe which was produced by press moulding of acrylic plastic is already high enough to compete very favorably with other available types of light guide. Furthermore improvements in manufacturing techniques will make it possible to use prism light guides for piping light to provide general interior illumination in buildings.

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