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CHARACTERIZATION OF TRANSMISSION PROPERTIES OF 3M LF120C PLASTIC OPTICAL LIGHT GUIDE

M. R. Cates, S. L. Jaiswal, L. C. Maxey, D. D. Earl
Oak Ridge National Laboratory
Oak Ridge, Tennessee

ABSTRACT

Transmission studies of 3M optical light guide, type LF120C with nominal 12.6 mm core diameter, were performed to characterize the material for use in hybrid solar lighting applications, in particular for the transport of sunlight from a collector to discrete lighting fixtures (luminaires). The light guide properties studied included: total transmission (in lumens) per unit length, transmission as a function of input angle and wavelength, transmission as a function of bend radius, and transmission through two bends. The preliminary value for total transmission is 96.6 % per meter. Angular input begins to drop significantly at angles greater than 25 degrees. Wavelength transmission has significant minima at about 643 and 750 mm. Losses through bends are much greater for light input at large angles. In addition to the data compilations and detailed summaries of measurement findings, the measurement system and error sources are described.

INTRODUCTION

As the United States moves into the 21st century and the post-September 11th era, our efforts to increase energy efficiency and minimize dependence on foreign oil take on increasing importance. In our active, industrialized society one of the leading energy costs continues to be lighting. The peak electric lighting bill, ironically, occurs when the sun is highest, near midday, and therefore, when solar light is maximally available. The Hybrid Solar Lighting (HSL) program, [1] centered at Oak Ridge National Laboratory and involving a number of industrial and government partners, conceived to take advantage of available solar light, is dealing directly with the challenge to produce lower-cost, higher quality lighting that can be included in new construction and retro-fit into older facilities. An important part of the HSL approach is the transport of solar light, collected by systems exterior to the buildings involved, or light from centralized artificial sources. Large-core plastic light guides are good candidate materials for this purpose because of their light-carrying capacities, relatively low cost, and flexibility. In this study, a commercial plastic guide has been evaluated both qualitatively and quantitatively in the attempt to determine its degree of utility for use in HSL systems.

Light Guide Characteristics

The plastic light guide used in this study, manufactured by 3M Corporation, is identified as type LF120C. Its core diameter is nominally 12.6 mm. Our random checks of the core diameters of various pieces of the material showed that it could vary between about 12.0 and 13.0 mm. The core index of refraction, n_1, is given as 1.498. The material is polymethylmethacrylate (PMMA). It was designed to be flexible down to 0 degrees centigrade. The cladding is a polyfluorocarbon similar to Teflon, with an index, n_2, of 1.35. In addition to this work, other investigations of the 3M light guide are focusing on improving coupling, surface polish, index matching materials, temperature dependent behavior, and other related properties. [2]

Applying Snell's Law to the two materials, the core and the cladding of the light guide, we can write

$$n_1 \sin\theta_1 = n_2 \sin\theta_2, \qquad (1)$$

where θ_1 is the angle from the normal to the two surfaces made by the light ray in the core, and θ_2 is the angle from the normal to the two surfaces made by the light ray in the cladding. The critical angle, θ_c, is reached when the light approaching the interface from within the core refracts 90 degrees to the normal, that is, when θ_2 reaches 90 degrees, its sine therefore, reaching unity. Solving the Snell's Law equation for those conditions gives the critical angle as

$$\theta_c = \sin^{-1}[n_2/ n_1]. \qquad (2)$$

For this material, then, the critical angle would be $\sin^{-1}[0.901]$ or 64.3 degrees. The numerical aperture is a practical measure of the angle of acceptance (or output) of the light guide. The numerical aperture, NA, is written

$$NA = \sin^{-1} [n_1^2 - n_2^2]^{1/2}. \qquad (3)$$

For the 3M LF120C light guide, the NA computes to about 40.5 degrees. This is the half angle of the full cone of light the fiber can accept or will produce when light exits it. The measure of the half angle is from the normal to the end surface, which corresponds to incidence angles for light described below. Were the material to be a perfect waveguide with no surface irregularities, it could be expected that no light with angle greater than 40.5 degrees could enter or exit the light guide. As it turned out, incident light in excess of 40.5 degrees was coupled into the core, but with very low efficiency, as will be shown.

Visible Light Transport Efficiency

The arrangement for measuring the total light through a light guide was comprised of a stable broad-band xenon light source, [3] a length of 3M light guide, an integrating sphere,[4] and an optical multi-channel analyzer (OMA). Both ends of the light guide were polished. The light-input end was pressed into a tapered aperture where the light exited the source. The light source with fiber pressed into the aperture is shown in Fig. 1. The process of pressing the fiber into the aperture was repeated a number of times under identical conditions to determine the repeatability of the process. It was found to vary by only around 1%. Other sources of error, described below, were somewhat more significant.

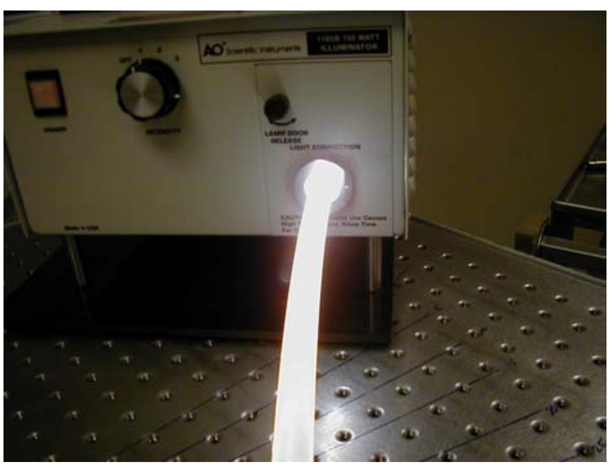


Fig. 1. Photograph of 3M light guide pressed into tapered aperture of light source

We tested a length of 3M LF120C light guide (core diameter about 12.6 mm) to determine the amount of light transported per unit length. Figure 2 shows a section of 3M plastic light guide attached to the integrating sphere, used to measure the light exiting the end of the guide. The light guide, at the onset of the measurements, was about 2.8 m long. Input light was supplied by a broad-band xenon lamp that provided a significant amount of light for each of the visible wavelengths. Spectra were recorded from the integrating sphere using the OMA. The measured spectra were then mathematically overlapped with the human-eye-response curve [5] to produce the total number of lumens collected. A series of measurements was made, beginning with the full length, followed by measurements after approximately 0.5 m was cut from the previous lengths, down to a final section less than 1 m long. In each case, the cut fiber end was polished to about a 0.5 micron finish [3] with the goal of providing uniform optical conditions for each input and output surface. We stress that this is a preliminary study. A larger scale study, using longer lengths of fiber has begun, and is expected to produce higher precision data. The current study, however, was able to give both a good estimate of the material performance and an increased understanding of the types of errors that plague measurements of this kind.

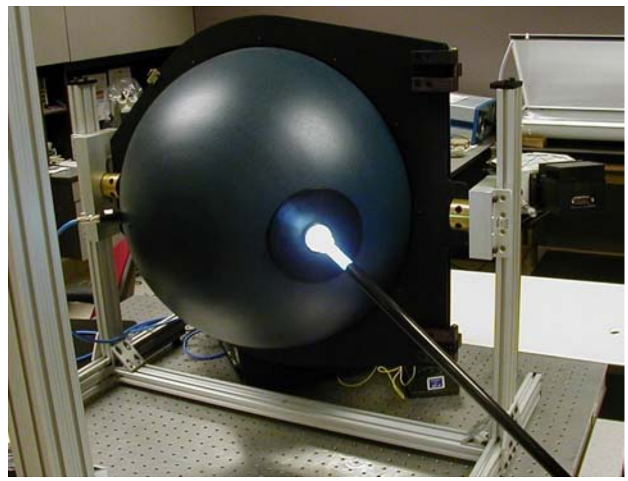


Fig. 2. Photograph of 3M light guide attached to integrating sphere

Figure 3 is a plot summarizing the data taken in the total transport study. Shown is the measured light as a function of wavelength that was transported through the various lengths of fibers, as indicated in the legend of the graph. The curve labeled “0 m” is light going directly into the integrating sphere from the light source, normalized to an extrapolation of the light through the various lengths. The extrapolation was required to put the zero-length data into the same geometry as the measurements with the light guides themselves. Three different output settings on the xenon source were used, so that three different measurements were made for each fiber length. Data were normalized so that each measurement was associated with a single input power (in this case, the lowest setting of the source), both to improve the statistics of the measurements and to look for inconsistencies that could be corrected before averaging the data. In Fig. 4 are plots of the ratio of data through a particular length of fiber to a zero length, that is, the fraction of the total light transported through the fiber. In the figure, the large absorption at 750 nm is clearly seen, as well as the significant absorption at about 643 nm. Note that between 350 and 450 nm the 0.69 and 1.15 m data are sometimes above unity. These values are artifacts both of the low signal-to-noise ratio of the data signal and the process of normalizing the zero length data to conform to the light guide optics. In general, however, the trends are shown clearly. Even these short lengths of material show significant loss in the visible near 645 nm and in the near infrared around 750 nm.

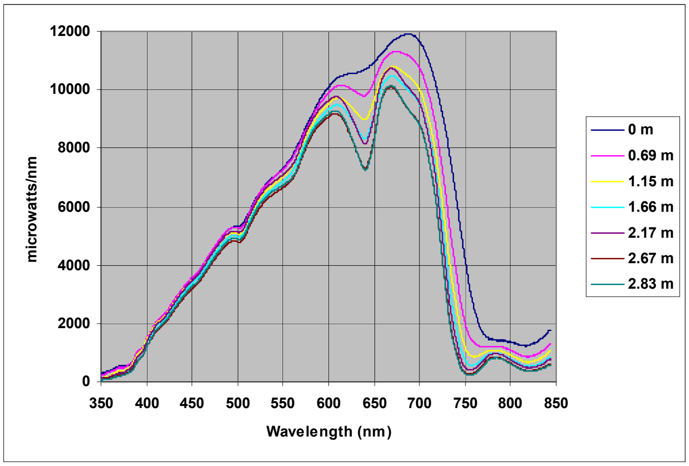


Fig. 3. Transmitted light versus wavelength for various lengths of 3M light guide

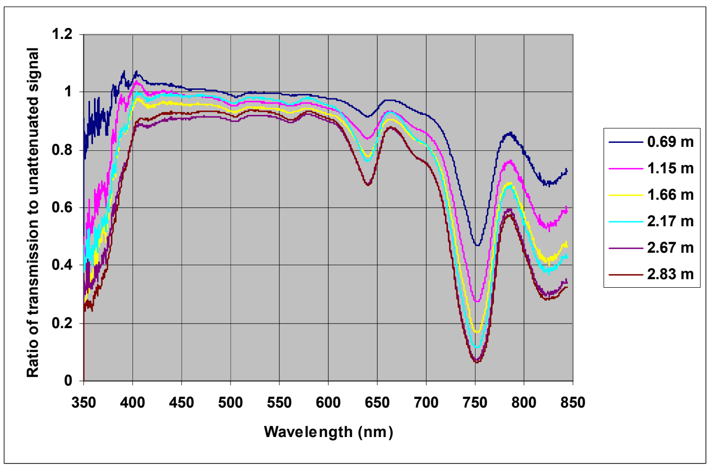


Fig. 4. Ratio of transmitted light through various lengths of 3M light guide to input light, as a function of wavelength

Each spectral measurement through the various light guide lengths was folded with the human eye response to determine the lumens transported into the integrating sphere for that particular set of conditions. The overlap calculation had been checked with measurements made with a calibrated integrating photodiode that viewed the averaged light in the integrating sphere. Table 1 gives the numbers of lumens obtained for each case. In Table 2 the ratio of the values to the zero length cases are shown. These values illustrate the statistical variation that can be expected for data of this type. When the averages of the transport fractions are taken and normalized to one meter of length, we arrive at the average transport fraction of 0.966 per meter. The number involves lumens; consequently, the losses in the red and infrared are not weighted as heavily as the yellow-green region that is the peak of the human eye response.

length (m)	setting 1	setting 2	setting 3
0	580	812	1051
0.689	571	798	1040
1.147	554	774	987
1.658	535	756	969
2.168	553	771	1006
2.666	515	720	949
2.832	525	735	945

Table 1. Lumens transported through different lengths of 3M waveguide, for three different light source settings

length (m)	setting 1	setting 2	setting 3
0	1	1	1
0.689	0.98223	0.980283	0.993712
1.147	0.952987	0.950801	0.943071
1.658	0.920303	0.92869	0.925872
2.168	0.951267	0.947116	0.961225
2.666	0.8859	0.884466	0.906762
2.832	0.903102	0.902893	0.90294

Table 2. Fraction of the lumens transported through different lengths of 3M waveguide, for three different light source settings

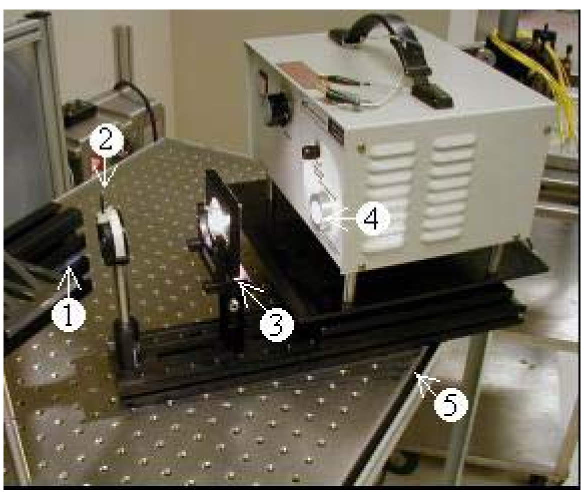
Several sources of error were present in the measurements described. Included are: (1) variations in the quality of the light guide surface (polish) at the input end, (2) drift of the light source intensity, (3) characteristic signal to noise ratio (SNR) of the OMA, and (4) possible variations in attaching input light source to light guide input. In particular, we found that the polish variations and the drift of the light source can each cause up to 2 or 3 percent uncertainty. The other two, the SNR and the light-input attachment variation, give less uncertainty. The SNR is unimportant because the lumen extraction of the data comes from a region where the SNR is quite large. When all these possible errors are folded into a single measurement, variations of 5 percent or more can be common; however, when the 18 separate measurements are averaged the reliability of the results becomes significantly higher.

Transmission as a Function of Input Angle

To efficiently couple solar light into a light guide, it can be required for large-area solar collectors, to focus the light, thereby distributing it into a distribution of approaching angles. The greater the angle, with zero degrees defined as the normal to the surface, the higher the likelihood that the light ray will reflect at the surface rather than be transmitted through it. For any optical surface, such as the polished end of a light guide, the numerical aperture limits the angle of incidence. However, surface polish, uniformity, and perhaps other optical properties of the light guide material can affect the transmission of the light at the incidence angles allowed by the numerical aperture.

With this in mind we assembled a measurement system to allow us to impinge a narrow column of light at any selected incidence angle on the end of a light guide. The assembly consisted of the broad-band xenon source, used in the previously described measurements, focused through a collimating lens and variable aperture, all mounted in a fixed geometry on a moveable platform. The input end of a length of 3M light guide was clamped into a holder so that the guide end surface was fixed, allowing the light source assembly to be positioned at any selected angle with respect to the normal to that surface. We facilitated the angle selection by scribing angle reference lines on the surface to which the light guide end clamp arrangement was attached. The light source assembly and light guide end clamp arrangement are shown in Fig. 5.

Because the xenon lamp was an extended source, the simple lens and collimator system used did not produce a perfectly collimated parallel beam of light for input into the light guides. However, the light-spread out of the collimator was low enough that a great majority of the light was centered on the selected incidence angle. Except at about 25 degrees, when the roll-off in the signal began to be significant, the less-than-perfect collimation had little effect on the measurement. Near 25 degrees, however, the input rays on the low side of the nominal angle would be transported somewhat better than the nominal, and those on the high side of the nominal 25 degrees would be transported significantly poorer. The upshot would be a slight rounding the curve, depressing the values slightly. These variations, however, are probably less than the variations in the measurements arising from the same four types of errors previously discussed.



1. **Light guide polished end (held in clamp)**
2. **Adjustable aperture**
3. **Collimating lens**
4. **While light source**
5. **Input angle positions**

Fig. 5. Source and collimator assembly for light input at various angles and clamp arrangement to hold the input end of the 3M light guide.

Angle study of a short length of light guide. The angle study was begun by examining a short length of 3M light guide, 21 inches (0.53 m) long. The goal of using a short length was to minimize the variation in losses that might occur in the guide from material absorption of the light propagated over the varying length light paths that result from variations in incidence angle. In other words, with a relatively short section of light guide the light transported into the integrating sphere would show losses that were dominantly caused by the angle of incidence. Surface reflections, then, would be the primary attenuators of the measured light, not the aggregate absorption losses along relatively long transport paths. Figure 6 summarizes the measurements made. The collimated input beam was approximately 3-mm diameter. For each measurement, a spectrum was recorded by the OMA and folded with human eye response to give a single lumen value. Little attenuation occurs until the angle of incidence exceeds 20 degrees, after which the drop-off is rapid until, at the maximum incidence angle measured (46.3 degrees), the fractional transport is only about 8 percent of the zero-degree value. Also, as the incidence angles increased the SNR of the data decreased; consequently, the uncertainties were greater at the higher incidence angles.

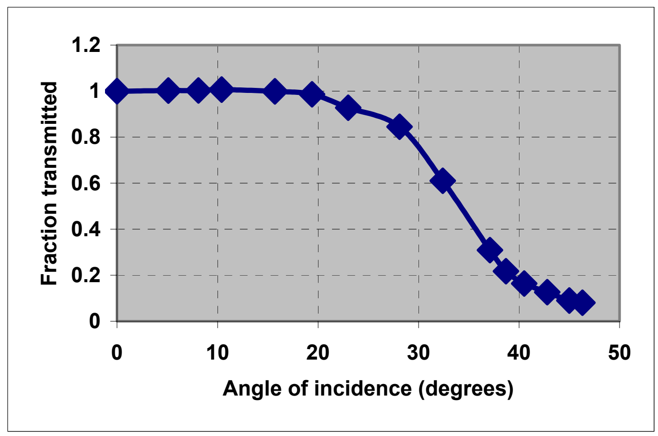


Fig. 6. Relative light transported through a 21-inch length of 3M light guide as a function of incidence angle

Angle study of a light guide with a 90-degree bend. A 5.0 meter (197 inches) length of 3M light guide was also studied, both to observe the material-dependent transport losses and to provide enough material so that a 90-degree bend could be imposed on the light guide, without the bend being too close to either end. Several bend radii were measured, in addition to no bend (infinite bend radius). An earlier preliminary evaluation of the effects of bends, done with a filtered diode (to approximate eye response) measuring the integrating sphere, indicated that bends of about a 6-inch radius or less were required to produce any significant effects on the light guide transport properties. In other words, only sharp bends made any appreciable difference in the transport properties of the light guide. Figure 7 is a graph of the incidence-angle dependent transport through each of the bend radii. The transmitted light was normalized to the zero degree data for the straight (no-bend) measurement. All data were taken as spectra by the OMA and overlapped to give an answer in lumens. Expressing data in terms of lumens, while useful for applications such as lighting where human vision is concerned, does not clearly illustrate the wavelength dependence of the phenomenon being measured. The trend of the data, however, clearly shows that tighter bends limit the total transmission. Because of the range of possible errors for individual measurements it is hard to quantify the total loss as function of bend radius. Future studies are planned to make similar measurements with higher precision so these trends can be better quantified.

Figure 8 shows the same data plotted as ratios of the transmitted light, at various angles of incidence for each bend radius, to the no-bend data for each angle of incidence. Plotted this way, it is easy to see the trend of lower transmission for higher incidence angles as the bend radius is reduced. The data for incidence angles greater than 40 degrees are not reliable, so the ratio tending to go up between 40 and 45 degrees is probably an artifact of the data.

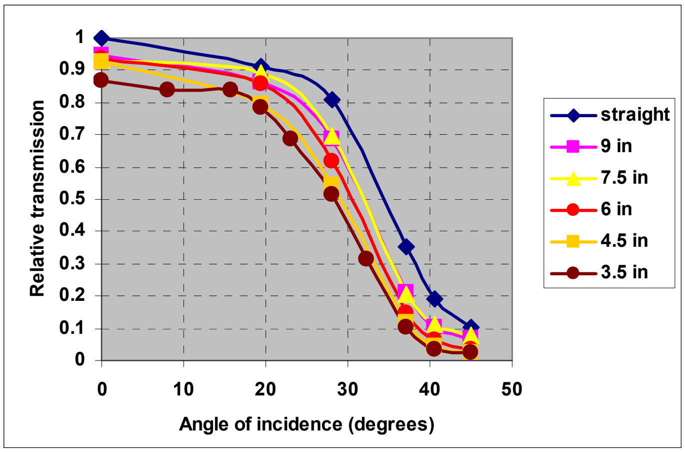


Fig. 7. Relative light transported through a 5-meter 3M light guide containing a 90-degree bend, as a function of incidence angle and bend radius

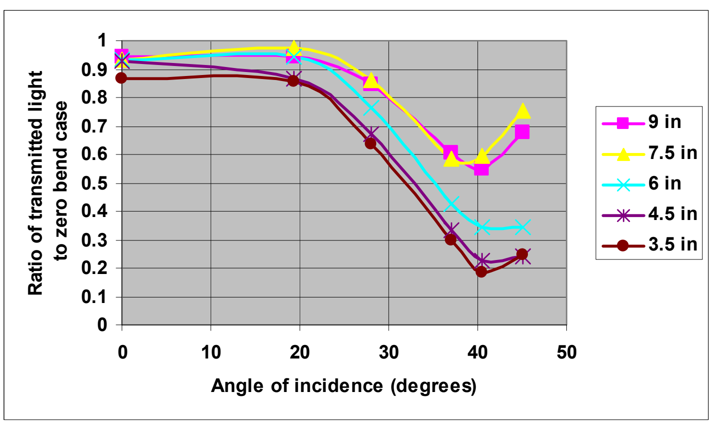


Fig. 8. Ratio of transported light at various bend radii to no-bend case, as a function of incidence angle

Light Transport Study of 7.5-Meter 3M Light Guide

A 7.5-meter (295-inch) section of 3M light guide was configured so that it could be aligned into a straight path from the light source, pass through a single 90-degree bend, or pass through two 90-degree bends, to the integrating sphere. It was noted during the measurements that when light was introduced at larger angles the bends showed significantly increased light leakage. Figure 9 is a photograph showing the effect. These light leaks are the expected result of rays of light approaching the core-cladding interface at angles that are reasonably close to the critical angle. Any irregularity in the optical surface can allow scattering, absorption, or losses from light exiting the core. The central beam of the quasi-collimated light source appears to be preserved for all the light guide lengths studied, maintaining the angle of internal scattering pattern corresponding to the incident angle.

Figure 10 is a compilation of data from the straight, one-bend, and two-bend conditions of the 7.5-meter light guide. Both bend radii were 4.0 inches (100 mm). As expected, the first bend causes considerable loss of light at the larger incidence angles, while the additional bend makes a less significant additional effect. For these data we used a photodiode to monitor the output of the light source; consequently, the drift in light intensity of the source was removed as a significant cause of error. Another important source of error, the input surface characteristics of the light guide, was also reduced for these measurements, because the same section of light guide, with no required cutting and polishing, was used for all three cases.

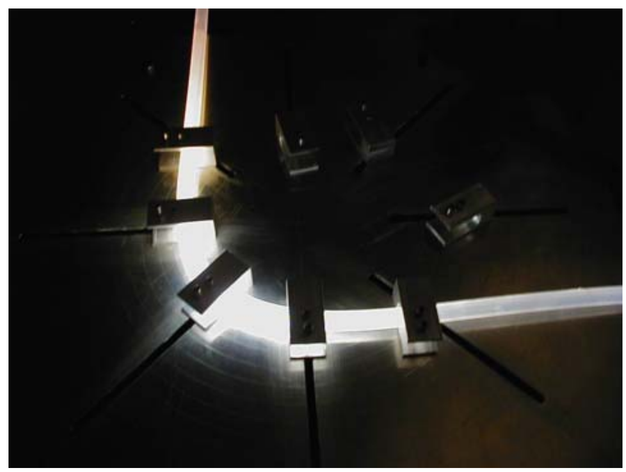


Fig. 9. Photograph of light loss at the 3M light guide bend

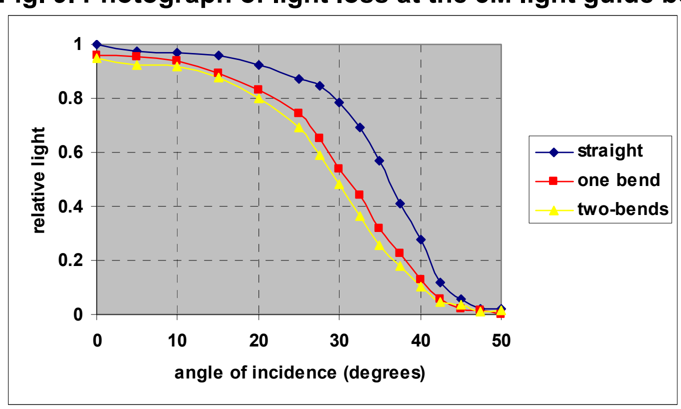


Fig. 10. Relative light transported through a 7.5-meter 3M light guide in three conditions: straight, containing one 90-degree bend, and two 90-degree bends, all as a function of incidence angle

Transmission as a Function of Both Angle of Incidence and Wavelength

A 6.5-meter (256-inch) straight length of 3M light guide was studied to evaluate the transmission characteristics as a function of both angle of incidence and wavelength. For this evaluation, the data measured by the OMA, comprised of 992 wavelength values extending from 350 to 844 nm, were compared by wavelength segment for angles of incidence out to 45 degrees. The data illustrate the influence of angle of incidence on the color characteristics of the transported light. Figure 11 is a compilation of the data taken. Data at each end of the wavelength range (below 400 nm and above 750 nm) are not plotted because of their low SNR for this light source. The numbers are the signal at any particular wavelength segment divided by signal from the corresponding segment for the zero-degree incidence case (with the light source centered on the center line of the light guide). These data represent only one of several lengths of 3M fiber measured in this way. In future work added data will improve the accuracy and allow for a determination of these wavelength-dependent properties per unit length of light guide.

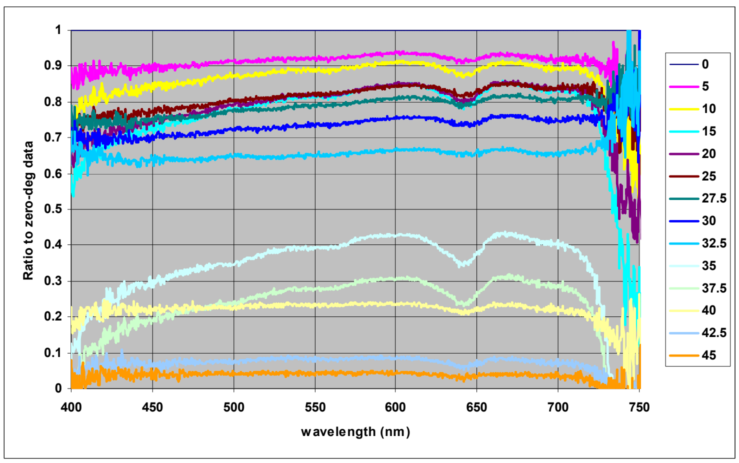


Fig. 11. Light guide transmission as a function of incident angle and wavelength

CONCLUSIONS

The 3M LF120C light guide studied has important potential as a light distribution medium for HSL applications. The preliminary value of total transmission per unit length, 96.6 % per meter, is consistent with the numbers quoted by the manufacturer, and is marginally adequate for many aspects of the prospective applications. Lengths of more than ten meters represent losses of 25% or more, thereby limiting some types of use. Investigation of other materials and types of light guide should continue, in the hope of finding guides that can transport with higher efficiency.

The absorption bands in the spectral transmission of the material may lead to the necessity for color correction in some instances. Other materials that have flatter color transmissions should be sought out and evaluated. The importance of angle of incidence on transport properties has to be taken into account with solar collectors, beam-splitters, and in laying lengths of the light guide for building applications. Continuing measurements on the 3M product, and other products as they become available, will help establish limits and types of use, and will be important in coordination with remote source and artificial lighting that is expected to be coupled with solar light in many future configurations.

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9. Photograph of light loss at the 3M light guide bend

10. Relative light transported through a 7.5-meter 3M light guide in three conditions: straight, containing one 90-degree bend, and two 90-degree bends, all as a function of incidence angle

11. Light guide transmission as a function of incident angle and wavelength